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Hydraulics of Wells

Design, Construction, Testing, and Maintenance of Water Well Systems

Task Committee on Hydraulics of Wells

Edited by

Nazeer Ahmed, Ph.D., P.E.
Stewart W. Taylor, Ph.D., P.E.
Zhuping Sheng, Ph.D., P.E.

ASCE

ENVIRONMENTAL & WATER RESOURCES INSTITUTE

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Prepared by
the Task Committee on Hydraulics of Wells of the
Groundwater Hydrology Technical Committee of the
Groundwater Council and Watershed Council of
the Environmental and Water Resources Institute of the
American Society of Civil Engineers

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MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to average engineers in their everyday work, rather than the findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however; nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

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In February 1962 (and revised in April 1982) the Board of Direction voted to establish

> a series titled "Manuals and Reports on Engineering Practice," to include the Manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such Manual or Report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past manuals. Numbering would be consecutive and would be a continuation of present manual numbers. In some cases of reports of joint committees, bypassing of journal publications may be authorized.

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CONTENTS

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CONTRIBUTORS

During the past few decades a large number of papers in the groundwater realm were presented at the annual conferences of the Hydraulics Division of the ASCE. From these presentations and resulting discussions, it became very clear that greater reliance is being placed on the extraction and utilization of groundwater resources for domestic and commercial water supplies. However, it also became apparent that there is no single document available in the market that addresses the problems facing the water well industry with regard to securing safe water supplies from groundwater resources and protection of water wells and pumping equipment. It was felt that design professionals were limited regarding reference material concerning the complete water well system design including the design of hydraulic parameters and deterioration caused by corrosion, incrustation, and poor maintenance. Also, there was a definite need for reliable information for repair and replacement of well materials and pumping equipment, as well as for testing procedures to design well discharge rates, total dynamic head, plant efficiency, and power parameters.

To achieve the desired objectives of worldwide economical supplies of groundwater, in August 1998 a Task Committee on Hydraulics of Wells of the future Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) was formed under the stewardship of the parent Groundwater Hydrology Technical Committee. The following are the members of the Control Group of the Task Committee on Hydraulics of Wells.

Nazeer Ahmed, *Chair and Secretary*
Tom W. Anderson, *Vice Chair I*

Bruce L. Jacobs, *Vice Chair II*
Otto J. Helweg, *Control Member*
Conrad G. Keyes, Jr., *Control Member*

The primary objective of the newly formed task committee was to review current published data most pertinent to water wells and deep-well turbine pumps, as well as to develop a manual describing well design, construction, testing, operation, rehabilitation, and maintenance of water wells and pumping equipment. The functionality of the manual required development of a comprehensive technical reference focusing on waters-supply wells and pumping equipment. Potential users of this manual were considered to be engineers, hydrogeologists, consulting firms, public officials, private well owners, state and federal agencies, business communities, administrators, managers, municipal personnel, and colleges and universities.

Well hydraulics is a multidisciplinary field in modern human history and, therefore, a global search was launched to solicit experts in a number of areas associated with hydraulics of wells, such as agriculture, agricultural engineering, biology, chemistry, chemical engineering, civil engineering, electrical engineering, hydrogeology, geochemistry, geophysics, geology, geological engineering, mechanical engineering, metallurgical engineering, microbiology, plant pathology, and the like. The writers, reviewers, advisors, and benefactors who volunteered to serve on the newly formed Task Committee on Hydraulics of Wells, their names along with their degrees, areas of expertise, and nationalities are given as follows.

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An original table of contents comprising 19 chapters, based on the module concept, was prepared by Nazeer Ahmed for development of the manual. As the writing progressed, individual chapters were submitted to the corresponding reviewers for their comments. Through the collective review process, it was determined that each chapter was written as a stand-alone product and that there was a lot of overlap and duplication of material. Therefore, a concerted effort was made to reorganize the table of contents as it would appear in the manual as the final printed version. The revised contents consists of eight chapters and six appendices and was prepared through mutual consultation and joint efforts of J. Paul Riley, Calvin Clyde, Dennis Williams, Nazeer Ahmed, Conrad G. Keyes Jr., Bruce Jacobs, Otto J. Helweg, Tom W. Anderson, Earl Greene, and Bangalore Lakshman. The writing and review assignments of individual authors and reviewers are given as follows.

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PREFACE

Groundwater is a vital resource in cultures and climates of all countries around the world. In the United States, for example, approximately half of the nation's drinking water supply is derived from groundwater resources. Because of its relatively high quality and dependability, groundwater frequently is used for drinking water supply, and demand is expected to rise worldwide as populations expand and technologies progress to accommodate all current and anticipated future growth.

Reasons for reliance on groundwater are many, including the ubiquity of groundwater reserves, its high quality, and the relatively low level of infrastructure required for storage and transmission. Groundwater, although reliable and readily accessed, is not free from costs and limitations, however. Aging wells and pumping equipment, as well as storage and transmission infrastructure, must be maintained to preserve the function of the well, as well as the quality of water produced. Well capacity and water quality also may be threatened by a variety of physical, chemical, biological, and environmental factors, such as pollution, overdraft, or dry periods, to name a few. Although lost capacity may be regained through renovation of equipment and well rehabilitation, sometimes it also may prove less costly and more advantageous to install new wells. Further, considering the expected energy shortages coupled with high maintenance and operational expenses, it may become prohibitively expensive to utilize this natural resource in the future. It is, therefore, necessary by all means to refine standard practices in the water well industry continually in order to improve current technology and to evolve cost-effective methodologies for the identification, development, and procurement of groundwater resources in the future.

To focus on the development and management of worldwide economical supplies of groundwater, in August 1998 the Task Committee on Hydraulics of Wells of the future Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) was assembled under the stewardship of the parent committee, the Groundwater Hydrology Technical Committee. Members of the Task Committee on the Hydraulics of Wells have contributed their expertise in various aspects of the water well industry to produce this international manual on hydraulics of wells. Also, it may be reiterated here that this manual was originally initiated, reviewed, and approved under the auspices of the then Watershed Council in charge. However, at a later date, it also was resubmitted for a fresher look and second review to the newly formed Groundwater Council. Additionally, all their review comments have been incorporated into the manual, and finally, it was approved by the Groundwater Council as well.

From the detailed contents of the manual, it is apparent that a large number of individuals have worked hard on its development and have provided useful technical information for the design professionals, state and federal executives, field supervisors, office managers, and private and corporate owners in the water well industry for public and private use and consumption. On behalf of EWRI–ASCE, I would like to thank all the authors, reviewers, advisors, Blue Ribbon Committee members, Watershed Council members, Groundwater Council members, ASCE Publications Committee members, EWRI Technical Executive Committee members, EWRI/ASCE editorial and technical staff members, and other private advisors, benefactors, and patrons for their enthusiasm, hard work, and professional contributions. They are the ones who have made the publication of this manual possible with their ingenuity, talents, sacrifices, experience, technical know-how, dedication, patience, perseverance, and kindness. Personally and professionally I am greatly indebted to all of them.

For future developments and improvements of the manual, please send your comments, recommendations, and published references to the Chair of the Task Committee on the Hydraulics of Wells. Thank you very kindly for your continued support and interest, as well as for all your selfless and zealous efforts.

Nazeer Ahmed, *Editor*
Las Vegas, Nevada

INTRODUCTION

The scope of *Hydraulics of Wells* was designed in a manner so as to familiarize the reader with the subject matter of hydraulics of wells as related to the production of groundwater for multipurpose usages. The potential topics, which were considered useful and pertinent to the water well industry for public and private consumers, were researched thoroughly and included in the text material. The following sections summarize the technical material presented in the manual through eight chapters and six appendices.

Chapter 1 provides basic information on groundwater as related to the hydrologic cycle, physical character of porous media, aquifer systems, ability of aquifer to store water, the Darcy equation (as applicable to flow in porous media), three-dimensional groundwater flow, anisotropy, groundwater flow equations, initial and boundary conditions, confined and semiconfined aquifers, and unconfined aquifers. Solved design examples demonstrate the fundamental concepts of flow in porous media.

Chapter 2, in general, outlines the determination process of total dynamic head consisting of different components of head loss, plus the static head as the groundwater flows from the outer limits of the cone of depression to the extraction well and the pumping equipment, which, in turn, moves the pumped groundwater to its final destination. The head loss components are studied thoroughly pertaining to the aquifer formation, damage zone, filter pack, well screen, wellbore, well casing, and suction and delivery pipes. The difference in the static water level and the pumping water level is designated as the total drawdown in the well. From a practical point of view, the design concept of total dynamic head is detailed for three different, real life situations: the groundwater discharge into the free atmosphere, service main, and overhead tank. To develop the total dynamic head in a pumping-plant configuration, the application of two independent, physical means of power supply—the electric motor and the internal combustion engine—is presented. This chapter, however, also describes three different types of pumping plant efficiency terms based on the concept of head loss, static head, well discharge, and power supply requirements as well efficiency at the level of total drawdown, wire-to-water efficiency at the level of electric motor, and the overall efficiency at the level of internal combustion engine. Solved design examples are provided to illustrate the application of the head losses, total drawdown, total dynamic head, and different efficiency terms.

Chapter 3 is devoted to the design considerations of water wells and pumping equipment on the basis of a number of criteria derived from different disciplines, such as flow in porous media, hydraulics, and economics. Design of boreholes, casing and screen pipes, filter packs, formation stabilizers, and the pumping units are described in detail. A number of flow equations and general information are provided to determine the dimensions of water wells and pumping equipment parameters. Because emphasis is placed on the economic considerations in the designing process, various cost-effective analyses are conducted, and actual test results are used for the determination of optimum well discharge and the selection of economical sizes of water wells and pumping equipment. Solved design examples are presented to explain various designing processes for water wells.

Chapter 4 deals with the well construction methods, installation of pumping equipment, well development, and testing for design of optimum discharge rate and pump settings. Specifically, it deals with the potential site assessment for a water well and commonly used drilling methods, such as the cable tool, direct circulation rotary drillings, and reverse circulation rotary drillings. The chapter describes a number of borehole logs as geophysical borehole logs, single-point resistivity logs, normal resistivity logs, guard resistivity (laterologs), spontaneous potential logs, acoustic/sonic logs, natural gamma logs, induction logs, and caliper logs. Isolated aquifer zone testing, water quality, and yield are described as well. The chapter also discusses destruction of old wells, placement of sealing materials, mechanical grading analyses, and lithologic description of formation materials. Installation of casing, screen, and filter pack; gravel feed pipes; sounding tubes; camera access tubes; centralizer installation; tremie pipes; compression sections; di-electric coupling sections; and interaquifer seals are portrayed in detail. Utilizing a number of techniques, principles of well development for artificially filter-packed and naturally developed wells are explained. Well and aquifer pumping tests are described utilizing the step-drawdown and constant-rate pumping techniques along with methods for analysis of pumping test data and collection of water quality samples. Finally, flowmeter and video surveys, plumbness and alignment surveys, and well disinfection are presented. For the benefit of the design professional, several field testing depictions of water wells are described. And, of course, a report summarizing the construction, development, and testing procedures of water wells then is required to be completed.

Chapter 5 describes the corrosion of pumping equipment and water well materials. It begins with a simple theory of corrosion by outlining the descriptions of electrode reactions, anode, cathode, passivity, and polarization. It presents a basic introduction of types of corrosion including electrochemical, microbial, galvanic, mechanical erosion, stray current, and crevice corrosions. Further, corrosive properties of water are explained in terms of dissolved ions, oxygen content, carbon dioxide, hydrogen sulphide, water discharge, pH, temperature, and scale deposits. Corrosion of well casings and screens is expanded by defining and describing different well zones with specific characteristics contributing to potential corrosion, such as external casing zone, atmospheric zone, splash zone, and submerged casing zone. In addition, the chapter provides detailed discussion of corrosion on pumping equipment, specifically by explaining the material selection, sand and gas contents, surface of pump impellers, cavitation, and general wear and tear on pumping equipment. To aid in the design of pumping equipment, prediction of corrosion rates are given in terms of scaling indexes, such as the Langelier Saturation Index and the Ryznar Stability Index. It is recommended that information on corrosion rate data be collected through laboratory, field, and service tests, as well as through electrochemical measurements, ASTM standards, and Internet resources. Evaluation of corrosion rate data can be computed in terms of weight loss and the length of time-exposure period. Corrosion protective measures include well screen placement and casing and well screen material selection. Protective measures are summarized, including materials, operation, protective coating, cathodic protection, and troubleshooting techniques for corrosion prevention. Finally, an example is presented based on field tests to determine the corrosion potential of various water well casing and screen materials. Analysis of corrosion rates and well life are analyzed for various materials.

Chapter 6 provides the fundamental definition of the theory of incrustation. It describes the chemical and bacterial analyses of groundwater responsible for causing the incrustation of pumping equipment and water well components, such as well screens. It describes the forms of incrustation and cites that water quality, dissolved solids, and the bacterial presence in water are main causes for the development and growth of incrustation. Also, it elaborates the effects of temperature, pressure, velocity changes, and thermodynamics of groundwater on the buildup of incrustation in the water-well systems. It enumerates forms of incrustation as chemical, physical, and biological. It elaborates chemical incrustation in the form of carbonate deposits, calcium sulfate, and metal oxides, such as iron oxide. Physical and biological incrustations and the character of iron oxide deposits are explained thoroughly. It emphasizes the field-testing of incrustation and critically reviews the timely maintenance of pumping equipment and components of water wells as a significant measure to arrest the further increase of incrustation. In addition, it narrates the methodologies of acid treatment, chlorine treatment, and polyphosphate treatment for incrustation and the extent of their benefits and advantages. Further, the concepts of chemical and bacterial incrustations are elaborated through two solved design examples.

Chapter 7 describes the wellhead protection concepts and EPA guidelines pertaining to the protection and quality control of groundwater for public consumption. It provides information about the fundamentals of groundwater flow, contaminant transport, wellhead delineation methods for the wellhead protection area including the arbitrary fixed radius, calculated fixed radius, standardized variable shapes, analytical methods, hydrogeologic mapping, and numerical flow and transport models. It provides a case study for a well site supported with numerical data for the protection of wellhead area comprising the wellhead delineation technique, hydrologic models, and vertical contaminant transport concepts. Further, it details a comparison between the wellhead protection area (WHPA) model and the analytical method. For this case study, after the field assessment is carried out, an actual contaminant inventory from the collected field data is compiled. This information then is used to implement and enforce the necessary precautions in the field to delineate the WHPA as mandated by U.S. EPA regulations to safeguard the groundwater resources. Solved design examples and other material presented illustrate the procedures for the determination of the wellhead protection areas.

Chapter 8 is devoted to the maintenance of operating water wells. It emphasizes the understanding of the usage of corrosion and incrustation preventive materials, design, and rehabilitation treatment choices to avoid well performance degradation and failure modes that may result during operation of water wells. In particular, it describes the prevention of corrosion, incrustation, and well fouling, as well as provides information for well cleaning chemicals, their handling, and safety features. Also discussed are preventive maintenance well treatment, well monitoring methods, records of well performance and well-component materials, troubleshooting guidance, and well maintenance schedules. It also details the importance of record keeping and computer software for preventive maintenance monitoring. It provides information about the economics of well maintenance, field and laboratory research on well maintenance, and emphasizes the importance of well maintenance through two solved design examples.

Several appendixes have been added as additional aids to the technical text material of the manual to advance the reader's understanding and to illuminate further the scientific and engineering field applications.

Appendix A offers an example of a complete water well system design that explains in detail the required information about well site investigations and sources of required data; geologic setting for drilling equipment; existence, quality, and availability of groundwater for its commercial exploitation; contamination potential, and remedial measures; compliance of groundwater laws and regulations; well construction, geologic logging, and aquifer zone testing; well design, filter pack design, and slot size selection procedure; pumping tests, optimal discharge, video survey, plumbness and alignment of wells; and rehabilitation, operation, and maintenance of water wells.

Appendix B provides detailed information about technical specifications for location, depth of well and other dimensions; hydrogeology, permits, certification, laws and ordinances; drilling methods and equipment; constructing and testing of water wells; geophysical borehole logs, yield, and water quality; design of casing, screen, and filter pack; casing and screen installation and alignment; development of the water well; well testing for yield and drawdown; step-drawdown test and constant rate pumping test; spinner and video surveys; well disinfection; well completion report; and bidding schedule.

Appendix C presents definitions and numerical data for the convenience of design computations, as well as testing, rehabilitation, maintenance, and operational procedures for water wells.

Appendix D includes a glossary with explanations of important terms used in the area of hydraulics of wells.

Appendix E lists SI unit prefixes, and Appendix F provides a conversion table for SI and U.S. customary unit systems, and numerical values of useful constants to help determine the solutions of practical design problems.

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CHAPTER 1

FUNDAMENTAL CONCEPTS OF GROUNDWATER FLOW

Bruce L. Jacobs

1.1 GENERAL

Groundwater is a valuable source of water because of its high quality, availability, and the minimal requirements for storage and transmission infrastructure. Today, in the United States, for example, approximately half of the nation's drinking water supply is derived from groundwater. Globally speaking, groundwater use is likely to increase in the future as groundwater is utilized at an increasing rate to serve rapidly expanding, worldwide suburban and exurban populations. Groundwater generally is a reliable, high-quality resource, but as with any natural resource, care must be taken to prevent pollution while at the same time maintaining the aging infrastructure. Well production may be limited by the aquifer yield and contamination, as well as environmental, economic, legal, and political factors. In addition, normal wear and tear of equipment, defects in manufacturing, material fabrications, and chemical and biological factors all tend to reduce well efficiency over time.

This first chapter introduces the fundamental concepts of groundwater flow needed to support the more focused chapters in the remainder of this Manual of Practice. The intent is to introduce basic principles and concepts with enough mathematical background to serve the reader in understanding the complex mathematical aspects of well hydraulics. The discipline of well hydraulics is by convention the mathematical analysis of flow in aquifers and water wells. The findings of this branch of well hydraulics have transformed the profession, providing a scientific basis for quantitative analysis and prediction of the behavior of aquifers and water wells subject to future stresses. A more expansive use of the term *well hydraulics* is used in this text to include both the far-field description of flow to a well, as well as the near-field flow, through the gravel pack and well screens. The text integrates the discussion of aquifer–well hydraulics with discussions of well design, and maintenance and rehabilitation.

Also, this chapter presents a broad summary of topics covered in greater detail in common textbooks and references that have educated the profession. Of necessity, many of the discussions herein are borrowed—consciously and unconsciously—from these other sources, including *Hydraulics of Groundwater* (Bear 1979), *Groundwater* (Freeze and Cherry 1979), *Basic Ground-Water Hydrology* (Heath 1983), and *Quantitative Hydrogeology* (de Marsily 1986). Another useful introductory text on groundwater flow is *Groundwater Hydraulics and Pollutant Transport* (Charbeneau 2000). In this chapter, equation numbers from Charbeneau's reference are provided for the convenience of the reader.

1.2 HYDROLOGIC CYCLE

Groundwater is a component of the hydrologic cycle mediating the circulation of water between the atmosphere and the land surface. A schematic representation of principal components of the hydrologic cycle is shown in Fig. 1-1. Water vapor in clouds condenses to form precipitation that falls on both water bodies and land areas. Near-surface permeability and moisture conditions will determine whether water that falls on the

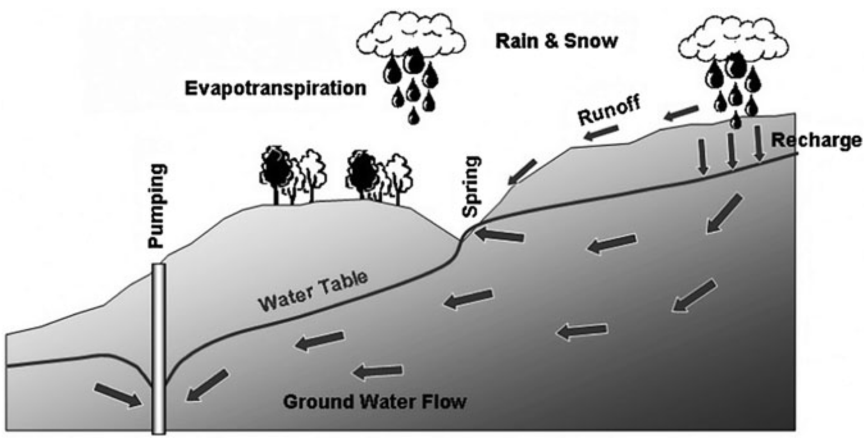

Fig. 1-1. A schematic representation of principal components of the hydrologic cycle
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

land surface will infiltrate into the ground or discharge as overland flow into streams and oceans. Some portion of rainfall will infiltrate downward through the vadose zone, eventually recharging aquifers. Groundwater flow is principally horizontal, with discharge occurring into down-gradient surface water bodies. Evaporation from moist land surfaces, vegetation, and surface water bodies completes the hydrologic cycle.

The volume of fresh water stored in aquifers greatly exceeds the volume of fresh water stored as surface water (Lvovitch 1973). Global groundwater storage, if spread evenly over the land surface, would reach a depth of approximately 47 m, whereas fresh water in lakes and reservoirs, if spread over the same land surface area, would amount to a depth of only 1 m. The large groundwater volume and its relatively slow velocity are reflected in long groundwater detention times relative to surface water bodies. Based on estimated volumes and flow rates, the average global groundwater residence time is 500 years compared to a surface water residence time of only 5 years.

The direction of groundwater flow generally follows descending surface topography and surface water flow. Groundwater typically recharges in upland regions and discharges into streams and other water bodies in low-lying portions of the watershed. On the basis of mass balance considerations, the vertical component of flow is downward in recharge areas and upward in regions discharging to surface waters. Consequently, upland regions contribute infiltrating flows to the deepest portions of the aquifer. This also affects the residence time of flowing groundwater such that groundwater originating as recharge in upland portions of the aquifer has significantly longer subsurface residence times.

During and immediately after large storms, streams receive surface runoff; however, these direct overland inflows dissipate quickly following the end of the storm. In temperate climates, streams continue to flow between rainstorms because of groundwater discharges that continue over far longer time scales than the surface runoff.

Typically, streams lose water to groundwater in upstream portions of a watershed and gain water from aquifers farther downstream. Seasonal fluctuations in surface water elevation may cause transient changes in the relation between groundwater and surface water. Temporarily elevated surface water elevations, for instance, may cause a stream or certain reaches of a stream to lose water to aquifers, whereas in other times of the year the stream is gaining.

1.3 POROUS MEDIA

Porous media are any number of solid substances that contain pores. In the context of this chapter the porous media of interest are unconsolidated deposits, consisting of mixtures of clay, silt, sand, and gravel. Although most of the topics covered in this manual may be applied (with caution) to wells completed in consolidated rock aquifers (e.g., limestone, sandstone, or basalt), the emphasis of the manual is with respect to wells completed in materials having primary porosity (e.g., sand and gravel). Fractures, fissures, and cavernous features associated with consolidated rocks are termed as *secondary porosity*.

Therefore, for purposes of this manual, the term porous media is used to denote groundwater flow through primary pore spaces (i.e., interstices) between individual grains.

A medium's total porosity, n, is defined as the fraction of the media volume occupied by pores (Charbeneau 2000, Eq. [1.3.1]):

$$n = \frac{V_p}{V_t} \tag{1-1}$$

where

n = total porosity, (dimensionless)
V_p = pore volume, (m^3)
V_t = total volume, (m^3).

A total porosity of 0.3, for instance, indicates that 30% of the medium by volume is occupied by pores.

Some portion of the total porosity consists of disconnected pore volumes or dead end pores. The interconnected, continuous pore space available for flow is somewhat less than the total porosity and is known commonly as the *effective porosity*. It is generally represented by the symbol, θ. The reader should be warned that the effective porosity sometimes is equated incorrectly to the specific yield, which is that portion of the total porosity that drains under gravity in an unconfined aquifer.

Fig. 1-2 shows a three-dimensional, X-ray image of the pore structure of a sample of sandstone. As is apparent from inspection of this figure, the pore volume is highly complex, with water pathways following a tortuous path through the media. While remaining aware of the presence of the small-scale pore space complexities and tortuous flow paths, the engineering applications discussed here are relevant at soil volumes averaged over many pores. The measurement of porosity—and most other properties of porous media—requires averaging over a finite representative elementary volume (REV) that encompasses multiple pores.

The porosity of unconsolidated deposits is largely a function of grain size uniformity. Porosity generally is lower in deposits with a range of grain sizes, because the small grains fill the intergranular spaces formed between the larger grains. The electrostatic charge on some clay minerals also may reduce the packing efficiency and increase porosity. Porosity is

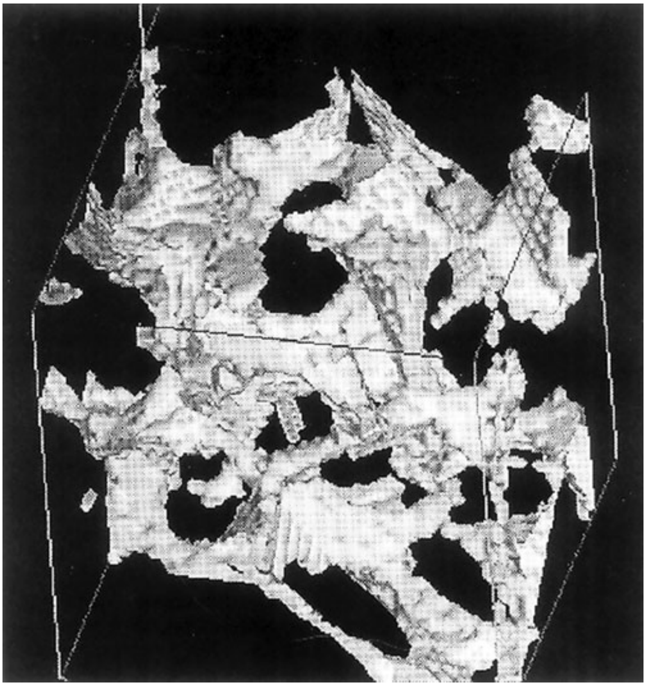

Fig. 1-2. A three-dimensional image of sandstone pore-structure
Source: Ferreol and Rothman (1995); reproduced with permission from Springer Science and Business Media

not a direct function of the diameter of the particles grains. Consider, for instance, the rectangular packing of spherical grains as shown in Fig. 1-3. The porosity of this type of "deposit" is 0.48 regardless of whether the grain diameters are 1 μm or 1 mm.

1.4 AQUIFER SYSTEMS

Aquifers are bodies of consolidated or unconsolidated deposits that store and transmit water in usable quantities. From a practical standpoint, aquifers are underground deposits with sufficient transmissivity and volume to serve as a water source for residential, commercial, or industrial purposes. Principally aquifers are found in one of the four categories of geological formations:

1. Unconsolidated sand and gravels,
2. Permeable sedimentary rocks (sandstones),

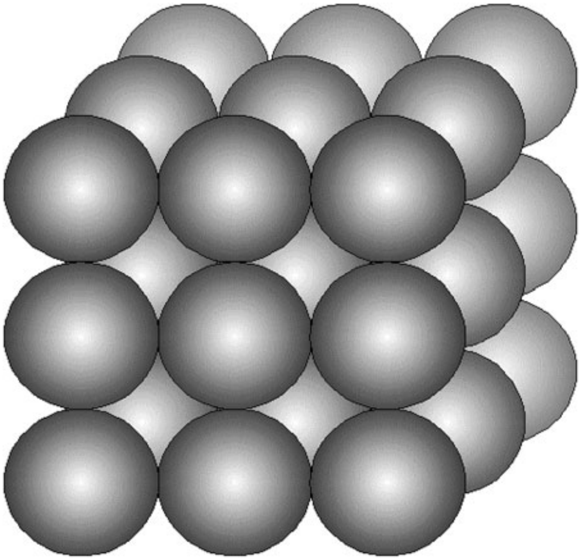

Fig. 1-3. Rectangular packing of spherical grains

3. Carbonate rocks (limestone and dolomite), or
4. Igneous rocks (heavily fractured volcanic and crystalline rocks).

The most productive aquifers are found in unconsolidated deposits generated in fluvial or glacial settings. Lacustrine deposits generally are finer grained and have relatively low hydraulic conductivity, limiting their viability as water sources. Aquifers also may be found and utilized in weathered or fractured bedrock, where water is conducted within the secondary porosity that is generated after the original formation of the rock. Clayey fine-grained soils generally have very low hydraulic conductivities; however, they are able to store water and release it slowly because of their relatively high porosities.

Aquitards are formations that have relatively low permeabilities but that are still capable of storing water. Frequently, aquitards consist of fine-grained soils, such as silt or sandy clay. Aquicludes are similar in nature to aquitards but with even lower permeabilities such that flow through aquicludes generally can be assumed to be negligible. Aquifuges—generally made up of solid rock—do not contain any interconnected pore space and thus are impermeable to flow. See Figs. 1-4 and 1-5.

Aquifers may be identified as confined, unconfined, or semiconfined, depending on the nature of their upper surface or boundaries. The three basic aquifer types are shown schematically in Fig. 1-6. Aquifers that are

Fig. 1-4. Aquifer, aquitard, aquiclude, and aquifuge
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

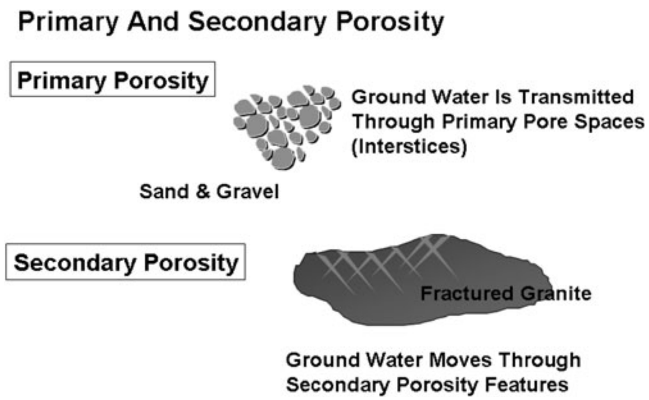

Fig. 1-5. Primary and secondary porosities
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

bounded from above and below by an aquifuge or aquiclude are referred to as confined aquifers. Typically, the upper confining layer contains clay or other fine-grained deposits. By definition, in a confined aquifer, the elevation of the hydraulic head exceeds the top of the aquifer (Fig. 1-7). In an artesian aquifer, the hydraulic head exceeds the elevation of the ground surface. The water level elevation recorded in a piezometer penetrating a confined aquifer defines the *piezometric* or *potentiometric surface*.

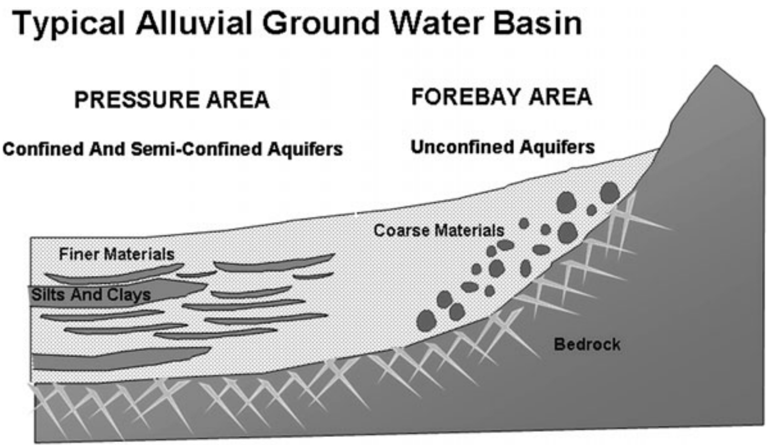

Fig. 1-6. A typical alluvial groundwater basin
Source: Courtesy of Dennis E. Williams, Geocience Support Services, Inc., Claremont, CA

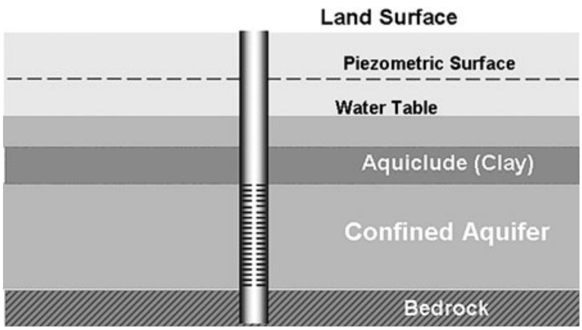

Fig. 1-7. A typical confined aquifer
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

In an artesian aquifer where the piezometric surface exceeds the land surface, *flowing wells* may result.

Unconfined or phreatic aquifers have an upper surface, known as the *water table* or *phreatic surface*, which is at atmospheric pressure (Fig. 1-8). Immediately above the water table of an unconfined aquifer the porous media remains saturated due to capillary action, but the water pressure is less than the ambient air pressure. Above the capillary fringe, the pores are saturated only partially, with decreasing saturation with distance above the water table. The region above the capillary fringe is referred to

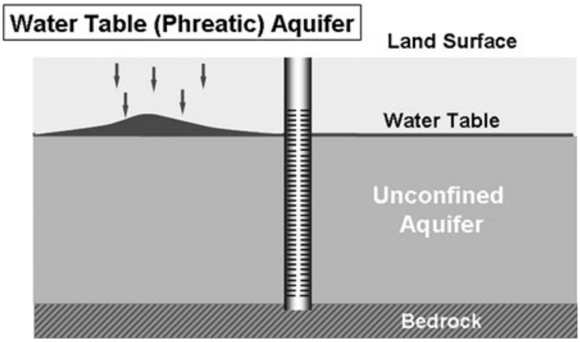

Fig. 1-8. A water table (phreatic) aquifer
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

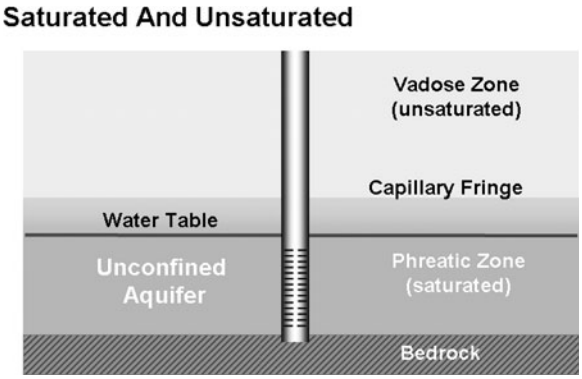

Fig. 1-9. Saturated and unsaturated aquifers
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

as the *vadose* or *unsaturated zone* (Fig. 1-9). The water is retained within the pores by the capillary forces exerted within the small-radii pore throats despite the fact that the gravitational forces would tend to drain the aquifer. A special case of an unconfined aquifer lying above the main water table (i.e., in the vadose zone) is shown by the *perched* aquifer in Fig. 1-10.

Semiconfined or leaky aquifers result when the upper or lower confining layer is sufficiently permeable to allow flow of water between it and overlying or underlying aquifers. In Figs. 1-11 and 1-12, water is depicted leaking out of and back into a semiconfined aquifer. Flow among aquifers occurs when the piezometric head in one unit is either higher or lower

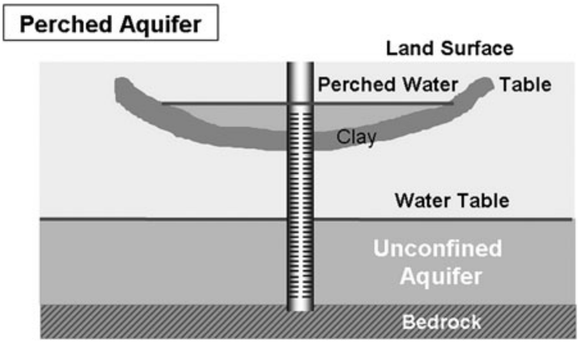

Fig. 1-10. A perched aquifer
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

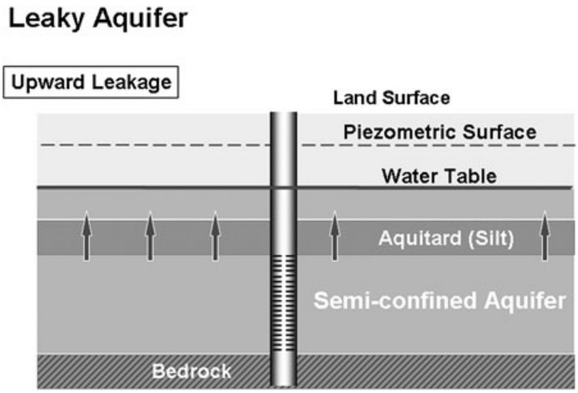

Fig. 1-11. A leaky aquifer with upward leakage
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

than the head in an adjacent unit. This interaquifer flow, or leakage, may represent a significant portion of aquifer recharge or loss. Leakage is usually a transient phenomenon, as in the case of leakage induced by pumping or natural fluctuations in recharge. In Fig. 1-11, the head in the upper unit has been reduced by pumping, as reflected by the depression in the water table. The hydraulic head measured in the water table aquifer, therefore, is lower than the head in the lower unit inducing upward leakage through the aquitard. In Fig. 1-12, the reverse occurs. Water levels in the deeper aquifer are less than in the shallow zone, inducing downward leakage. Long-term leakage also may occur as part of the natural flow pattern where unconfined aquifers receive recharge, leak to the

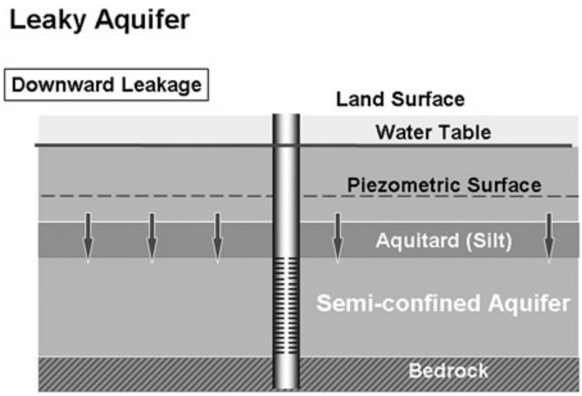

Fig. 1-12. A leaky aquifer with downward leakage
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

underlying semiconfined unit, and then receive water back from the semiconfined aquifer in low-lying areas.

Assuming vertical flow among units and relatively small changes in aquitard water storage, the leakage may be approximated using a modified form of the Darcy equation:

$$q = -K' \frac{\Delta h}{b'} \tag{1-2}$$

where

q = Darcy velocity, bulk velocity, or specific discharge through the aquitard, (m/s)
K' = hydraulic conductivity of the aquitard, (m/s)
Δh = head differential between confined and unconfined aquifers, (m)
b' = thickness of aquitard, (m)
$\frac{K'}{b'}$ = Leakance, (1/s).

Fig. 1-13 gives a simple example of quantifying leakage.

1.5 AQUIFER STORAGE

Moisture content is defined as the liquid volume within a porous medium per unit volume of the medium. For a fully saturated porous medium, where the pores are filled completely with water, the moisture content is equivalent in magnitude to the porosity.

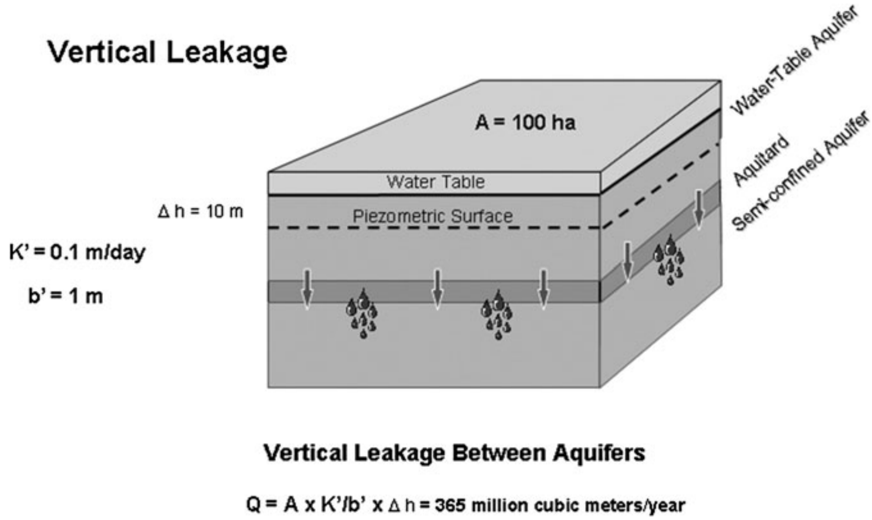

Fig. 1-13. A vertical leakage configuration
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

In principle, there are two mechanisms by which the water volume in storage in a porous medium may change. Both of these are responses of the aquifer to changes in hydraulic head. The first mechanism, which occurs in unconfined aquifers, is by simple gravity drainage of water from the pore volume. This might occur in the drainage of water near the upper surface of an unconfined aquifer in response to nearby pumping. The second mechanism, which occurs in confined and semiconfined aquifers, is a reduction in hydraulic head, which leads to expansion of the water and compaction of the aquifer. As might be anticipated, relatively small amounts of water typically are derived from this second process.

Capillary forces tend to retain water in small pore spaces, resulting in the sequential drainage of the largest pores followed by the smaller pores. These same capillary forces and the presence of isolated pores cause some portion of water to be retained within the media after gravity drainage is complete. Fig. 1-14 shows a portion of the aquifer that has been drained by gravity because of a change in the elevation of the water table of Δh = 10 m. The ratio of the water volume that drains under gravity, V_w, to the total dewatered volume, V_t, is referred to as the specific yield, S_y (Charbeneau 2000, Eq. [2.3.2]):

$$S_y = \frac{V_w}{V_t} = \frac{V_w}{A \times \Delta h} \tag{1-3}$$

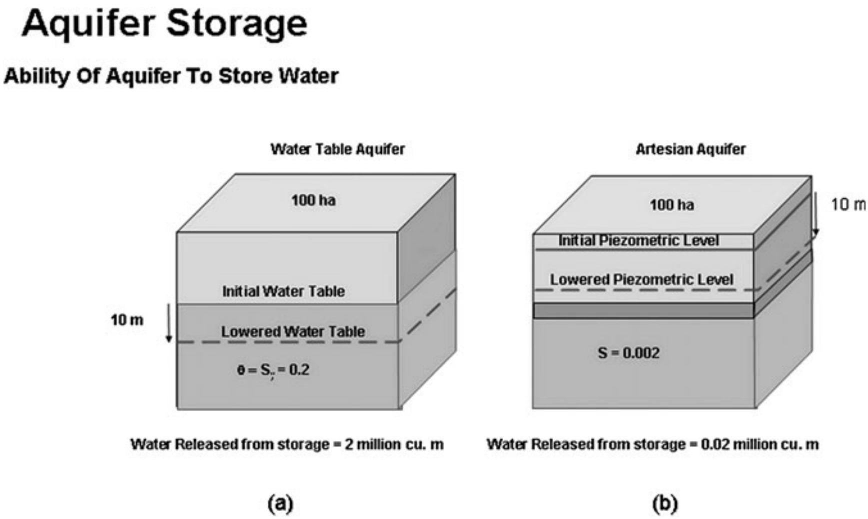

Fig. 1-14. Aquifer storage: (a) water table or phreatic aquifer; (b) artesian aquifer
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

where

S_y = specific yield, (dimensionless)
V_w = volume of water drained by gravity from the media, (m^3)
V_t = total volume, (m^3)
A = cross-sectional area of the porous media sample, (m^2)
Δh = drop in the water elevation level in the sample media due to drainage under gravity, (m).

The specific yield is often referred to as the "drainable porosity," because it is the portion that is able to drain under gravity. Because the total volume of water per unit volume of a saturated media is the total porosity, n, the porosity is a physical upper bound to the magnitude of specific yield in any media sample (i.e., $S_y \leq n$).

Fine-grained soils tend to retain more water and thus have lower specific yields than coarse-grained soils. Table 1-1 shows typical values of total porosity and specific yield for various aquifer materials.

In confined and semiconfined aquifers, lesser water volumes may be derived from storage without drainage of the pore volumes by the reduction of the pore water pressure and the resultant compaction of the aquifer matrix. Even though the water pressure is reduced, the buried soil volume

Table 1-1. Typical Specific Yield and Total Porosity Values for Unconsolidated Materials

Material	Total Porosity, n (dimensionless)	Specific Yield, S_y (dimensionless)
Gravel	0.25–0.40	0.15–0.30
Sand and Gravel	0.1–0.35	0.15–0.25
Sand	0.25–0.40	0.10–0.30
Silt	0.35–0.50	
Clay	0.45–0.55	0.01–0.10

Source: American Society of Civil Engineers (1996)

still must bear the unchanged overlying load imposed by the soil column. This results in a shift of the burden carried by the water to the soil matrix. In the case of an unconsolidated media, this results in an increase in the intergranular stress—the compressive forces at the point of contact between grains. Most frequently, the grains themselves are assumed to be incompressible, so reductions in pore volume occur through the rearrangement of the matrix grains in response to increases in intergranular stress. Generally this is considered to be a reversible process in that later increases in pore water pressure can cause a return to the original pore volume. A secondary effect of the reduction of water pressure is the expansion of water and the consequent reduction of water mass within a given pore volume, akin to removing water by suction from a sealed volume of saturated porous media. In summary, confined and semiconfined aquifer systems are elastic. Fig. 1-14(b) illustrates release of storage from a confined aquifer.

Specific storage, S_s, is defined as the volume of water removed per unit volume of porous media per unit change in hydraulic head. That is

$$S_s = \frac{S}{b} = \frac{\Delta V_w}{\Delta h V_B} = \gamma\beta\theta - \gamma\sigma \tag{1-4}$$

where

S_s = specific storage, (1/m)
S = aquifer storativity or storage coefficient, (dimensionless), defined as the volume of water that a permeable unit will expel from storage per unit surface area per unit change in hydraulic head.
b = saturated aquifer thickness, (m)
ΔV_w = change in the volume of water, (m^3)

Δh = change in the hydraulic head, (m)
V_B = bulk volume of porous medium, (m^3)
γ = specific weight of water, (N/m^3)
β = compressibility of water, (m^2/N)
θ = effective porosity, (dimensionless)
σ = compressibility of aquifer skeleton, (m^2/N).

Porous media with high specific storage values, due to high matrix compressibility, provide more water for a given reduction in the hydraulic head. Specific storage values range between $10^{-2}\,m^{-1}$ for highly compressible clays to $10^{-7}\,m^{-1}$ for low porosity rock (deMarsily 1986). The term $\gamma\beta\theta$ represents the amount of water released from aquifer storage because of expansion of the water itself. The term $\gamma\sigma$ represents the amount released owing to aquifer compression.

1.6 DARCY EQUATION

The first quantitative expression of groundwater flow through porous media is commonly attributed to the nineteenth century French engineer Henri Darcy. The apparatus shown in Fig. 1-15 depicts a simple experiment of flow through a vertical column filled with sand. This is essentially the same type of apparatus used by Darcy in his original experiments on filter sands in Dijon, France, in 1856. The reservoirs on the right control the hydraulic head at the top and the bottom of the sand column. The free surface elevation in the two manometers at the left is a direct measure of the hydraulic head in the sand column. The total vertical flow through the column, Q, is given by the product of the Darcy velocity or specific discharge, q, and the media's bulk cross-sectional area, A.

Darcy observed that the flow per unit area through a porous medium is proportional to the rate of decrease in hydraulic head. The constant of proportionality between the flow per unit area and the rate of hydraulic head decrease is called the hydraulic conductivity, K. Specifically, Darcy found through empirical observations that for one-dimensional flow in his apparatus (Charbeneau 2000, Eqs. [2.2.1]; [2.2.4]):

$$q = -K\frac{\Delta h}{\Delta x} \tag{1-5}$$

$$h = z + \frac{p}{\rho g} \tag{1-6}$$

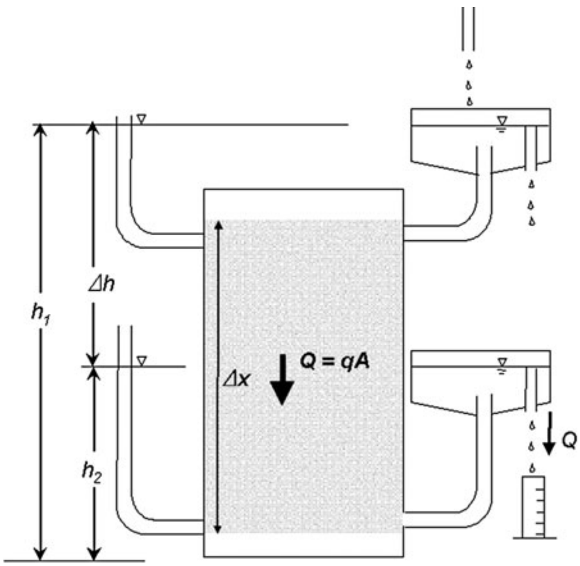

Fig. 1-15. A laboratory permeameter arrangement to measure hydraulic conductivity

where

q = specific discharge computed as water flow per unit bulk area, (m/s)
K = hydraulic conductivity, (m/s)
h = hydraulic head or piezometric head, (m)
z = elevation head above an arbitrary datum, (m)
p = water pressure, (kPa)
ρ = water density, (kg/m^3)
$\frac{\Delta h}{\Delta x}$ = rate of change of hydraulic head, (m/m)
g = gravitational acceleration, (9.81 m/s^2).

For one-dimensional flow, Eq. (1-5) is known as the Darcy equation and also more appropriately as the Darcy's Law. In this case, because the manometer penetrating the top of the soil column has a higher water elevation, h_1, than the bottom manometer, h_2, the flow is downward at a rate proportional to the hydraulic head or the piezometric head difference, Δh. The concept of hydraulic head is shown in Fig. 1-16.

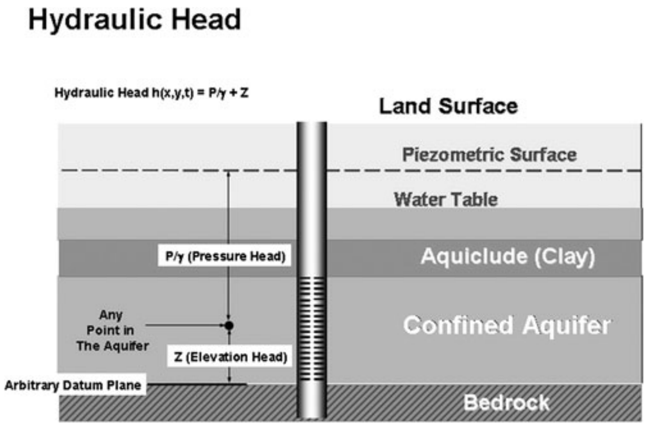

Fig. 1-16. Hydraulic head in porous media flow
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

The rate of change of hydraulic head, $\frac{\Delta h}{\Delta x}$, or its differential equivalent the hydraulic gradient, $\frac{dh}{dx}$, is a measure of the rate of energy loss of water as it passes through the soil. That energy loss occurs principally through the frictional forces resisting flow at the interface of the porous media grain surfaces and the flowing water. Not surprisingly, then, as the ratio of the grain-surface area to unit media volume increases, the resistance to flow also increases, resulting in a decrease in the hydraulic conductivity. Considering the grains as rectangular-packed spheres, such as shown in Fig. 1-3, the ratio of surface area to media volume decreases as one over the grain radius. This leads to an intuitively satisfactory result that the resistance to flow in coarse-grained soils is less than in fine-grained soils.

Hydrologists typically classify unconsolidated deposits based on their grain size. Table 1-2 shows the grain size classification adopted by the American Society for Testing and Materials (ASTM 2011).

It would be unusual to find natural deposits that are not mixtures of grains of varying size. The uniformity of the deposit grain size is largely a function of the sorting capacity of the depositional process. Typical hydraulic conductivities are reported for various unconsolidated aquifer materials in Table 1-3. These values reflect a trend of decreasing hydraulic conductivity with reduced grain size. The range of hydraulic conductivities within any single soil type still varies over several orders of magnitude.

Table 1-2. Grain Size Classification for Unconsolidated Deposits

Porous Material	Grain Size (mm)
Boulder	>305
Cobbles	76–305
Coarse gravel	19–76
Fine gravel	4.75–19
Coarse sand	2–4.75
Medium sand	0.42–2
Fine Sand	0.075–0.42
Silt or clay	<0.075

Source: Data from American Society for Testing Materials (2000)

Table 1-3. Typical Hydraulic Conductivity Values for Unconsolidated Deposits

Porous Material	Hydraulic Conductivity, K (m/day)
Gravel (fine to coarse)	450-150
Sand (fine to coarse)	2.5–45
Silt or loess	0.08
Clay	0.0002

Source: Todd and Mays (2004). Reproduced with permisison from Wiley

A crude mathematical model of flow through porous media may be constructed by considering the media to behave as slow, steady, horizontal flow through a network of parallel tubes. By integration of the Navier-Stokes equation along the length of the tube, the specific discharge, q, of this ideal media would be (Bear 1972, Eq. [5.10.2])

$$q = -\left(\frac{Nd^2\rho g}{32\mu}\right)\frac{\Delta h}{\Delta x} \tag{1-7}$$

where

q = bulk velocity of equivalent media, (m/s)
N = number of parallel tubes in the network per unit area, (dimensionless)
d = tube diameter, (m)
ρ = density of water, (kg/m^3)

g = gravitational acceleration, (m/s^2)
Δh = finite differential of hydraulic head, (m)
μ = dynamic viscosity of water, (Pa s)
Δx = finite length of network of parallel tubes, (m).

This produces a relationship not unlike Darcy's empirical observation that flow is proportional to the hydraulic gradient. In this case, the constant of proportionality between the head gradient and the specific discharge is shown to be related to the square of the pore throat diameter and inversely proportional to the fluid viscosity.

The result obtained for the idealized media of parallel tubes suggests that the hydraulic conductivity is the product of a term collectively representing the soil's resistance to flow (k in Eq. [1-8] following) and a separate collection of terms connected to the properties of the flowing fluid (Charbeneau 2000, Eq. [2.1.11]).

$$K = \frac{k\rho g}{\mu} \tag{1-8}$$

where

K = hydraulic conductivity, (m/s)
k = intrinsic permeability, (m^2).

Estimates of hydraulic conductivity made for one fluid may be generalized by calculation of the media's intrinsic permeability based on the unit weight and viscosity of the fluid. Henceforth, using the media's intrinsic permeability, the hydraulic conductivity may be estimated for any alternate fluid in the same media.

Considering Eqs. (1-7) and (1-8), it is easily seen that the intrinsic permeability, k, of the parallel tube model is given by $Nd^2/32$. On the basis of this analysis, it is apparent, intuitively, that the hydraulic conductivity is a function of both the effective porosity and the grain size. Natural soils are, of course, not a bundle of parallel tubes. Besides effective porosity, the hydraulic conductivity of natural soils also is affected by other geometric properties of the porous medium, for example, its tortuosity representing the character of winding flow paths, grain shapes, grain orientations, angularity of grains, packing of grains, and level of interconnectivity of pore structures.

As noted, the Darcy equation, Eq. (1.5), is consistent with a model of laminar, or viscous flow, in parallel tubes. In high-velocity conditions, such as near a pumping well or in fractured rock, velocities may be high enough such that a purely viscous description is inadequate. This occurs, of course, at turbulent velocities but also may occur at subturbulent flow velocities. The nonlinear and transitional flow conditions are associated with an additional source of head loss that increases with the square of the flow velocity. Experimental evidence shows that these ranges are achieved for Reynolds numbers, R_e exceeding something between 1 and 10, where the Reynolds number is typically evaluated as

$$R_e = \frac{\rho q d}{\mu} = \frac{qd}{\upsilon} \tag{1-9}$$

where

R_e = Reynolds number, (dimensionless)
ρ = density of water, (kg /m^3)
q = specific discharge or Darcy velocity, (m /s)
d = a characteristic spatial length parameter associated with the pore size, (m)
μ = dynamic viscosity of water, (Pa s)
υ = kinematic viscosity of water, (m^2/s).

Different researchers have used different soil properties to represent the spatial scale for the characteristic length parameter, *d,* including the median grain size, mean grain size, 10th percentile grain size, and square root of intrinsic permeability.

For the nonlinear flow regime before the onset of turbulence, the Forchheimer equation frequently is used as an alternative to the Darcy equation (Charbeneau 2000, Eq. [2.2.31]).

$$-\frac{dh}{dx} = aq + bq^2 \tag{1-10}$$

where

a = a dimensional velocity coefficient, (s /m)
b = a dimensional velocity coefficient, (s^2 /m^2).

Other symbols are the same as defined previously.

1.6.1 Three-Dimensional Groundwater Flow and Anisotropy

The previous discussion considered only one-dimensional flow. Flow in the subsurface is typically three-dimensional and varies both in space and time. A three-dimensional corollary to the one-dimensional Darcy equation, Eq. (1.5), relates the three-dimensional specific discharge vector, (q_x, q_y, q_z), to the hydraulic gradient vector, $\left(\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \frac{\partial h}{\partial z}\right)$, such that (Charbeneau 2000, Eq. [2.2.20])

$$
\begin{aligned}
q_x &= -K_x \frac{\partial h}{\partial x} \quad \text{Darcy velocity in the x-direction} \\
q_y &= -K_y \frac{\partial h}{\partial y} \quad \text{Darcy velocity in the y-direction} \\
q_z &= -K_z \frac{\partial h}{\partial z} \quad \text{Darcy velocity in the z-direction}
\end{aligned}
\tag{1-11}
$$

where K_x, K_y, and K_z are the hydraulic conductivies in the x, y, and z directions, respectively.

Porous media for which $K_x = K_y = K_z = K$ are referred to as *isotropic*. More frequently, porous media are *anisotropic* with the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity being less than one. Anisotropy of the system in general may persist, even when soils at a small scale exhibit isotropic conditions.

Anisotropy most often occurs because of the horizontal deposition of sediments, resulting in a layer cake of material of varying gradation. Media whose soil properties vary from point to point are referred to as *heterogeneous*, in contrast to *homogeneous* media with spatially uniform properties. Media with layered heterogeneity are referred to as *stratified*. See, for example, the stratified media in Fig. 1-17 on an exposed surface in a sedimentary deposit.

Stratified systems are anisotropic. If the layers are continuous horizontally, then the vertical flow must pass through both fine and coarse media, with varying hydraulic conductivities. Horizontal flow, by contrast, is channeled preferentially through high hydraulic conductivity units while bypassing lower conductivity units. This results in anisotropic systems with vertical hydraulic conductivities less than horizontal conductivities.

Consider, for example, the horizontal flow through several of these layers of thickness b_i and contrasting hydraulic conductivity, K_i, as shown in Fig. 1-18. If the head does not vary significantly over the vertical direction, then the total horizontal flow per unit width of aquifer, Q, is the sum of flows through each of these layers:

$$Q = \sum_i b_i q_i = -\sum_i b_i K_i \frac{dh}{dx} \tag{1-12}$$

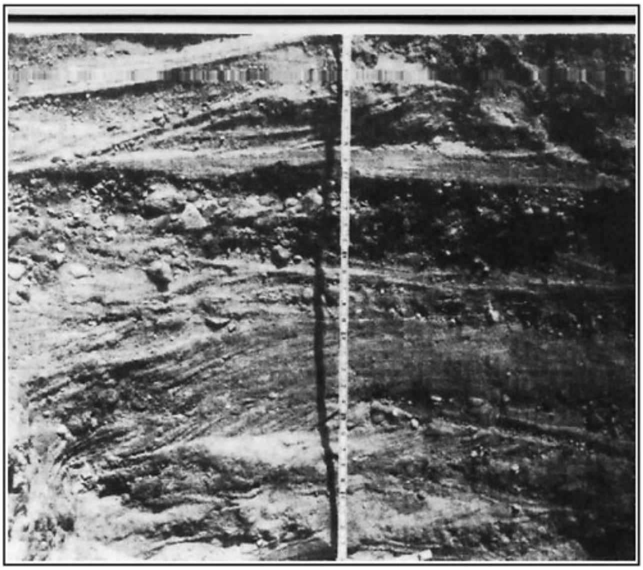

Fig. 1-17. Stratified media in unconsolidated glacial deposits
Source: LeBlanc et al. (1991); reproduced with permission

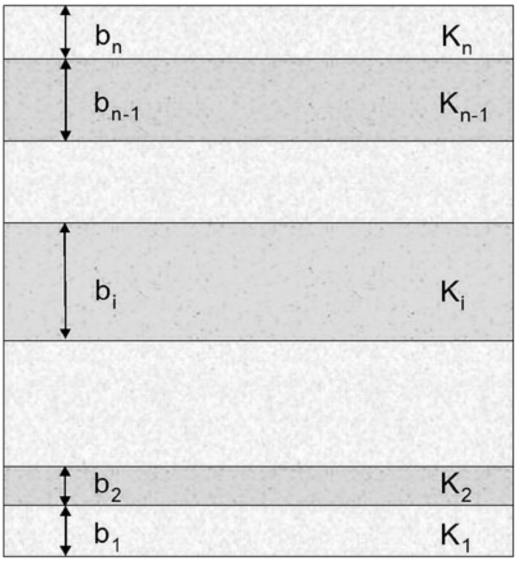

Fig. 1-18. Stratified, anisotropic media
Source: Courtesy of Bruce L. Jacobs, HydroAnalysis, Inc., Brookline, MA

where

Q = total flow per unit width moving through all the layers, (m^2/s)
q_i = specific discharge, (m/s)
b_i = layer thickness, (m)
K_i = hydraulic conductivity, (m/s).

The magnitude of the average horizontal flow per unit area is, therefore, the product of the arithmetic mean of the horizontal conductivity and the head gradient (Charbeneau 2000, Eq. [2.2.9]).

$$q = \frac{Q}{\sum_i b_i} = \frac{-\sum_i b_i K_i}{\sum_i b_i} \frac{dh}{dx} = -\bar{K} \frac{dh}{dx} \tag{1-13}$$

where $\bar{K}$ is the arithmetic mean of hydraulic conductivity and may be considered as an effective conductivity of the unit as a whole.

Now consider the case of vertical flow through the same units or layers of porous media. The total head drop in the direction of flow across multiple layers, Δh_T, is the sum of the drop in head within each layer, $\sum_i \Delta h_i$.

$$\Delta h_T = \sum_i \Delta h_i = -\sum_i \frac{q b_i}{K_i} \tag{1-14}$$

where Δh_T= total vertical head loss, (m).

This also may be written in the form of the Darcy equation (Charbeneau 2000, Eq. [2.2.10]).

$$q = -\frac{\Delta h_T}{\sum_i \frac{b_i}{K_i}} = -\frac{\sum_i b_i}{\sum_i \frac{b_i}{K_i}} \left(\frac{\Delta h_T}{\sum_i b_i} \right) = -\bar{K}_h \frac{dh}{dz} \tag{1-15}$$

where $\bar{K}_h$ is the harmonic mean of the hydraulic conductivity.

The harmonic mean in general is controlled by the value of low conductivity units and always will be less than the value of the arithmetic mean. This leads to the characteristic anisotropy of stratified systems, where the horizontal hydraulic conductivity (generally parallel to the media stratigraphy) is greater than the vertical hydraulic conductivity.

1.7 BASIC EQUATIONS OF GROUNDWATER FLOW

Solutions for the head loss and flow through porous media may be obtained by combining the basic principle of conservation of mass and the Darcy equation (Jacob 1940; Hantush 1964). Equating the change in storage per unit volume $S_s \frac{\partial h}{\partial t}$ to the sum of a point sink, w, and the flow divergence (the net flow out of an infinitesimal aquifer volume), the mass balance equation is (Charbeneau 2000, Eq. [2.3.32])

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} + S_s \frac{\partial h}{\partial t} + w = 0 \tag{1-16}$$

The point sink term, w, expressed as the rate of water volume released per unit aquifer volume, is used to represent wells or drains where water leaves the aquifer.

Now, by substitution of Darcy velocity, Eq. (1-11), the standard form of the mass balance is written as

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} + w \tag{1-17}$$

It is sometimes useful to represent the flow equation in cylindrical coordinates for derivation of aquifer response with distance, r, from a pumping well. The following is the mass balance equation of groundwater flow in an anisotropic aquifer in cylindrical coordinates:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(K_r r \frac{\partial h}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(K_\theta \frac{\partial h}{\partial \theta}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} + w \tag{1-18}$$

where

r = radial distance, (m)
θ = angle, (rad).

1.7.1 Initial and Boundary Conditions

Specifications of domain boundaries, initial conditions, and boundary conditions are necessary for solution of the groundwater flow equation. There are three boundary conditions typically applied to groundwater flow problems, as follows.

1. Specified Head

The specified head boundary condition involves specifying the value of head on the boundary. The specified head may be a constant, or it may vary along the boundary or vary with time. The head at any point on such boundaries is maintained at the specified value despite variations in head within the problem domain. This implies the presence of a source or sink that enables the boundary head to remain at its specified value. Typically, specified head boundaries occur along surface water bodies of sufficient size that their water elevation is not affected significantly by groundwater flow over the period of interest. A pumping well with operating rules that maintain a particular design head or subsurface drains also might be represented using a specified head condition.

2. Specified Flux

Specified flux boundaries are most typically zero-flux (i.e., no flow) boundaries such as might occur along low-permeability bedrock surfaces vertically or horizontally bounding an aquifer. The value of the specified flux need not be zero and may vary with both space and time over the boundary. Under some conditions, a water table may be considered as a zero-flux boundary if recharge and the water volume made available by the water table movement are not significant relative to other fluxes.

3. Mixed Boundary

A mixed-type boundary condition occurs when the boundary flux is a function of the head along that boundary. This may occur, for example, along a surface water body hydraulically connected to the aquifer, where the flux through the stream bed is proportional to the difference between the stream elevation and the head in the underlying aquifer. In this case, reductions in head due to pumping of water from the aquifer will induce recharge, increasing the water flux from the stream to the aquifer.

Representing the boundary condition at the water table is particularly challenging, because fluxes at this boundary may result in changes to the location of the boundary itself. One method employed in analysis of transient conditions in an unconfined aquifer (deMarsily 1986) is to assume that the location of the water table does not change while the boundary flux, q_z, is approximated as

$$q_z = -K_z \frac{\partial h}{\partial z} = S_y \frac{\partial h}{\partial t} \tag{1-19}$$

where

q_z = vertical specific discharge or Darcy velocity at the water table, (m/s)
K_z = hydraulic conductivity in the direction of z-axis, (m/s).

Analytical solutions for flow to a well most typically are evaluated assuming the head initially is constant uniformly within the solution domain. Application of these solutions to field conditions, where the head is not initially uniform, necessitates a summation of the preexisting condition and the invoked response to the pumping stress. The summation of the two responses is referred to as *superposition* and is permissible only because the groundwater mass balance equation is linear with respect to the piezometric head.

Generally, solutions are evaluated for an initial uniform piezometric head of zero. In this case, the solution for a pumping condition consists of negative head values that may then be added to the existing measured field conditions to obtain the predicted response under field conditions. Superposition also implies that the response will be linearly proportional to the pumping stress so that doubling the pumping rate will induce twice the predicted response.

1.8 AQUIFER FLOW

An aquifer's horizontal extent almost always is significantly greater than its thickness. In this type of setting, horizontal flow and changes in the piezometric head in the horizontal direction are often of greater significance than those that occur in the vertical, and it may be that only vertically averaged values of piezometric head are of importance. Under these conditions, the water table elevation or piezometric surface are thought of as average values over the vertical and used in understanding the horizontal distribution of piezometric head in the aquifer.

If a purely horizontal characterization is appropriate, then the mass balance equation may be integrated over the vertical direction, resulting in a two-dimensional, horizontal mathematical characterization of aquifer flow given as

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial \bar{h}}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial \bar{h}}{\partial y}\right)=S\frac{\partial \bar{h}}{\partial t}+w \qquad (1\text{-}20)$$

where

T_x, T_x = transmissivity of the aquifer in x and y directions, (m^2/s)
S = aquifer storativity, (dimensionless)
w = point sink in volume of water per unit of time per unit of horizontal area, (m/s).

Transmissivity is the integrated form of the horizontal hydraulic conductivity, where the limits of integration depend on whether the aquifer is confined or unconfined. For an aquifer with uniform hydraulic conductivity in the vertical direction, the transmissivity is simply the product of the aquifer thickness and its hydraulic conductivity, as shown in Fig. 1-19.

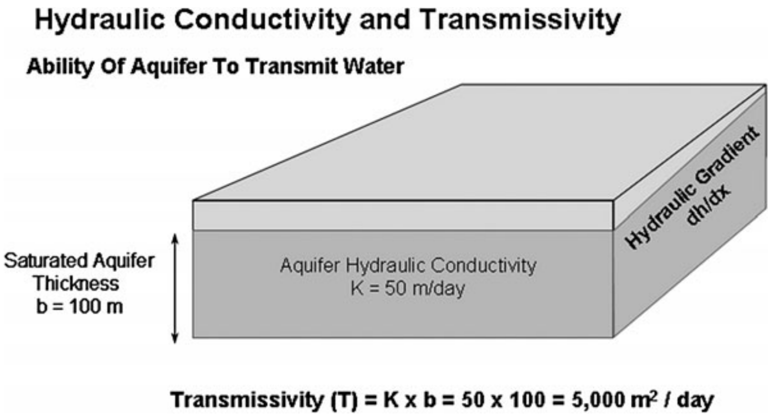

Fig. 1-19. Hydraulic conductivity and transmissivity concepts in porous media flow
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

The average hydraulic head or the average piezometric head is shown in Eq. (1-20) as $\overline{h}$, indicating that it is actually the vertically averaged piezometric head. Frequently, in reports and references, the overbar is omitted, leaving it to the reader to understand that aquifer calculations are for an average piezometric head.

The aquifer equation may be simplified under conditions of isotropic, homogeneous media, in which case, Eq. (1-20) reduces to

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} + \frac{w}{T} \tag{1-21}$$

In radial coordinates, Eq. (1.21) is given as (Charbeneau 2000, Eq. [3.3.1])

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} + \frac{w}{T} \tag{1-22}$$

In isotropic, homogeneous aquifers the mass balance equation may be written in the form of what is commonly referred to as the diffusion equation:

$$D\left(\frac{\partial^2 \overline{h}}{\partial x^2} + \frac{\partial^2 \overline{h}}{\partial y^2}\right) = \frac{\partial \overline{h}}{\partial t} + \frac{w}{S} \tag{1-23}$$

where the aquifer diffusivity is defined as the ratio of transmissivity to storativity, $D = T/S$.

The diffusion equation is used in describing heat flow in a plane for example and is illustrative of the analogy between heat flow and groundwater flow. From inspection of the equation, it is apparent that value of the aquifer diffusivity determines how quickly the aquifer will respond to imposed stresses. Confined aquifers rely on compressive storage mechanisms and, therefore, have storativity values that are typically several orders of magnitude less than that of unconfined aquifers. The aquifer diffusivities of confined aquifers are, therefore, larger, implying significantly more rapid responses to imposed stresses.

1.8.1 Confined and Semiconfined Aquifers

For confined and semiconfined aquifers, T_x, T_y, and S are defined, respectively, as the integrals of hydraulic conductivity and specific storage over the vertical thickness of the aquifer as follows (similar to Charbeneau 2000, Eq. [2.3.16]):

$$T_x = \int_{z_1}^{z_2} K_x \, dz \tag{1-24}$$

$$T_y = \int_{z_1}^{z_2} K_y \, dz \tag{1-25}$$

$$S = \int_{z_1}^{z_2} S_s \, dz \tag{1-26}$$

where

z_1 = elevation of the lower bounds of the aquifer, (m)
z_2 = elevation of the upper bounds of the aquifer, (m).

1.8.2 Unconfined Aquifers

For unconfined aquifers, the transmissivity is defined as the integral over the saturated thickness of the aquifer extending from the base of the aquifer, z_1, up to the water table elevation, h. In an unconfined aquifer, the storage coefficient includes both the integral of the specific storage and the storage derived by movement of the water table as quantified by the specific yield, S_y (Charbeneau 2000, Eq. [2.3.35]).

$$T_x = \int_{z_1}^{h} K_x \, dz \tag{1-27}$$

$$T_y = \int_{z_1}^{h} K_y \, dz \tag{1-28}$$

$$S = S_y + \int_{z_1}^{h} S_s \, dz \tag{1-29}$$

In almost all calculations involving unconfined aquifers, the effective porosity (specific yield), is far greater than the integral of the specific storage over the saturated aquifer thickness. In other words, in unconfined systems, these elastic components (i.e., expansion of the water and compaction of the aquifer) may be disregarded and storativity for all practical purposes is equal to the effective porosity (i.e., $S \approx \theta$). The differential equation representing horizontal flow in an unconfined aquifer is a nonlinear equation, because the transmissivities are themselves dependent on the solution of the equation. If the aquifer is thick relative to the anticipated drawdown, then a linear approximation of the equation may be used by substituting in some initial guess of the water table elevation to approximate the aquifer transmissivity. This type of linearity is invoked frequently by hydrologists, because it allows for superposition of the independently calculated effect of multiple stresses.

1.9 SUMMARY

This chapter provides an introduction to the basic concepts of groundwater flow through porous media to help in understanding the material presented in the rest of this manual. Groundwater is an important component of the hydrologic cycle, having significantly larger total volume and typically longer detention times than surface water. Although groundwater is contained within fractured rock and unconsolidated deposits, emphasis in this manual is on the flow through porous media, in other words, deposits having primary porosity. The concept of porosity is used as a measure of the water volume stored within subsurface porous materials. Water may be released from storage by simple drainage, as well as elastic changes in the groundwater/aquifer system. Frictional energy losses that occur as a result of flow within the porous media are expressed by the Darcy equation, Eq. (1.5), relating the rate of change in hydraulic head to the rate of groundwater flow into the water well. The groundwater flow system also is characterized mathematically by a combination of the mass balance equation and the Darcy equation. Both the three-dimensional, as well as two-dimensional, horizontal forms of the mass balance equation are used frequently to quantify the amount of groundwater that enters the water well through the intake pipes.

1.10 SOLVED DESIGN EXAMPLE 1

A well is pumped from the unconfined aquifer at Cape Cod at a constant rate of 320 gal./min for 12 h, and the depression of the water table is measured at a set of monitoring wells at distances of 23.9 to 225.7 ft from the center of the pumping well (Moench et al. 1993). Estimate the specific yield, S_y, based on the drawdown measurements shown in the following Table 1-4, where the quantities shown for each monitoring well are the radial distance from the pumping well and the drawdown after this 12-h test.

Solution The specific yield can be estimated simply by dividing the water volume removed from the aquifer by the dewatered soil media volume. Nwankor et al. (1984) describe this as the volume-balance technique for estimating specific yield. The removed water volume is simply the product of the pumping rate and the duration of pumping. For a constant pumping rate of 320 gal./min pumped for 12 h, the volume of water removed from the aquifer is 30,800 cu ft.

The dewatered soil volume is given by the area below the drawdown curve plotted in Fig. 1-20 and rotated around a vertical axis coinciding

Table 1-4. Drawdown versus Radial Distance Data from the Pumping Test

Monitoring Well Reference Number	Radial Distance from Center of Pumping Well, r (ft)	Drawdown, S_w (ft)
F505-032	23.9	0.84
F504-032	46.6	0.62
F383-032	93.0	0.37
F384-033	137.3	0.28
F381-056	159.8	0.24
F347-031	225.7	0.16
F434-060	38.6	0.69
F476-061	65.6	0.48
F478-061	101.3	0.34

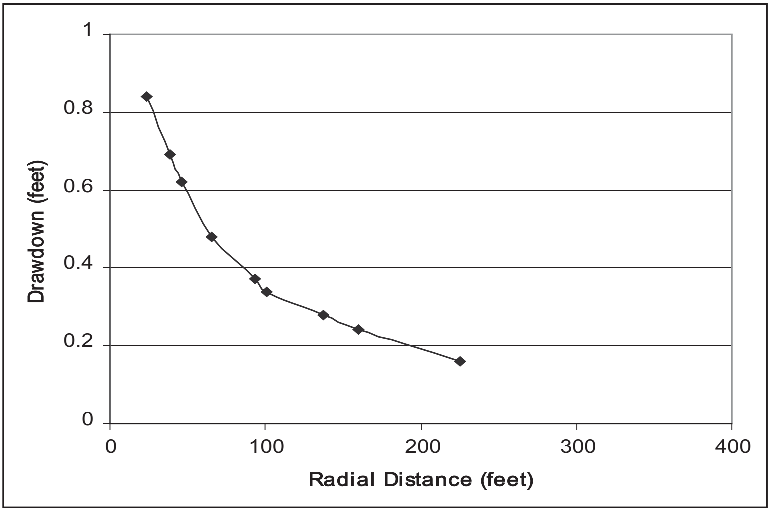

Fig. 1-20. A graphical plot of drawdown, s_w*, versus radial distance,* r*, from the center of the pumping well to the center of the respective monitoring well*
Source: Moench et al. (1993); reproduced with permission

with the pumping well. It's important to extrapolate the data out to a drawdown of zero in order to reach an accurate result. In this case, the dewatered soil volume was estimated to be 85,500 cu ft resulting in a specific yield estimate of 0.36.

1.11 SOLVED DESIGN EXAMPLE 2

A 0.001 m^3 saturated sample of a poorly sorted, coarse sand has a mass of 0.210 kg. Determine the hydraulic properties of the sand based on the experimental investigation described following.

a. The soil was weighed after oven drying and was found to be 0.183 kg. Determine the total porosity, n, of the soil. Comment on the reasonableness of the porosity value.
b. The coarse sand was packed into a tall column with a cross-sectional area of 0.01 m^2. After the sand in the bottom half of the column was saturated, 250×10^{-6} m^3 of water was drained from the soil column, dropping the level in the manometer by 0.10 m. Estimate the specific yield, S_y, of this sand. Does this estimate seem reasonable? Why? Assume that the manometer diameter is small relative to the diameter of the column.

c. The entire length of the column was filled with water to ensure complete saturation of the sand in the column. A constant head permeameter test was performed with a head difference of 30 mm maintained over a distance of 1 m in the direction of flow. What would be the expected rate of flow (L^3/T) through the column? Determine the specific discharge (Darcy velocity) (L/T).

d. A slug of a conservative tracer was introduced into the column sometime after the flow had reached a steady rate. The center of mass of the tracer was observed at the bottom of the column, a distance of 1 m after 3 h. Estimate the effective porosity, θ. Is the estimate reasonable? Why?

e. The water is drained from the sand and replaced with a viscous oil having the following characteristics:

$$\rho_{oil} = \frac{1}{2}\rho_w$$

$$\mu_{oil} = 10\mu_w$$

where

$\rho_w = 1{,}000\,\text{kg/m}^3$
$g = 9.81\,\text{m/s}^2$
$\mu_w = 0.001\,\text{Pa s}$.

The permeameter experiment was repeated with the same 30 mm difference in the manometer levels. Note that this time the manometers were filled with oil. How long would it take for the conservative tracer to travel the same distance of 1 m?

Solution

a. The difference in the saturated mass and dry mass is due to the water volume occupying the pores. The water volume is computed as

$$V_w = \frac{M_{wet} - M_{dry}}{\rho_w} = \frac{(0.210 - 0.183)}{1\,000} = 27 \times 10^{-6}\ \text{m}^3 = 27 \times 10^3\ \text{mm}^3$$

The total porosity, n, of the sand sample, therefore, can be determined as

$$n = \frac{V_w}{V_{total}} \times 100 = \frac{27 \times 10^3\ \text{mm}^3}{100 \times 10^3\ \text{mm}^3} \times 100 = 27\ \%$$

This is on the low side for sand but probably about right for poorly sorted sand. Poorly sorted sands have a mix of grain sizes, so the anticipated porosity is less than if it were well sorted.

b. The volume of water drained is the product of the specific yield, the change in the water table elevation, and the surface area perpendicular to the direction of flow. Therefore

$$V_w = S_y \times \Delta h \times A$$
$$250 \times 10^{-6}\ \text{m}^3 = S_y \times 0.1\ \text{m} \times 0.01\ \text{m}^2$$
$$S_y = 0.25$$

c. There is not really enough information to make a reasonable guess of the hydraulic conductivity, because the range for sands is over several orders of magnitude. For the given sand, assume a hydraulic conductivity of 10^{-7} m/s. The rate of flow, Q, and the specific discharge, q, or Darcy velocity can be obtained from the Darcy equation, Eq. (1.5), as follows:

$$Q = Aq$$

where A is the area of flow cross section

$$Q = KA\frac{\Delta h}{L} = 10^{-7} \times 0.01 \times \frac{0.03}{1} = 3 \times 10^{-11}\ \text{m}^3/\text{s}$$
$$q = \frac{Q}{A} = \frac{3 \times 10^{-11}\ \text{m}^3/\text{s}}{0.01\ \text{m}^2} = 3 \times 10^{-9}\ \text{m/s}$$

d. The velocity of the particle is simply the specific discharge (Darcy velocity) divided by the effective porosity, θ. The elapsed time would be the distance divided by the velocity:

$$t = \frac{L}{v} = \frac{L}{q/\theta}$$

$$\theta = \frac{qt}{L} = \frac{(3 \times 10^{-9}\ \text{m/s})(3\ \text{hr})(3{,}600\ \text{s/hr})}{1\ \text{m}} = 3.24 \times 10^{-5}$$

That seems to be too low a value for effective sand porosity.

e. First, compute the intrinsic permeability of the sand, and then use its value in the Darcy equation, Eq. (1.5), to obtain the oil flow rate. Remembering Eq. (1-8) that for water is

$$K = \frac{k\rho_w g}{\mu_w}$$

The intrinsic permeability for the sand is then

$$k = \frac{\mu_w K}{\rho_w g} = \frac{(0.001\,\text{Pa s})\,(1\times10^{-7}\ \text{m/s})}{(1\,000\,\text{kg/m}^3)\,(9.81\,\text{m/s}^2)} = 1\times10^{-14}\ \text{m}^2$$

The intrinsic permeability represents the properties of the porous media only and is independent of the fluid properties and thus can be used for any fluid. Therefore, the oil specific discharge or the Darcy velocity for the oil flow is given by

$$q = \frac{k\rho_{oil} g}{\mu_{oil}}\frac{\Delta h}{L} = \frac{(1\times10^{-14}\ \text{m}^2)\,(500\,\text{kg/m}^3)\,(9.81\,\text{m/s}^2)}{(10\times0.001\,\text{Pa s})}\times\frac{0.03}{1}$$

$$q = 1.5\times10^{-10}\ \text{m/s}$$

The flow rate of oil or the discharge, Q, then is given as

$$Q = Aq = 0.001\,\text{m}^2\times1.5\times10^{-10}\ \text{m/s} = 1.5\times10^{-7}\ \text{m}^3/\text{s}$$

or,

$$Q = 1.5\times10^{-7}\,\frac{\text{m}^3}{\text{s}}\times10^{6}\,\frac{\text{mL}}{\text{m}^3}\times3\,600\times\frac{\text{s}}{\text{h}} = 540\,\text{mL/h}$$

Use the effective porosity, θ, as obtained with the prior experiment, even though it seems a bit low. This line of thinking would provide a better estimate of the value of travel time, t, through the porous media sample of the poorly sorted sand as

$$t = \frac{L}{v} = \frac{L}{q/\theta} = \frac{1\,\text{m}\times3.24\times10^{-5}}{\left(1.5\times10^{-10}\ \text{m/s}\right)/\left(3600\,\text{s/h}\right)} = 60\,\text{h}$$

where v is the average velocity and is commonly known as the pore velocity. The travel time, t, for the oil flow is 20 times larger than that for the water.

This makes sense, because the oil viscosity is 10 times as high as that of water and it is, of course, less dense than water.

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CHAPTER 2

HEAD LOSSES, TOTAL DRAWDOWN, TOTAL DYNAMIC HEAD, AND EFFICIENCY OF WATER-WELL SYSTEMS

Nazeer Ahmed and James A. Cardle

2.1 GENERAL

A typical water well consists of a casing and screen “string” centered within a borehole and usually surrounded by an artificial filter pack. The terms filter pack, filter envelope, gravel envelope, gravel pack, and gravel filter are used interchangeably in this manual to indicate material placed between the casing or screen and the wall of the borehole (see Figs. 2-1 and 2-2).

The process of well completion is such that the well screen is placed to penetrate through the water-bearing materials in order to withdraw groundwater. In practice, multiple aquifers may be encountered, requiring multiple sections of blank casing and well screen. Groundwater flows from the aquifer through the filter pack and then through the well screen into the well. The well casing is “blind,” that is, it has no perforations to admit groundwater into the well. A pump is suspended inside the well by means of a delivery or discharge pipe. A series of spacers at each joint of the discharge pipe keeps the pipe and the pump bowl assembly centered inside the water well. For electrically driven pumps, the pump motor may be mounted at the surface and rotate impellers by means of a long shaft. The pump also may be powered by an electric motor that is submerged with the pump as a single unit. Electric power is supplied to the submerged motor by a power cable attached to the discharge pipe. It is required that the motor remain submerged at all times for cooling purposes. Normally, a small suction pipe is attached to the pump, but in some installations, a long suction pipe may be used, depending on field conditions or specific requirements of design specifications.

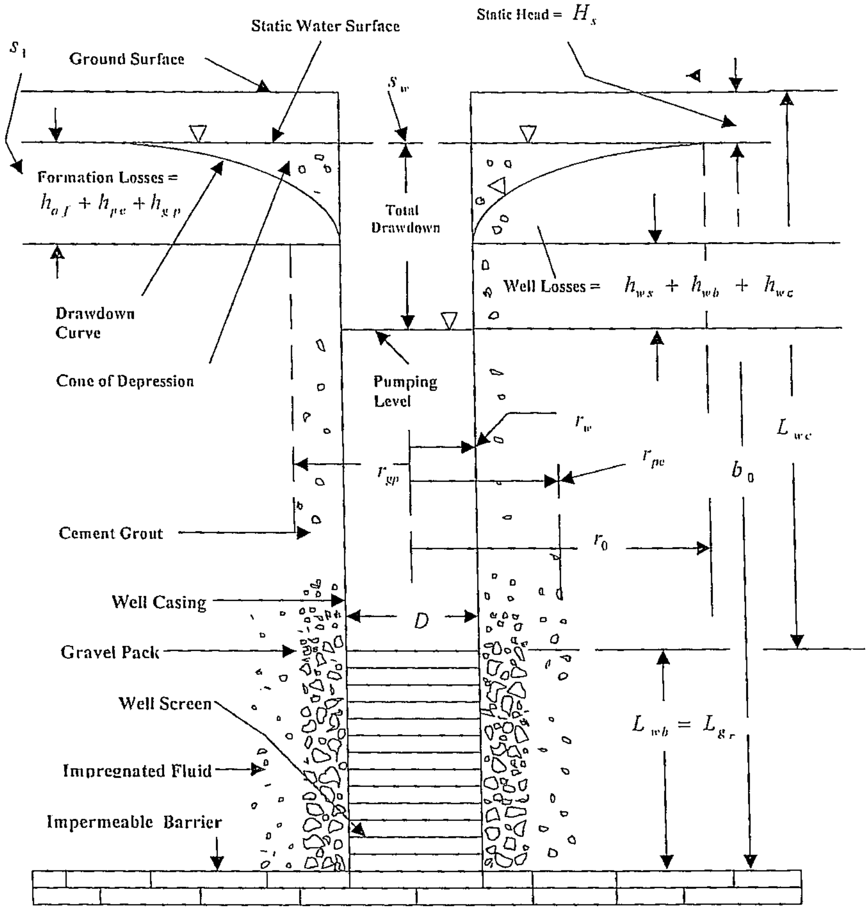

Fig. 2-1. A water well in an unconfined aquifer formation

When water is withdrawn from a well, an expenditure of energy is incurred; this is commonly known as the *head loss*. This chapter discusses the various head loss components (see Fig. 2-3) and elaborates their effect on the efficient performance of a water-well system as a whole. In the water-well industry, the sum total of component head losses is known commonly as the total dynamic head. Pumping results in the development of drawdown (see Figs. 2-1 and 2-2) by lowering the level of water in the vicinity of the well in order to create the hydraulic gradients necessary to move groundwater toward the well. In the water-well industry, the total dynamic head and associated drawdown have a major effect on the operating costs, because power consumption increases in proportion to the total dynamic head. A good water-well design minimizes the total

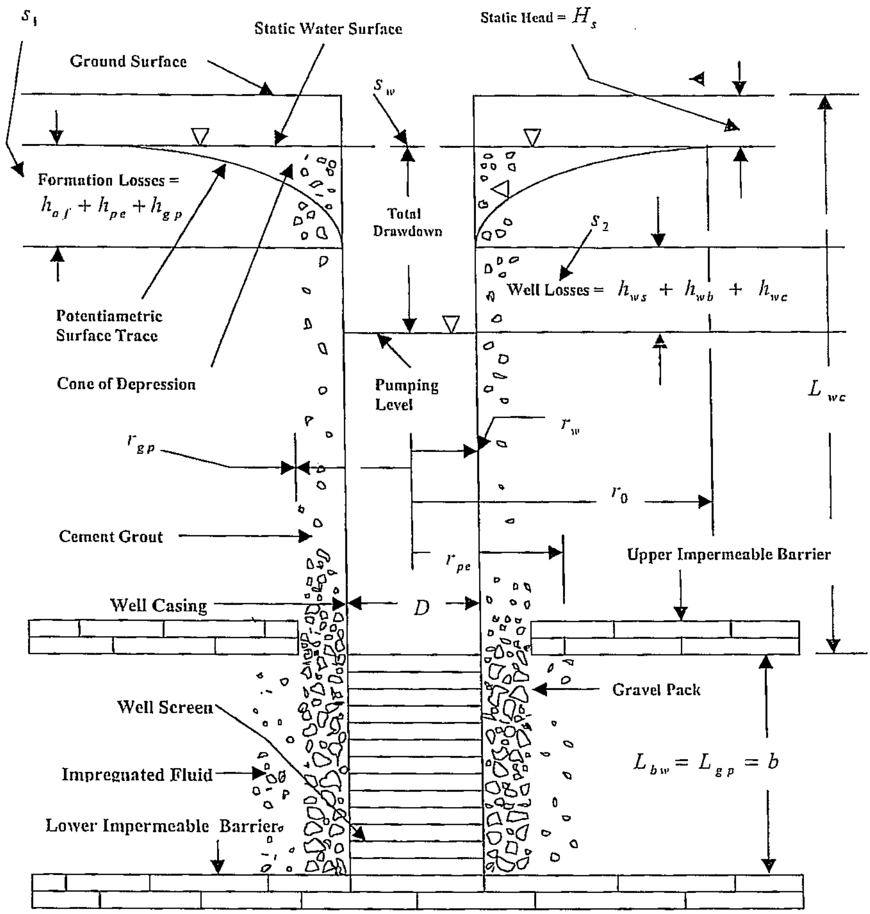

Fig. 2-2. A water well in a confined aquifer formation

dynamic head and power consumption as much as possible. Because water wells can be pumped for extended periods, small head losses resulting from poor design, inefficient pumping units, and underdeveloped boreholes can lead to significantly increased power costs over time. The hydraulic losses, mechanical losses, transmission losses, and power consumption, and the much needed efficiency in a water-well system play a significant role in the decision-making process that frequently are unaccounted for and, hence, usually ignored. Power is not only consumed by the total dynamic head but also by the power generating plant, power transport system, prime mover, and pumping unit to overcome their frictional and other nonfrictional losses. An important goal in the design

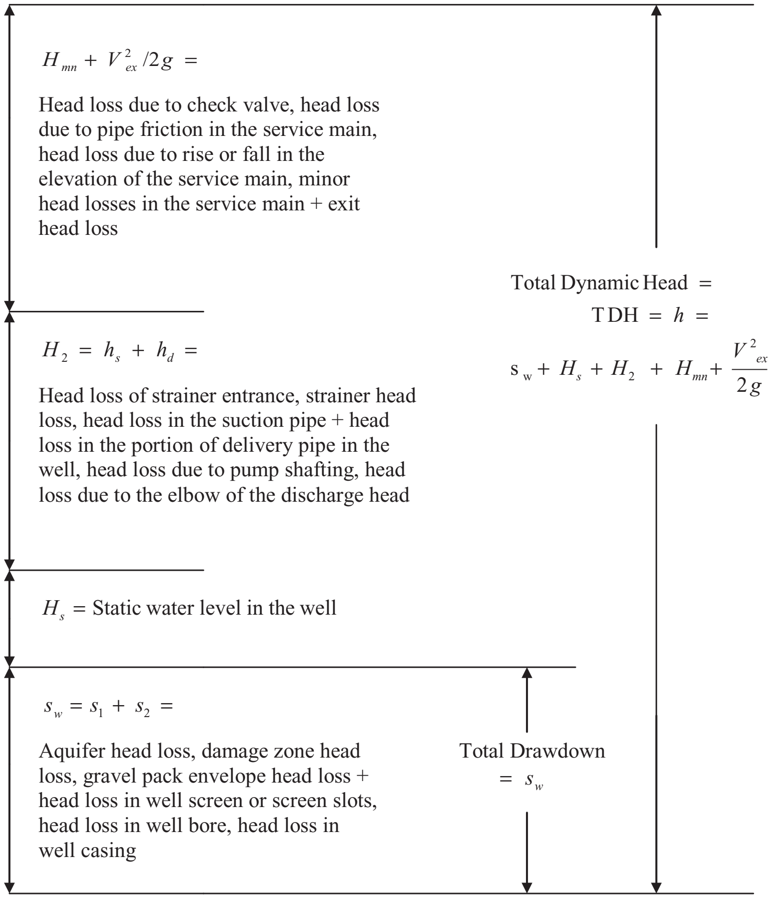

Fig. 2-3. Total dynamic head and its components

of an efficient water-well system at optimum performance level is to minimize the frictional and other nonfrictional losses, thereby minimizing power consumption. Lower efficiency because of poor performance of the water-well system results in larger than necessary operating costs and smaller than expected yields.

The main objective of this chapter is to provide the reader with a basic understanding of total dynamic head. This includes the ability to calculate different head loss components, including the identification of total drawdown, as well as recognition and measurement of gravitational lift. With this understanding, one should be able to estimate the total dynamic head as needed to design a water-well system. In addition, the reader should be able to use well performance data to estimate the total dynamic head associated with a given water-well system. In particular, this section provides detailed information about component head losses, total drawdown, gravitational lift, total dynamic head, and several efficiency terms based on the optimum performance of water-well systems.

2.1.1 Aquifer Head Loss

Head loss for steady-state flow in a confined, homogeneous, and isotropic aquifer with an initially horizontal piezometric surface (see Figs. 2-1 and 2-2) can be estimated using the steady-state Thiem Equation (Todd and Mays 2004):

$$h_{af} = \frac{Q}{2\pi T}\ln\left(\frac{r_0}{r_e}\right) \qquad (2\text{-}1)$$

where

h_{af} = head loss in the aquifer formation between radii r_0 and r_e, (m)
Q = constant discharge of the water well, (m^3/s)
T = transmissivity of the aquifer formation, (m^2/s)
r_0 = radius of influence measured from the center of a water well, (m)
r_e = effective well radius measured from the center of a water well, (m).

In using Eq. (2-1), it is assumed that the water well fully penetrates the saturated thickness of the confined aquifer and that the drop in the hydraulic head is small in comparison to the height of the undisturbed or static piezometric surface (Todd and Mays 2004).

When the drawdown, s_w, is small relative to the saturated thickness ($s_w/D_0 < 0.25$), the drawdown around a water table well may be analyzed using the artesian well equations, provided that drawdown (s_w), transmissivity (T), and storativity (S) are replaced with $s_w - s_w^2/2D_0$, KD_0, and θ, respectively (where D_0 = initial saturated thickness and θ = effective porosity) (Hantush 1964).

The effective well radius is a hypothetical, empirically determined radius that gives the actual drawdown outside the screen of an artesian well when substituted in the drawdown equation of the well (Hantush 1964). In the *near-well zone*, proper well development removes the finer materials, resulting in a local increase in the hydraulic conductivity and the reduction in the head loss. The effect is the same as increasing the effective well radius, r_e. However, small adjustments in r_e will have a negligible effect on head loss calculations. In a fully developed well, assuming no damage zone losses, r_e may be assumed to be that of the outer radius of the filter-pack envelope, if one exists, or the radius of the well casing, r_w.

The radius of influence, r_0, represents the distance to the outer edge of the cone of depression. The zone of influence is the region near the well in which a measurable decline in the piezometric head surface can be observed. Beyond the radius of influence, the drawdown in the aquifer is negligible. There are a number of empirical and semi-empirical formulas available, listed by Bear (1979), for determining r_0. One of those formulas, applicable for both the unconfined (i.e., phreatic) and confined (artesian) aquifers, is presented as follows:

$$r_0 = 575 s_w \sqrt{dK} \tag{2-2}$$

where

s_w = total drawdown in the pumping well measured below the static water level, (m)
d = saturated thickness of phreatic or confined aquifer, (m)
For an unconfined aquifer, $d = b_0$, see Fig. 2-1.
For a confined aquifer, $d = b$, see Fig. 2-2.
K = hydraulic conductivity of the aquifer, (m/s).

As the radius terms in Eq. (2-1) appear as arguments of the logarithmic function, only an order of magnitude approximation is required to achieve a reasonably accurate estimation of aquifer head loss.

2.1.2 Head Loss in the Damage Zone

The damage zone or the zone of penetration is the annular vertical envelope of aquifer next to the filter pack envelope that was penetrated by drilling fluids. This usually alters the hydraulic properties of the aquifer, in particular, the hydraulic conductivity. Proper well development is essential to minimizing the damage zone or eliminating it altogether. A new water well usually is pumped at a very high rate in order to remove drilling fluids and fine-grained materials in the near-well zone. Typically in practice, the well is surged by pumping at a higher rate than the design discharge (typically 1.5 × design rate) and then shutting the pump off and letting the water flow back into the well. This technique also is known as *rawhiding*. Another method involves inserting a *surge block* and oscillating the block up and down like a piston so as to create a strong surging action. This loosens fine-grained materials and breaks up the drilling fluids, which then are pumped out.

The head loss in the damage zone, for steady-state flow in a homogeneous, isotropic aquifer with an initially horizontal piezometric surface, may be estimated using the Thiem equation (Todd and Mays 2004) as

$$h_{pe} = \frac{Q}{2\pi K_{pe} L_{wb}} \ln\left(\frac{r_{pe}}{r_{gp}}\right) \tag{2-3}$$

where

h_{pe} = head loss in the damage zone between the radii r_{pe} and r_{gp}, (m)
r_{pe} = radius of damage zone, measured from the center of water well to the outer edge of the damage zone, (m)
r_{gp} = radius of gravel pack, measured from the center of water well to the outer edge of the gravel pack, (m)
K_{pe} = hydraulic conductivity of the damage zone, (m/s)
L_{wb} = length of the wellbore, (m)
$L_{wb} = L_{gp}$ = length of gravel pack for both unconfined and confined aquifers, (m).

Proper development of the well will reduce or eliminate the damage zone and, therefore, also eliminate this loss term in the head loss computation. However, under certain circumstances, it may not be possible to eliminate the damage zone altogether. In these cases, the effects should be taken into consideration.

2.1.3 Head Loss in the Filter Pack

An important consideration in well hydraulics is the head loss associated with the velocity of groundwater movement in the vicinity of the wellbore. Because head losses are larger for turbulent flow than for laminar flow, head losses in the region of the filter pack would be minimized if laminar or viscous flow conditions could be made to exist. The groundwater velocity toward a pumping well is controlled by the hydraulic conductivity and effective porosity of the aquifer material and hydraulic gradient. As groundwater nears the well, the hydraulic gradient increases with a corresponding increase in groundwater velocity (assuming, of course, uniform aquifer materials). As the flow velocity increases, a transition from laminar to turbulent flow together with a corresponding increase in the head loss may occur. An artificial filter pack placed adjacent to the well screen will tend to minimize this increase in head loss. For further information about design and placement of filter packs, the reader is referred to Chapter 3, Sections 3.3 and 3.3.1 through 3.3.5, and Chapter 4, Section 4.12.

Because of the existence of turbulent flow conditions, wells constructed in consolidated rocks in which fractured flow conditions exist usually are less efficient than wells completed in unconsolidated materials. The radial distance from a well at which turbulent flow may occur in consolidated rock aquifers is controlled to a degree by fracturing and the openness and interconnection of the fractures. As such, head losses near the well may be high. Wells constructed in consolidated rock aquifers typically do not have a filter pack envelope, because it is not required to stabilize formation materials. Head losses associated with turbulent flow may be larger for wells completed in unconsolidated material with an artificial filter pack than in consolidated formations.

The head loss across the filter pack may be determined by utilizing the Thiem equation (Todd and Mays 2004):

$$h_{gp} = \frac{Q}{2\pi K_{gp} L_{gp}} \ln\left(\frac{r_{gp}}{r_w}\right) \tag{2-4}$$

where

h_{gp} = head loss in the gravel pack between radii r_w and r_{gp}, (m)
r_w = radius of water well, (m)
K_{gp} = hydraulic conductivity of the gravel pack, (m/s).

2.1.4 Head Loss in the Well Screen

The well screen is placed in the borehole in conjunction with the well casing and filter pack for the sole purpose of allowing water from the aquifer to enter into the well. Well screens consist of lengths of perforated pipes or engineered components produced by various manufacturers for this specific purpose. The size of the openings usually is chosen so that approximately 10 to 20% of the filter pack material will pass through the well screen (Roscoe Moss Company 1990). Head loss across the well screen can be a very important component of the overall head loss in a well. Careful attention should be paid to the design of the well screen so as to minimize the head loss. For photographic views of different types of well screens, the reader is referred to Chapter 3, Fig. 3-6.

Flow through the well screen can be modeled as flow through an orifice so that the head loss across the well screen is given as

$$h_{ws} = \frac{Q^2}{2gA_{ws}^2 C_c^2 C_g^2} = \frac{Q^2}{2g\left(2\pi p_{ws} r_w L_{ws}\right)^2 C_c^2 C_g^2} \tag{2-5}$$

where

h_{ws} = head loss across the well screen, (m)
A_{ws} = cross-sectional area of well screen, (m^2)

$A_{os} = 2\pi\, p_{ws}\, r_w\, L_{ws}$ = open area of circumferential surface of well screen, (m^2)
p_{ws} = percentage of open surface of well screen with a length of L_{ws}, (dimensionless)
g = gravitational acceleration, (9.81 m/s^2)
L_{ws} = length of well screen, (m)
C_c = contraction coefficient accounting for losses across well screen, (dimensionless)
C_g = clogging factor accounting for the clogged portion of well screen, (dimensionless).

Typical values of $C_c = 0.61$ and $C_g = 0.50$ commonly are used for design of well screens. The velocity through the well screen, $V_{ws} = Q/A_{ws}$, should be kept less than 0.46 m/s by using sufficient screen open area. However, experience has shown that the entrance velocity is not a primary design criterion for a properly designed and constructed well. Detailed characteristics of a particular well screen should be obtained from the well screen manufacturers.

2.1.5 Head Loss in the Wellbore

Barker and Herbert (1989) investigated head losses in the wellbore and found that the head loss produced by the vertical flow along the screen length within the wellbore can be described by

$$h_{wb} = \left(\frac{1}{4}\alpha L_{wb} + \frac{1}{3}\beta\right)Q^2 \tag{2-6}$$

where

h_{wb} = head loss produced by the vertical flow along the screen length, (m)
L_{wb} = length of the well bore or aquifer thickness or simply the length of the well screen, (m)
α = empirical constant that depends on the type of well screen, (s^2/m^6)
β = empirical constant that depends on the type of well screen, (s^2/m^5).

Values of α and β measured by these investigators for different well screen materials are given in Table 2-1 (Herbert and Barker 1990).

Values of the empirical constants α and β exhibit rather wide variation, but these parameters seem to correlate most strongly with the screen

Table 2-1. Head Loss Coefficients for Flow along Well Screens

S. No.	Make	Pipe Material	Pipe Diameter (mm)	α (s^2/m^6)	β (s^2/m^5)
1	JO	SS	150	26.00	540.0
2	BC	GRP	150	18.50	652
3	JO	SS	150	31.00	523.0
4	NO	SS	150	31.20	637.0
5	NO	SS	150	23.20	662.0
6	DU	P	150	18.80	732.0
7	DU	P	150	16.00	746.0
8	DU	P	150	17.70	730.0
9	HY	P	150	23.70	759.0
10	PR	P	150	15.80	712.0
11	PR	P	150	11.80	686.0
12	DE	P	150	17.00	813.0
13	DE	P	150	20.30	738.0
14	DE	GRP	150	20.00	492.0
15	JO	SS	100	138.00	2240.0
16	NO	SS	100	76.40	3610.0
17	DU	P	100	72.90	3490.0
18	DU	P	100	123.00	3530.0
19	HY	P	100	156.00	3750.0
20	JO	SS	200	6.14	173.0
21	BC	GRP	200	3.49	201.0
22	DU	P	200	3.47	220.0
23	HY	P	200	3.25	229.0
24	JO	SS	250	2.46	78.3
25	NO	SS	300	0.81	41.6
26	DU	P	300	0.71	42.8
27	HY	P	300	0.71	43.7
28	BC	GRP	150	13.10	646.0

Note: SS = Stainless steel; P = Plastic; GRP = Glass reinforced plastic; JO = Johnson; BC = Bristol Composite; NO = Nold; DU = Durapipe; HY = Hydrotech; PR = Preussag; DE = Demco

Source: Table 1 in Herbert and Barker (1990). Reproduced with permission from Routledge.

diameter. Fitting an exponential curve to these data gives the following empirical equations:

$$\alpha = 877e^{-0.618D} \tag{2-7}$$

$$\beta = 18,963e^{-0.5369D} \tag{2-8}$$

where $D = 2r_w$ = diameter of well screen, (in.).

2.1.6 Head Loss in the Well Casing

The casing diameter usually is chosen to accommodate the size of the pump required. In the case of wells larger than 100 mm (4 in.), the diameter of the well casing typically should be two sizes larger than the pump size. This will give sufficient clearance for installation and efficient operation of the pumping equipment. If the screened interval is located at a much lower depth than the pump, the casing below the pump can be of a smaller diameter. For wells smaller than 100 mm (4 in.), a casing that is only one size larger than the pump is satisfactory. In shallow wells where the pump is connected directly to the top of the well casing or connected to a suction pipe inside the well, the casing diameter should be selected in relation to the diameter of the suction inlet of the pump. A general rule-of-thumb relationship between design discharge and well-casing diameter has been proposed by Domenico and Schwartz (1997) as given in Table 2-2.

Table 2-2. Values of Water Discharge and Corresponding Well-Casing Inside Diameter

Design Discharge (Q)			Well-Casing Inside Diameter (D_{wc})	
(m^3/s)	(L/s)	(gpm)	(mm)	(in.)
0.00789	7.89	125	150	6
0.0189	18.9	300	200	8
0.0379	37.9	600	250	10
0.0757	75.7	1200	300	12
0.126	126	2000	350	14
0.189	189	3000	400	16
0.315	315	5000	450	18

Source: Domenico and Schwartz (1997); reproduced with permission from Wiley

For flow inside the unscreened sections of the well casing, the associated head loss can be determined as described by the Darcy-Weisbach equation as

$$h_{wc} = \frac{8fL_{wc}}{\pi^2 g D_H^5} Q^2 \tag{2-9}$$

where

$$D_H = \frac{4A_{wc}}{P_{wc}} \tag{2-10}$$

$$R_{wc} = \frac{\rho V_{wc} D_H}{\mu} = \frac{V_{wc} D_H}{\upsilon} \tag{2-11}$$

and

h_{wc} = head loss occurring inside the well casing over a length, L_{wc}, (m)
f = friction factor of well casing, (dimensionless)
L_{wc} = length of well casing pipe over which the head loss, h_{wc}, is computed, (m)
D_H = hydraulic diameter, (m)
$2r_w$ = diameter of well casing, (m)
A_{wc} = cross-sectional area of well-casing pipe, (m^2)
P_{wc} = wetted perimeter of the cross-section of well casing, (m)
R_{wc} = Reynolds number for well casing, defined as the ratio between inertial forces and viscous forces, (dimensionless)
ρ = density of water, (kg/m^3)
V_{wc} = flow velocity in the well-casing pipe, (m/s)
μ = dynamic viscosity of water, (Pa s)
υ = kinematic viscosity of water, (m^2/s).

The hydraulic diameter is an approximation of the real flow cross section when it is not flowing full, such as flow in the casing pipe past the delivery pipe, pump bowl assembly, suction pipe, or submersible electric motor. In this case, the flow cross section of the casing pipe is noncircular in shape. The concept of hydraulic diameter represents an imaginary pipe of circular cross section, flowing full, and having a diameter equal to D_H so that the laws of frictional flow can be applied to flow systems in noncircular pipes. The flow in a fictitious pipe having a diameter equal to D_H does not depict the true flow picture in a noncircular pipe; therefore, a determination of a unique relationship between D_H and the nominal diameter D of a circular pipe has not been pursued rigorously.

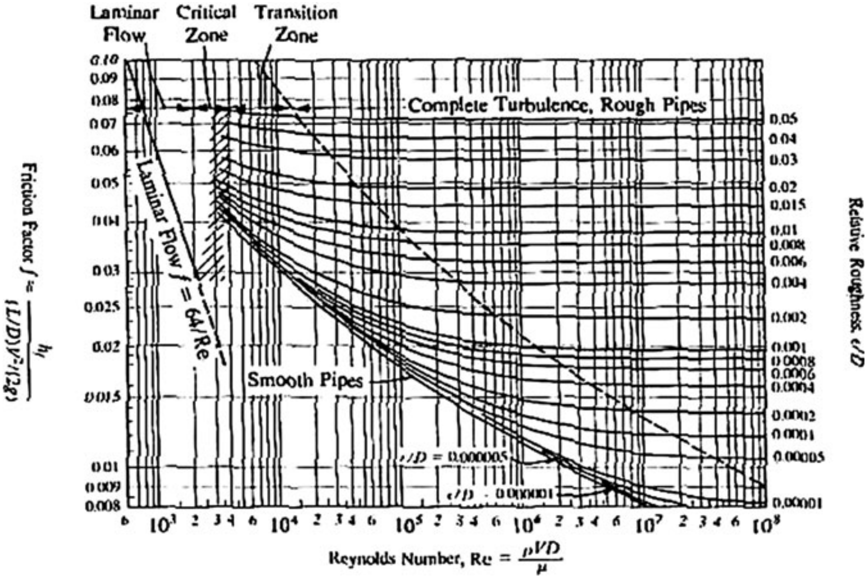

Fig. 2-4. Friction factors for pipe flow
Source: Moody 1944; reproduced with permission from ASME

However, the application of the fictitious hydraulic diameter, D_H, has been employed generously to solve practical problems in a remarkable and successful manner. As a trivial notion, it may be pointed out that a circular pipe has a hydraulic diameter equal to the nominal diameter of the pipe. Also, it is reiterated here that one can use Reynolds number based on the hydraulic diameter, D_H, with confidence to determine the friction factor from Fig. 2-4 to solve practical problems for flow in noncircular cross sections.

The Darcy-Weisbach friction factor, f, should be chosen to account for the roughness of the casing and for the joints between sections of the casing. One must note a difference between Eqs. (1-9) and (2-11): the former equation represents a Reynolds number for flow in a porous medium, whereas the latter equation represents a Reynolds number for flow in a circular pipe. Porous media flow and pipe flow represent two different flow regimes. For pipes, the flow is fully turbulent at Reynolds numbers greater than 4,000, whereas turbulence develops in a porous medium at a much lower Reynolds number, between 1 and 10.

For turbulent flow, the friction factor, f, is a function of the relative roughness and the Reynolds number. Different pipe materials have been correlated with equivalent sand-grain roughness heights. The ratio of this equivalent sand-grain roughness height, ε, to hydraulic diameter, D_H, is called the relative roughness, ε / D_H. The dimensionless Reynolds number is the ratio of inertial to viscous forces in a fluid flow, ρ is the fluid density, V_{wc} is the average fluid velocity in a casing pipe, μ is the dynamic viscosity of the fluid, and $\upsilon = \mu / \rho$ is the kinematic viscosity of the fluid.

To compute the head loss in a well casing, the velocity of flow is determined by dividing the flow rate by the cross-sectional area of flow, $V_{wc} = Q / A_{wc}$, and the hydraulic diameter is calculated from the flow geometry. An estimate is made of the equivalent sand-grain roughness for the pipe material. The Reynolds number and relative roughness then are calculated and used to find the friction factor from a Moody diagram, given in Fig. 2-4. Normally, the friction factors, f, for the piping system to be used should be obtained from the manufacturer or its distributor. If the friction factors for the pipes to be used are not available, then they could be estimated as outlined previously by utilizing the values of absolute roughness from Table 2-3 for the materials under consideration.

In a situation where a large portion of the flow is coming through well screens located above the pump intake and then through blind sections, flow is passing through an annular region between the well casing and either the pump discharge pipe, pump bowl assembly, pump intake pipe, or submersible electric motor that are suspended down the center of the well. It is important, then, to calculate the flow velocity based on the area of this annular region and to use the hydraulic diameter of this annular region in computing the Reynolds number and relative roughness. Corrosion and deposition of scale (see Chapter 5) will increase the roughness and decrease the cross-sectional area of flow so that the head loss in the casing pipe will increase over time. Increasing the diameter of well casing

Table 2-3. Values of Absolute Roughness, ε, for New Pipes

Material	ε (mm)
Concrete	0.3–3.0
Riveted Steel	0.91–9.1
Wood Stave	0.18–0.9
Asphalted Cast Iron	0.12
Cast Iron	0.26
Welded Steel Pipe	0.046
Commercial Steel or Wrought Iron	0.046
Drawn Tubing	0.001 5
Galvanized Iron	0.15
Glass, brass, copper, lead	“smooth”

Source: Moody (1944); reproduced with permission from ASME in concert with the well screen will reduce the velocities inside the well casing and thus reduce the turbulent head loss to some degree and increase the efficiency of the water-well system.

2.1.7 Total Drawdown in the Water Well

In general, the total drawdown in the water well is related to head losses in the aquifer formation, damage zone, filter pack or filter-pack envelope, well screen, wellbore, and well casing. Normally, flow in an aquifer formation is laminar. However, it has been shown that near-well turbulence may exist in high-discharge wells in thin aquifers composed of coarse-grained materials (Williams 1985). Also, a preferential flow system may develop due to removal of fines within the aquifer, allowing a major portion of the flow to occur through preferential flow pathways. In the absence of well-established turbulent flow formulas for the preferential flow system, it is theorized here that the viscous flow regime is preserved and that the Darcy equation applies for the sake of convenience. Flow through the damage zone and the filter-pack envelope may be turbulent, but the region is small compared to the large volume of the aquifer body such that turbulence effects are usually ignored. For practical purposes, therefore, the flow in these three regions is always considered laminar or viscous (AWWA 1997, 2004).

The head loss that occurs in these three zones causes a drawdown in the vicinity of the well and, as a result, water flows into the well under the influence of gravity. As a consequence of well drawdown, this head loss performs useful work in allowing water to flow into the well. The head losses that occur in these three regions commonly are known as formation losses. In equation form these losses may be expressed as

$$s_1 = h_{af} + h_{pe} + h_{gp} \tag{2-12}$$

where s_1 = drawdown caused in the well due to the effects of head losses in the aquifer formation, damage zone, and filter pack, (m).

The flow that occurs through the well screen slots, well bore, and well casing is a combination of laminar-sublayer flow, turbulent flow, and flow of large-size eddies. This flow is definitely a nonlinear flow for all practical purposes. The head losses that occur in these three regions are known as well losses. No useful work results when power is used to overcome these losses. The well losses may be expressed as

$$s_2 = h_{ws} + h_{wb} + h_{wc} \tag{2-13}$$

where s_2 = drawdown caused in the well due to the effects of head losses in the screen slots, well bore, and well casing, (m).

The total drawdown, s_w, estimated or measured in a pumping well and represented or caused by the formation losses, s_1, and well losses, s_2, can be summed as

$$s_w = s_1 + s_2 \tag{2-14}$$

Also, when data are available from a step-drawdown test, then the total drawdown, s_{wd}, is written as a function of the well discharge, Q, as follows:

$$s_{wd} = BQ + CQ^2 \tag{2-15}$$

where

B = coefficient of formation losses
C = coefficient of well losses.

Both coefficients, B and C, can be written as follows. For steady-state flow, combining Eqs. (2.1), (2.3), and (2.4), results in

$$\text{Formation losses} = s_{1d} = h_{af} + h_{pe} + h_{gp}$$

or,

$$s_{1d} = \frac{Q}{2\pi T}\ln\left(\frac{r_o}{r_{pe}}\right) + \frac{Q}{2\pi K_{pe} L_b}\ln\left(\frac{r_{pe}}{r_{gp}}\right) + \frac{Q}{2\pi K_{gp} L_{gp}}\ln\left(\frac{r_{gp}}{r_w}\right)$$

or,

$$s_{1d} = \left[\frac{1}{2\pi T}\ln\left(\frac{r_o}{r_{pe}}\right) + \frac{1}{2\pi K_{pe} L_b}\ln\left(\frac{r_{pe}}{r_{gp}}\right) + \frac{1}{2\pi K_{gp} L_{gp}}\ln\left(\frac{r_{gp}}{r_w}\right)\right]Q$$

or,

$$s_{1d} = BQ \tag{2-16}$$

where

$$B = \frac{\ln(r_0 / r_{pe})}{2\pi T} + \frac{\ln(r_{pe} / r_{gp})}{2\pi K_{pe} L_b} + \frac{\ln(r_{gp} / r_w)}{2\pi K_{gp} L_{gp}} \tag{2-17}$$

Alternatively, for transient flow, the first term on the right-hand side of Eq. (2-17) can be replaced by the well function, $W(u)$, divided by the product, $2\pi T$, as follows (Todd and Mays 2004):

$$B = \frac{1}{2\pi T} W(u) + \frac{\ln\left(r_{pe} / r_{gp}\right)}{2\pi K_{pe} L_b} + \frac{\ln\left(r_{gp} / r_w\right)}{2\pi K_{gp} L_{gp}} \tag{2-18}$$

For steady-state flow, combining Eqs. (2-5), (2-6), and (2-9), the following is obtained:

$$\text{Well losses} = s_{2d} = h_{ws} + h_{wb} + h_{wc}$$

$$s_{2d} = \frac{Q^2}{2g\left(2\pi p_{ws} r_w L_{ws}\right)^2 C_c^2 C_g^2} + \left(\frac{1}{4}\alpha L_{wb} + \frac{1}{3}\beta\right)Q^2 + \frac{8 f L_{wc}}{\pi^2 g D_H^5} Q^2$$

or,

$$s_{2d} = \left[\frac{1}{2g\left(2\pi p_{ws} r_w L_{ws}\right)^2 C_c^2 C_g^2} + \left(\frac{1}{4}\alpha L_{wb} + \frac{1}{3}\beta\right)Q^2 + \frac{8 f L_{wc}}{\pi^2 g D_H^5}\right] Q^2$$

or,

$$s_{2d} = CQ^2 \tag{2-19}$$

where

$$C = \frac{1}{2g\left(2\pi p_{ws} r_w L_{ws}\right)^2 C_c^2 C_g^2} + \left(\frac{1}{4}\alpha L_{wb} + \frac{1}{3}\beta\right)Q^2 + \frac{8 f L_{wc}}{\pi^2 g D_H^5} \tag{2-20}$$

In the unsteady flow case, $W(u)$ is the well function of Theis (as stated previously) and $u = r^2 S/4Tt$, where r is the radial distance from the center of pumping well to the point of interest. The unsteady or transient model can be applied either to confined or unconfined aquifer flow with the proper corrections (see Section 2.1.1). In the case of confined flow, S is the aquifer storativity. When the flow is unconfined, S is the specific yield or effective porosity of the unconfined aquifer. In the transient case, losses in the damage zone and across the filter pack also are modeled using steady-state equations so that the transient effects are confined to the undisturbed aquifer around the well.

The loss coefficient B is indicative of the level of losses in various porous media surrounding the well, whereas the loss coefficient C is a representation of the level of losses across the well screen and losses due to friction and turbulence inside the well. This expression conforms to the classic equation given by Jacob (1947) and shows a theoretical basis for the exponent 2 in Eq. (2-15). A more general form of Eq. (2-15) is

$$s_{wd} = BQ + CQ^n \tag{2-21}$$

where

s_{wd} = total drawdown in the well due to formation and well losses for a step-drawdown test, (m)
n = exponent.

The exponent, n, is in the range of $1.5 \le n \le 3.5$, a marked deviation from the theoretical value of 2. Apparently, even higher values can be obtained for wells constructed in fractured rock (Boonstra 1999).

Parameters B and C may be estimated from a step-drawdown test. In this test, the well is pumped at a low rate and the drawdown recorded at different times until the head loss in the well stabilizes. The pumping rate then is stepped up or increased, and the head loss is again allowed to stabilize. A minimum of three steps are required. An estimate of the equilibrium of the drawdown at the well for each pumping rate can be made even if equilibrium is not entirely achieved during each step. For further discussion, see Chapter 4, Section 4.16 (pumping tests).

If Jacob's relation, Eq. (2-15) holds, a Cartesian plot of specific drawdown (inverse of specific capacity), s_{wd}/Q, versus discharge, Q, should plot as a straight line, that is

$$\frac{s_{wd}}{Q} = B + CQ \tag{2-22}$$

The slope of the straight line, (Eq. [2-22]), is the coefficient C, and its intercept is B.

If the plot of specific drawdown versus discharge is not linear, then the exponent n is not equal to 2 and the more general approach of Rorabaugh (1953) must be used. Rearranging Eq. (2-21) and taking logarithms of both sides gives

$$\log\left(\frac{s_{wd}}{Q} - B\right) = \log C + (n-1)\log Q \tag{2-23}$$

In solving for values of B and C, the procedure is to select a value of B and make a log-log plot of $s_{wd}/Q - B$ versus Q. The correct choice for the value of B will result in a straight-line plot. The slope of the line is $n - 1$. The constant C can be determined by picking a value of Q and a corresponding value of $s_{wd}/Q - B$ from the plot. Using these values, C can be determined from

$$\log C = \log\left(\frac{s_{wd}}{Q} - B\right) - (n-1)\log Q \tag{2-24}$$

To eliminate the second term in Eq. (2-24), it is convenient to pick a point where $Q = 1$; therefore

$$C = \frac{s_{wd}}{Q} - B \qquad (2\text{-}25)$$

2.2 HEAD LOSS IN THE SUCTION PIPE

In the case of a turbine pump, the suction pipe is located below the pump bowl assembly within the well casing. A strainer is fixed to the lower end of the suction pipe to keep the pumping unit free from debris at all times. The total head loss, h_s, through the suction line can be written as

$$h_s = h_{ent} + h_{str} + h_{su} = \left(k_{ent} + k_{str} + f\,\frac{L_s}{D_s} \right) \frac{Q^2}{2gA_s^2} \qquad (2\text{-}26)$$

where

h_s = total head loss through the suction line, (m)
h_{ent} = head loss due to flow at the entrance into the strainer, (m)
h_{str} = head loss due to flow in the strainer, (m)
h_{su} = head loss due to flow in the suction pipe, (m)
k_{ent} = loss coefficient for the flow entrance into the strainer, (dimensionless)
k_{str} = loss coefficient for the strainer, (dimensionless)
L_s = length of the suction pipe, (m)
D_s = diameter of the suction pipe, (m)
A_s = cross-sectional area of the suction pipe, (m^2).

For normal installations of turbine pumps, the head losses in the strainer, strainer itself, and suction pipe are usually small in magnitude and can be considered negligible. For long suction pipes, head losses in the suction pipe and strainer, and the entrance loss to the strainer are included in the total dynamic head. For long suction pipes, the head losses can be obtained from Fig. 2-4. Flow into the pump intake or suction pipe usually passes first through the strainer. Minor loss coefficients for a basket strainer fall in the range $0.4 \le k_{str} \le 2.0$. The inlet itself also will produce a minor loss. The minor loss coefficients for the inlet fall in the range $0.05 \le k_{ent} \le 1.0$ depending on the design of the entrance. A rounded bell mouth inlet will have a loss coefficient of 0.05, while a squared-off inlet will have a loss coefficient of 1.0.

2.3 HEAD LOSS IN THE DELIVERY PIPE

In the case of a turbine pump, the delivery pipe is fitted to the pump bowl assembly at its upper end within the well casing. The total head loss, h_d, through the vertical portion of delivery pipe line up to and including the delivery end of the discharge head can be written as

$$h_d = h_{dp} + h_{sh} + h_{dis} = f\frac{L_d}{D_d}\frac{Q^2}{2gA_d^2} + h_{sh} + h_{dis} \tag{2-27}$$

where

h_d = total head loss through the vertical portion of delivery pipe column, (m)
h_{dp} = head loss due to flow resistance in the vertical portion of delivery pipe column in the well, (m)
h_{sh} = power loss due to friction of the shaft arrangement in the vertical portion of the delivery pipe (nonexistent for submersible pumps), (N m/s)
h_{dis} = head loss due to flow resistance in the elbow of the discharge head at the ground surface, (m)
L_d = length of the vertical portion of delivery pipe in the well, (m)
D_d = diameter of the delivery pipe, (m)
A_d = cross-sectional area of the delivery pipe, (m).

The head loss, h_d, for the delivery pipe system can be estimated by utilizing the Darcy-Weisbach Eq. (2-9) and appropriate minor loss coefficients. Alternatively, Figs. 2-5 through 2-8 can be used to determine the head loss terms included in Eq. (2-27), thus avoiding the need to solve these equations. For example, for submersible pumps, the head loss, h_{dp}, due to the delivery pipe column may be determined from Fig. 2-5. The head loss, h_{dp}, due to the delivery pipe column in the well for both the oil- and water-lubricated turbine pumps can be determined from Fig. 2-6. The head loss, h_{sh}, or the so-called power loss term due to the rotation of the shaft, for both the oil- and water-lubricated turbine pumps, can be calculated from Fig. 2-7. The head loss, h_{dis}, due to the elbow in the discharge head at the ground surface can be obtained from Fig. 2-8. For computational purposes, the head loss due to the elbow in the discharge head usually is neglected, but for precise computations its inclusion may be considered necessary for a given design problem. If the pumping unit is supplying water to an external distribution system, such as an overhead tank (Fig. 2-11), then the additional head loss term needs to be added in Eq. (2-27) to determine total dynamic head accurately.

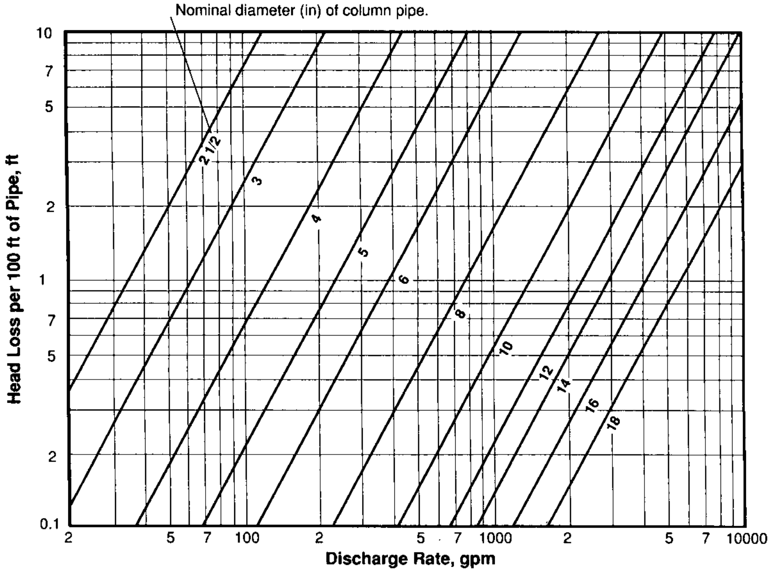

Fig. 2-5. Head loss due to column friction
Source: AWWA Standard E101-88. Copyright 1988, American Water Works Association; reprinted with permission

For the delivery pipeline portion beyond the discharge head, the minor loss coefficient for a check valve with a flanged fitting is $k_v = 2.0$, and for a screwed fitting, the range is $2.0 \le k_v \le 8.0$, depending on the pipe diameter. For better accuracy, reliable values of the loss coefficients should be obtained from the valve manufacturers. Other minor losses caused by valves, bends, and various fittings also may occur in the delivery pipe when the water is being delivered to an overhead tank or pumped directly into the main service pipeline.

In this case, Eq. (2-27), may be rewritten in a slightly different way to account for all types of minor head losses, h_i, and minor loss coefficients, Σk_i, as

$$h_d = h_{dp} + \sum h_i + h_{sh} + h_{dis} = \left(f \frac{L_d}{D_d} + \sum k_i \right) \frac{Q^2}{2gA_d^2} + h_{sh} + h_{dis} \qquad \text{(2-28)}$$

where

Σh_i = sum of several minor head losses due to flow resistance in pipe fittings and other obstructions in the flow system, (m)

Σk_i = sum of several loss coefficients for pipe fittings and other obstructions in the flow system, (dimensionless).

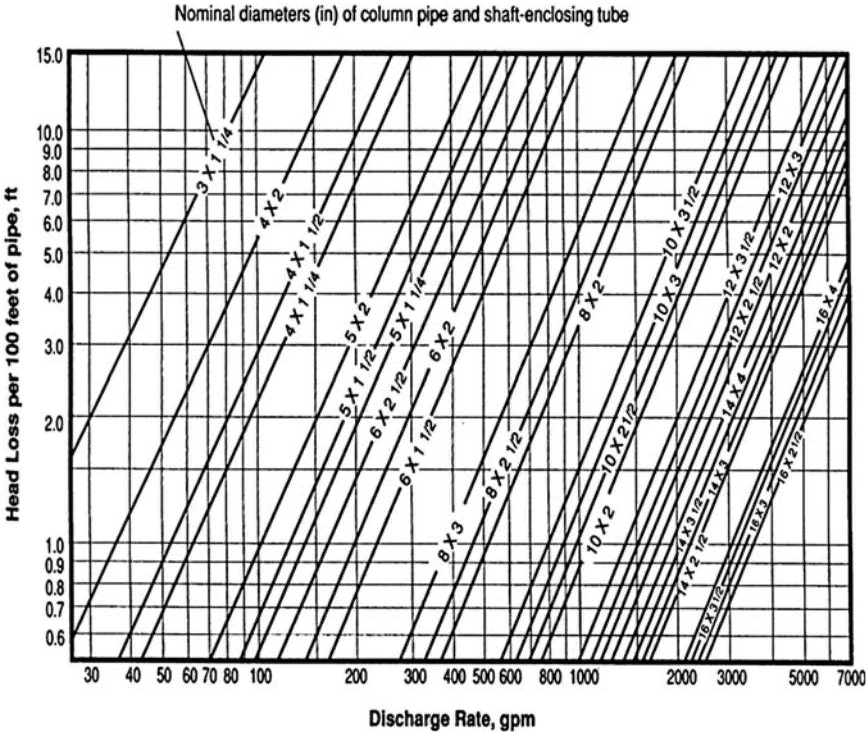

Fig. 2-6. Head loss due to column pipe and shaft-enclosing tube
Source: AWWA Standard E101-88. Copyright 1988, American Water Works Association; reprinted with permission

All other symbols in Eq. (2-28) have been defined previously.

Different lengths and diameters of the delivery line should be considered appropriately for additional head loss terms and Eq. (2-28) should be adjusted accordingly. Suction and delivery pipes may have the same diameters, usually for the sake of convenience for design and installation purposes, but they may have different lengths and hydraulic diameters as well. If different pipe diameters exist on the delivery side and water is being pumped into an overhead tank or directly into main-service line, then contraction and expansion losses should be accounted for appropriately on the delivery end.

2.4 TOTAL DYNAMIC HEAD

Thus far, the discussion has dealt with the concept of head loss for a number of components of a water-well system; however, it is now

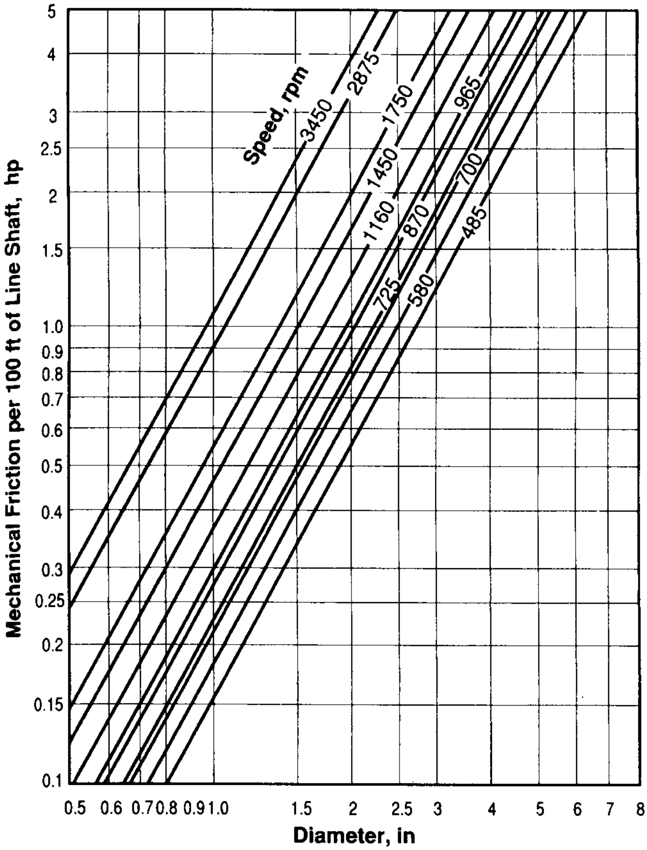

Fig. 2-7. Power loss due to drive shaft friction; drive shaft losses
Source: AWWA Standard E101-88. Copyright 1988, American Water Works Association; reprinted with permission

possible to determine the total dynamic head imposed on the pumping unit by unifying these individual component head losses. The total drawdown, s_w, either computed on theoretically or empirically or measured physically in the water well, is given as the total sum of component head losses, shown in Fig. 2-1 or 2-2, as

$$s_w = h_{af} + h_{pe} + h_{gp} + h_{ws} + h_{wb} + h_{wc} \qquad (2\text{-}29)$$

In Eq. (2-29), the sum of the first three terms on the right-hand side usually is termed the formation losses (Eq. [2-12]), whereas the sum of the last three terms is called the well losses (Eq. [2-13]).

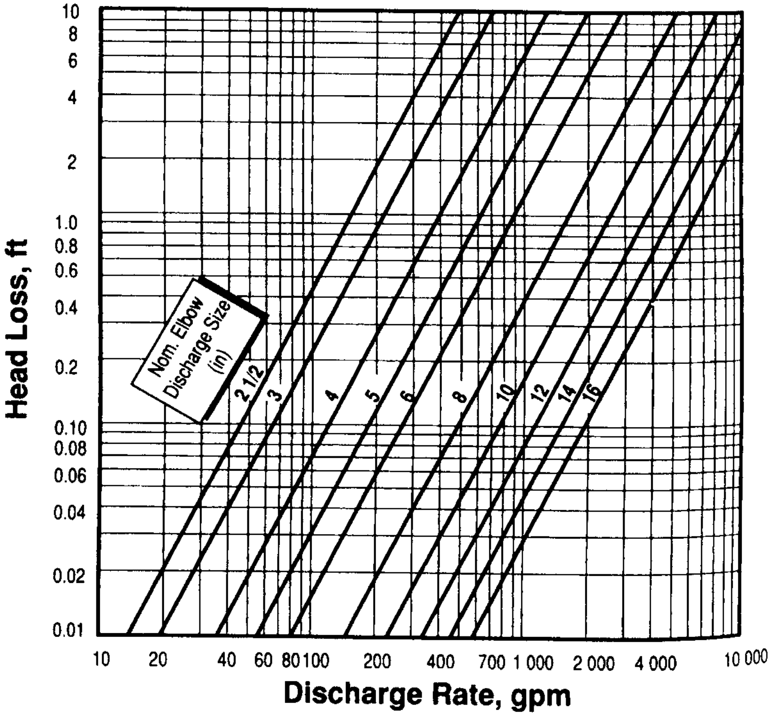

Fig. 2-8. Head loss for elbow of discharge head
Source: AWWA Standard E101-88. Copyright 1988, American Water Works Association; reprinted with permission

If the static head in the water well is H_s, then, when the pumping unit is operating, the total dynamic lift, H_1, from the surface of water in the pumping well up to the ground surface (i.e., up to centerline of the discharge end of the elbow of the discharge head) would be the sum of the static head and the total drawdown, or

$$H_1 = H_s + s_w \tag{2-30}$$

where

H_1 = total dynamic lift from the surface of water in a pumping well to the ground surface, (m)
H_s = static head in a nonpumping well, (m).

The total drawdown, s_w (Eq. [2.14]), can be replaced by s_{wd} (Eq. [2.15]) when the total drawdown is computed on the basis of a step-drawdown test data.

The head loss from the entrance of the strainer at the bottom of suction pipe to the exit on the delivery end of the elbow of discharge head consists of the sum of head losses incurred at the entrance of the strainer, strainer itself, suction pipe, body of the pumping unit, vertical portion of delivery pipe in the well with the shafting arrangement, elbow of the discharge head at the ground surface, check valve, and exit head loss $V_{ex}^2/2g$. Not counting the head loss, h_p, in the body of the pumping unit and the exit head loss, $V_{ex}^2/2g$, the head loss, H_2, from the entrance of the strainer to the delivery end of the elbow of discharge head is given as

$$H_2 = h_s + h_d \tag{2-31}$$

At the delivery end of the elbow at the discharge head, a check valve usually is installed to control the flow rate. Starting from the delivery end of the discharge head, three situations can be considered for the exiting flow in order to determine the total dynamic head being imposed on the pumping unit.

2.4.1 Water Discharge into the Free Atmosphere

When water is being discharged into the free atmosphere (see Fig. 2-9), the check valve would generate an additional head loss, h_{val}. Not counting the head loss, h_p, in the body of the pump, the total dynamic head, h, being imposed on the pumping unit is the sum

$$h = H_1 + H_2 + h_{val} + \frac{V_{ex}^2}{2g} \tag{2-32}$$

2.4.2 Water Discharge into the Service Main

If water is being pumped directly into the service main (see Fig. 2-10), then the additional head loss or the external head loss in the service main, H_{mn}, should be read from the delivery gauge fixed to the delivery flange of the discharge head. The external head loss, H_{mn}, would consist of head loss due to the check valve, h_{val}, head loss due to pipe friction in the service main, h_{mn}, any rise or fall in the elevation head of the service main, h_{me}, and other minor losses in the service main, h_{mi}, or in equation form

$$H_{mn} = h_{val} + h_{mn} \pm h_{me} + h_{mi} \tag{2-33}$$

Whenever there is a rise in elevation for the main service line, a positive sign (+) would precede the head loss, h_{me}, in Eq. (2-33), but whenever there

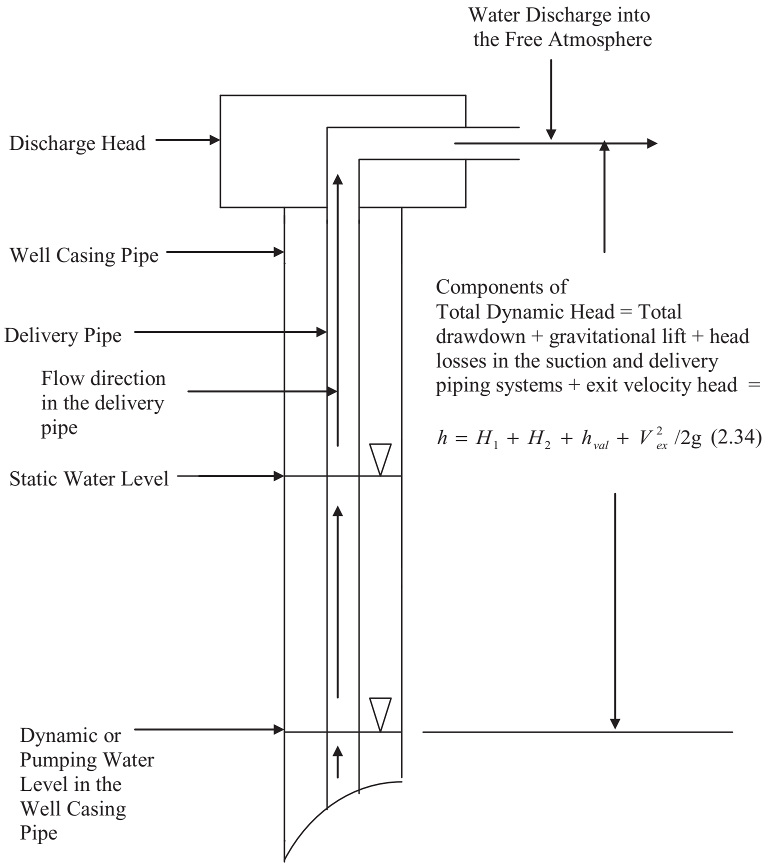

Fig. 2-9. Components of the total dynamic head for water discharge issuing from the delivery pipe into the free atmosphere

is a fall in elevation, a negative sign should be substituted instead. Again, not counting head loss, h_p, in the body of the pump, the total dynamic head, h, being imposed on the pumping unit when the water is being pumped into the service main is then the sum

$$h = H_1 + H_2 + H_{mn} + \frac{V_{ex}^2}{2g} \tag{2-34}$$

2.4.3 Water Discharge into the Overhead Tank

If water is being pumped into an overhead tank (see Fig. 2-11), the additional head loss or the external head loss in the overhead tank

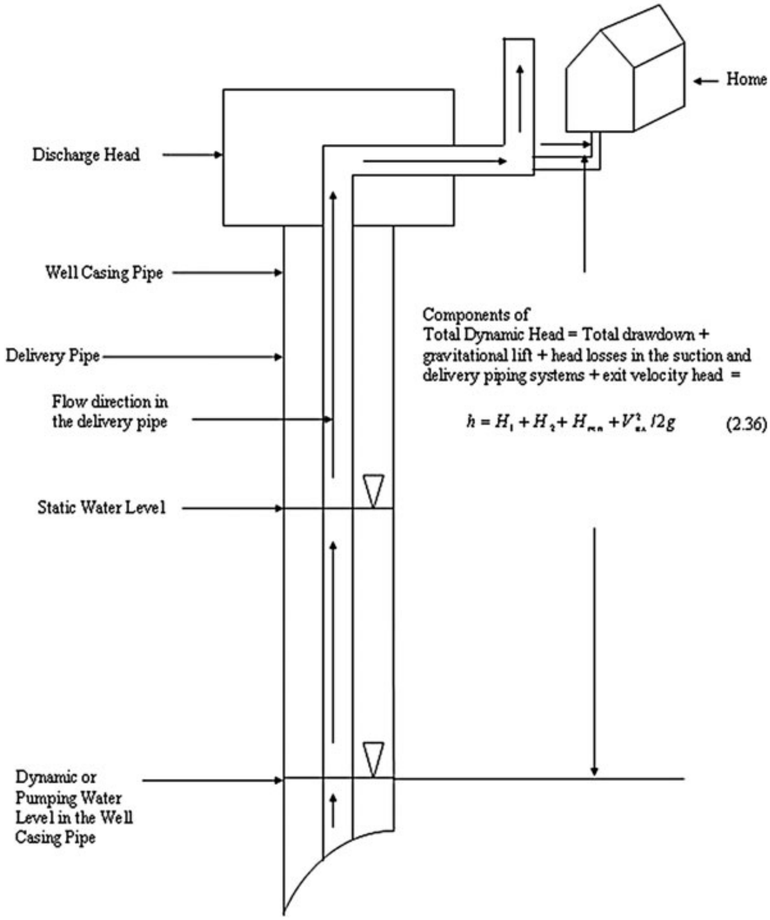

Fig. 2-10. Components of the total dynamic head for water discharge issuing from the delivery pipe into the service main

arrangement, H_{ot}, should be read from the delivery gauge fixed to the delivery flange of the discharge head.

The external head loss, H_{ot}, would then consist of head loss due to check valve, h_{val}, head loss due to pipe friction in the horizontal portion of the delivery pipe on the ground beyond the check valve, h_{ot1}, head loss because of the 90° bend between the horizontal portion of the delivery pipe beyond the check valve and the vertical portion of the delivery pipe leading to the overhead tank, h_{be}, head loss due to pipe friction in the vertical portion of the delivery pipe between the bend and the overhead tank, h_{ot2}, head loss due to flow expansion at the junction of the vertical portion of the delivery pipe and the overhead tank, h_{exp}, friction loss in the overhead tank, h_{fot}, and

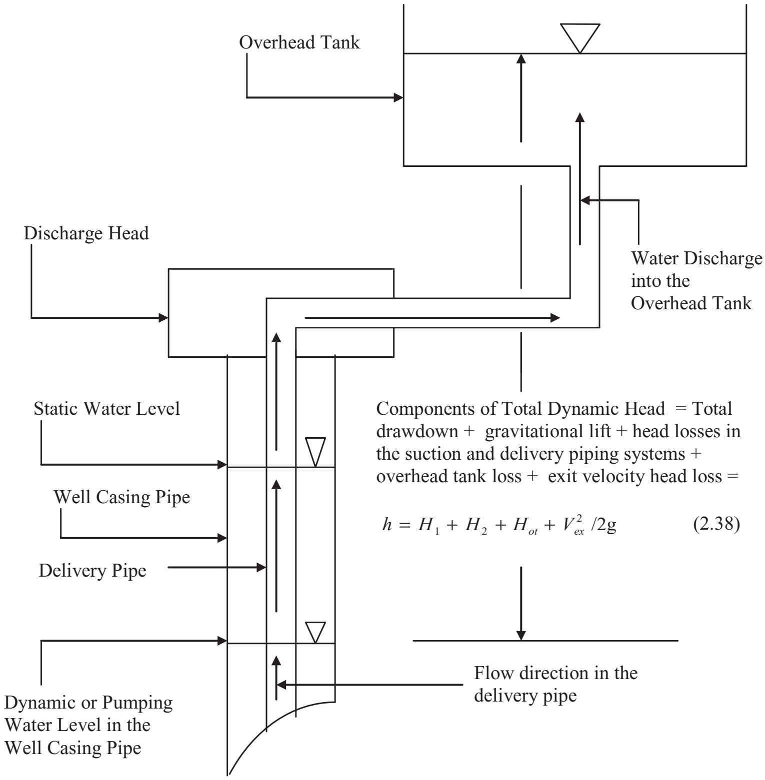

Fig. 2-11. Components of total dynamic head for water discharge moving through the delivery piping system into the overhead tank

the elevation head from the centerline of the elbow of discharge head to the free surface in the overhead tank, h_{el}, or in equation form

$$H_{ot} = h_{val} + h_{ot1} + h_{be} + h_{ot2} + h_{exp} + h_{fot} + h_{el} \tag{2-35}$$

Again, not counting head loss, h_p, in the body of the pump, the total dynamic head, h, being imposed on the pumping unit when the water is being pumped into the overhead tank is then the sum

$$h = H_1 + H_2 + H_{ot} + \frac{V_{ex}^2}{2g} \tag{2-36}$$

Also, the existence of the exit velocity head, $V_{ex}^2 / 2g$, always should be verified for inclusion either in Eq. (2-34) or in Eq. (2-36) for proper determination of the total dynamic head. However, the head loss in the overhead tank and the velocity head usually are neglected in Eq. (2-36).

2.5 EFFICIENCY OF WATER-WELL SYSTEMS

From a practical standpoint, three types of efficiencies can be defined for a given water-well system:

1. Efficiency as related to total drawdown in a water-well system (well efficiency),
2. Efficiency as related to an electric motor coupled to a water-well system (wire-to-water efficiency), and
3. Efficiency as related to an internal combustion engine coupled to a water-well system (overall efficiency).

Efficiency determined at the level of total drawdown, s_w, (or s_{wd}), indicates the performance of the water well. Normally it is called the *well efficiency*. This efficiency term indicates neither the overall efficiency of a water-well system nor any relevance to the pumping unit, piping system, prime mover, or power supply system. It is related only to the hydraulics of aquifer formation, damage zone, filter envelope, well screen, wellbore, and well casing.

Efficiency determined at the level of an electric motor generally is known as the *wire-to-water efficiency.* This efficiency term is neither an overall efficiency of a water-well system nor does it explain any relationship to the power supply system. Also, it is neither practically feasible nor economically desirable to determine the overall efficiency for electrically driven water-well systems. It does, however, point out the combined performance of aquifer formation, damage zone, filter pack envelope, well screen, wellbore, well casing, suction and delivery piping systems, pumping unit, and prime mover (the electric motor).

Efficiency determined at the level of an internal combustion engine normally is known as the *overall efficiency*, complete in every respect for a given water-well system. This efficiency term is related to the entire water-well system and gives a complete picture of total system performance. It is related to the total combined performance of aquifer formation, damage zone, filter pack envelope, well screen, wellbore, well casing, suction and delivery piping systems, pumping unit, prime mover (gear drive), and power supply system (internal combustion engine).

Applying the power concept to well hydraulics, the efficiency, E, on a percentage basis of a given water-well system can be defined as the ratio of output power to input power times 100 (Stramel 1965), or

$$E = \frac{\text{Output Power of Water-Well System}}{\text{Input Power to Water-Well System}} \times 100\% \qquad (2\text{-}37)$$

In the light of Eq. (2-37), the three types of efficiencies as described are detailed for three water-well systems, respectively, as follows. This process includes equations comprising the brake power (or input power), water power (or output power), and efficiency for each one of the three water-well systems.

2.5.1 Water-Well System I at the Level of Total Drawdown

Water-Well System I consists of the aquifer formation, damage zone, filter pack envelope, well screen, well casing, suction and delivery piping systems, pumping unit, prime mover (electric motor or gear drive), and power supply source (electric or thermal). Determination of well efficiency at the level of total drawdown, s_w (or s_{wd}), is equally applicable to all water-well systems, regardless of the type of either the prime mover or the power supply source being used for their operations.

2.5.1.1 Input Power of Water-Well System I The total drawdown, s_w, usually is ascertained either by analytical or semi-analytical means for new wells or by direct measurement for pumping wells. Similarly, the total drawdown, s_{wd}, also can be determined either through computational procedures or by step-drawdown tests of pumping wells. However, distinction always should be drawn when using either one of those total drawdown quantities as shown following.

Assuming the discharge of the pumping well is given in cubic meters per second, (m^3/s), then Eqs. (2-38) and (2-39) can be used to determine the brake power (or input power), $(bp)_1$, of Water-Well System I at the level of total drawdown, either s_w, or s_{wd}, (Ahmed 1987). For s_w using Eq. (2-14)

$$(bp)_{ww-\mathrm{I}} = \frac{\rho g Q s_w}{1{,}000} \tag{2-38}$$

For s_{wd} using Eq. (2-15) or (2-21)

$$(bp)_{ww-\mathrm{I}} = \frac{\rho g Q s_{wd}}{1{,}000} \tag{2-39}$$

where $(bp)_{ww\text{-}\mathrm{I}}$ = brake power (or input power) of Water-Well System I at the level of total drawdown, either for s_w or for s_{wd}, (kW).

2.5.1.2 Output Power of Water-Well System I The total drawdown, s_w, is composed of two parts, (Eq. [2-14]). The drawdown, s_1 (Eq. [2-12]), based on the head loss due to flow through the aquifer, damage zone, and filter pack envelope, performs a useful function and provides the water power or output power that makes the water flow toward the well. The drawdown, s_2 (Eq. [2-13]), is based on the head loss due to flow through the well screen, along the borehole, and within the well casing and is lost permanently. This part of the head loss does not perform any useful function, and it does not move any water in Water-Well System I either. Similarly, the total drawdown, s_{wd} (Eq. [2-15]), is based on step-drawdown test data, which also has two components. The drawdown, s_{1d}, (Eq. [2-16]), performs a useful function, allowing water to move toward the well, but the drawdown, s_{2d} (Eq. [2-19]), does not perform any useful function and is lost permanently. It is advisable that distinction always should be drawn when using either s_1 or s_{1d}.

Assuming the discharge of the pumping well is given in cubic meters per second, (m^3/s), then Eqs. (2-40) and (2-41) can be used to determine the water power (or output power) of Water-Well System I at the level of partial drawdown, either at s_1 or at s_{1d} (Ahmed 1987). For s_1 using Eq. (2-12)

$$(wp)_{ww-\mathrm{I}} = \frac{\rho g Q s_1}{1{,}000} \tag{2-40}$$

For s_{1d} using Eq. (2-16)

$$(wp)_{ww-\mathrm{I}} = \frac{\rho g Q s_{1d}}{1{,}000} \tag{2-41}$$

where $(wp)_{ww\text{-}\mathrm{I}}$ = water power (or output power) of Water-Well System I at the level of partial drawdown, either for s_1 or for s_{1d} , (kW).

2.5.1.3 Efficiency of Water-Well System I The well efficiency, $E_{ww\text{-}\mathrm{I}}$, of Water-Well System I at the level of total drawdown, either at s_w or at s_{wd}, in the well is given as

$$E_{ww-\mathrm{I}} = \frac{\text{Output Power of Water-Well System 1}}{\text{Input Power to Water-Well System 1}} \times 100\%$$

or,

$$E_{ww-\mathrm{I}} = \frac{(wp)_{ww-1}}{(bp)_{ww-1}} \times 100\% \tag{2-42}$$

where $E_{ww\text{-}\mathrm{I}}$ = well efficiency for a Water-Well System I at the level of total drawdown, either at s_w (Eq. [2.14]) or s_{wd} (Eq. [2-21]) in the well, (dimensionless).

By substituting the values of water power (or output power), $(wp)_{ww\text{-I}}$, and brake power (or input power), $(bp)_{ww\text{-I}}$, into Eq. (2-42), equations can be developed for the well efficiency, $E_{ww\text{-I}}$, of Water-Well System I at the level of total drawdown, either at s_w or s_{wd}, respectively, and can be determined as follows (Bierschenk 1964). For s_w use Eq. [2.14]. Substitute Eq. (2-40) for water power and Eq. (2-38) for brake power into Eq. (2-42) as follows:

$$E_{ww-\mathrm{I}} = \frac{\rho g Q s_1 / 1{,}000}{\rho g Q s_w / 1{,}000} \times 100\%$$

or,

$$E_{ww-\mathrm{I}} = \frac{s_1}{s_w} \times 100\% \qquad (2\text{-}43)$$

For s_{wd} use Eq. (2-15). Substitute Eq. (2-41) for water power and Eq. (2-39) for brake power into Eq. (2-42) as follows:

$$E_{ww-\mathrm{I}} = \frac{\rho g Q s_{1d} / 1{,}000}{\rho g Q s_{wd} / 1{,}000} \times 100\%$$

or,

$$E_{ww-\mathrm{I}} = \frac{s_{1d}}{s_{wd}} \times 100\% \qquad (2\text{-}44)$$

2.5.2 Water-Well System II at the Level of Electric Motor

Water-Well System II consists of the aquifer formation, damage zone, filter pack envelope, water well (screen and casing), pumping unit, suction and delivery piping systems, prime mover (electric motor), and electric power supply system. Determination of efficiency for the Water-Well System II at the level of electric motor will be indicative of the wire-to-water efficiency and will not include any discussion pertaining to the electric power supply systems (Fink and Beaty 2012).

2.5.2.1 Input Power of Water-Well System II The brake power (or input power), $(bp)_{ww\text{-II}}$, of the electric motor for the Water-Well System II at the level of electric motor is given in SI units as (Kaiser 1998)

$$(bp)_{ww-11} = \frac{1.73EI(pf)}{1{,}000} \qquad (2\text{-}45)$$

where

$(bp)_{ww\text{-II}}$ = brake power (or input power) of Water-Well System II at the level of electric motor, (kW)
E = line voltage in volts, (V)
I = line current in amperes, (A)
pf = lagging power factor, (dimensionless).

The three electrical quantities, E, I, and pf, associated with the electric motor and given in Eq. (2-45), can be measured in the field using the requisite instruments and thus the brake power (or input power), $(bp)_{ww\text{-II}}$, of Water-Well System II at the level of electric motor can be computed.

2.5.2.2 Output Power of Water-Well System II Assuming the discharge of the pumping well is given in cubic meters per second, (m^3/s), and utilizing the concept of total dynamic head, h, as given in Eqs. (2-32), (2-34), or (2-36), the water power (or output power), $(wp)_{ww\text{-II}}$, in kilowatts, kW, of Water-Well System II can be obtained as (Ahmed 1987):

$$(wp)_{ww-11} = \frac{\rho g Q h}{1{,}000} \tag{2-46}$$

where $(wp)_{ww\text{-II}}$ = water power (or output power) of Water-Well System II, (kW).

2.5.2.3 Efficiency of Water-Well System II The wire-to-water efficiency, $E_{ww\text{-II}}$, of Water-Well System II, at the level of electric motor is given as

$$E_{ww-\text{II}} = \frac{\text{Output Power of Water-Well System II}}{\text{Input Power to Water-Well System II}} \times 100\%$$

or,

$$E_{ww-\text{II}} = \frac{(wp)_{ww-\text{II}}}{(bp)_{ww-\text{II}}} \times 100\% \tag{2-47}$$

where $E_{ww\text{-II}}$ = wire-to-water efficiency of Water-Well System II at the level of electric motor, (dimensionless).

Assuming the discharge of the pumping well is given in cubic meters per second, (m^3/s), then Eq. (2-48) can be used to determine the wire-to-water efficiency of Water-Well System II at the level of electric motor, $E_{ww\text{-II}}$. Substituting the values of water power (or output power), $(wp)_{ww\text{-II}}$, of Water-Well System II from Eq. (2-46) and brake power (or input power),

$(bp)_{\text{ww-II}}$, of Water-Well System II at the level of electric motor from Eq. (2-45) into Eq. (2-47) gives the percentage wire-to-water efficiency, $E_{ww\text{-II}}$, of Water-Well System II at the level of electric motor as:

$$E_{ww-\text{II}} = \frac{\rho g Q h / 1{,}000}{1.73 EI(pf)/1{,}000} \times 100\%$$

or,

$$E_{ww-\text{II}} = \frac{0.578 \rho g Q h}{EI(pf)} \times 100\% \qquad \text{(2-48)}$$

2.5.3 Water-Well System III at the Level of Internal Combustion Engine

Water-Well System III consists of the aquifer formation, damage zone, filter pack envelope, water well (screen and casing pipes), pumping unit, piping system, prime mover (gear drive), and a power source (the internal combustion engine). The Water-Well System III operates through the arrangement of thermal power as generated by burning a fuel supply in an internal combustion engine. Internal combustion engines commonly are used as a power source to run pumping units all over the world where fossil fuels are abundantly available and are cheaper than the electric power supplies (Ganesan 1996; Heywood 1988; Pulkrabek 2003).

2.5.3.1 Input Power of Water-Well System III The brake power (or input power) of the internal combustion engine will be considered as the brake power (or input power) of Water-Well System III at the level of internal combustion engine.

Assuming the mass flow rate of the engine fuel is given in kilograms per second, (kg/s), Eq. (2-49) can be used to determine the brake power (or input power) of Water-Well System III, considering the conversion factors, 1 J/s = 1 W, 1 kJ/s = 1 kW, and 1 kW = 1,000 W. The brake power (or input power), $(bp)_e$, of Water-Well System III is given directly in kilowatts, kW (Ganesan 1996):

$$(bp)_e = \frac{mC}{1{,}000} \qquad \text{(2-49)}$$

where

$(bp)_e$ = brake power (or input power) of Water-Well System III, in kilowatts, (kW), at the level of internal combustion engine
m = mass flow rate of engine fuel, kilograms per second, (kg/s)
C = calorific value of engine fuel, Joules per kilogram, (J/kg).

2.5.3.2 Output Power of Water-Well System III Assuming the discharge of the pumping well is given in cubic meters per second, (m^3/s), and utilizing the concept of total dynamic head, h, as given in Eqs. (2-32), (2-34), or (2-36), the water power (or output power), $(wp)_{ww\text{-III}}$, in kilowatts, kW, of Water-Well System III can be obtained as (Ahmed 1987):

$$(wp)_{ww-\text{III}} = \frac{\rho g Q h}{1{,}000} \tag{2-50}$$

where $(wp)_{\text{ww-III}}$ =water power (or output power) of Water-Well System III, (kW).

2.5.3.3 Efficiency of Water-Well System III The overall efficiency of Water-Well System III, $E_{0\text{-III}}$, at the level of internal combustion engine can be determined as

$$E_{0-\text{III}} = \frac{\text{Output Power of Water-Well System III}}{\text{Input Power to Water-Well System III}} \times 100\%$$

or,

$$E_{0-\text{III}} = \frac{(wp)_{ww-\text{III}}}{(bp)_{ww-\text{III}}} \times 100\% \tag{2-51}$$

where $E_{0\text{-III}}$ = overall efficiency of Water-Well System III at the level of internal combustion engine, (dimensionless)

Assuming the discharge of a pumping well is given in cubic meters per second (m^3/s), then Eq. (2-52) can be used to determine the overall efficiency of Water-Well System III at the level of internal combustion engine. Substituting values of water power (or output power), $(wp)_{ww\text{-III}}$, of Water-Well System III from Eq. (2-50) and brake power (or input power), $(bp)_{ww\text{-III}}$, of Water-Well System III from Eq. (2-49) into Eq. (2-63) gives the percentage overall efficiency, $E_{0\text{-III}}$, of Water-Well System III at the level of internal combustion engine as

$$E_{0-\text{III}} = \frac{\rho g Q h / 1{,}000}{mC / 1{,}000} \times 100\%$$

or,

$$E_{0-\text{III}} = \frac{\rho g Q h}{mC} \times 100\% \tag{2-52}$$

2.6 SOLVED DESIGN EXAMPLE 1

A water well 70 m deep and 200 mm diameter fully penetrates a 45 m thick gravel-sand phreatic aquifer. The hydraulic conductivity of the aquifer material is known to be $K = 10^{-1}$ mm/s so that the transmissivity, $T = Kb_0 = 388.8\,\text{m}^2/\text{d}$. The static head is $H_s = 25$ m. From observation wells, the radius of the zone of influence is estimated to be $r_0 = 100$ m. The design discharge is $Q = 3{,}000\,\text{m}^3/\text{d} = 0.0347\,\text{m}^3/\text{s}$. The well is screened along the entire 45 m depth of the aquifer, and the screen is 25% porous. The thickness and hydraulic conductivity of the filter pack envelope are given as 100 mm and 3.25 mm/s, respectively. Water is being pumped directly into the service main, and the pressure of the delivery gauge fixed to the delivery end of the discharge head at the ground surface is 400 kPa. The pump is submerged at the end of a 75 mm diameter steel discharge pipe. The suction pipe is 2 m long with a strainer on the end and is positioned 6 m above the bottom of the well. The end of the suction pipe is squared off. In addition, the well was developed carefully so that a minimal amount of drilling fluid remains in the adjacent portion of the aquifer. The equivalent sand-grain roughness for the piping as provided by the manufacturer is $\varepsilon = 0.045$ mm. Calculate the total dynamic head.

Solution The total dynamic head, h, imposed on the pumping unit is given by Eq. (2-34) as

$$h = H_1 + H_2 + H_{mn} + \frac{V_{ex}^2}{2g}$$

The total dynamic lift, H_1, from the water surface in the pumping well to the ground surface is given by Eq. (2-30) as the sum of the static head, H_s, and the total drawdown, s_w, or

$$H_1 = H_s + s_w$$

From the data given in the design problem, the depth of the static water level from the ground surface can be calculated as

$$H_s = \text{total depth of the well} - \text{thickness of the aquifer} = 70 - 45 = 25\text{ m}$$

The total drawdown, s_w, measured in the water well is given as the total sum of component head-losses by Eq. (2-29) as

$$s_w = h_{af} + h_{pe} + h_{gp} + h_{ws} + h_{wb} + h_{wc}$$

The various component head losses of the total drawdown can be computed individually as follows. The drawdown, h_{af}, caused by the flow resistance in the aquifer can be determined by Eq. (2-1) as

$$h_{af} = \frac{Q}{2\pi T}\ln\left(\frac{r_0}{r_e}\right) = \frac{3,000}{2\pi(389)}\ln\left(\frac{100}{0.2}\right) = 7.63 \text{ m}$$

As the damage zone does not exist, therefore

$$h_{pe} = 0$$

The head loss due to the filter pack envelope can be determined by Eq. (2-4) as

$$h_{gp} = \frac{Q}{2\pi K_{gp} L_{gp}}\ln\left(\frac{r_{gp}}{r_w}\right) = \frac{(0.0347)(1,000)}{2\pi(3.25)(45)}\ln\left(\frac{200}{100}\right) = 0.026 \text{ m}$$

The open or porous area of the well screen is

$$A_{ws} = \pi D_w L_{ws} p_{ws} C_g = \pi(0.2)(45)(0.25)(0.50) = 3.53 \text{ m}^2$$

Assuming that 50% of the entrances to the screen are clogged, the head loss h_{ws} across the well screen, according to Eq. (2-5), is

$$h_{ws} = \frac{Q^2}{2gA_{ws}^2 C_c^2} = \frac{(0.0347)^2}{2(9.81)(3.53)^2(0.61)^2} = 10^{-5} \text{ m}$$

which is quite small. The velocity through the screen is $V_{ws} = Q/A_{ws} = 10^{-2}$ m/s, which is quite acceptable and accounts for the low head loss through the screen.

In this example, the most important loss apart from the loss in the aquifer is the turbulent head loss in the well casing due to flow along the well screen. Using the empirical Eqs. (2-7) and (2-8), estimates for the coefficients α and β can be made:

$$\alpha = 877e^{-0.618(200/25)} = 6.25 \text{ s}^2/\text{m}^6$$

$$\beta = 18,963e^{-0.5369(200/25)} = 258.5 \text{ s}^2/\text{m}^5$$

The wellbore loss due to flow along the well screen is then

$$h_{wb} = \left(\frac{1}{4}\alpha L_{wb} + \frac{1}{3}\beta\right)Q^2 = \left[\frac{1}{4}(6.25)(45) + \frac{1}{3}(258.5)\right](0.0347)^2 = 0.19 \text{ m}$$

Finally, in this example, there is no flow along any blind casing so that the friction loss inside the casing is zero, or

$$h_{wc} = 0$$

Collecting all of these losses, the total drawdown, s_w, produced by the well-aquifer system is estimated to be

$$s_w = h_{af} + h_{gp} + h_{pe} + h_{ws} + h_{wb} + h_{wc}$$

or,

$$s_w = 7.63 + 0.026 + 0 + 10^{-5} + 0.19 + 0 = 7.85 \text{ m}$$

According to Eq. (2-30), the gravitational lift, H_1, to the water surface is equal to the depth of the static piezometric surface plus the total drawdown, or

$$H_1 = H_s + s_w = 25 + 7.85 = 32.85 \text{ m}$$

To find the frictional losses in the suction pipeline and discharge pipeline up to the delivery end of the discharge head, the average flow velocity in the suction and delivery pipes is calculated as

$$V_s = V_d = Q / A = 0.0347 / 0.00442 = 7.86 \text{ m/s}$$

In this case, while determining the velocity in the delivery pipe, the effect of the shafting arrangement has been neglected. The Reynolds number is then

$$R_e = \frac{VD}{\upsilon} = \frac{(7.86)(0.075)}{10^{-6}} = 6 \times 10^5$$

and the relative roughness for a 75 mm diameter pipe is

$$\frac{\varepsilon}{D} = \frac{0.045}{75} = 0.0006$$

Using these values of the Reynolds number and relative roughness, the friction factor is found from the Moody diagram to be $f = 0.018$. The entrance loss coefficient, strainer loss coefficient, and check valve loss coefficient are $k_{ent} = 1.0$, $k_{str} = 1.0$, and $k_v = 2.0$, respectively.

The head loss in the suction pipe may be estimated from Fig. 2-4, or it can be calculated by utilizing Eq. (2-26) as

$$h_s = h_{ent} + h_{str} + h_{su} = \left(k_{ent} + k_{str} + f\frac{L_s}{D_s} \right) \frac{Q^2}{2gA_s}$$

or,

$$h_s = \left(1.0 + 1.0 + 0.018 \times \frac{2}{0.075} \right) \frac{(0.0347)^2}{(2)(9.81)(0.00442)^2} = 7.79 \text{ m}$$

Likewise, the head loss in the delivery pipe may be estimated from Fig. 2-4, or it can be calculated by utilizing Eq. (2-27) as

$$h_d = h_{dp} + h_{sh} + h_{dis} = f\frac{L_d}{D_d}\frac{Q^2}{2gA_d^2} + h_{sh} + h_{dis}$$

or,

$$h_d = 0.018 \times \frac{62}{0.075} \times \frac{(0.0347)^2}{(2)(9.8)(0.00442)^2} + 0 + 0 = 46.74 \text{ m}$$

In this computation the shafting loss, as well as the head loss due to the elbow of the discharge head, has been ignored, or

$$h_{sh} = h_{dis} = 0$$

According to Eq. (2-31), the head loss, H_2, occurring in the suction pipeline and the delivery pipeline up to and including the delivery end of the discharge head can be calculated as

$$H_2 = h_s + h_d = 7.79 + 46.74 = 54.53 \text{ m}$$

The large head loss in the vertical portion of the delivery pipe in the well is because of a very high velocity in the pipe. Increasing the diameter of the discharge pipe, which would require an increase in the well diameter, would decrease this head loss term. However, it should be remembered that such changes in the design would cause additional expenditures.

The required pressure head, H_{mn}, at the ground surface, not counting the velocity head or the exit loss, to counter balance the rise in elevation and the external resistance to flow is

$$H_{mn} = \frac{p}{\gamma} = \frac{p}{\rho g} = \frac{400{,}000}{(1{,}000)(9.81)} = 40.77 \text{ m}$$

The total dynamic head under the prevailing conditions that the pump must provide to the fluid, according to Eq. (2-34), is

$$h = H_1 + H_2 + H_{mn} + \frac{V_{ex}^2}{2g}$$

Ignoring the exit head loss (i.e., $V_{ex}^2 / 2g = 0$)

$$h = 32.85 + 54.53 + 40.77 + 0 = 128.15\,\text{m}$$

2.7 SOLVED DESIGN EXAMPLE 2

A three-phase electric motor is driving a deep-well turbine pump. The line current for the electric motor was measured to be 96 A at a voltage of 250 V with a lagging power factor *pf* of 0.80. The static head ($H_s = 15\,\text{m}$) and total drawdown ($s_w = 20\,\text{m}$) for the pumping well are shown in Fig. 2-12.

The discharge line is delivering water to an overhead tank, and the vertical distance between the centerline of the horizontal portion of the discharge pipe at the ground surface and the free surface of water in the overhead tank, or the elevation head, is $h_{el} = 33\,\text{m}$. The head loss for the discharge column containing the shafting arrangement is $h_{dp} = 0.39\,\text{m}$. The head loss for the discharge line leading from the discharge head to the overhead tank is $h_{dl} = 0.42\,\text{m}$, with $h_{ot1} = 0.12\,\text{m}$, for the horizontal portion on the ground level, and $h_{ot2} = 0.3\,\text{m}$, for the vertical portion of the discharge line. The mechanical loss for the shaft line is 1.96 kW. The head loss for the discharge-head elbow is $h_{dis} = 0.035\,\text{m}$, whereas the head loss for the elbow in the discharge pipe leading to the overhead tank is also $h_{be} = 0.07\,\text{m}$. The head loss for the suction pipe in the well is $h_{su} = 0.07\,\text{m}$. Ignore the head losses at the entrance of the strainer and the strainer, as well as the exit head loss; in other words

$$h_{ent} = h_{str} = h_{val} = h_{exp} = h_{fot} = \frac{V_{ex}^2}{2g} = 0$$

For a well discharge of $0.0315\,\text{m}^3/\text{s}$, determine the wire-to-water efficiency, E_2, of the Water-Well System II at the level of electric motor.

Solution The brake power (or input power), $(bp)_{ww\text{-II}}$, of the electric motor for the Water-Well System II at the level of electric motor is given by Eq. (2-45), in SI units, as

$$(bp)_{ww-\text{II}} = \frac{1.73EI(pf)}{1{,}000} = \frac{(1.73)(250)(96)(0.80)}{1{,}000} = 33.22\,\text{kW}$$

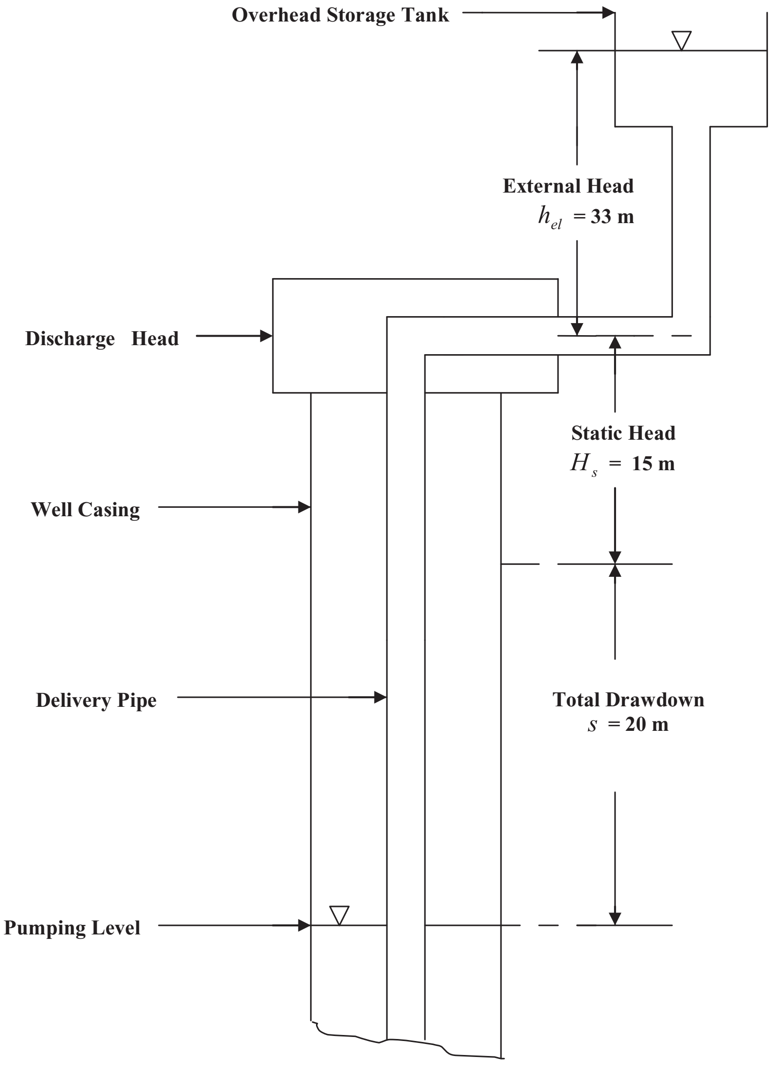

Fig. 2-12. Delivery pipe and overhead tank connection

Using Eq. (2-36), the total dynamic head imposed on the turbine pump is

$$h = H_1 + H_2 + H_{ot} + \frac{V_{ex}^2}{2g}$$

Using Eq. (2-30)

$$H_1 = H_s + s_w = 15 + 20 = 35 \text{ m}$$

Using Eq. (2-26), the head loss in the suction piping system is

$$h_s = h_{ent} + h_{str} + h_{su} = 0 + 0 + 0.07 = 0.07 \text{ m}$$

Using Eq. (2-27), the head loss in the delivery piping system is

$$h_d = h_{dp} + h_{sh} + h_{dis} = 0.39 + h_{sh} + 0.035 = 0.425 + h_{sh}$$

The head loss from the entrance of the strainer to the delivery end of the elbow of the discharge head is determined from Eq. (2-31) as

$$H_2 = h_s + h_d = 0.07 + 0.425 + h_{sh} = 0.495 + h_{sh}$$

Using Eq. (2-35), the external head loss from the elbow of the discharge head to the overhead tank is

$$\begin{aligned} H_{ot} &= h_{val} + h_{ot1} + h_{be} + h_{ot2} + h_{exp} + h_{fot} + h_{el} \\ &= 0 + 0.12 + 0.07 + 0.30 + 0 + 0 + 33 = 33.49 \text{ m} \end{aligned}$$

Substituting the values of H_1, H_2, and H_{ot} into Eq. (2-36), the total dynamic head imposed on turbine pump

$$h = H_1 + H_2 + H_{ot} + \frac{V_{ex}^2}{2g} = 35 + 0.495 + h_{sh} + 0 + 33.49 = 68.985 + h_{sh}$$

Using Eq. (2-46), the water power (or, output power) of Water-Well System II

$$(wp)_{ww-\text{II}} = \frac{\rho g Q h}{1{,}000} = \frac{\rho g Q(68.985 + h_{sh})}{1{,}000} = \frac{\rho g Q(68.985)}{1{,}000} + \frac{\rho g Q h_{sh}}{1{,}000}$$

$$(wp)_{ww-\text{II}} = \frac{(1{,}000)(9.81)(0.0315)(68.985)}{1{,}000} + \frac{\rho g Q h_{sh}}{1{,}000}$$

$$(wp)_{ww-\text{II}} = 21.32 + 1.96 = 23.28 \text{ kW}$$

Using Eq. (2-47), the wire-to-water efficiency, $E_{ww\text{-II}}$, of Water-Well System II, at the level of electric motor is given as

$$E_{ww-\text{II}} = \frac{(wp)_{ww-\text{II}}}{(bp)_{ww-\text{II}}} \times 100\%$$

Substituting values of the water power = $(wp)_{ww\text{-II}} = 23.28\,\text{kW}$ and brake power = $(bp)_{ww\text{-II}} = 33.22\,\text{kW}$ for the Water-Well System II into the previous equation is

$$E_{ww-\text{II}} = \frac{23.28}{33.22} \times 100 = 70.1\%$$

2.8 SOLVED DESIGN EXAMPLE 3

A deep-well turbine pump is being driven by an internal combustion engine. The fuel consumption of the engine was gauged to be $1/3 \times 10^{-2}\,\text{kg/s}$ with a calorific value of 42,000,000 J/kg. The water level in the pumped well (Fig. 2-12) was measured between the centerline of horizontal portion of the discharge pipe at the ground surface and the pumping level in the discharge well to be 35 m (static head of $H_s = 15\,\text{m}$ and total drawdown of $s_w = 20\,\text{m}$). The discharge line is delivering water to an overhead tank, and the vertical distance between the centerline of the horizontal portion of the discharge pipe at the ground surface and the free surface in the overhead tank, or the elevation head, is $h_{el} = 33\,\text{m}$. The head loss for the discharge column is $h_{dp} = 0.39\,\text{m}$. The head loss for the discharge line leading to the overhead tank is $h_{dl} = 0.42\,\text{m}$, with $h_{ot1} = 0.12\,\text{m}$ for the horizontal portion on the ground level, and $h_{ot2} = 0.3\,\text{m}$ for the vertical portion of the discharge line. The mechanical loss for the shaft line in the discharge column is 1.96 kW. The head loss for each of the two elbows, one for the discharge head and the other for the vertical pipe leading to the overhead tank, is 0.035 m. The head loss for the suction pipe is $h_{su} = 0.07\,\text{m}$. Ignore head losses for the entrance to the strainer, strainer, check valve, and exit head loss (i.e., $h_{ent} = h_{str} = h_{val} = h_{exp} = h_{fot} = V_{ex}^2/2g = 0$). For a water-well discharge of $0.0315\,\text{m}^3/\text{s}$, determine the overall efficiency, E_3, of Water-Well System III.

Solution Using Eq. (2-49), the brake power (or input power) at the level of the internal combustion engine is

$$(bp)_e = \frac{mC}{1{,}000} = \frac{(1/3 \times 10^{-2})(42{,}000{,}000)}{1{,}000} = 140\ \text{kW}$$

Using Eq. (2-36), the total dynamic head imposed on the turbine pump is

$$h = H_1 + H_2 + H_{ot} + \frac{V_{ex}^2}{2g}$$

Using Eq. (2-30)

$$H_1 = H_s + s_w = 15 + 20 = 35 \text{ m}$$

Using Eq. (2-26), the head loss in the suction piping system is

$$h_s = h_{ent} + h_{str} + h_{su} = 0 + 0 + 0.07 = 0.07 \text{ m}$$

Using Eq. (2-27), the head loss in the delivery piping system is

$$h_d = h_{dp} + h_{sh} + h_{dis} = 0.39 + h_{sh} + 0.035 = 0.425 + h_{sh}$$

The head loss from the entrance of the strainer to the delivery end of the elbow of the discharge head is determined from Eq. (2-31) as

$$H_2 = h_s + h_d = 0.07 + 0.425 + h_{sh} = 0.495 + h_{sh}$$

Using Eq. (2-35), the external head loss from the elbow of the discharge head to the overhead tank is

$$\begin{aligned} H_{ot} &= h_{val} + h_{ot1} + h_{be} + h_{ot2} + h_{exp} + h_{fot} + h_{el} \\ &= 0 + 0.12 + 0.07 + 0.30 + 0 + 0 + 33 = 33.49 \text{ m} \end{aligned}$$

Substituting the values of H_1, H_2, and H_{ot} into Eq. (2-36), the total dynamic head imposed on turbine pump

$$h = H_1 + H_2 + H_{ot} + \frac{V_{ex}^2}{2g} = 35 + 0.495 + h_{sh} + 0 + 33.49 = 68.985 + h_{sh}$$

Using Eq. (2-46), the water power (or, output power) of Water-Well System III

$$(wp)_{ww-\text{III}} = \frac{\rho g Q h}{1{,}000} = \frac{\rho g Q (68.985 + h_{sh})}{1{,}000} = \frac{\rho g Q (68.985)}{1{,}000} + \frac{\rho g Q h_{sh}}{1{,}000}$$

$$(wp)_{ww-\text{III}} = \frac{(1{,}000)(9.81)(0.0315)(68.985)}{1{,}000} + \frac{\rho g Q h_{sh}}{1{,}000}$$

$$(wp)_{ww-\text{III}} = 21.32 + 1.96 = 23.28 \text{ kW}$$

Using Eq. (2-51), the overall efficiency of Water-Well System III at the level of internal combustion engine is

$$E_{0-\text{III}} = \frac{(wp)_{ww-\text{III}}}{(bp)_e} \times 100\%$$

Substituting values of the water power = $(wp)_{ww\text{-III}} = 23.28\,\text{kW}$ and brake power = $(bp)_e = 140\,\text{kW}$ for the Water-Well System III into the previous equation

$$E_{0-\text{III}} = \frac{23.28}{140} \times 100 = 16.6\%$$

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CHAPTER 3

DESIGN OF WATER WELLS

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3.1 GENERAL

An important objective of this chapter is the realization of an optimum, efficient well system that would deliver the maximum quantity of water at the least cost. In other words, the objective function (criterion of an efficient system) is to maximize net present worth while maintaining the system within the necessary physical constraints. This will be explained in more detail in Section 3.5. For the benefit of the reader, parallel to the concept of pumping plant efficiency, the premise of economic efficiency is introduced in this chapter for the design of most efficient water well systems.

The design discharge of an efficient water well system is constrained by the hydrogeology of the aquifer. Some of the aquifer information that can be obtained from historical data includes depth to water below the ground surface, saturated aquifer thickness, transmissivity, storativity, water quality, and aquifer type (e.g., confined, unconfined, or semiconfined, and whether the aquifer is consolidated or unconsolidated.) Well logs, historical production data, and specific capacity history also may be obtained from nearby wells to provide an estimation of the technical and economic feasibility of constructing a water supply well in the area. Once an evaluation is made and it appears that it is technically and economically feasible to construct a well at the site, a more detailed analysis should be made prior to the actual construction of the well (see Appendix A for an example of a water well system design). This may include information for preliminary design obtained from a test hole at the selected site. Site selection should be on the basis of the following considerations:

1. Hydrogeology, previous drilling history,
2. Quantity of water (discharge rate, Q) desired and water quality,
3. Legal aspects such as federal, state, and local laws, wellhead protection, and any subdivision regulations,
4. Disposal of borehole cuttings and water used in drilling and testing, and
5. Location of the desired water supply.

A typical test borehole (usually a 6- or 8-in. [150 or 200 mm] diameter) is drilled at the proposed site to collect lithologic and water quality information necessary to design the well. The test borehole may be logged geophysically and sampled for water quality analyses, and if desired, completed as a small diameter observation well (e.g., 2- or 4-in. [51 or 102 mm]) diameter casing and screen. Another common method of gathering lithologic and water quality data before completion of the water well project is to first drill a 17 ½-in. (445 mm) diameter pilot borehole in which geophysical borehole logs are run and aquifer zone testing is performed to determine the vertical variation in water quality (and to a certain degree the production potential; see Chapter 4, Section 4.6). In this case, if the pilot borehole shows promising results, the borehole may be enlarged (i.e., reamed) and completed with the permanent casing, screen, and filter pack. Chapter 4 discusses well drilling and testing in detail.

The information collected from a test borehole or small-diameter test well includes

- Depth to water below ground surface,
- Thickness of the water bearing formation,
- Samples of the aquifer material,
- Water samples for quality analysis, and
- Geophysical and geological logs.

For a large-diameter production well, it is assumed that the hydraulic rotary drilling method will be used (details on different drilling methods and logging are covered in Chapter 4). Most drilling methods deliver a disturbed sample of the aquifer, which requires some judgment and experience to analyze. There are other methods for collecting undisturbed samples, and their costs need to be weighed against the additional data obtained. Shallow wells and wells with smaller discharge rates (e.g., a well that might service a rural, domestic dwelling) may be drilled by an auger or jetting tool, or by some other less expensive method.

3.2 DESIGN OF BOREHOLE, CASING, AND SCREEN

Borehole diameter and depth are the major criteria in well design. These dimensions are determined by estimating well discharge rate, depth to bedrock, and other constraints, such as finances available for well construction. However, the main limitation on discharge rate and depth is dependent directly on the aquifer parameters and aquifer thickness.

3.2.1 Determination of Borehole, Casing, and Screen Dimensions

The actual diameter of the borehole depends on the diameter of the casing and screen, which, in turn, depends on the proposed pump impeller diameter. The pump impeller diameter is contingent on the design discharge rate, Q. Normally the borehole diameter is 8 to 12 in. (200 to 305 mm) greater than the casing and screen diameter (Roscoe Moss Company 1990). Assuming that the well casing diameter is the same as that of the well screen, the annular space between the casing, screen, and borehole needs to be great enough so that a filter pack can be placed. Also known as the filter envelope, filter pack, gravel pack, or gravel envelope, it is a specially graded sand or gravel that is clean and well-rounded, and placed in the annular space of a water well between the borehole wall and the well screen to stabilize formation materials and prevent material from migrating into the well. Placement of the filter pack usually is accomplished using a tremie pipe through which the filter pack material is fed into the well starting from the bottom. This prevents preferential sorting of the filter pack, which may occur if the filter pack is dumped into the well (see Chapter 4).

In some cases the borehole is “under reamed” after the casing is installed. This is accomplished by enlarging the borehole diameter below the casing. Under reaming may be performed to enlarge boreholes below preexisting casings or screens to create the desired annular space or filter pack placement in a telescoped well (Roscoe Moss Company 1990).

The relationship between the minimum casing diameter and the pump impeller diameter is shown in Table 3-1. The inside diameter of the pump house casing normally should be 2 in. (51 mm) larger than the largest pump component (Roscoe Moss Company 1990). The nominal pump bowl diameter is determined by the estimated discharge rate, which is found from the pump specifications published by the pump manufacturer. It may be possible to have pump impellers of different diameters designed to deliver the same discharge rate. The maximum potential pumping rate from the well can be roughly estimated by the following method:

- Obtain an estimate of the hydraulic conductivity (K) of the aquifer from surrounding wells, from the results of a small test hole, or general knowledge of the area’s geology.

Table 3-1. Recommended Casing Diameters for Various Discharges

Discharge, Q, gpm or L/s		Minimum Casing Diameter In or mm	
1770 RPM			
(gpm)	(L/s)	In	mm
<150	<9.5	8	200
150-600	9.5-38	8-10	200-250
600-1000	38-63	10-12	250-305
1000-2500	63-158	12-14	305-355
2500-3000	158-189	14-16	355-406
3000-5000	189-315	16-20	406-508
5000-7000	315-442	20-22	508-560
7000-9000	442-568	22-26	560-660
3450 RPM			
<120	<7.6	4-6	102-152
120-400	7.6-25	6-8	152-200
400-1000	25-63	8-10	200-250
1000-1400	63-88	10-14	250-355

Source: Courtesy of Zohrab Samani, Design of Wells and Pumps Manual. New Mexico State University.

- Estimate the saturated aquifer thickness, H.
- Calculate the transmissivity, $T = KH$.

According to Driscoll (2008) the theoretical specific capacity, SC_T, of the well in liters/sec/meter (L/s/m) may be estimated by

$$SC_T = T/90; \text{ for an unconfined aquifer}$$
$$SC_T = T/120 \text{ for a confined aquifer}$$

where T = transmissivity, (m^2/day).

The theoretical specific capacity is then multiplied by the anticipated total drawdown in the well (s_w) and the well efficiency (E) to estimate the well discharge rate (Q). Well efficiency is the ratio of the actual specific capacity divided by the theoretical specific capacity. Or, expressed in another way, the drawdown right outside the well casing (i.e., the near-well zone) is divided by the drawdown as measured inside the pumping well. The estimated discharge rate then is entered into Table 3-1 to find the suggested minimum diameter of the well casing.

3.2.2 Solved Design Example 1

From surrounding wells and geophysical studies, the piezometric surface of a confined aquifer is located 76 m (250 ft) below the ground surface. The confining layer is located 159 m (522 ft) below the ground surface, and the bottom of the aquifer is 190 m (623 ft) below ground surface. The average hydraulic conductivity (*K*) from several surrounding wells is estimated to be 3.5 m/day. The total saturated thickness of the confined aquifer (*H*) will be screened, which is 31 m (102 ft). Determine the minimum size of casing and screen diameter.

Solution Therefore, the transmissivity (*T*) of the water well is $T = HK = (31)(3.5) = 109\ \text{m}^2/\text{day}$. Theoretical specific capacity of the water well is then

$$SC_T = 109/120 = 0.91\ \text{L/s/m (liters/sec for each meter of drawdown)}$$

If the pump intake is placed 5 m above the confining layer, the maximum drawdown, s_w, will be 78 m (256 ft). Assuming a water well efficiency at the level of total drawdown to be $E_{ww-1} = 0.80$ or 80%, the theoretical discharge (*Q*) is then estimated to be

$$Q = SC_T \times s_w \times E_{ww-1} = 0.91 \times 78 \times 0.80 = 57\ \text{L/s (or 900 gal./min)}$$

From Table 3-1, the minimum casing diameter is 14 in. So the borehole should be between 22 and 26 in.

3.2.3 Determination of Casing Materials

Another major decision in designing a well casing is to specify the material from which the casing is to be constructed. Material selection depends on the required strength and the water quality. The casing must have sufficient strength to withstand water and drilling mud pressure during installation. The material also needs to withstand corrosion if corrosion potential exists in the well site area (see Chapter 5 for more information). If the same material is not used for both screen and casing, one needs to be sure that the dissimilar materials do not produce galvanic action, and therefore a *mechanical connector* or other di-electric coupling must be installed between the two dissimilar metals (see Chapter 4).

When considering well design, materials should be evaluated in terms of three strengths: tensile, compressive, and collapse. In very deep wells, the weight of the casing itself may be substantial, although it is usually much less than the compressive strength of the casing material. Collapse forces most common are from water, mud, cement (e.g., annular seals), and aquifer formation pressure. Under static conditions, formation pressures usually are small due to sheer strength and the ability of the formation to support itself and, therefore, are neglected.

In those cases where an upward movement of groundwater effectively suspends the formation materials (i.e., the formation particles are in loose contact and cannot support the weight of the overlying formation) transient or "quick" conditions may arise. In these cases, higher pressures may arise from dynamic forces. Under static conditions, the petroleum industry uses the following relationship for overburden (Roscoe Moss Company 1990)

$$p = 2.3\rho g h \tag{3-1}$$

where

p = overburden pressure (Pa)
ρ = density of water (kg/m^3)
g = gravitational acceleration (m/s^2)
h = overburden depth (m)
2.3 = average specific gravity of rock (dimensionless).

However, for water-well design purposes, the primary design strength calculation performed is with regard to collapse strength. Collapse strength theory and calculations are discussed following.

Under pumping conditions, water level differences between the inside and outside of the casing exert an unbalanced hydrostatic pressure. When the external pressure sufficiently exceeds the internal pressure, the casing will collapse. Collapse normally occurs below the pumping level at a point of maximum eccentricity. The casing will first deform to an elliptical shape and then "fold in" on itself (Roscoe Moss Company 1990). Calculations of theoretical collapse pressure for a cylinder with eccentricity (e) are made using Timoshenko's Formula, namely

$$P_d^2 - \left\{\frac{2Y_p}{D/t-1} + \left[1 + 3\left(\frac{D}{t} - 1\right)e\right]P_{cr}\right\}P_d + \frac{2Y_pP_{cr}}{(D/t-1)} = 0 \tag{3-2}$$

where

D = outside diameter of the casing (m)
t = wall thickness of the casing (m)
P_d = design collapse pressure (kPa)[1]
P_{cr} = critical collapse pressure of a perfect cylinder

$$(\text{kPa}) = \frac{2E}{(1-\mu^2)\left(\frac{D}{t} - 1\right)^3}$$

where

μ = Poisson's ratio (0.28 for steel)
E = Young's modulus (3×10^7 psi) for steel
Y_p = yield strength (kPa)

$$e = \text{eccentricity} = \frac{D_M}{D_m} - 1 \text{ (dimensionless)}$$

where

D_M = diameter of the major axis of an ellipse
D_m = diameter of the minor axis of an ellipse.

Application of Timoshenko's formula to some common casing sizes is summarized in Table 3-2 (Roscoe Moss Company 1990).

3.2.4 Solved Design Example 2

A well was drilled 400 ft (91.4 m) deep in an unconsolidated sand formation. The unconfined water table is 30 ft (9.1 m) below the ground surface and the maximum drawdown in the well is estimated to be 100 ft

Table 3-2. Collapse Strength Characteristics of Common Steel Casing Pipes

Outside Diameter (OD)		Wall Thickness		Collapse Strength	
Nominal size in.	in.	in.	mm	psi	kPa
6	6.625	0.25	6.35	1288	8898
8	8.625	0.25	6.35	755	5220
10	10.75	0.25	6.35	461	3185
12	12.75	0.25	6.35	306	2115
14	14.00	0.312	7.93	417	2882
16	16.00	0.312	7.93	302	2086
18	18.00	0.312	7.93	225	1553
20	20.00	0.312	7.93	172	1185
22	22.00	0.375	9.53	215	1489
24	24.00	0.375	9.53	172	1190

Note: Eccentricity = 1% and 35,000 psi yield strength.
Source: Courtesy of Zohrab Samani, *Design of Wells and Pumps Manual*, New Mexico State University.

(30.5 m). The outside diameter (OD) of the well casing has been designed to be 20.0 in. (508 mm) with a wall thickness of 0.375 in. (9.53 mm). Determine if the 20.0 in. (508 mm) OD casing from Table 3-2 would have sufficient collapse strength.

Solution The critical condition for collapse would occur during pumping at maximum drawdown of 30.5 m. In most situations, the shear strength and the ability of the formation to support itself are sufficient so that only the differential head (difference between the inside and outside of the casing) need to be considered. From Table 3-2, the collapse strength of the proposed blank casing is 1,185 kPa. As the maximum differential head is only 30.5 m (299.2 kPa), the proposed 20.0 in. (508 mm) OD casing would be more than adequate to withstand collapse forces.

However, when working with some unconsolidated formations, as in this example, the additional formation pressure should be considered. Writing Eq. (3-1)

$$p = 2.3\rho g h$$

The external pressure of the overburden on the casing is as follows. Here, ρ = 1,000 kg/m^3; g = 9.81 m/s^2; and h = 91.4 m. Substituting these values in the previous equation, one obtains

$$p = 2.3 \times 1{,}000 \times 9.81 \times 91.4 = 2{,}062{,}258.2 \text{ Pa}$$

The internal hydrostatic pressure on the casing at maximum drawdown follows:

$$P' = \rho g h'$$

Here, ρ = 1,000 kg/m^3; g = 9.81 m/s^2; h' = 60.9 m. Substituting these values in the previous hydrostatic equation, one has

$$P' = 1{,}000 \times 9.81 \times 60.9 = 597{,}429.0 \text{ Pa}$$

The net external pressure on the casing is as follows:

$$\Delta p = 1{,}464{,}829.2 \text{ Pa} = 1464.83 \text{ kPa}$$

Converting this pressure into an equivalent head becomes the following:

$$\Delta h = \frac{\Delta p}{\rho g} = \frac{1{,}464{,}829.2}{1{,}000 \times 9.81} = 149.3 \text{ m}$$

From Table 3-2, the collapse strength of the proposed blank casing is 1,185 kPa. As the differential hydrostatic pressure is 1,464.83 kPa, the casing is unsafe and will collapse. From Table 3-2, a casing with outside diameter of 16.0 in. with a collapse strength of 2,086 kPa is recommended.

3.3 DESIGN OF FILTER PACK

As discussed in Chapter 4, the nature of the aquifer formation plays an important role in the type of well completion: naturally developed, artificial filter pack, or open borehole. Unless the well is being drilled in a consolidated rock formation that will maintain its integrity with time, an artificial filter pack (i.e., gravel envelope) is recommended. As a result, filter-packed wells are common in alluvial/colluvial, unconsolidated, and poorly consolidated formations. In wells with an artificial filter pack (i.e., gravel envelope) the region immediately adjacent to the well screen is replaced with very permeable material, typically quartz-grained. A gravel envelope usually is pregraded and designed to stabilize aquifer materials and prevent migration into the well (see Fig. 3-1). A filter pack is distinguished from a formation stabilizer, which has a more limited scope and acts primarily to fill the annular space between the borehole and casing. This section deals with the important aspects of filter pack design.

As an example, if the mean of the particle size distribution is coarser than 0.03 in. with a uniformity coefficient more than 2.0, then a formation stabilizer with gravel gradation shown in Table 3-5 and a well screen with 3/32 in. (2.38 mm) openings would suffice. Aquifer gradations with average particle size between 0.02 and 0.03 in. may require more care, even though formation stabilizers are likely to work. If the aquifer gradation has average size of less than 0.02 in., then a filter pack is most likely required.

3.3.1 Characteristics of Filter Pack

A filter pack serves the following purposes:

i. Stabilizing the aquifer materials, thereby preventing migration of fine-grained materials into the well,
ii. Creating a highly permeable zone between the aquifer and the well, thereby increasing the effective well radius, r_e, (see Section 2.1.1, Chapter 2), and
iii. Minimizing rate of incrustation permitting the use of larger screen slot openings in cases of relatively thin, permeable aquifers, and where the chemical properties of groundwater suggest a potential for incrustation (see Chapter 6).

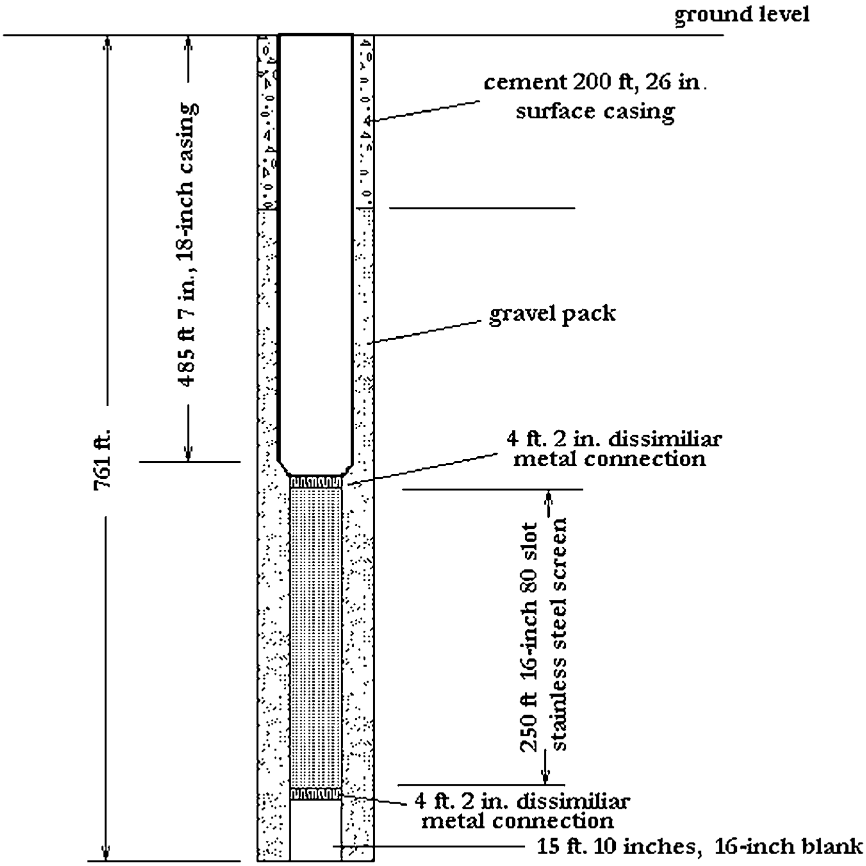

Fig. 3-1. A schematic sketch of an artificially filter packed well
Source: Courtesy of Jorge Garcia, Director of Utilities, City of Las Cruces, Las Cruces, NM.

The purpose of the filter pack is to stabilize the aquifer. The highly permeable nature of the filter pack also increases the effective well radius because of the higher hydraulic conductivity of the filter pack. To ensure high permeability, the filter pack is washed and screened to remove finer particles and angular grains that tend to lower permeability and reduce effectiveness. It is important to center the casing and screen string in the borehole and properly place the filter material (e.g., using a tremie pipe; see Chapter 4) to ensure that there is an adequate filter pack around the well screen (see Fig. 3-1).

In most applications, the filter pack is placed to the surface, resulting in a complete filter envelope. Such wells have a simple design and are easy to construct and maintain. In cases where a deep annular seal is placed (e.g., to seal off contaminated zones), gravel feed lines are required to periodically "top up" the filter pack (see Chapter 4).

A partial filter pack also may be used with a gravel feed line. In addition, filter packs are provided for telescoped well screens and wells with multiple-zone completion. The latter is utilized when two or more aquifers are separated by aquicludes. Unless gravel feed lines are installed, there is no way to replenish the filter pack. These, and many other uses of filter packs, are described by Roscoe Moss Company (1990) in greater detail.

3.3.2 Factors Favoring the Use of Filter Pack

Generally it is accepted that a filter pack (gravel envelope) is not required if 90% of the aquifer material is coarser than 0.010 in., and the material has a uniformity coefficient greater than 2 (Bennison 1947; Williams 1981). The uniformity coefficient is the 40% retained divided by the 90% retained from the sieve analysis. Similarly, if the uniformity coefficient of any aquifer is greater than 5, then a filter pack is not recommended, as the aquifer material can develop a natural filter. If the formation consists of uniformly large gravel with the larger pores filled with sand, however, then a filter pack is required to prevent excessive sand production.

In the following paragraphs, examples are described to illustrate appropriate uses of filter packs.

1. Unconsolidated alluvial aquifers (coastal plains of southern California, Magothy Formation of Long Island, New York; alluvial deposits of the San Joaquin Valley of California; the Santa Fe Formation of central New Mexico; some coastal plain deposits of North Carolina; and Ogallala Formation of the high plains region): These aquifers are highly stratified in the vertical direction consisting of alternative layers of fine, medium, and coarse materials. The determination of precise locations of each individual stratum—and the choice of the proper length of each section of a multiple-slot screen that matches the stratification—is never practical. Therefore, only one filter pack gradation and well screen slot size usually is chosen for design. Generally, the finer aquifers completed are used for design purposes. An artificial filter pack is well suited in these cases, as a gravel envelope enables a uniform design. The gradation of the filter pack is determined on the basis of the aquifer containing the finest material.
2. Fine uniform sand: In galcio-fluvial, alluvial, and aeolian aquifers, the presence of a filter pack may permit the use of larger slot sizes for the well screen, resulting in larger area of open screen. If the

slot size selected on the basis of a naturally developed well is less than 0.254 mm (0.010 in.), then an artificial filter pack would be advantageous. However, the mineral content of the water may permit some deviation from this recommendation. For instance, if the water is extremely incrusting, according to Johnson (1966), a limit of 0.015 or 0.020 in. may be used instead of 0.010 in. Examples where filter packs have been used in fine formations include tertiary sands in the gulf coastal plains of the southern United States; the Ogallala Formation in West Texas, Kansas, and Nebraska; Raritan sand in New Jersey; and Sparta sand in Louisiana.

3. Loosely cemented sandstones: Many highly productive sandstone aquifers are cemented poorly, causing sloughing of sand particles from the walls of the borehole and thereby resulting in a sand-pumping well. Examples of such semiconsolidated (friable) sandstones include the Dakota sandstone in North and South Dakota, the Jordan sandstone in areas of Minnesota, and the Garber and Elk City sandstones in Oklahoma. For fine-grained sandstones that require a screen opening of 0.127 mm (0.005 in.) for natural development, an artificial filter pack will allow for the use of a larger slot size. Moreover, some sandstone aquifers may "slump" against the screen during development, potentially causing failure of the casing. The presence of a filter pack will minimize the possibility of such a failure.

The presence of a filter pack allows water to enter the well more freely, thereby reducing corrosion and incrustation and requiring less maintenance. The filter pack should be composed of clean particles to minimize development time and loss of material during development. When well-rounded grains are chosen, the resulting filter pack has a higher hydraulic conductivity and effective porosity leading to reduced drawdowns in the near well zone. The presence of a high percentage of quartz grains in the filter pack is desirable, as this prevents cementing associated with dissolution of minerals.

3.3.3 Design Criteria of Filter Pack

Karl Terzhagi (1925) pioneered filter pack design based on the findings of his extensive research in soil mechanics and stabilization of earthen dams. Terzhagi's criteria for filter pack design relates to the following:

$$\frac{D_{15}\,filter}{d_{85}\,formation} < 4 < \frac{D_{15}\,filter}{d_{15}\,formation} \tag{3-3}$$

where

D_{15} = 15% passing size of the filter material
d_{85} = 85% passing size of the finest aquifer material
d_{15} = 15% passing size of the coarsest aquifer material.

The left side of this relationship (migration factor) states that the finest 15% of the filter (D_{15}) should be less than four times the coarsest 15% of the formation (d_{85}). The finest aquifer materials are selected for the migration factor criteria, which stabilizes the aquifer and prevents migration of fine-grained materials into the well.

The right-hand side of Terzhagi's relationship states that the finest 15% of the filter pack should be larger than four times the finest 15% of the formation. This is known as the "permeability factor." For the permeability factor determination, the coarsest aquifer generally is used. The Terzhagi principles have been well tested with regard to gravel envelopes (Roscoe Moss Company 1990).

A common modification of the Terzhagi equation uses the following ratio:

$$\frac{D_{50}\,filter}{d_{50}\,formation}$$

where

D_{50} = 50% passing filter pack size
d_{50} = 50% passing formation size (usually the finest aquifer material screened).

Although researchers have recommended this "pack/aquifer" ratio to range from 4 to 5.8 (Roscoe Moss Company 1990), a general consensus from drilling contractors is recommended for a satisfactory design when the pack/aquifer ratio ranges between 4 and 6.

Filter pack gradation will depend somewhat on aquifer materials. Generally a filter pack uniformity coefficient D_{60}/D_{10} should be less than 2 for coarse-grained aquifers. Experience has shown that filter packs with uniformity coefficients up to 2.5 have been successful in stabilizing fine-grained aquifers. As a rule, high uniformity coefficients (i.e., greater than 3) should not be used for filter pack materials.

3.3.4 Design Considerations for Filter Pack

Design of a filter pack involves the following steps:

Step 1: Particle Analysis of Aquifer Materials

- A complete sieve analysis (mechanical grading analysis) for all strata that comprise the aquifer (see Fig. 3-2)

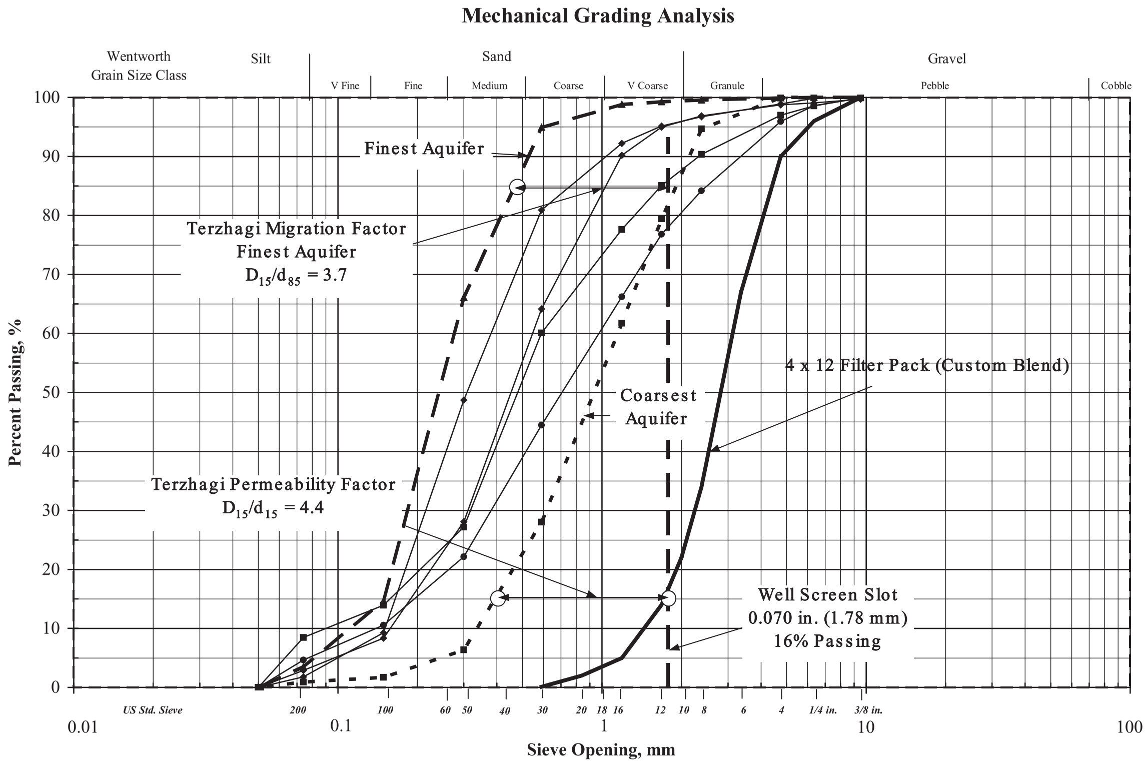

Fig. 3-2. Filter pack design
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

- A determination of the finest and coarsest aquifer materials to be screened; the grading of the filter pack is selected on the basis of sieve analysis of this material, and generally the unfavorable parts of the aquifer are disregarded; use of blank casing between sections of the screen should be minimized, because this hinders well development.

Step 2: Apply Terzhagi Migration and Permeability Criteria

Terzhagi Migration Factor

- The 85% passing value (of the finest aquifer to be screened) is multiplied by a factor of 4; this represents the 15% passing of the filter pack (see Fig. 3-2).
- In practice, commercially available filter materials are first tested to see if criteria are met; however, "custom" blends are commonly specified.
- The Terzhagi migration factor for the example shown in Fig. 3-2 is 3.7.

Terzhagi's Permeability Factor The 15% passing of the filter should be larger than the 15% passing of the coarsest aquifer to be screened. The Terzhagi permeability factor for the example shown in Fig. 3-2 is 4.4.

Step 3: Determine Well Screen Slot Size

- The well screen slot size should range between 10 and 20% passing of the filter pack (Roscoe Moss Company 1990).
- In the design example, a 0.070 in. (1.78 mm) slot opening was selected that theoretically allows 16.5% of the filter material to pass through the well screen slots.

Experience has shown that the previous design example guidelines may be applied to most alluvial aquifer systems. However, other special cases and recommended design guidelines are listed as follows.

Aquifer Material with Uniformity Coefficient between 2.5 and 5.0 The 30% passing value (or the 70% retaining value) is multiplied by a factor of between 4 and 6 to 1. A factor of 4 is used if the formation is fine and uniform, and 6 if is coarse and non-uniform. A multiplication factor ranging from 6 to 9 may be used when the formation sand gradation is extremely non-uniform and includes silt as well.

The D_{30} of the aquifer is multiplied by 6 and 9, and these points are located on the sieve analysis graph. Two parallel lines are drawn through these points having a uniformity coefficient of 2.5 or less. A filter pack material is specified that falls between these two lines.

Aquifer Material with Uniformity Coefficient Greater Than 5 The D_{30} of the aquifer material is multiplied by 6 and 9, and the corresponding points are located on the sieve analysis graph. Two parallel lines are drawn between these two points, so that the uniformity coefficient is 2.5 or less, and a filter pack material is specified that falls between these two lines.

Table 3-3 provides a well filter pack and screen slot design example.

3.3.5 Thickness of Filter Pack

Theoretically, a thickness of two to three grain diameters would be sufficient for this purpose. In practice, however, a minimum thickness of 4 to 6 in. (102 to 152 mm) is required to ensure a complete gravel envelope around the well screen. The minimum thickness often is dictated by the type of construction material being used, the drilling conditions, and experience of the drilling contractor.

Under most conditions, an upper limit of the gravel-pack thickness should not exceed 200 mm (8 in.). Energy created by the development procedure must be able to penetrate the filter pack to repair the damage done by drilling operations, break down any residual drilling fluid along the borehole wall, and remove the finer particles near the borehole. Increasing the thickness of the filter pack may, therefore, increase the effort needed to develop the completed well and add to construction costs while yielding little or no appreciable improvement in yield or decrease in sand pumping. The potential for sand pumping is controlled mainly by the ratio of the grain size of the pack material to the formation material.

3.3.6 Secondary Design Considerations for Filter Pack

In practice, the designer begins by plotting the aquifer materials and noting aquifer heterogeneities carefully in a log. The finest material to be used in well design is selected on the basis of this formation sample. Different filter pack gradations rarely are used in the same well due to difficulties in ensuring proper placement.

After identifying the finer material in the aquifer, adjacent zones must be examined carefully. If coarser areas occupy a substantial portion of the aquifer, then the finer zone may be sealed off by placing a blank section of casing adjacent to finer zones. Because the finer aquifer material effectively has been sealed off, the filter pack can be designed based on the coarser aquifer materials.

3.3.7 Materials for Filter Pack

Filter pack material typically occurs naturally in large deposits of sand and gravel. However, it is not always possible to find natural deposits

Table 3-3. Well Filter Pack and Screen Slot Design Example

Design Criteria	Depth [ft]	Formula (D = Filter Pack) (d = Aquifer)	Value	Recommended Value
Pack/Aquifer Ratio (Finest Zone)	770-780	D_{50}/d_{50}	11.8	4 to 10
Terzhagi Migration Factor (Finest Zone)	770-780	D_{15}/d_{85}	3.7	less than 4
Terzhagi Permeability Factor (Coarsest Zone)	630-640	D_{15}/d_{15}	4.4	greater than 4
Screen Slot [in.]	—	—	0.070	—
Percent Filter Pack Passing Screen Slot	—	—	16.5	10% to 20%
Uniformity Coefficient of Filter Pack	—	$C_u = D_{60}/D_{10}$	2.2	—

4 × 12 Custom Blend

U.S. Standard Sieve Size	Opening [in.]	Opening [mm]	Cumulative % Retained	Cumulative % Passing
3/8″	0.375	9.53	0.0	100.0
1/4″	0.250	6.35	4.0	96.0
4	0.187	4.75	10.0	90.0
6	0.132	3.36	33.0	67.0
8	0.094	2.38	66.0	34.0
10	0.079	2.00	78.0	22.0
12	0.066	1.68	86.0	14.0
16	0.047	1.19	95.0	5.0
20	0.033	0.84	98.0	2.0

Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA.

that meet the exact specifications of a required gravel pack, and the designer may need to have the gravel pack "custom-mixed" by the supplier. This often requires combining various mixtures of fine, medium, and coarse sands. In this regard, the designer aims to mix an adequate distribution of grain sizes to obtain the right grain size distribution for the filter pack.

Usually filter pack materials should consist of siliceous rather than calcareous particles. Generally calcareous material (including gypsum and anhydrite) should be less than 5%. This limitation is particularly important for wells that are acid treated. If a large percentage of filter packs is calcareous, then much of the acid is used up in dissolving the carbonates rather than for removing incrusting deposits of calcium and iron. Clean and well-rounded, uniform gravel grains are preferred to increase the hydraulic conductivity and porosity of the filter pack. Uniform materials also minimize hydraulic separation during placement.

A common filter pack gradation used with 1/16 in. (1.59 mm) screen openings under a wide variety of wells completed in alluvial formations is shown in Table 3-4.

3.3.8 Formation Stabilizer

In the water well industry, a distinction is made between carefully designed filter packs and formation stabilizers. The annular space surrounding a well screen, installed in wells drilled by hydraulic rotary methods, is filled with clean coarse sand or a sand-gravel mixture to assist in well development. A sand mixture of the same grading or slightly coarser than the aquifer is sufficient and is placed before completing a naturally developed well.

When drilling through a formation, the borehole is made larger than the diameter of the well screen to allow for easy installation. Typically, a 4- to 6-in. annular space is anticipated and factored into the borehole size during drilling. This space needs to be filled completely for proper well development. The stabilizer material can help prevent caving of silt and clay materials when well development starts.

Unlike filter packs that are designed to stabilize formation material, design of a formation stabilizer is not as crucial. Placement of the stabilizer material, however, does warrant reasonable care during placement, and

Table 3-4. Gravel Gradations For Filter Packs for a 1/16 in Screen

U.S. Standard Sieve Numbers	6	8	12	16
mm	3.35	2.36	1.7	1.18
Cumulative Percent retained	0–5	20–30	75–85	95–100

the quantity of formation stabilizer should be sufficient to fill the annular space. During development, removal of finer particles from the stabilizer (and aquifer) tend to increase the permeability of materials in the near-well zone, increasing the well's effective well radius (see Section 2.1.1, Chapter 2).

A typical mix for formation stabilizer often used with large screen openings is shown in Table 3-5. If the average particle size distribution is coarser than 0.03 in. and the uniformity coefficient is more than 2, then the gravel gradation in Table 3-5 and 3/32 in. screen aperture would suffice.

3.4 DESIGN OF WELL SCREEN

The main criteria in designing the well screen are the diameter and thickness, type, slot size, and material. There are, however, a number of different types of well screens ranging from vertical milled slots to continuous wire wrap. The most common are the horizontal louver and the continuous wire wrap. Some other commonly used well screens are shown in Fig. 3-3.

3.4.1 Calculating Entrance Velocity into Well Screen

Experience has shown that entrance velocity is not a critical design parameter, and successful designs have been demonstrated from 0.1 ft/s (0.03 m/s) up to 2.5 ft/s (0.76 m/s) (AWWA 1997). American Water Works Association (1997) recommends an upper limit of 1.5 ft/s (0.46 m/s) and recommends that well designers thoroughly examine upper limits of entrance velocities for their particular site conditions. Furthermore, Williams (1985) has found that to maximize well efficiencies, entrance velocities should be between the range of velocities of 2 and 4 ft/s (0.6 and 1.2 m/s).

Sand particles surrounding the screen slots may decrease the entrance area of the screen. When using the orifice equation to calculate entrance velocity, this fact needs to be kept in mind. Roscoe Moss Company (1990) suggests Eq. (3-4) to calculate screen entrance velocity, V, as

$$V = \frac{Q}{235rbP} \tag{3-4}$$

Table 3-5. Gravel Gradation for Formation Stabilizer

U.S. Standard Sieve Numbers	4	8	16	20
mm	4.75	2.36	1.18	0.85
Cumulative percent retained	5–15	65–75	80–95	90–98

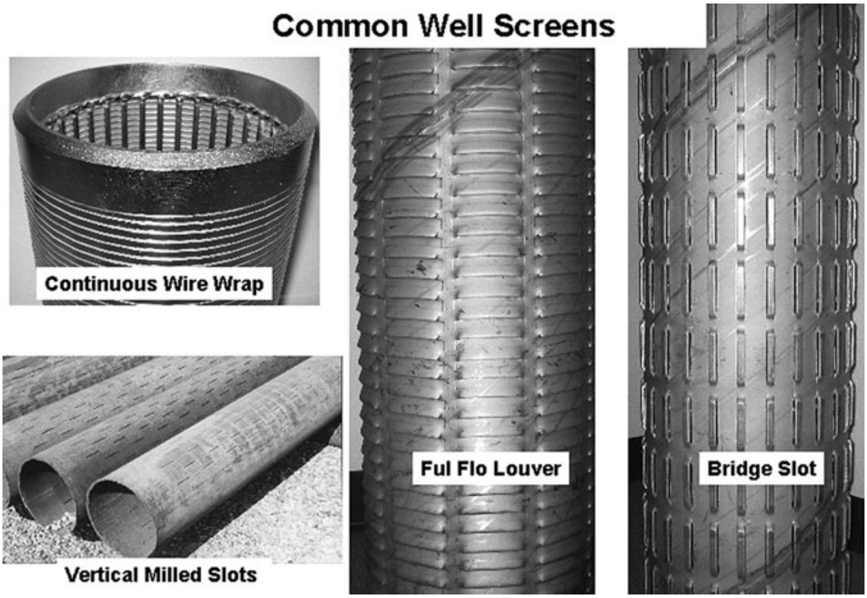

Fig. 3-3. Commonly used well screens
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

where

V = screen entrance velocity, (ft/s)
Q = well discharge, (gpm)
r = screen radius, (in.)
b = screen length, (ft)
P = percent open area of well screen, (dimensionless).

In some instances, the well may experience "sand drive," or "sand sealing." Sand drive occurs when the filter pack around the well screen becomes compacted from the natural surging. This happens due to the fact that when the pump is being turned off and on, the well screen slot size is too small to allow the fine-grained materials to pass through. It is a common phenomenon that at the "start up" of wells, a small amount of finer materials in the near-well zone migrates to the well. In a properly designed well, these fine-grained materials move on through the well screen and are carried out with water that is "pumped to waste." Pump-to-waste times of a few minutes are typical before the well clears up. However, if the well screen slots are quite small (e.g., 0.010–0.030 in.), many times these fine-grained particles cannot pass through the well screen and thus form a low permeability barrier adjacent to the well screen. This phenomenon causes the well to become "sand sealed." Compaction decreases the hydraulic conductivity of the filter pack, thereby increasing the well losses with a corresponding significant decrease in the well efficiency.

3.4.2 Selection of Materials for Casing and Screen Pipes

The casing and screen materials are chosen on the basis of a number of factors, including strength requirements, cost of material, and to a lesser degree water quality (i.e., the potential for corrosion). Well screen and casing may be manufactured from a several varieties of steel with a wide range of physical properties and prices. The commonly available steels are carbon steel (equivalent to Grade B transmission line pipe), copper-bearing steel (ASTM 139 Grade B with the addition that the steel has 0.2% copper by Ladle Analysis), high strength–low alloy steel, and stainless steel (most frequently stainless steels types 304L and 316L) (Roscoe Moss Company 1990).

For relatively shallow, small-diameter wells, PVC (manufactured to ASTM specification D1784) screen may be a cost-effective option that provides good service, as PVC is not affected by most water quality problems.

3.4.3 Designing Well Screen Dimensions

Placement of casing and screen mainly depends on the design discharge rate and design depth. Exact depths are selected from geophysical borehole logs, as well as from specific zone testing (see Chapter 4).

Table 2-2 shows guidelines for different casing and screen diameters versus desired discharge rates. Well casing and screen thickness are calculated primarily based on hydraulic collapse strength (see Table 3-2).

The relationship between the length and diameter of the screen and their effect on screen specific capacity may be seen by applying the Dupuit-Forchheimer Eq. (3-5) for a water table aquifer:

$$Q = \frac{1.366K(H^2 - h^2)}{\log\left(\frac{R}{r}\right)} \tag{3-5}$$

where

Q = constant well discharge, (m^3/day)
K = hydraulic conductivity of the aquifer formation, (m/day)
H = static water level, (m)

h = dynamic water level in the well, (m)
R = distance to the edge of the cone of influence, (m)
r = radius of the water well, (m).

Note that for the idealized assumptions of Eq. (3-5), decreasing h, the pumping water level (which is largely dependent on the length of the well screen), increases the drawdown (H-h) and produces a greater discharge than increasing the well screen radius (r), which only affects discharge as log R/r. In other words, it can be shown that doubling the well diameter increases specific capacity only by 10% (Williams 1985).

Fig. 3-4 has been constructed from Eq. (3-5) and shows a linear specific capacity curve, which occurs only under ideal conditions (i.e., no well losses, e.g., turbulent flow losses through the screen slots and well casing). However, this is rarely the case, if ever.

Fig. 3-5 shows the same graph as Fig. 3-4 but for an actual well outside of Denver. Notice that not only the percent discharge curve is different but also that the specific capacity, SC, curve is extremely nonlinear.

3.4.4 Solved Design Example 3

A well is drilled in a water table aquifer. To achieve a discharge rate of 1,500 gal./min (95 L/s), a screen length of 225 ft. (69 m) and screen diameter of 16 in. (406 mm) are chosen. From the filter pack specifications, the slot size is selected as 0.060 in. (1.52 mm). According to the manufacturer's specifications, the percentage of open area for the aforementioned slot size

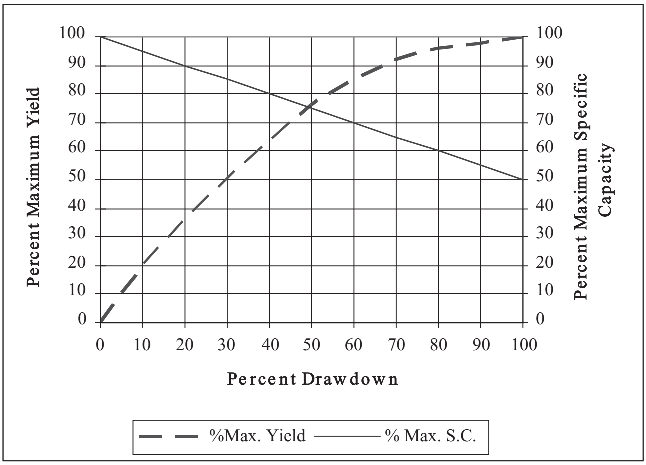

Fig. 3-4. Discharge and specific capacity curves for an ideal water well derived from Eq. (3-5)

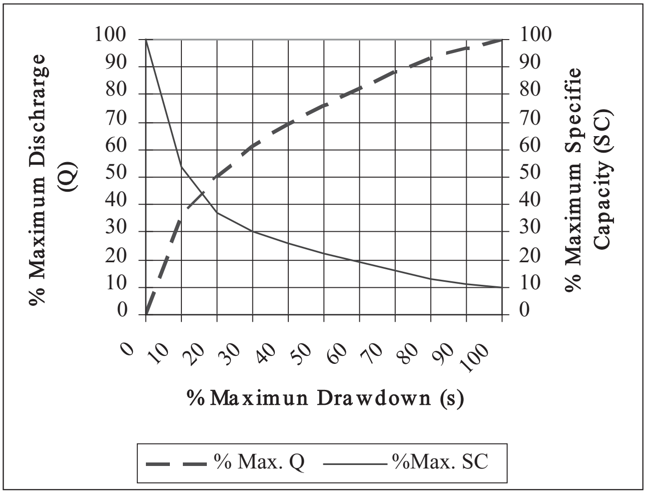

Fig. 3-5. Maximum discharge and specific capacity of an actual well

and the 16-in. (406 mm) diameter well screen is equal to 3%. Determine the design velocity through the chosen slot size.

Solution Using Eq. (3-4):

$$V = \frac{Q}{235rbP} = \frac{1,500}{235 \times 8 \times 225 \times 0.03} = 0.12\ \text{ft/s}\ (0.04\ \text{m/s})$$

The example shows that the screen has ample capacity to conduct the design discharge without violating the maximum allowable entrance velocity into the screen.

3.5 ECONOMIC CONSIDERATIONS IN DESIGN

To design an economically feasible well, the net present worth (NPW) should be maximized. To do this, the costs of drilling different depths and diameters need to be added to the other costs, casing, screen, pump system, and so on. The discounted costs then are subtracted from the discounted benefits (value of the discharge) to determine optimal design parameters.

Theoretically, the economic optimum dimensions of the borehole, casing, and filter pack design would be a trade-off between diameter and length of casing, screen, and volume of the filter pack. However, such an exercise normally is not worth the effort, because the design criteria usually are constrained by the geohydrology of the aquifer.

The efficient operation of a groundwater system (a water well and a pumping plant) may be measured by two basic means: hydraulic (physical) and economic. The hydraulic aspects measure physical output power (i.e., output horsepower) divided by the input power (or input horsepower). Also, see Section 2.5, Chapter 2. The economic efficiency is measured by comparing the benefits with the costs. Both the water well and pumping plant efficiencies need to be measured separately and used as needed to aid in developing the concept of economic efficiency. Besides, for usage purposes, each of these system components (well and pump) of a groundwater system may be divided into subsystems. These are covered in detail in Chapter 2.

3.5.1 Review of Economic Analysis

There are a number of methods to evaluate a groundwater supply system economically. The two main ones, under which others may be classified, are net present worth (NPW) and rate of return (ROR). Whereas both of these approaches will give the same answer if used properly, the NPW method is more direct and easier to apply; consequently, it will be the method used in this chapter. In replacement analysis, net annual worth (NAW) also is used, but it is merely the annualized NPW (Helweg et al. 1984).

The basic calculation in any economic analysis (cost–benefit analysis) is to convert benefits and costs to one point in time. That is, money has time value and can be shown on a cash flow diagram, such as shown in Fig. 3-6. One thousand dollars one year from now is not as valuable as $1,000 now, because the present money could be invested, so one would

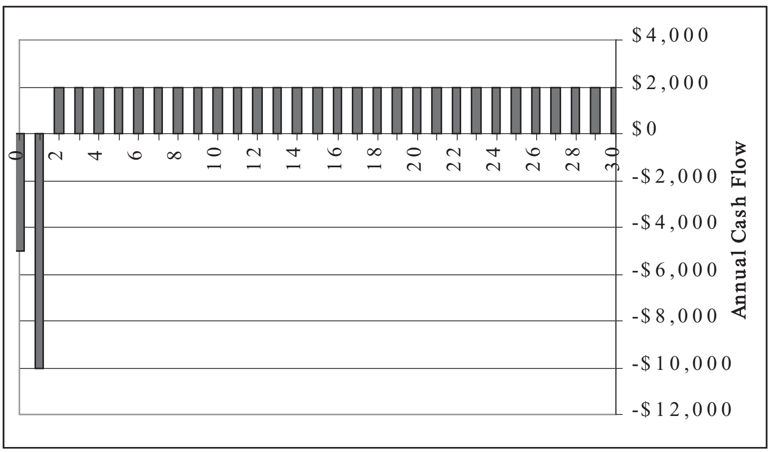

Fig. 3-6. Net cash flow diagram for solved design example IV

have more at the end of one year. For example, earning 10%, a $1,000 investment would be worth $1,100 at the end of one year.

The usual steps in most economic analyses are as follows:

1. Estimate the costs and benefits over the life of the project.
2. Construct a cash flow diagram.
3. Convert the cash flows to present time (time zero) using the appropriate discount rate.
4. Subtract the costs from the benefits to calculate the NPW.

Table 3-6 lists the most common factors that convert cash flows (money) occurring at different times to a common time, usually the present. Explanations of cost–benefit analysis are found in any basic text on engineering economics (Newnan 2011; White et al. 2009). All cash flows are assumed to occur at the end of each year:

P = present worth
F = future worth
A = a series of uniform payments (usually annual)
i = interest rate (rate of return)
n = number of time periods (usually years).

For our purposes, the objective function will be to maximize NPW while remaining within the constraints, such as limiting the entrance velocity of water flowing into the well screen. Doing this will maximize

Table 3-6. Compound Interest Factors

Find	Given	Factor	Symbols
P	F	$\frac{1}{(1+i)^n}$	$(P/F, i, n)$
F	P	$(1+i)^n$	$(F/P, i, n)$
P	A	$\frac{(1+i)^n-1}{i(1+i)^n}$	$(P/A, i, n)$
A	P	$\frac{i(1+i)^n}{(1+i)^n-1}$	$(A/P, i, n)$
F	A	$\frac{(1+i)^n-1}{i}$	$(F/A, i, n)$
A	F	$\frac{i}{(1+i)^n-1}$	$(A/F, i, n)$

Source: Compiled by Otto Helweg.

economic efficiency. In other words, terms such as "cost effectiveness" and "maximizing net benefits" also are used but are considered synonymous in this chapter. It is the thesis of this chapter that maximizing the economic efficiency of a well is the most rational objective to maximize well efficiency. Merely maximizing hydraulic efficiency does not tell the engineer how deep to drill the well or what the design discharge should be.

Connected with the two design aspects, well and pumping plant, there is an optimal (most economic) well discharge. Because this is the estimated design discharge before drilling, after the well has been drilled and developed, a pumping test is needed to determine the optimal (most economic) discharge. Fig. 3-7 illustrates the approach to determine the most economic discharge. Note that the benefit function is assumed to be linear, which is the usual case and will be explained in greater detail later. The value of the optimal discharge is designated at a point where the marginal benefits equal the marginal costs, that is, where the slope of the cost function equals the slope of the benefit function. Of course, the cost function becomes more nonlinear when the water flow into and around the well screen become turbulent. Whether a higher value of discharge should be allowed in the well has been a hotly debated topic (Driscoll 2008; Roscoe Moss Company 1990).

3.5.2 Solved Design Example 4

Constructing a groundwater supply system costs $5,000 for mobilization and $10,000 when the project is completed at the end of year one. The

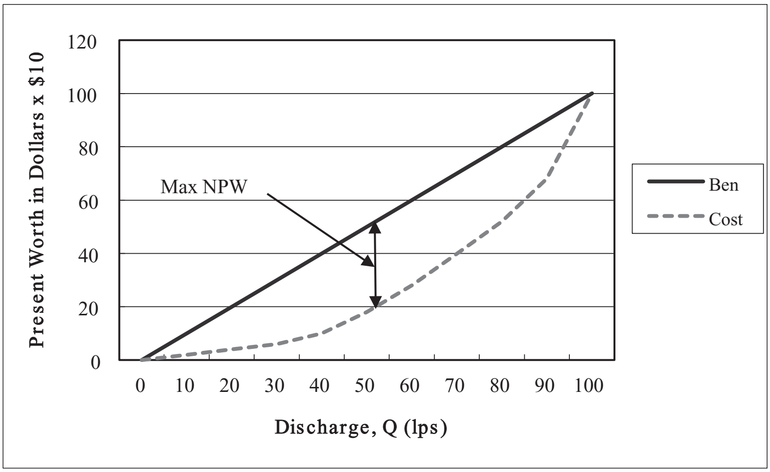

Fig. 3-7. Present worth of benefits (Ben) and costs (Cost) for a well versus discharge

benefits of the water are estimated to be \$2,500 per year for 30 years from time zero, the economic life of the project. The annual operation and maintenance (O&M) costs are estimated to be \$500. The discount rate is 7%. Determine the NPW of the groundwater supply system under consideration.

Solution The cash flow diagram is given in Fig. 3-6.

$$\text{NPW} = \text{PWB} - \text{PWC}$$

$$\text{PWB} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]\left[\frac{1}{(1+i)}\right] = 2{,}000\left[\frac{(1.07)^{29} - 1}{0.07(1.07)^{29}}\right]\left[\frac{1}{(1.07)}\right] = \$26{,}700$$

$$\text{PWC} = P + F\left[\frac{1}{(1+i)^n}\right] = 5{,}000 + 10{,}000\left[\frac{1}{(1.07)^{29}}\right] = \$14{,}346$$

$$\text{NPW} = \$26{,}700 - \$14{,}346 = \$12{,}354$$

3.5.3 Economic Design of Water Well

In most cases, designing a groundwater supply system will start with the well design. The steps in well design are as follows:

1. Determine the desired discharge. Dealing with a large water supply demand, which requires a well field, is beyond the scope of this manual. If dealing with a well in a well field, we will assume the most economical distances and arrangements have been estimated and a design discharge designated for the well in question. For more on well field design, see Pezeshk et al. (1994).
2. Estimate aquifer productivity. If the aquifer appears to be able to supply the required water, fine. If not, the maximum safe yield of the aquifer will determine the design well discharge. As the concept of safe yield has been debated, we will assume safe yield to be the amount of water that can be withdrawn from the aquifer over the indefinite future without causing permanent harm to the aquifer. There are, of course, cases in which groundwater is mined like any nonrenewable resource. This will not be discussed here.

   The knowledge of the aquifer and its yield may require a good deal of engineering judgment. Whether the aquifer is confined or unconfined, whether it is fairly uniform, what are its overall characteristics (transmissivity or storativity), where is its recharge area, what kind of cone of depression should be tolerated, and so on—all enter into the well design consideration.

3. Select a trial pump that will deliver the design discharge at peak efficiency. The size of the pump will determine the minimum diameter of the well casing and screen as covered in Section 3.2.
4. Calculate the dimensions and specifications of the well. Here it is helpful to run a simulation model to estimate these design variables, such as screen diameter, screen length, location of the pump inlet, screen slot size, filter pack (sand filter) specifications, and so on. For example, the theoretical equations (Thiem and Theis) ignore well losses and suggest that well discharge is proportional to screen length. The costs of screen and casing show a general linear relationship with respect to both length and diameter.

The relationship between cost and diameter (see Fig. 3-8) is linear, with an increase after 12 in., ID due to an increase in wall thickness from 0.25 in. to 0.3125 in. Analogous to Fig. 3-8, well casing has a similar cost curve. The capital cost of the well is calculated by

$$AC_c = P\frac{i(1+i)^n}{(1+i)^n - 1} \tag{3-6}$$

where

AC_c = annualized capital cost of the water well
P = present worth of the well cost (i.e., the total cost of the well)
i = discount rate
n = number of years (economic life of the well).

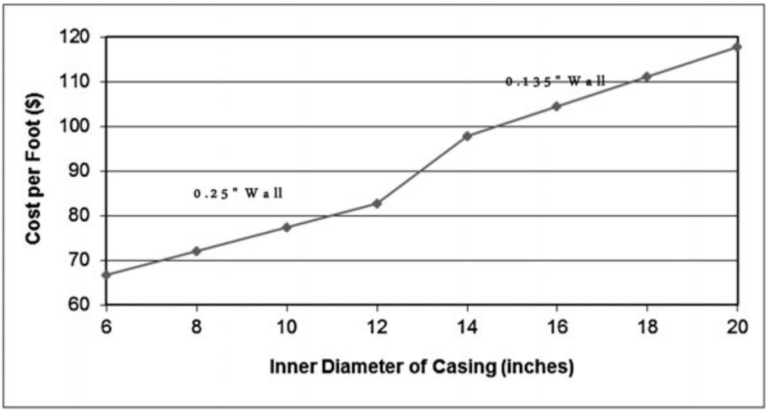

Fig. 3-8. Cost per foot length of copper-bearing louvered well screen versus inner diameter
Source: Data from Roscoe Moss Company (1990). Courtesyof Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

The pumping cost is considered later; however, it is usually nearly twice the annualized capital cost.

3.5.4 Design of Pumping Plant

The first step in designing the pumping plant is to select the most economical pump that will deliver the most economic (optimal) discharge of the well. To do this, one must run a step-drawdown test. The step-drawdown test involves pumping a well at a series of constant rates, each larger than the previous rates (Labadie and Helweg 1975). This is covered in Chapter 4.

The results of time drawdown and recovery (both step-drawdown and constant rate tests) may be used to calculate transmissivity. Although step-drawdown tests may be used to estimate aquifer transmissivity, constant-rate time drawdown tests are preferred (see Chapter 4). The step-drawdown equation (Jacob 1947) is presented as follows:

$$s_{wd} = BQ + CQ^p \tag{3-7}$$

where

s_{wd} = drawdown in the well, (m)
B = formation-loss coefficient resulting from laminar flow (day/m^2)
C = well-loss coefficient for turbulent flow due to well losses in the borehole and screen (day^p/m$^{3p\text{-}1}$)
p = severity of the turbulence (usually 2)
Q = discharge of the well (m^3/day).

The first term, BQ (formation loss), in Eq. (3-7), approximates the laminar head loss, which occurs in the aquifer. The second term, CQ^p (well loss), in the equation approximates the head losses associated with turbulence of water entering the well screen and moving axially inside the well toward the pump. The step-drawdown Eq. (3-7) is the basis for the cost curve shown in Fig. 3-8. In calculating the cost for an electrically driven pump, the two main inputs are the power cost and the total dynamic head (TDH = s_{wd} + SWL + h_1 + h_p). Following is the standard formula for calculating the power in kilowatts, kW:

$$(bp)_{ww-\mathrm{II}} = \frac{0.746Q(s_{wd} + SWL + h_1 + h_p)}{3960E_{ww-\mathrm{II}}} \tag{3-8}$$

where

$(bp)_{ww-\mathrm{II}}$ = brake horsepower (or input horsepower) of water well system at the level of electric motor in kilowatts (kW)

0.746 = conversion factor to convert input horsepower into kilowatts (1 horsepower = 0.746 kW)

Q = constant water well discharge in gallons per minute, (gal./min) (L/s × 15.85 = gal./min; 450 gal./min = 1 cfs)

s_{wd} = Total drawdown in the well computed on the basis of the step-drawdown test data, (ft) (m ÷ 0.3048 = ft)

SWL = static water level measured from the ground surface to the water surface in a nonpumping well, (ft) (m ÷ 0.3048 = ft)

h_1 = head loss incurred at the entrance of the pump strainer, the strainer itself, the suction pipe, the delivery pipe (inside the casing), and losses associated with the discharge head, (ft)
Note: Except the head loss in the vertical portion of the delivery pipe, if the sum of other component head losses of h_1 is small, then those losses may be neglected.

h_{sp} = external system pressure head in feet of water measured by a gauge fixed to the delivery flange of the discharge head elbow, (ft) (m ÷ 0.3048 = ft)

3,960 = conversion factor to convert gal./min × ft into horsepower.

$E_{ww-\mathrm{II}}$ = wire-to-water efficiency of the electric motor (dimensionless), assumed to be 70% if the value is not known.

When testing the performance of water-well systems the density changes of water usually are neglected, and water is considered to be an incompressible fluid. This assumption simplifies the computation process to determine the input horsepower to the water well system at the level of electric motor as detailed following:

$$(bp)_{ww-\mathrm{II}} = \frac{\rho g Q \times TDH}{550 E_{ww-\mathrm{II}}} \tag{3-9}$$

For water, in Eq. (3-9) ρ = 1.94 slugs/ft^3; g = 32.174 ft/s^2; and discharge $= \dfrac{Q}{450}$ cfs, when Q is given in gal./min. Substituting this information, Eq. (3-9) may be written

$$(bp)_{ww-\mathrm{II}} = \frac{\rho g Q \times TDH}{550 E_{ww-\mathrm{II}}} = \frac{1.94 \times 32.174 \times Q \times TDH}{450 \times 550 E_{ww-\mathrm{II}}} = \frac{Q \times TDH}{3960 E_{ww-\mathrm{II}}} \tag{3-10}$$

The input horsepower to the water well system at the level of electric motor is given by Eq. (3-10). To express the horsepower in terms of kilowatts, simply multiply the right-hand side by the conversion factor, 1 horsepower = 0.746 kW, to obtain Eq. (3-11):

$$(bp)_{ww-\mathrm{II}} = \frac{0.746Q \times TDH}{3960E_{ww-\mathrm{II}}} \tag{3-11}$$

where total dynamic head, $TDH = s_{wd} + SWL + h_1 + h_p$.

The total cost, C', of power in dollars over time is the cost per kilowatt-hour of electricity times the kilowatt drawn by the pump (from Eq. [3-11]) times the number of hours pumped:

$$C' = \frac{0.746Q(s_{wd} + SWL + h_1 + h_p)T_2K_2}{3960E_{ww-\mathrm{II}}} \tag{3-12}$$

where

T_2 = time pumped, in hours, = $T_1/60$, where T_1 is time the well is pumped in minutes
K_2 = cost of electricity, in dollars per kilowatt hour.

Other symbols in Eq. (3-12) have been defined previously.

Because there is no market that yields a valid economic benefit for water, an approximation is made by what the economists call "the alternate cost" method, that is, finding the cost of the next best source of water and using that as the benefit function. In most instances, when groundwater is being used, the next best source is another well. Having found the alternative cost of water, K_1, the benefit is

$$B' = K_1T_1Q \tag{3-13}$$

where

K_1= value of water, in dollars per gallon (dollars/L × 3.785 = dollars/gal.)
T_1= time the well is pumped, in minutes
Q = discharge, in gallons per minute (L/s × 15.85 = gal./min).

From Eqs. (3-12) and (3-13), the objective function for maximizing B' and C' is

$$\underset{Q}{Max}\left[K_1T_1Q - K_2(T_1/60)(0.746/3{,}960E_{ww-\mathrm{II}})(Q)(s_{wd} + SWL + h_1 + h_p)\right] \tag{3-14}$$

When drawdown, s_{wd}, is formulated as a function of Q, then the objective function becomes a one-dimensional maximization problem. For s_{wd}, substitute the step-drawdown Eq. (3-7) so that Eq. (3-14) becomes

$$\underset{Q}{Max}\left\{T_1\left[K_1Q - K_2K_3BQ^2 - K_2K_3CQ^{p+1} - K_2K_3(SWL + h_1 + h_p)(Q)\right]\right\} \quad (3\text{-}15)$$

where $K_3 = (1/60)(0.746/3\,960\ E_{ww-\mathrm{II}})$, a lumped conversion constant.

As shown in Fig. 3-8, this function is concave over the possible values of Q. Consequently, the maximum occurs at the stationary point, which is found by differentiating Eq. (3-15) and setting it equal to zero. The equation then can be solved by Newton's method using the computer program, QOPTIM (Helweg et al. 1984).

3.5.5 Selection of Pumping Equipment

Operating requirements include the amount of water to be supplied, location of delivery (elevation), discharge pressure, and pumping duration (e.g., continuous or intermittent). Proper pump selection is based on a number of factors relative to the desired operating capabilities.

Pump selection for a well is a process of matching a particular pump to specific characteristics of a well so that a required rate and volume of water will be delivered. When this combination is achieved at the lowest cost, the flow is called "optimal discharge." It is the discharge from a well that maximizes net benefits or delivers the required amount of water at the lowest cost. The most efficient discharge is the discharge of a pump (not necessarily the optimal well discharge) at which the pump achieves maximum efficiency (i.e., the discharge that corresponds to the highest point of the pump efficiency curve; see Fig. 3-9). The table in the upper right-hand corner of Fig. 3-9 indicates that for adding additional stages to a pump, the efficiency curve is lowered a corresponding number of points. Note that the pump curves are for only one stage. If the total dynamic head (TDH) is greater than that of the curve, additional stages are added until the required TDH is achieved.

There are two situations that require two different methods for selecting the appropriate pump. The first is when the required discharge is less than the optimal well discharge, and the second is when the required discharge is or will be equal to or greater than the optimal well discharge. Before either of these methods can be applied, the well characteristics must be determined. That is, the relationship between well discharge and drawdown (the discharge-drawdown curve) must be calculated. This may be estimated by assuming that discharge and drawdown are linear

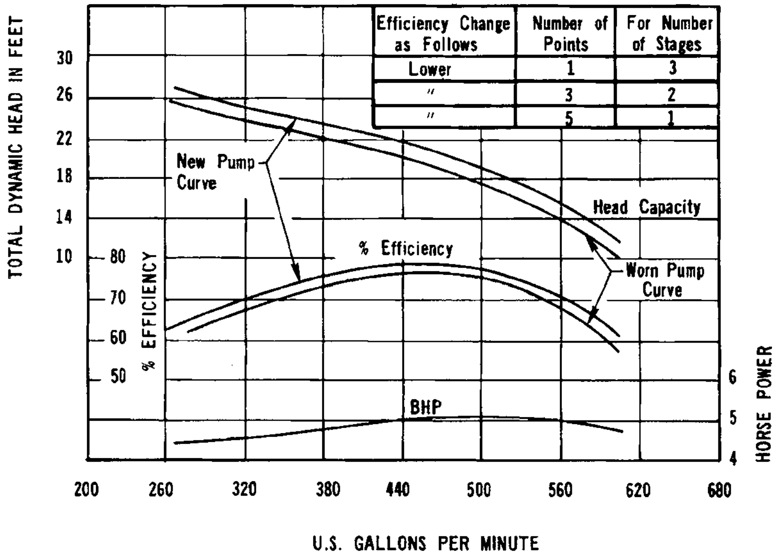

Fig. 3-9. Two sets of pump curves, one from a new test and the other at a later date

and by drawing a straight line from the origin of $Q - s_{wd}$ to plot the drawdown for a given discharge. The discharge–drawdown relationship also may be found from the step-drawdown test. The first method is less accurate but is permissible for the first situation in which the required discharge is less than the optimal well discharge; otherwise, the step-drawdown test should be used.

3.5.6 Pump Selection for Discharges Less than Optimal

As a general rule the discharge of a pump should be the least possible. In other words, water usually is delivered at the lowest cost when the pump is operated 24 hours per day. One exception to this is when there is a differential rate structure in which off-peak power is less expensive than peak power. Given the necessary volume of water required per day, the required discharge of the well is calculated easily.

A pump is selected that gives the highest efficiency at this discharge. If the water table fluctuates widely during the year, a pump that has a flat efficiency curve is preferred to a pump with a steep efficiency curve, other considerations being equal. The pump selection using Fig. 3-9 also requires that the TDH be calculated in order to select the number of stages required. This should be done before the pump is selected, because the number of stages affects the efficiency of the pump.

3.5.7 Pump Selection for Discharges Equal to or Greater than Optimal

For this situation, the step-drawdown test should be completed so that the relationship between discharge and drawdown may be calculated over all possible discharges. The optimal discharge is calculated as described previously, and a pump is selected that achieves maximum efficiency at that discharge. Sometimes, if slightly more water is required than the optimal discharge can provide, a larger pump is selected rather than drilling another well.

It may be advisable to select a pump that delivers less than the optimal discharge, because a greater discharge would harm the well. For example, high entrance velocities might cause clogging of the screen. Consequently, always check to be sure the pump selected does not violate the design constraints of the well. However, if the well is designed properly, the screen diameter will be such that the entrance velocity is within design constraints. If the engineer is in the design phase of the well project, the dimensions of the well, primarily the diameter of the well screen, may need to be increased to decrease the entrance velocity.

Fig. 3-10 shows the relationship among the pump curves and the well curve. The well represented in Fig. 3-10 has an optimal discharge of 58 liters per second (L/s); consequently, a pump has been selected that yields its maximum efficiency at or near that point. Finally, the number of stages is added to the pump to bring the pump head curve up to the intersection of the well curve with 58 L/s. Recall that the water the well delivers must

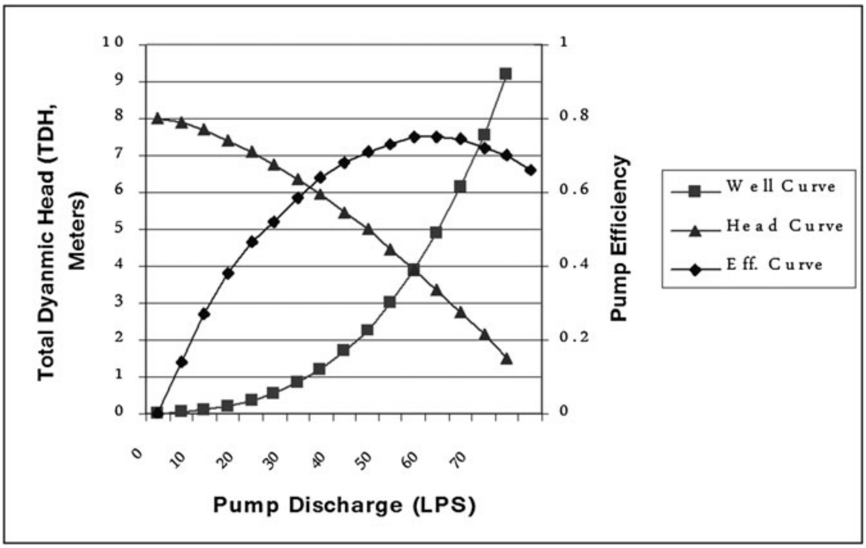

Fig. 3-10. Pump efficiency and well curves for an optimal discharge of 58 L/s

be at the intersection of the well curve and the pump head-discharge curve.

3.5.8 Evaluating Water Wells

The primary test necessary to evaluate both wells and pumps is the step-drawdown test. After recovery data are collected (i.e., a "baseline" trend of pretest levels is established), the test not only gives the relationship between discharge and drawdown (Eq. [3-7]) but also an estimate of transmissivity. Transmissivity may be estimated from the slope of the time drawdown curves for each discharge step using Jacob's analysis. Further, the test provides the relationship between specific capacity (SC) of the well and discharge (i.e., specific capacity diagram). If possible, wire-to-water efficiency, $E_{ww-\mathrm{II}}$, tests also would be conducted along with the step-drawdown test. If this is done, then the relationship between efficiency, head, and discharge (i.e., pump characteristics curves) may be obtained.

There are several terms for discharge and specific capacity that should be understood. The optimal discharge has been defined as the discharge from a well that maximizes net benefits. In other words, it is the discharge for which the pump should be selected, provided the other design constraints are met. The most efficient discharge is the discharge of a pump (not necessarily the optimal well discharge) at which efficiency is maximized (i.e., the discharge that coincides with the highest point on the pump efficiency curve).

The original specific capacity (SC_{max}) is measured when the well is new, assuming proper development. The measured specific capacity (SC_{act}) is the actual specific capacity at the time of measurement. Specific capacity generally decreases with both time and increasing discharge rate as shown in Fig. 3-11. The theoretical specific capacity (SC_{theo}) may be calculated from Jacob's equation:

$$SC_{theo} = \frac{Q}{S_{wd}} = \frac{5.46T}{\log \frac{2.25Tt}{r_e^2 S}} \tag{3-16}$$

where

$SC_{theo} = \frac{Q}{s}$, theoretical specific capacity (m^2/day)

T = transmissivity, (m^2/day)

t = time pump is operated, (days)

r_e = effective well radius, (m)

S = storativity, (dimensionless)

Q = well discharge rate, (m^3/day).

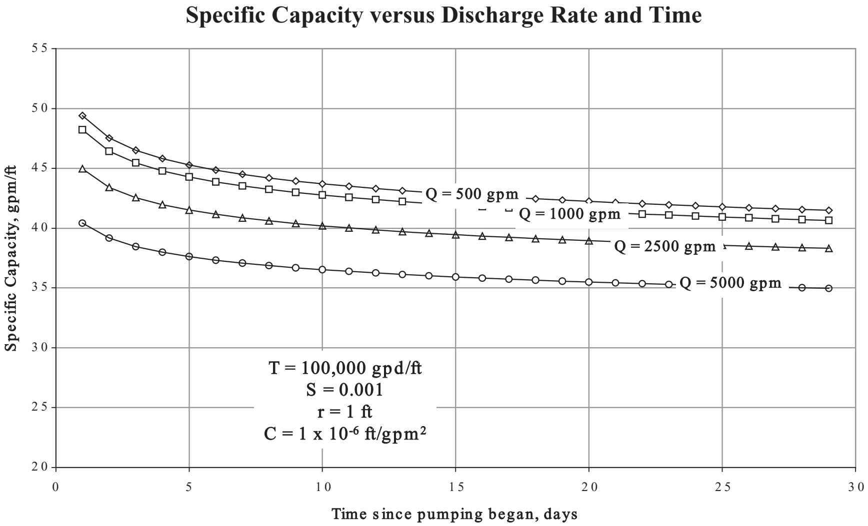

Fig. 3-11. Specific capacity versus time for various discharge rates
Source: Courtesy of Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA

In English units

$$SC_{theo} = \frac{Q}{s_{wd}} = \frac{T}{264\log\frac{0.3Tt}{r_e^2 S^2}} \quad (3\text{-}17)$$

where

T = transmissivity, (gpd/ft)
t = time, (days)
r_e= effective well radius, (ft)
S = storativity, (dimensionless)
Q = well discharge rate, (gal./min).

3.5.9 Analyzing Results of Step-Drawdown Test

The most important information obtained from the step-drawdown test is the functional relationship between discharge rate and drawdown. Although this relationship may be assumed to be linear for discharges that are significantly less than the maximum discharge of the well, it always will be nonlinear for a sufficiently high discharge. From the discharge–drawdown curve, the relationship between the specific capacity and discharge, well efficiency, and optimal discharge (Q^*) may be calculated.

It is necessary to know the relationship between specific capacity and discharge so that future specific-capacity measurements can be normalized for monitoring well efficiency and for determining whether the well needs rehabilitation. The efficiency of a new well may be estimated by comparing the theoretical specific capacity to the actual specific capacity. Some authors have suggested that the two terms of the step-drawdown test be used to estimate well efficiency (Biershenk 1963; Jacob 1947; Lennox 1966). As stated, the first term of the equation estimates the laminar flow losses and the second term the turbulent flow losses (Eq. [3-7]).

It should be noted that some wells may show losses such that a small well loss does not necessarily reflect a highly efficient well, as the well loss term depends on the maximum discharge at which the test was run; that is, the higher the discharge rate, the greater the well loss term. Comparisons always should be made at the design discharge rates.

As previously discussed, well efficiency decreases with both discharge rate and time (Fig. 3-9). Knowing the efficiency of a new well is necessary for determining the loss in well efficiency over time. Efficiencies for a number of different pumping rates also are necessary so that future values of well efficiency may be normalized (i.e., compared to a corresponding efficiency for the discharge at the time of measurement).

3.5.10 Solved Design Example 5

Assume Memphis Light, Gas, and Water (MLGW) Company Well No. 23 is a new well whose well and aquifer characteristics are given as follows. Estimate the well efficiency of this new well.

$B = 0.0187$ ft/gpm
$C = 1.198 \times 10^{-6}$
$p = 2.193$
$T = 87{,}085$ gpd/ft
$S = 2.3 \times 10^{-5}$
$r = 1.25$ ft
$t = 0.0694$ days
$Q = 2{,}000$ gpm

Solution Using Eq. (3-17) gives

$$(s_{wd})_{theo} = \frac{(264)(2000)}{(87{,}080)} \log \frac{(0.3)(87{,}080)(0.0694)}{(1.25)^2(2.3 \times 10^{-5})} = 46.7 \text{ ft}$$

$$SC_{theo} = \frac{Q}{(s_{wd})_{theo}} = 2{,}000/46.7 = 42.8 \text{ gal./min/ft}$$

Assume, a present test yields an actual specific capacity, SC_{act}, of 35 gal./min/ft, then the well efficiency, $E_{ww-\mathrm{I}}$, is

$$E_{ww-\mathrm{I}} = \frac{SC_{act}}{SC_{theo}} \times 100 = \frac{35}{42.8} \times 100 = 81.8\ \%$$

3.6 SUMMARY

A primary thesis of this chapter is that economics as well as engineering concepts should be considered in conjunction with each other for the design of water well systems. Economic efficiency always should be the primary objective whereby the economic benefits can be obtained by providing maximum discharge at the lowest possible cost. These same economic principles also may be used to provide guidelines as to the repair or replacement of pumping equipment, or when to rehabilitate the water well systems to achieve maximum monetary benefits with minimum investments (Helweg et al. 1984).

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CHAPTER 4

CONSTRUCTION, DEVELOPMENT, AND TESTING OF WATER WELLS

Dennis E. Williams

4.1 GENERAL

Currently, due to increasing population growth in arid and semi-arid areas, large-diameter, deep, high-capacity vertical wells are required to provide large quantities of water needed for municipal, industrial, agricultural, and domestic supplies. Modern water wells are constructed in a wide variety of geologic and hydrologic conditions, from unconsolidated alluvium to bedrock. No single well construction method works perfectly in every situation; therefore, a number of drilling and well construction methods have been developed to suit a variety of downhole conditions that exist. This chapter concentrates on the drilling, construction, development, and testing of high-capacity, large-diameter municipal water wells that are typical of those being drilled globally. Environmental drilling methods are mentioned only for basic information but are not discussed to a great extent in this chapter. If greater detail is desired, other references should be used.

Although well drilling and construction techniques have evolved over several thousand years, only recently has the full importance of the effect of proper well design, construction, and development practices based on optimal well efficiency been appreciated and understood. This chapter is an attempt to assist in providing necessary information on practices and techniques needed to reach optimal well performance.

The primary steps involved in the construction of a large-diameter municipal water-supply wells are provided in the Well Construction Decision Tree shown in Fig. 4-1. Key steps are illustrated in Fig. 4-2.

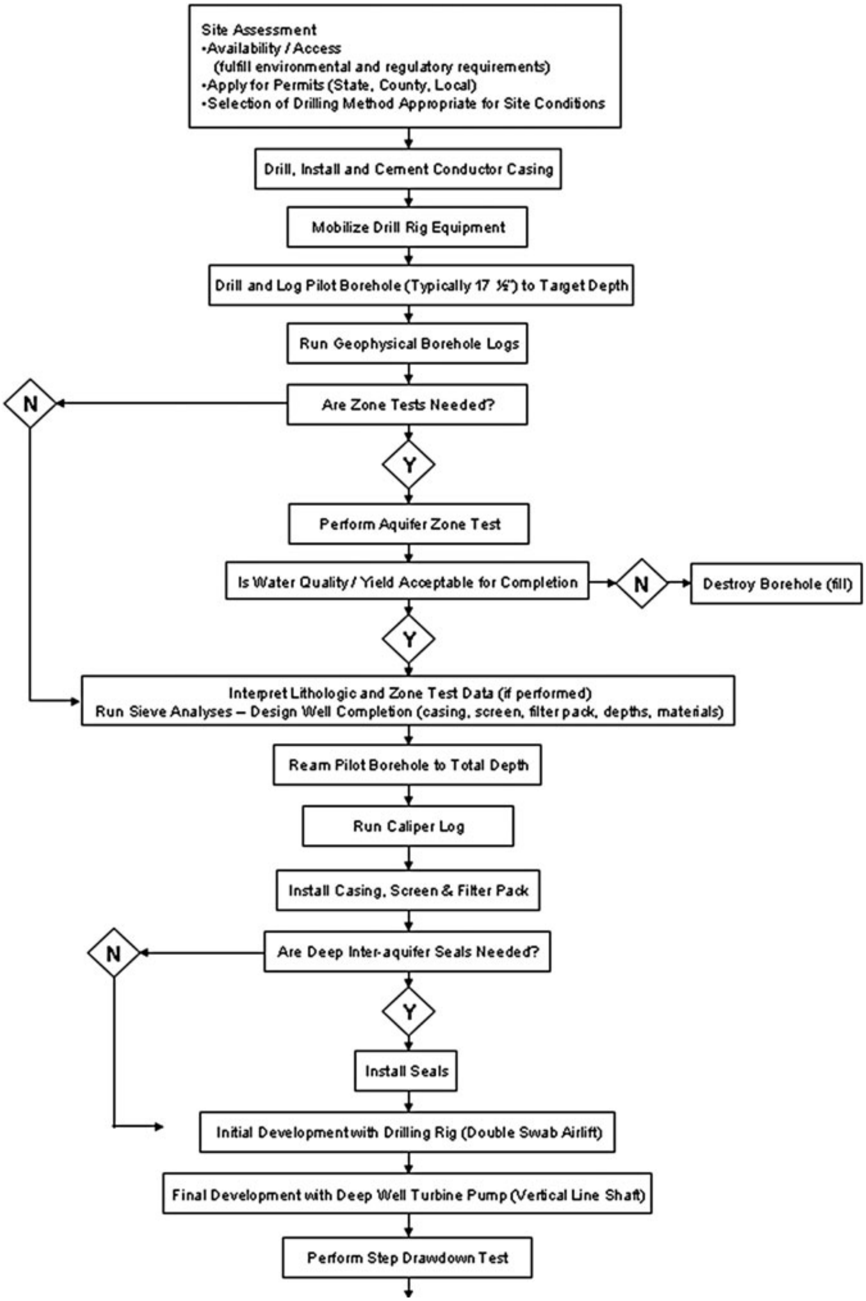

Fig. 4-1. Well construction decision tree
Source: Geoscience Support Services (2000)

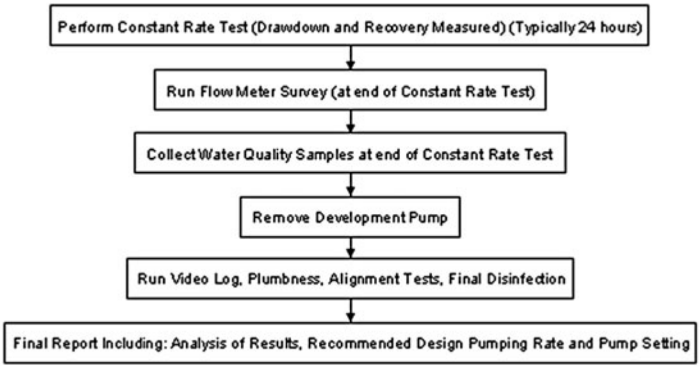

Fig. 4-1. (Continued)

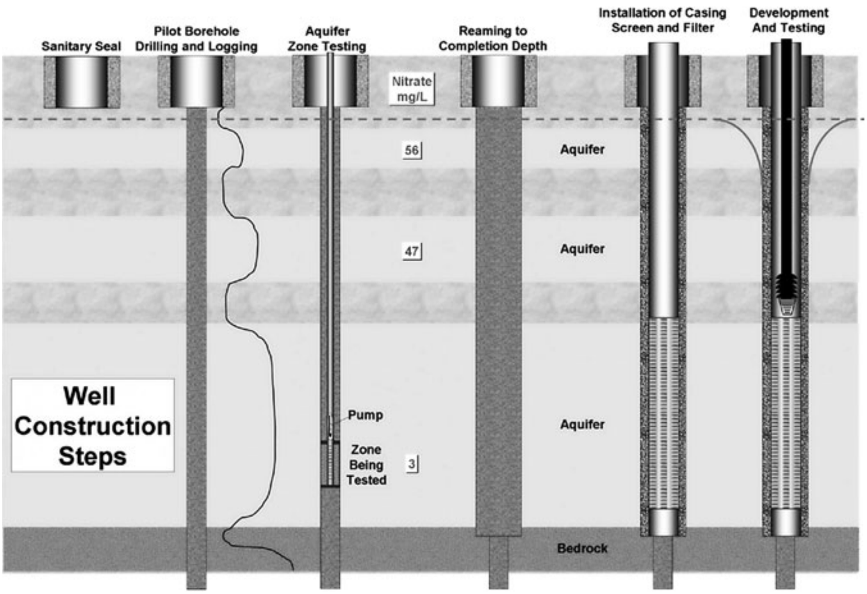

Fig. 4-2. Common steps in the construction of deep municipal water supply wells Source: Geoscience Support Services (2000)

4.2 SITE ASSESSMENT FOR POTENTIAL MUNICIPAL WATER WELL SITES

After a potential municipal water well site has been selected, a hydrogeologic study usually is conducted to determine whether aquifers beneath the site could provide enough water that is of acceptable quality to meet demand requirements. The amount and quality of groundwater available for pumping will determine the borehole and casing diameters, total depth, and screen length.

4.2.1 Hydrogeologic Assessment

A hydrogeologic assessment should be conducted before the final selection of a potential site. Hydrogeologic data can be collected from nearby wells (if they exist) regarding water quality, production history, well construction details, operating cycles, and interference with other wells in the area. A general sense of hydrogeology of an area can be obtained from local and state regulatory agencies, as well as local water districts. A background check should include local and regional geology and cross sections, pumping and other test data, water quantity and quality records, and well construction and production information. As ultimately the diameter of the production casing and screen will be determined by the amount of water that will be available from aquifers occurring under the well site, useful knowledge is gained from the production history of other wells in the area.

In addition, any selected well site must be located upgradient from any known or potential source of groundwater contamination and must be located outside any area of known or potential flooding. Appendix A (Example of a Water-Well System Design) provides a good case history example of well site selection.

4.2.2 Water Quality Considerations

Because of continually changing regulatory requirements, the quality of water produced by wells is becoming increasingly important. Natural groundwater quality is the direct result of the type of subsurface materials through which groundwater travels, as well as the length of time that groundwater has been in contact with these materials. Poor water quality can occur naturally in groundwater if it is affected by even low concentrations of basic elements, such as arsenic, boron, or vanadium. In addition, in areas of industrial and agricultural activities, groundwater contamination from volatile organic compounds, nitrates, and pesticides may pose serious constraints on well site selection areas. Special investigative tools, such as isolated aquifer zone testing, should be used globally and are being used widely throughout the southwestern United States to determine the vertical variation of water quality prior to completing the well (see Section 4.6). The final design of the well is based on the results of aquifer zone testing, analysis of geophysical borehole logs, lithology, and mechanical grading analyses of potential aquifers.

4.2.3 Noise Constraints

In most cases, there are activities during well construction that must take place on a continuous basis, 24 hours per day, and 7 days per week. Drilling equipment can be very loud even with the use of residential mufflers and noise suppressers. For the cable tool method of construction and even some direct rotary drilling operations, shutdowns can occur without compromising the desired progress of well construction. However, normal drilling operation shutdowns seriously compromise the integrity of the borehole and add a risk of borehole collapse. Common noise suppression techniques include the use of padded and insulated sound control barriers (at least 6 or 7 m (20 to 24 ft) high completely surrounding the drilling site. These sound barriers, if properly designed and installed, have been proven to reduce the noise levels significantly that are generated by the drilling and testing equipment.

4.2.4 Site Configuration and Accessibility

Access to the well site must be adequate to accommodate the well construction equipment and later, pump maintenance equipment. According to California, U.S.A., Well Standards, Bulletin 74-81 (supplemented by Bulletin 74-90) (California Department of Water Resources 1981, 1991), site restrictions can occur in the form of restricted lot size and configuration; overhead power lines; underground electrical, telephone, and television cable lines; proximity to sewer lines; solid waste disposal sites; septic tanks or leach fields; sewage or industrial waste water reservoirs; livestock enclosures or feedlots; or oil, gas, and water-supply pipelines. The site should be separate from areas with known or suspected soil or water contamination. In addition, the well site must be located at a distance from all bodies of surface water to avoid the occurrence of groundwater under the direct influence of surface water. Site topography and drainage patterns are also important matters when selecting a well site.

The site must be large enough to accommodate large drilling equipment consisting of the drilling rig, drill pipe and casing trailers, fluid circulation reservoirs, generators, various pumps and air compressors, wastewater storage tanks, and other necessary support equipment, such as backhoes, front-end loaders, and forklifts. Also, during well construction, there must be adequate room to store the piles of filter pack material that may be delivered in bulk to the site, as well as other supplies, such as casing and screen pipes. Increasingly, tight locations and the risk of contamination during transportation by bulk haul trucks require that the filter pack be delivered in approximately 0.76 cu m (1 cu yard) bulk bags, or super sacks rather than as bulk stockpiles.

Typically, a site that measures 23 m (75 ft) wide by 30 m (100 ft) long with direct access to a public, paved road or street has enough space to move about with the equipment without being too limiting. However, sites with smaller dimensions have been known to be workable if they possess the right configuration for the equipment. A site that is too narrow will not allow free movement around the drill rig, pipe trailer, fluid reservoirs, and cuttings storage area. If a site is too restrictive, it may dictate that the cable tool drilling method is the most feasible method, because less space typically is required for this drilling method.

In addition, pump houses and control buildings must be designed so that ongoing maintenance may take place without added hazards. Openings must be large enough to allow work to take place over the well, or the buildings may be designed to be at least partially removable to allow access for servicing pump equipment.

4.2.5 Source of Water and Disposal of Excess Fluids

The availability of potable water for a potential well site also may determine the drilling method. If no water is available, the likely choice of drilling method is either the cable tool method or the direct rotary method, as fluid reverse (i.e., reverse rotary) drilling method requires an uninterrupted water supply of at least 760 L/min (200 gal./min) during the drilling and well construction processes.

Cable tool drilling may require minimal water supply on the order of only 1,000 gal./day, which can be met easily using a water truck, whereas the direct rotary drilling method may require several hundred to a few thousand gal./day depending on the diameter of the borehole and its depth, as long as loss of circulation does not occur. As with all rotary-drilled boreholes, it is essential that the borehole remain filled with fluid at all times to maintain the hydrostatic head on the formation, which prevents borehole collapse.

Usually it is necessary to thin drilling fluids in the drilling fluid holding tank when an excessive buildup of solids occurs (e.g., during the filter packing or cementing procedures or during initial stages of development). As such, the site must be large enough to accommodate several large (approximately 79,500 L or 21,000 gal.) storage tanks in which to store these excess fluids for a long enough time to allow the finer grained materials to settle out. Once the tank has been allowed to stand undisturbed for a period of time, the clearer fluids found at the top of each tank can be decanted to allow for additional fluid storage. Containment of dirty fluids is especially important in urban areas where U.S. National Pollutant Discharge Elimination System (NPDES) regulations are enforced and dirty fluids are not allowed to be discharged to storm drains, flood control channels, or natural waterways. Disposal of large quantities of water, even in rural areas, may pose problems when drainage capabilities are exceeded. Fluid disposal facilities must be taken into serious consideration before making the final decision of well site selection.

4.2.6 Regulatory Requirements

State, county, local, and private agencies should be contacted and consulted to determine the local requirements that must be fulfilled, because they may and sometimes do affect the design of the well. The design of the well may be affected by the depth of the sanitary or annular seals, the maximum pumping rate that will be allowed, or other environmental concerns, such as the presence of endangered or threatened species. In some cases, the presence of these plants or animals may affect the construction of the well or its operating schedule after being placed online. A full review of the local environmental quality assessment requirements would prevent costly errors.

A title search of the potential property may reveal the existence of easements or rights-of-way that may affect placement and future operation of a well. Zoning also should be investigated prior to selecting a well site.

4.2.7 Drilling Permits

Once the technical specifications and contract documents have been prepared and the drilling contractor selected by either negotiation or public bid process (see Appendix B, Detailed Technical Specifications for Drilling, Construction, and Testing), the contractor must apply for any drilling or other permits that may be required by the local enforcing agencies. State, county, and local agencies always should be contacted and often consulted to determine the current regulations that are in effect and that must be followed to the letter and fulfilled conscientiously.

4.2.8 Selection of Drilling Method

Because no single drilling technique is suited perfectly for all conditions, a wide variety of techniques have been developed to allow for parameters, such as the depth and diameter of the borehole required, the characteristics of the formation to be drilled in, space restrictions imposed by the particular site selected, and most of all the proposed project budget availability. The intent of this chapter is to focus on the reverse rotary circulation drilling method, which is the method typically best suited for large-diameter, high-capacity, municipal water-supply wells. However, it should be recognized that much of the knowledge and technology involved with this method also applies to other drilling methods, particularly with regard to proper drilling fluid control and well development procedures. This chapter also will touch on drilling methods frequently used in other parts of the country for other uses, such as environmental drilling. Table 4-1 lists pros and cons of three common drilling methods.

In drilling large diameter municipal water wells, the drilling methods most often used are either one of the hydraulic rotary methods (reverse

Table 4-1. Comparison of Three Primary Drilling Methods

CABLE TOOL METHOD

PROS	CONS
Rigs are initially relatively inexpensive, with lower transportation, fuel, equipment, and personnel costs.	A more costly, heavier wall may be required, and larger diameter casings.
Machines have low energy requirements.	Penetration rates are usually slow.
Rigs are simple in design and require little sophisticated maintenance.	Experienced cable tool drillers are becoming rare.
Generally, only one person is needed to operate the drilling rig, although for safety, a helper should be available to assist.	Drilling efficiency declines with greater depth.
Water samples can be bailed at any time to determine the approximate yield at that depth.	Pulling back long strings of casing in some geologic conditions may be difficult, unless special equipment is available.
Casing is used rather than drilling fluid to support and stabilize formations.	There may be an inability to drill open a borehole when gravel envelope completion is required.
More efficient drilling operations in formations with open cavities, where loss of circulation to caverns is a severe problem.	Multiple strings of telescoping casings may be required.
Borehole is stabilized during the entire drilling operation.	
Operation is easier in remote locations or less accessible terrain and can be used in any climate and for drilling sites where available space is restricted.	
Relatively low makeup water is required.	
Recovery of reliable samples is possible from every depth unless heaving (sloughing under pressure) conditions occur.	
Wells can be drilled with little chance of cross contamination.	
Wells can be drilled in formation where lost circulation is a problem, as the method does not require a circulation system.	

Table 4-1. Comparison of Three Primary Drilling Methods (*Continued*)

DIRECT ROTARY DRILLING METHOD

PROS	CONS
There is the ability to drill small diameter, low-cost boreholes (which are later destroyed) for formation sampling and geophysical logging only.	Mobility of the rigs may be limited based on the slope and surface condition of the drilling site.
Work can take place either 24 hrs/day or daylight only shifts as needed as the open borehole is maintained in a stable condition in a wide variety of formations and downhole conditions.	Collection of accurate formula samples requires special procedures.
Penetration rates are relatively high for small diameter boreholes.	Greater daily operating cost than cable tool is due to greater equipment and manpower requirements.
Well screens can be set easily as a part of the casing string.	There are higher bit costs, particularly in hard formations and a high cost of drilling in karstic formations.
Minimal surface casing is required during the drilling of the borehole.	There are relatively high equipment transportation costs for projects requiring large diameter boreholes.
Ability to drill and maintain open borehole allows the use of geophysical borehole logs and facilitates installation of casing and screen, installation of gravel envelope, and annular cement seals.	A more complex drilling system is involved than the cable tool method.
A wide variety of casings and screen designs and material may be installed in open boreholes.	Relatively high makeup water is required.
	Drilling fluid management requires additional knowledge and experience, because improper use can damage aquifers.
	Drilling rigs and the multiple pieces of support equipment are costly and require a high level of maintenance.
	High noise levels created by operating equipment may be a problem in residential and urban areas.
	Rigs cannot be operated economically in extremely cold temperatures, because fluids will freeze when drilling operations are shut down.
	Most contractors do not have adequate mud pump capacity to drill large diameter boreholes without increasing mud weight or viscosity (which may cause formation damage).

Continued

Table 4-1. Comparison of Three Primary Drilling Methods (*Continued*)

FLUID REVERSE (REVERSE ROTARY) DRILLING METHOD	
PROS	CONS
Large-diameter holes can be drilled quickly and economically. Ability to drill and maintain open borehole allows the use of geophysical borehole logs and facilitates installation of casing and screen, installation of gravel-pack envelope, and annular cement seals. Most geologic formations can be drilled easily, though cemented alluvium or igneous and metamorphic rocks require button bits. Lower risk of washouts in the borehole is due to the low velocity of the drilling fluid traveling down the borehole. There is a lower capital cost than equivalent capacity direct rotary equipment. For drilling large diameter boreholes in unconsolidated formations, this is the most economical system. Formation sampling is more accurate than with direct rotary drilling, as drilling fluids are less viscous and return to the surface very quickly without being cross contaminated by the borehole. High return velocity inside the drill pipe lowers drilling fluid viscosity requirements. There are lower noise levels with insulated sound barriers and engine covers. Simpler, less costly circulating system and fluid cleaning equipment is required. Typically fewer drilling additives are required. Other than the conductor casing, no casing is required during drilling operations. Well screens can be set easily as part of the casing string without the need for telescoping sections. Less development is required when properly controlled drilling fluids are used.	Some drill sites are inaccessible because of the rig size. A starter or conductor casing is required in order to start the reverse (airlift) process. The system is not suited for drilling through consolidated rock formations, or karstic formations, where loss-of-circulation is a concern. When drilling through long sections of clay and shale, drilling fluid additives may be required. It is difficult to use where static water level is higher than 4.6 m (15 ft), as the airlift system needs to make the fluid column buoyant in order to provide flow at the surface. For efficient operation, at least two people per shift are required. In most cases, boreholes smaller than 17.5 in. in diameter cannot be drilled with standard 5 to 6 in. diameter drill pipe due to erosion caused by high fluid velocity down the annulus (the ratio of the borehole diameter vs. drill pipe diameter must remain high). Large water supply in high permeability formations is required.

or direct rotary) or the cable tool method. The direct rotary (also known as the mud rotary) drilling method is acceptable when the borehole being drilled is less than 400 mm (16 in.) in diameter, whereas typically reverse rotary drilling begins with a minimum 445 mm (17.5 in.) pilot borehole. This pilot borehole often is reamed (sometimes in stages) to the desired final diameter of the borehole.

4.3 DRILLING, INSTALLATION, AND CEMENTING OF CONDUCTOR CASING

State water-well standards for municipal wells require that the conductor casing be installed to a minimum depth of 15 m (50 ft) below ground surface. The cement seal on the outside of the conductor casing assists in preventing contamination of the well at the surface. Ideally, the bottom of the conductor casing should be landed in impervious material, such as clay or other fine-grained material. However, if the depth to groundwater is very deep (i.e., in excess of 30 m or 100 ft) or if an annular seal is planned, it is acceptable to land the conductor in coarse-grained materials. Many cases have been documented where inadequate sanitary seals have allowed seepage of contaminated surface water into the groundwater.

It should be recognized that the conductor casing is used not only as a sanitary seal but also to provide near-surface borehole stability during the drilling process by conducting drilling fluids and cuttings to and from the surface in a way that avoids erosion of the borehole near the ground surface. On occasion, short sections of temporary surface casing (that are not cemented into place) and even intermediate casing strings are required to combat difficult drilling conditions caused by loose surface soils, elevated water levels, heaving sands, swelling clays, or loss-of-circulation zones.

Typically conductor casings are made from relatively inexpensive materials, such as low-carbon (mild) steel, following ASTM Specifications No. A139 Grade B, as this string of casing will not be in direct contact with water that is produced from the well. The wall thickness of the conductor casing must be designed to have adequate strength to support without collapse the entire column of cement slurry during pumping. In addition, it must be larger in diameter than the drilling bit that will be used for the anticipated final reaming pass of the borehole.

The conductor borehole typically is drilled using a bucket auger (see Section 4.4.6.1) drilled in a single pass with the bucket or auger being the diameter of the desired borehole. Once the conductor borehole has been drilled, sections of conductor casing are welded together as they are lowered into the borehole. Centralizers should be attached at 6-m (20-ft) intervals to keep the casing from lying against the walls of the borehole, ensuring a complete seal between the borehole and the casing during cementing, around the entire circumference of the casing.

Following installation of the conductor casing, the annular space between the conductor casing and the borehole is filled with a sand-cement slurry that meets the requirements of local ordinances. For example, a 10.3 sack sand-cement mixture consists of Portland Type I or Type II cement (ASTM C150-95 Standard Specification for Portland Cement), sand and water in the ratio of 2 : 1. This mixture contains 85.28 kg (188 lb) of washed sand per 42.64 kg (94 lb) bags of Portland cement (California Department of Water Resources 1981, 1991). Clean water in the amount of 6.5 to 7 gal. per bag of cement should be added to make the mixture fluid for pumping. A small amount of additional water may be added if necessary; however, it is important to avoid adding excessive quantities of water, because this will cause the grout mixture to separate and become watery as it is being pumped.

If desired, bentonite powder in the amount of a maximum of 2% (by weight) of the cement slurry can be added to the makeup water (prior to its addition to the sand and cement mixture) to make the mixture more fluid for pumping. The addition of bentonite also will reduce shrinkage and cracking of the cement seal. If a faster setting time for the cement seal is needed, as much as 2% (by weight) of powdered calcium chloride can be added to the sand-cement slurry.

Whether or not the borehole contains fluid, it is a good practice to use a tremie pipe to place the cement slurry positively into the annular space. A small diameter tremie pipe should be installed as close to the bottom of borehole as is practical before the cement seal is pumped. The cement slurry is pumped through the tremie pipe, the lower end of which remains submerged in the wet cement mixture, lifting the column of cement under pressure in an uninterrupted pour from the bottom of the borehole to the top.

It is important that no more than two hours is allowed to elapse between the time of adding water to the cement mixture at the ready mix plant, and the pumping of the slurry into the borehole.

4.4 DRILLING THE BOREHOLE

4.4.1 Cable Tool Drilling Method

The cable tool drilling method is the oldest and most versatile drilling method; it is still a commonly used method for drilling water wells throughout the world. Water wells as deep as 1,500 m (5,000 ft) have been drilled using this method. The cable tool drilling method can be used in a variety of difficult conditions, such as in formations where open caverns or other loss-of-circulation conditions exist that would preclude the use of fluid circulation methods (Driscoll 2008) or in challenging drilling locations where poor accessibility and a lack of a reliable water source compound the difficulties of constructing a water well. The cable tool drilling method can provide water wells that are extremely efficient and have very low well losses. These very low well losses are caused by implementing construction methods that use large openings in the intake section of the well and are naturally developed (i.e., do not use a gravel pack envelope). However, the cable tool drilling method can be extremely slow, requiring several months to complete a single, relatively shallow water well.

4.4.1.1 Cable Tool Drilling Equipment Cable tool drilling rigs are relatively simple, typically requiring little maintenance, and are usually inexpensive to operate regarding both initial capital cost of equipment and ongoing maintenance, making this drilling method one of the most economic. Because cable tool rigs are smaller and less complex, and require less support equipment, they are easier and less expensive to transport from location to location. The cable tool drilling method frequently is used for locations that are inaccessible to other types of drilling equipment, especially when the site has no existing water source (Driscoll 2008; Roscoe Moss Company 1990). Cable tool drilling rigs have been used in such isolated locations as Santa Cruz Island off the California coast and at the bottom of the Grand Canyon in Arizona to drill and construct wells for use as a local water source.

The drill string consists of five components—the drilling bit, drill stem, drilling jars, swivel socket, and drilling cable—all linked by coarse-threaded, right-hand tool joints (see Fig. 4-3). From the drill string, the drilling cable passes up and over the crown sheave (located at the top of the mast) and passes through the spudding sheave on the walking beam that is attached to the working side of the draw works (i.e., drilling drum or bull reel) (Driscoll 2008).

The drilling bit itself is a massive alloy steel bar that can weigh more than 1,000 lb depending on the desired diameter of the borehole. All points of wear on the drilling bit are typically hard-faced. Because the drilling bit repeatedly strikes downhole formational deposits with great force, frequent sharpening or refacing is necessary. In addition, the drilling bit may have durable tungsten carbide inserts added to its striking face for use in harder formations (Roscoe Moss Company 1990). The drill stem, attached above the drilling bit, gives additional weight to the drill string. The drill stem adds length and stiffness to assist in maintaining a straight borehole (Roscoe Moss Company 1990).

The next components of the drill string are the drilling jars, consisting of a set of linked telescoping loops of steel that allow a specific amount of movement (Driscoll 2008; Roscoe Moss Company 1990). These drilling jars are used to administer sharp upward blows if the drilling bit and

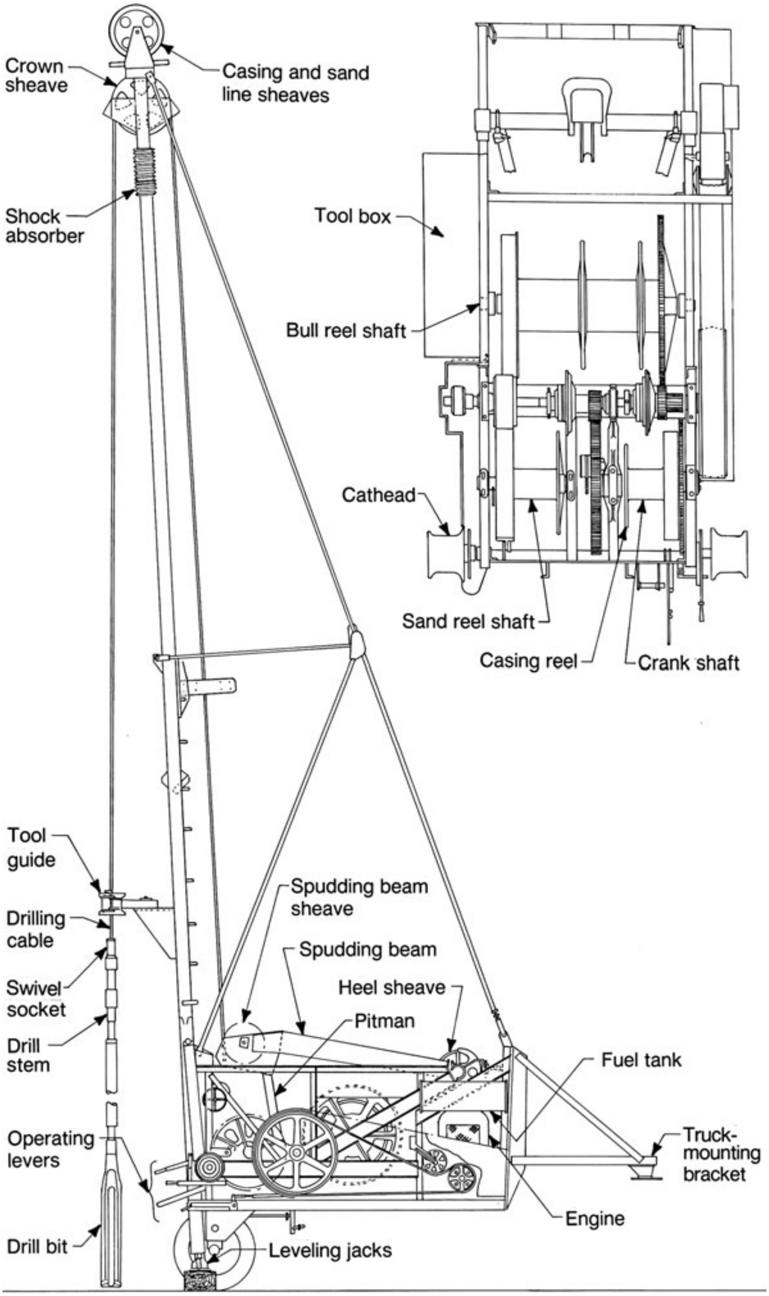

Fig. 4-3. Cable tool drilling rig and components
Source: Driscoll (2008); reproduced with permission from Johnson Screens

other downhole tools become stuck, providing an action similar to that of a slide hammer. It should be noted that fishing jars are similar in construction and in practice; however, they are much longer with a stroke of 460 to 920 mm (18 to 36 in.) as opposed to the typical 230 to 460 mm (9 to 18 in.) stroke of drilling jars (Driscoll 2008). Finally, a swivel socket attaches the drilling tools to the wire-line cable. The drilling cable, or drill line, is typically 15.8 to 25.4 mm (5/8 to 1 in.) diameter left-hand lay cable that provides tension to the tool joints on the upstroke while keeping the right-hand thread tool joints from coming apart, as well as to provide rotation to the downhole tool string on the down stroke. The rotating action induced by the drilling cable causes the drilling bit to turn with each stroke of the walking (or spudding) beam, cutting a round, straight borehole (Driscoll 2008).

4.4.1.2 Cable Tool Drilling Methodology The cable tool drilling method uses a simple apparatus consisting of a framework that supports a heavy suspended weight that is lifted repeatedly and dropped to loosen, crush, and mix subsurface formation materials. The size of the material that is broken by the bit is a function of the hardness, as well as the type of formation being drilled. Unconsolidated materials, such as alluvium (sand, gravel, and pebbles), will be loosened and removed in an intact manner; however, cobbles and boulders must be broken into pieces small enough for the bailer to pick up. Consolidated formations, such as hard rock or cemented sedimentary materials, will be pounded and pulverized to very small particles by the bit. Casing (with a drive shoe attached to its lower end to prevent bending or buckling) is advanced with the bit to support the walls of the borehole and to prevent caving.

The repetitive motion of the cable tool is supplied by a single or double pitman connection that is attached to a crankshaft at the moving end of the walking, or spudding, beam (Driscoll 2008). As the walking beam moves up and down, the weighty tool string at the end of the drilling cable is lifted repeatedly and dropped, allowing the face of the bit to strike against the bottom of the borehole with great force. The length of the stroke, as well as its frequency, can be changed to accommodate each drilling situation. The goal in drilling with the cable tool method is to have the bit strike the bottom of the borehole in a quick, snapping motion so that a sharp blow is delivered to the formation material at the bottom of the borehole. To achieve this, the cable must remain in full tension on the downward fall, rebounding sharply after it hits the bottom (Driscoll 2008; Roscoe Moss Company 1990).

Engineers have attempted to characterize the motion of the tool at the end of the cable mathematically in order to maximize the bit's force when striking substrate in such a way that reduces the loss of inertia and energy to extraneous motion and friction. More detailed information and an indepth account with equations and reasoning can be found in the *Handbook of Ground Water Development*, published by Roscoe Moss Company, 1990. Although at this point no one has found a satisfactory mathematical definition of this motion, an experienced driller can adjust the motion of the tools and their position in the borehole to ideal or near-ideal conditions to ensure efficient penetration on the basis of the feel of the drill line (Driscoll 2008).

4.4.1.2.1 Removal of Drill Cuttings Every 2 to 3 m (5 to 10 ft), loosened and crushed materials must be removed from the borehole, because the free-fall action of the bit hitting the bottom of the hole is impeded increasingly. Interference with the free-fall action of the bit results in poor drilling progress. Poor drilling progress also can be caused by cable whip, resulting in nonsynchronized action from a combination of poor engine speed, the hampered vertical fall of the tools, cable stretch, and poor borehole alignment, which can cause the cable to bounce off the walls of the borehole, releasing energy prematurely. Cobbles and boulders that may protrude into the borehole also may hinder the action of the drilling cable or drilling bit causing them to strike in an ineffective manner (Roscoe Moss Company 1990; Driscoll 2008).

The broken formation material is mixed with fluids as they build up during the drilling process until a slurry is formed. This slurry periodically is removed from the borehole using a bailer or a mud scow (Driscoll 2008). The advancement of the borehole can be fairly slow as the drilling process is halted frequently for the removal of these accumulated drill cuttings. When drilling by the cable tool method in dry formations or in formations containing minimal water, water must be added periodically to the borehole to create slurry that is needed for removal. It should be noted that lithologic information obtained with the cable tool drilling method is excellent, because the formation materials being removed are unmixed with other strata found within the borehole.

Generally bailers consist of a length of pipe that has been fitted with either a flapper valve or a ball-and-tongue dart valve at its lower end. When the bailer is raised and lowered, cuttings are washed into the body of the bailer and are trapped by the valve. The unit then is raised and emptied at the surface. A sand pump, also called a suction bailer, consists of a 3 to 6 m (10 to 20 ft) length of pipe that is equipped with a plunger and a flapper valve. When this apparatus is raised off the bottom of the borehole, the sand line pulls up on the plunger, creating suction that both opens the valve and draws cuttings into the body of the bailer where the material is trapped by the closing valve when the sand pump is again lowered (Driscoll 2008). This up-and-down motion is repeated until the pump is filled to the desired level. The sand pump is retrieved to the surface where the slurry is dumped into appropriate receptacles. Once the borehole is cleaned, the string of drilling tools is again placed in the borehole, and drilling is resumed.

4.4.1.3 Well Construction Using the Cable Tool Drilling Method It may be possible to complete the well as a partially cased well or even as an open borehole in more consolidated formations, rather than installing casing throughout its entire length. Many water wells are completed using casing only to support loose, unconsolidated near-surface materials. Once competent formation materials are encountered, the bottom of the borehole is left uncased.

4.4.1.3.1 Driven Casings In loose, unconsolidated formations, a casing often is driven simultaneously with drilling so that the newly driven casing supports the walls of the borehole as the bit progresses to the desired depth or until the amount of friction produced by the casing rubbing against the borehole walls prevents the casing from being advanced any farther. Because of this limitation, a well drilled using the cable tool method may have a series of progressively smaller diameters of casing with depth, telescoping downward (Driscoll 2008; Roscoe Moss Company 1990). Because casing is driven to support the walls of the borehole as it is advanced, heavier (and therefore more expensive) casing is needed to withstand the driving forces (Roscoe Moss Company 1990) even with the use of a casing shoe that has been attached to the leading end of the casing. In most cases (other than with the pull-back method of well construction) the use of a gravel pack envelope is precluded, resulting in native formation materials being in contact with the intake section of the water well.

When necessary, a drive block is attached to the drill string to assist in hammering the casing into place. The drive block is used to strike a drive head that is placed on top of the casing string, preventing it from bending or buckling. The driving action on the downhole tools is caused by manually pulling on a rope that has been wrapped around a cathead drum. Formation material is removed from the inside of the casing using a mud scow (Driscoll 2008).

Once the casing has been installed to the desired depth, it is perforated adjacent to selected coarse-grained aquifers using either a Roscoe Moss Company hydraulic perforator (which will control the size of the openings), or a Mill's knife (where there is no real control over the resulting size of the openings) (Roscoe Moss Company 1990).

4.4.1.3.2 California Stovepipe Method The California stovepipe method is a variation on the basic cable tool method, where casing is driven concurrently while advancing the borehole in loose alluvial materials. A heavy mud scow is used as both bit and bailer to excavate loose, unconsolidated alluvium from the borehole while sections of steel casing are advanced in the borehole by pulling downward using hydraulic jacks. Heavy anchors are placed within a pit that surrounds the borehole and are covered and braced with heavy timbers before the pit is backfilled. Depending on the diameter of the casing, two to four hydraulic jacks are fastened to these anchors (Roscoe Moss Company 1990). The hydraulic jacks operate with a pressure of two 109,415 kg/m^2, or approximately 3,000 lb/sq in. (psi), with positive displacement pumps that can generate hundreds of tons of pull-down force. Such jacks are capable of driving casing to depths of more than 455 m (1,500 ft) without collapse of the casing, as long as the pull-down force of the jacks (when divided by the cross-sectional area) does not exceed the yield point of the casing material (Roscoe Moss Company 1990). Double-walled casing that has been fabricated in short lengths (1.5 m, or 5 ft) often is used for this process.

Once the borehole has been cased to the desired depth, a perforator (either Mill's knife or Roscoe Moss Company downhole casing perforator) is lowered into the casing to the desired production level and is used to puncture the casing, creating the intake portion of the well. Because these perforations are relatively crude, wells perforated in this manner do not have a gravel envelope to assist in controlling the migration of fine-grained materials from the formation into the well; they must be developed naturally (see Section 4.14.2) and often have problems with sand production (Driscoll 2008). The implementation of thorough development practices can reduce potential sand production problems.

Pull-Back Method The pull-back method of casing installation works well with either the cable tool drilling method, or air rigs equipped with casing drivers. In utilizing the pull-back method for well construction, a large diameter casing is driven to desired total depth before a smaller diameter section containing a short piece (approximately 6 m, or 20 ft) of blank casing is installed above the perforated interval. The perforated section is lowered into the borehole within the larger diameter string of casing that has been left in place to support the borehole walls and to prevent caving during well construction. When reference is made to the *screened* section or the *perforated* interval, the use of either horizontally louvered perforations or of wire-wrapped well screens is implied for use as the intake portion of the well. Once the perforated section has been placed within the cased borehole, the outer, larger diameter string of casing is pulled back only far enough to expose the perforated section to the aquifer, leaving the 6.5 m (20 ft) of blank casing above the perforated interval overlapping within the larger diameter casing. The perforated intake section of the well then is developed naturally, because this construction method does not utilize a gravel pack envelope. Wells constructed in this manner must be designed so that the outer casing is strong enough to withstand the force of pulling on the casing as it is being extracted from the borehole using hydraulic jacks.

Packers, typically consisting of stacked neoprene discs surrounding a steel coupler, are attached to the top of the perforated section. The outer diameter (OD) of the packer is designed to fit tightly within the larger diameter casing to create a sand-tight seal between the upper casing and the lower telescoping perforated section. Multiple neoprene packers should be installed as the rough surface of the casing is inclined to damage the packers.

4.4.1.3.3 Telescoping Well Screens Telescoping blank and perforated intervals allow the flexibility to drill, case, and cement intervals with potential or known problem zones that occur above the targeted production interval, before drilling and completing the well. Telescoping lengths of casing and perforations can be used in both cable tool and rotary-drilled boreholes.

The cemented upper casing string (pump house casing) will isolate and stabilize problem areas in the upper part of the well so that construction can proceed. Once the lower portion of the borehole has been drilled, the perforated interval that is smaller in diameter than that of the upper casing is installed to the designed depth. The perforated interval should contain a minimum of 6.5 m (21.32 ft) of casing located on its upper end in order to overlap within the larger pump house casing. A back-off joint, or a special coupling containing a left-hand thread, is used to connect the casing string containing the perforated interval to the drill pipe before it is lowered into the borehole. While the drill pipe suspends the perforated sections, filter pack material is pumped into place through a small diameter tremie pipe. The tremie pipe has been placed inside the upper casing and outside the screen section. After placement, the left-hand thread then is used to "back off" from the perforated section and to expand the mechanical packer that seals the space between the two diameters of casing.

When using telescoping perforated intervals, the diameter of the lower portion of the borehole is limited by the diameter of the upper casing. If a larger diameter is desired for the perforated interval, under-reaming of the production interval (below the cemented portion of casing) can be used to achieve an increased borehole diameter to accommodate the gravel-pack envelope. However, under-reaming can be achieved only using the direct, or mud rotary, drilling method, because the pressure of the drilling fluid being pumped down the drill string holds the blades of the under-reamer open during drilling (see Fig. 4-4).

4.4.1.3.4 Casing and Screen Reducers To reduce the cost of well construction materials, the diameter of the perforated interval sometimes is reduced through the production interval and a fabricated tapered cone-shaped transition section, or reducer, joins the two diameters of casing and screen. The reducer typically is fabricated from the same material as used in the upper (larger diameter) portion of the casing. The use of reduced diameter casings or reduced diameter intake sections are not recommended for good water well design applications. The minimal cost savings perceived by reducing the diameter of either casings or screens is offset greatly by the added difficulties that arise, such as considering future rehabilitation or the need to lower pumps due to declining regional water levels.

4.4.2 Direct Rotary Drilling Method

Normally, the direct rotary drilling method, also commonly known as mud rotary drilling method, is used when drilling small diameter water wells in consolidated, semiconsolidated or alluvial materials. The drilling method was developed primarily during the early 1900s for use in the oil industry, initially for exploratory boreholes and wells (Driscoll 2008). The direct rotary drilling method had the advantage over cable tool drilling in that it has increased drilling speed and was able to achieve greater depths. In addition, by using a fluid system, downhole problems, such as high-pressure environments or high temperatures, could be overcome. A drawing of a direct rotary rig is shown in Fig. 4-4.

4.4.2.1 Equipment In the direct rotary drilling method, (Driscoll 2008; Roscoe Moss Company 1990) a rotating drilling bit is operated at the end of a rotating drill string to provide the cutting power to advance the borehole. Fluids are used to convey formation materials to the surface as the borehole is advanced. As the mud pump forces fluid through the interior of the drill string, it is discharged through nozzles located in the face of the drilling bit. The drilling fluid serves to lubricate, cool, and clean the face of the bit as it assists in breaking up and mixing with the cuttings (or broken formation materials). This enables the cuttings to be carried in suspension as the fluid moves upward within the annulus of the borehole to the surface. Upon reaching the surface, the drilling fluid is discharged into baffled (divided) fluid reservoirs that contain, as minimum equipment, a shaker table and several desanding cones. This minimum equipment is necessary to assure that solid material carried by the drilling fluid is separated physically from the drilling fluid through the use of the shaker table and the multiple desanding cones, as well as by gravity once the fluid velocity has slowed in the fluid reservoir. The fluid reservoir should be of sufficient size to allow the drill cuttings to settle out before the fluid returns to the borehole.

To maintain the volume of fluid in the reservoir and to maximize its cleaning effectiveness, cuttings that have settled out must be removed

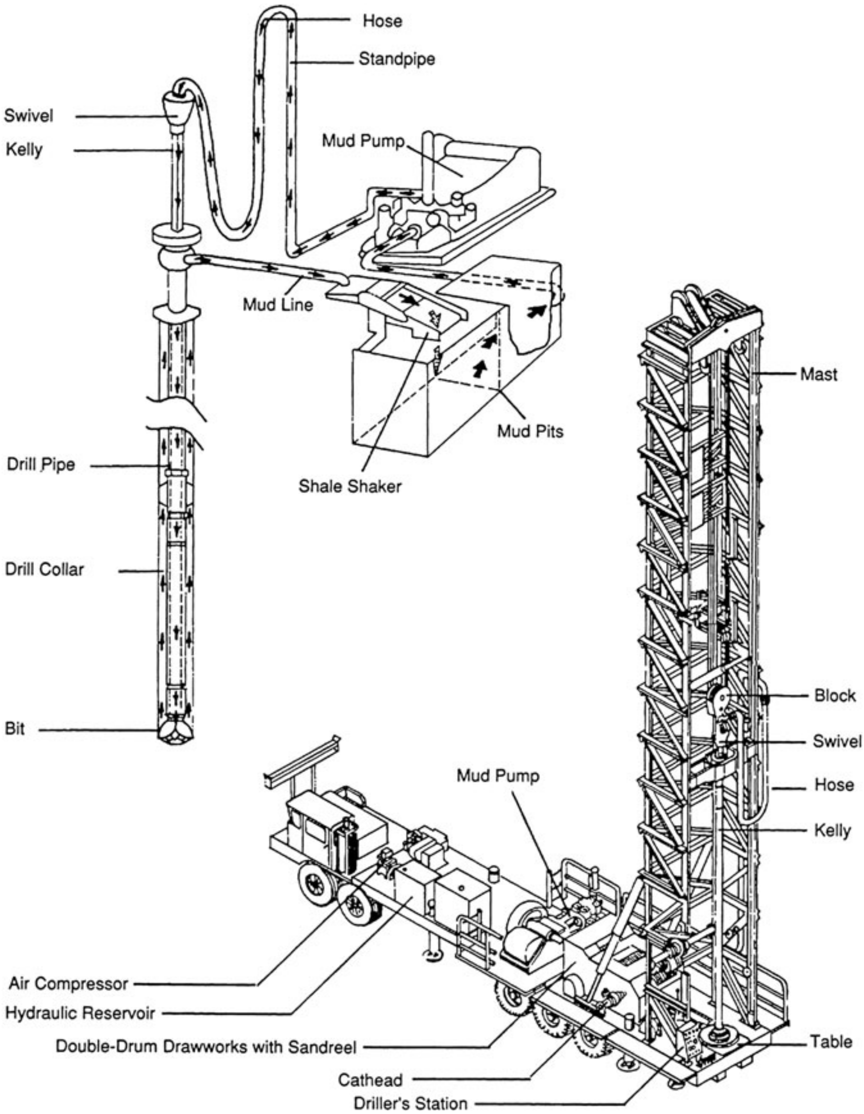

Fig. 4-4. Direct hydraulic rotary drilling system
Source: Modified from Roscoe Moss Company (1990), p. 132; reproduced with permission from Wiley

frequently. Once the fluid acceptability is sand-free and has been cleaned and conditioned (mixed to a uniform consistency), it is returned to the borehole by way of the mud pump. A properly sized fluid reservoir used for direct rotary drilling must be at least three times the final volume of the borehole. Only aboveground reservoirs, having several connecting compartments that are separated by baffles, should be used. Because of difficulties in solids control and fluid losses, the use of in-the-ground reservoirs is not recommended.

The basic drill string for the direct rotary drilling method consists of a drilling bit, drill collars or stabilizer bars, drill pipe, and the kelly (Driscoll 2008; Roscoe Moss Company 1990). Most small direct rotary drilling rigs are powered by a top-head drive; however, the larger drilling rigs typically are driven by a rotary table.

A variety of drilling bit configurations are available for use in direct rotary (as well as reverse rotary) drilling as are required to achieve the desired results when a variety of subsurface materials are encountered. Drilling bits vary in configuration and composition; however, two general types are used for water-well drilling. The drag bit, which has a short-bladed winged bit and no rotating parts, is used to cut the borehole rapidly, using a shoveling action, to break through sands, clays, and other very soft, unconsolidated formations. The roller cone rock bit, containing three to four intermeshing toothed cones that rotate independently from one another, is used to crush and chip both unconsolidated alluvial materials containing cobbles, gravels, sands and clays, as well as more consolidated formations. The action of intermeshing teeth on the roller cones assist in keeping the surfaces of the teeth clean (Roscoe Moss Company 1990). The roller-cone drilling bit was developed by the Hughes Tool Company in the early 1900s for oilfield use and revolutionized the drilling industry by allowing advances in the development of the mud rotary drilling technique.

Two main types of roller cone drilling bits are used: mill-tooth, consisting of mild steel cutting teeth of varying lengths determined by the amount of consolidated formation encountered (i.e., longer teeth are used for softer formations), and the button bit, having teeth made of tungsten carbide, also varying in length as determined by the amount of consolidated formation encountered. For example, cemented alluvial formations may require a long-tooth button bit, whereas granitic bedrock may require a short-tooth button bit. Button bits are much more expensive than mill-tooth bits; however, they will not show wear nearly as easily as mill-tooth bits.

The drill collar, a heavily weighted length of drill pipe, adds weight to the drill string to allow the operator to maintain proper cutting pressure on the drilling bit (Driscoll 2008). The primary way that borehole alignment is preserved is by holding back on the weight of the drill string, using the kelly block, and by not allowing the entire weight of the drill string to rest on the drilling bit. The drill string will act as a driveline and will assist in maintaining a straight borehole. Stabilizers with drill collars can be used to maintain a straight borehole by minimizing the amount of whip in the drill string above the drilling bit. In larger boreholes, the drill collars themselves may be fitted with stabilizer bars. In addition, stabilizers also may be used to straighten a crooked borehole and can be fitted with stiff bars or rollers to maintain contact with the walls of the borehole as the bit is advanced (Driscoll 2008).

Lengths of drill pipe are added behind the drill collars as the borehole is advanced. The sections of drill pipe are connected by either threaded tool joints or by flanges, which add length and weight to the drill string as the borehole advances.

The final component is the kelly, which is typically a square or fluted bar that is at least 3 m (10 ft) longer than each section of drill pipe being used. Differing lengths of drill pipe are available, with the length being a matter of choice—that which is best suited for the configuration of each particular drilling rig. The kelly passes through the drilling rig's rotary table, which is the rotating portion of the drilling rig. The shape of the kelly corresponds to the bushings that are set within the rotary table (i.e., kelly bushings) so that the kelly is locked within the rotary table while drilling. With the kelly bushings in place, the turning rotary table causes the entire drill string to rotate. The rotating action of the kelly, driven by the table, and conveyed through the drill pipe to the drilling bit, provides the bit with its ability to cut at depth (Driscoll 2008; Roscoe Moss Company 1990).

The weight of the drill string is supported at the top of the kelly by the kelly swivel that is suspended from the kelly block. The kelly assembly hangs from the crown sheave in the mast by drilling line (Roscoe Moss Company 1990). This allows the operator to lower or raise the drilling string, sliding the kelly through the rotary table. As the borehole is advanced, the kelly is picked up slightly off the bottom of the borehole and is disconnected from the drill string before an additional length of drill pipe is added to increase the length of the drill string. The kelly then is reconnected to the drill string before it is again drilled down its entire length before making the next connection, (i.e., adding the next section of drill pipe) (Driscoll 2008).

4.4.3 Sequence of Drilling

In all rotary drilling, a pilot borehole initially is drilled to the targeted total depth. Once total depth is reached, the borehole is circulated a period of time to clean and condition the borehole and the drilling fluid by removing all residual cuttings. The time spent in circulating the borehole is needed to balance the fluids within the borehole, as well as to condition the wall cake that protects the wall of the borehole. Immediately following removal of the drilling string from the borehole, geophysical borehole logs typically are run within the open borehole to gather additional information regarding the character of the subsurface materials. From information gained from both the geophysical borehole logs and the lithologic samples that are gathered while drilling the pilot borehole, several intervals for isolated aquifer zone testing are selected (see Section 4.6). The reaming pass (enlarging the borehole to it final diameter) should not begin until all water quality results from the isolated aquifer zone testing have been reported and a final well design has been provided to the drilling contractor.

4.4.4 Drilling Fluid Systems

Direct and reverse rotary drilling methods rely on a drilling fluid (or mud system) to remove broken or loosened formation materials from the borehole. Specifically designed drilling fluid additives are used to assist in the removal of formation materials from the borehole, for cleaning, conditioning, and stabilizing the borehole, improving borehole advancement through increased drilling efficiency, and for improved production from the well at completion and development.

Water, bentonite gel, and polymer additives are the most commonly used drilling fluid additives and are used to adjust the drilling fluid's physical and chemical properties. Only water-based drilling fluids are discussed in this chapter, as oil-based drilling fluids are used principally in the oil industry and typically are not used in drilling water-supply wells.

Because the borehole is filled with drilling fluid at all times, the hydrostatic pressures support the walls of the borehole, allowing boreholes to remain open to great depths during geophysical borehole logging, as well as during installation of the casing, screen, and gravel pack envelope. At the beginning of any drilling project, the direct rotary drilling method has high makeup water demands when filling the fluid reservoirs and initially mixing the drilling mud. Proper fluid control for direct rotary drilling requires costly, specialized equipment that is operated by knowledgeable, well-trained, and experienced staff as is required to monitor and correct drilling fluid properties as dictated by changes in borehole conditions during the drilling process (Driscoll 2008; Roscoe Moss Company 1990).

4.4.4.1 Role of Drilling Fluids in Water-supply Wells The primary functions of the drilling fluid are to lubricate the drill pipe and mud pump, including all moving equipment components within the circulation system, as well as to cool the bit surfaces, clean cuttings from the face of the drilling bit, lift cuttings from the bottom of the borehole and suspend them so that they are discharged at the surface, enable the collection of representative formation samples of the materials being penetrated, and protect the productivity of the formation. Secondary functions of the drilling fluids include dropping the cuttings from the fluid once they reach the circulation reservoirs, assisting in the removal of the drill string and installation of casings, preventing cave-ins and wash-out zones, controlling formation pressures, preventing the loss of fluid to "thief" zones, and reducing corrosion and excess wear to drill string components.

If temperatures resulting from friction (caused by the bit working against formation materials) are allowed to increase to excessive levels, premature bit failure can occur. Because of this, provisions must be made to cool and lubricate the bit by continuous circulation of clean drilling fluid. As an additional benefit, lubrication of the borehole walls with slippery drilling fluid reduces abrasion to the drill string and its rotating components.

Only high-quality bentonite clays should be used as drilling-fluid additives. These high-quality clays must be mixed in the manner that is recommended by the manufacturer to achieve the desired properties. Complete hydration of drilling fluids does not occur immediately upon mixing with water; the fluid needs time to hydrate fully as it is circulated continuously within the borehole and fluid reservoir. As the borehole is advanced, additional drilling fluid must be mixed continually to compensate for the increased borehole volume as material is removed from the subsurface.

Large volumes of material are removed from the borehole for high-capacity water wells as they are being drilled. For example, the calculated volume of a 305-m (1,000-ft) borehole that is approximately 1,000 mm (39.4 in.) in diameter is nearly 239.5 cu m (313.3 cu yds) of material. Considering an average specific gravity of rock of 2.65 and a U.S. ton of 2,000 lb, this amount of material can weigh more than 634 Mg (699 tons), increasing the importance of proper drilling fluid properties for effective removal. The drilling fluid properties of weight, viscosity, and uphole velocity will determine both the size and density of the drill cuttings that are capable of being removed from the borehole. The rate at which the drill cutting will drop from the column of drilling fluid in the borehole is a function of the size, shape, and density of the cuttings themselves. The viscosity, density, and velocity of the drilling fluid must be sufficient to lift and carry these cuttings to the surface (Roscoe Moss Company 1990).

If the drilling fluid system (in combination with the positive displacement mud pump) is not capable of lifting the larger fragments, they must be broken by the bit to a smaller size until conditions are such that the drilling fluid is able to lift them. As the particles of the cuttings become smaller, the rate at which they will drop out of suspension will decrease, which will allow the drilling fluid's density, viscosity, and velocity to lift them from the borehole more easily. If continuous regrinding of cuttings is occurring at the bottom of the borehole, the result will be increased wear on the drilling bit, as well as a negative effect to the penetration rate.

Other downhole problems may be caused by allowing clays within the formation to hydrate, resulting from the ability to absorb excessive water from the drilling fluid. This may result in reduced borehole diameters caused by swelling clays or squeezing zones.

The thickness of the residual material that remains on the filter paper after the 30-min water loss test is measured as the wall cake. The buildup of solid material on the filter paper that has been removed from the filter press is measured physically to determine the thickness and character of the wall cake that is forming within the borehole.

4.4.4.2 Field Tests and Evaluation of Drilling Fluid Properties Proper drilling fluid control is essential for maintaining the required properties to promote successful drilling and well completion operations, as well as for optimal well efficiency following the development. Drilling fluids are capable of performing many functions depending on the chemical and physical conditions encountered while drilling the boreholes.

The effectiveness of the drilling fluid primarily depends on its physical properties. It is essential that the physical properties be measured frequently during the drilling process to determine how the fluid is performing. The primary tests for measuring the physical properties of the drilling fluid are viscosity, weight or density, wall cake thickness, 30-min water loss, sand content, and pH. Other properties may be measured, but they will not be discussed here. For further information, see American Petroleum Institute standard 13-B “Standard Procedure for Testing Drilling Fluids,” 5th edition, 1974.

4.4.4.2.1 Fluid Weight (Density) The measurement of the fluid weight, or density, is very simple yet is one of the most significant parameters of field tests. Fluid weight is measured by weighing a known volume of drilling fluid and recording it in easily used units, such as lb/gal., lb/ft^3, or kg/m^3. Fluid weight is used to control formation pressures when fluid in the formation exceeds the hydrostatic pressure of the column of drilling fluid in the borehole.

$$\text{Hydrostatic pressure, psi} = \text{depth} \times \text{fluid weight, in lb/gal.} \times 0.052.$$

However, excessive fluid weight against the formation also may cause a loss of circulation condition if the fluid weight is too great.

It should be recognized that solids carried by the drilling fluid do not always contribute productively, especially if they are native clay materials that have been derived from the drill cuttings. Sand and other abrasive materials carried in the drilling fluid will cause excessive wear on the bit, drill string, and mud pumps while the drilling rate can be significantly affected. High solids content will result in a thick, sludgy wall cake being deposited on the borehole walls adjacent to permeable formations. If excessive fluid losses are allowed to occur because of poor wall cake condition, borehole stability and other problems—including stuck drill pipe—are risked. Periodic measurement of fluid weight will help avoid potential problems, as well as formation damage resulting from excessive solids being carried in the mud system. Removal of unwanted solids is accomplished by good fluid reservoir design and the use of shale shakers and desander cones.

Field Measurement of Fluid Weight A mud balance is used to measure the fluid weight. The cup on the mud balance is filled to the top with a freshly collected sample of the mud that has been taken from the return, or suction end, of the fluid reservoir. The lid to the mud balance is dropped into place and rotated so that mud is squeezed from the hole in the lid. Excess drilling fluid should be wiped away from the exterior of the mud balance apparatus before balancing the scale. The stand is placed on a level surface. The balance is seated on the knife-edge of the stand and is leveled using the sliding weight. The fluid density is read directly from the inside edge of the sliding weight where it is marked. The cup can be filled with fresh water periodically to check calibration. Fresh water weighs 1.00 kg/L (8.34 lb/gal.).

Optimally, the fluid weight should be kept below 1.08 kg/L (9.0 lb/gal.). Water can be added to thin the fluid and decrease the mud weight. Products, such as powdered barite, can be added to increase the mud weight. Drilling contractors should use a qualified mud engineer to address unusual drilling conditions with specialized drilling fluid programs.

4.4.4.2.2 Fluid Viscosity The viscosity and velocity of the drilling fluid will determine the effectiveness of the removal of drill cuttings from the face of the drilling bit and from the borehole. Viscosity is the resistance to flow of a liguid or gas. In drilling fluids, this is observed as the thickness of the fluid and is a measure of the carrying capacity of the drilling fluid. Low viscosity drilling fluids are preferred for both the effective cleaning of the bit face and borehole, and for the swift settlement of cuttings and solids from the drilling fluid within the circulation reservoirs. However, under special circumstances, it may be necessary to increase the viscosity of the drilling fluid in order to remove large formation particles from the borehole (such as coarse sands and gravel) or to stabilize loose sand and gravel formations. Increased viscosity of the drilling fluid must be countered with the realization that the rate of settlement of solids within the fluid reservoirs will be reduced.

Development of gel strength is associated closely with viscosity in water-based drilling muds (i.e., bentonite drilling muds), which are inclined to thicken, or "gel," when they stop moving. The gel strength of a drilling fluid is the amount of force that is required to break the gel and start it moving again. However, if the gel strength of a drilling fluid is allowed to become too high, excessive mud pump pressure is required to move the fluid. This can cause loss of circulation in the borehole when weak formations are forced to take on large amounts of fluid from the borehole under high mud pump pressure. Rapid gel development will reduce the ability of a drilling fluid to drop its cuttings in the circulation reservoirs. However, when properly controlled, high gel strength is useful for stabilizing troublesome loose sand and gravel formations.

Field Measurement of Fluid Viscosity A Marsh funnel is used to measure fluid viscosity. The funnel is held in an upright position with a finger placed over the outlet as fresh drilling mud is poured through the screen until the level of the fluid reaches the underside of the screen. The drilling fluid sample should be collected from the suction side of the circulation reservoir close to where it enters the borehole. The funnel is held over a one-quart container, and once the finger is removed, the flow is timed in seconds until the one-quart mark is reached in the measuring cup. The number of seconds required to fill one quart is the funnel viscosity. The Marsh funnel can be calibrated using fresh water, which has a funnel viscosity of 26 s at 70°F. The rate at which the drilling fluid gels will affect the viscosity measurement. Because of this characteristic, the Marsh funnel is used for field-testing only and does not replace more accurate measuring devices, such as rheometers or viscometers.

The drilling fluid should remain as thin as possible while still allowing formation stability and retaining its capacity to lift and carry formation particles. The fluid viscosity should be kept at 32 to 38 s for satisfactory performance of the drilling fluid in average drilling conditions.

4.4.4.2.3 Water Loss and Wall Cake Thickness A very important function of the drilling fluid is its ability to form a thin, tough, low-permeability filter or wall cake on the borehole walls. This characteristic will increase borehole stability and allows the drill string and casing strings during installation to move freely, without sticking, within the borehole. A good wall cake will assist in obtaining accurate lithologic information from the borehole by reducing the potential for mixing and cross contamination of samples with other materials found within the borehole.

The drilling fluid, carrying suspended solids, contacts porous formations and allows a bridging of the particles to occur. Tiny platelets of high-quality bentonite clay are deposited in flat layers, which lie tightly against the borehole wall. As the wall cake is deposited, pressure operates as a function of depth (0.433 psi/ft of depth) pressing water from the drilling fluid and leaving behind the thin coating of clay platelets. As successively smaller particles are filtered out of the drilling fluid by the porous formation, only a small amount of liquid is allowed to pass through into the formation and also into the near-well zone. The ability of water to pass through the wall cake is a function of the permeability of the wall cake and the pressure differentials involved. For example, if the wall cake has a very low permeability due to many closely layered platelets, the drilling fluid will not be able to pass through it easily. A wall cake with high permeability typically has misaligned platelets that are not closely layered. This allows drilling fluids to pass through easily, creating high water loss, formation damage, and other problems.

As the borehole is advanced, periodic field tests of the drilling fluid are run (using a small filter press operating at 70,300 kN (70,300 kg-force/m^2; 100 lb-force/sq in. [psi]) to measure the amount of water loss to the formation (Roscoe Moss Company 1990). In addition, it should be noted that a good wall cake permits optimal production from the completed well (following development) by reducing formation damage caused by the drilling fluid.

The texture of the wall cake is an important property. If the wall cake is gritty, additional wear will occur on the rotating components of the drill string, and friction will drag at the drill pipe and bit requiring additional work to rotate the drill string. A gritty wall cake indicates excessive amounts of sand are being allowed to return to the borehole and the circulating reservoirs are not effective in sand removal. Sand returning to the borehole will clog pore spaces and will increase well development time.

Field Measurement of Water Loss A small filter press, using a carbon dioxide cartridge or compressed air, is used to measure water loss and wall cake properties in drilling fluids. The pressure regulator should be set at 100 psi for the test. The pressure vessel should be prepared by placing a disc of filter paper on the screen located at the bottom of the pressure cell. The pressure vessel is filled with freshly collected drilling fluid before placing the cap on top. The pressure vessel then is placed on the frame and held clamped firmly into place and pushing down on the cap of the pressure vessel. A graduated cylinder is placed under the opening at the bottom of the pressure vessel. The pressure regulator is adjusted to 100 psi, and the pressure is maintained for 30 min. The total amount of clear fluid collecting in the graduated cylinder for the 30 min is recorded. (If the test is run for 7.5 min, the result is multiplied by two; however, it is more accurate to run the test for the entire 30 min.)

Field Measurement of Wall Cake Once the test is concluded, the pressure on the vessel must be released gradually by slowly opening the relief valve. Once the pressure vessel has been removed from the clamp and frame, the top of the vessel is removed and the mud remaining within the cup is discarded. The wall cake remaining on the filter paper should be rinsed using a gentle stream of clean water, which will remove any loose mud. The thickness of the wall cake then is measured to the nearest millimeter. The texture of the wall cake should be felt for grittiness, stickiness, slipperiness, or any other characteristic that is observed readily. An effective wall cake should be thin (<2 mm), firm, and slippery, and may be tough enough to peel off the filter paper without tearing. Increasing the ratio of effective colloidal solids in the drilling fluid will increase the thickness of the wall cake.

4.4.4.2.4 Sand Content Excessive sand will create a thick wall cake, cause excessive wear on the rotating components of the drilling system, and cause problems when dropped out of the drilling fluid should circulation in the borehole be interrupted. Measurement of the sand content should be made at frequent intervals during drilling and circulation in the borehole. The sand content is defined as the percentage of solids (by volume) in the drilling fluid that is not able to pass a 200-mesh screen. The amount of abrasiveness due to sand content—and therefore wear on the drilling equipment—is not only a function of particle size but also of hardness and angularity of the particles themselves.

Field Measurement of Sand Content A small sample of freshly collected drilling fluid is added to a special glass vial manufactured by Baroid (1992) to the mark labeled "Mud to Here." Water is added to the mark indicated by "Water to Here." The top of the glass vial is covered and inverted several times to mix before the mixture is poured through a small 200-mesh screen. The resulting fluid is discarded, and the screen is inverted over the glass vial. Clean water is used to rinse the screen back into the glass vial and is allowed to settle until clear water is formed in the tube. The quantity of sand then is read directly from the tube in percent sand by volume of mud. The maximum volume of sand allowed in the drilling mud is 2% by volume. With the reverse rotary drilling method when minimal drilling additives are used, or if Baroid's Poly-Bore product (Baroid 1992) is used, sand content measurements are commonly known to be recorded at less than 1% by volume.

If excessive amounts of sand are found to occur in the drilling fluid, they can be reduced by dilution with water that will reduce the viscosity or by increasing the amount of settling time within the circulation reservoirs by good pit design having adequate baffles or dividers or by the addition of mechanical separation devices, such as shale shakers and banks of desander cones. Good practice dictates that the suction of the mud pump not be allowed to rest on the bottom of the fluid reservoir.

4.4.4.2.5 pH For maximum yield and performance of bentonite drilling mud, the pH of the makeup water must be adjusted to 8 to 9 pH units. Soda ash typically is used to raise the pH, whereas sodium bicarbonate is used to reduce the pH to within the desired range. In the field the pH can be tested using either pHydrion paper or calibrated pH field test meters.

pH of Makeup Water Hard water containing dissolved calcium and magnesium salts will impede the hydration of bentonite drilling muds. If excessive quantities of these compounds occur in the makeup water, it must be treated prior to the addition of drilling additives. For example, soda ash may be used to reduce hardness in the makeup water. Calcium salts seriously impede the hydration properties of the bentonite (reduced viscosity and gel development resulting from inadequate hydration), which will affect the suspension and sealing qualities of the mud system directly. A simple test for calcium in the makeup water easily can avoid the nuisance of fighting poor mud performance. For optimal hydration of the bentonite clay, it is desirable to carry the calcium concentration at less than 100 mg/L.

Excessive chloride concentration in the makeup water will cause increased wall cake thickness and inadequate hydration of the clays resulting in lowered viscosity and gel development. For optimal mud performance, the chloride concentration must be less than 500 mg/L in the makeup water.

Other nuisance situations occurring from the makeup water include strongly acidic water that may require the addition of caustic soda. If sulfides are present in large quantities in the makeup water, the pH may need to be carried at 10 pH units or more to combat corrosion. If the makeup water is highly saline, a specialized drilling fluid program must be implemented, because there are no chemical additives that will remove sodium or potassium salts.

When drilling potable water wells the makeup water must be potable, free from any type of contamination or microorganisms.

4.4.4.3 Common Drilling Problems A common problem that may occur when drilling through thick sequences of heavy clay materials is that of *balling up* the bit. If the bit becomes balled and drilling continues without attempting to correct the situation, premature bit failure may occur if it is not being cooled or lubricated. In addition, when conditions are such as to allow bit balling, the environment is also right to allow the development of *mud rings*. Mud rings are formed when a large mass of highly viscous and plastic drilling fluid has been allowed to build. Mud rings can become so large that they effectively form a packer between the drill string and the borehole wall. When this occurs, excessive pressure may be induced on the formation below, resulting in a loss of circulation condition.

The creation of a thick, sludgy, or highly viscous wall cake causes an increased risk for sticking the drill pipe in the hole or other severe problems. If a zone of thickened and sloppy wall cake has been allowed to form within the borehole and rotation of the drill string halts for even a short time, as when making a connection, *sidewall sticking* can occur. Sidewall sticking is the condition where the drill pipe touches the borehole wall in the area were the thickened wall cake occurs, and the pressure differential effectively pushes the drill pipe into the wall cake. Excessive torque is necessary to free the drill string when this occurs (Roscoe Moss Company 1990).

Another form of stuck drill pipe occurs when circulation is interrupted, and because of the very high solids content of the drilling fluid, the drilling mud begins to thicken and gel within the borehole. When this occurs, it is extremely difficult to resume circulation without washing a tremie down along the drill string in an effort to free it.

Key holing can occur if the borehole deviates from vertical at depth (i.e., forms a dogleg) and a thick buildup of wall cake occurs. Circulation is possible, as is downward movement of the drill string, but upward movement of the drill string is hampered when the drill pipe digs into the convex wall of the borehole at the dogleg.

Sometimes, excessive fluid loss is experienced in what appears to be a complete loss of circulation when no drilling fluid is returned to the surface. This situation results from over-pressurizing the formation at depth due to excessive fluid weight, which drives the available drilling fluid into the formation adjacent to the borehole, rather than allowing it to return up the borehole to the surface.

4.4.5 Reverse Circulation Rotary Drilling

The reverse circulation method of drilling is suited particularly to soft, sedimentary rocks and unconsolidated sand, and gravel formations for the construction of large diameter, high-capacity water-supply wells. As in direct rotary drilling, the walls of the borehole are supported during drilling by the hydrostatic pressure of drilling fluids in the borehole, allowing geophysical logging and well completion to take place in an open borehole. Reverse circulation rotary drilling is used primarily to construct large diameter boreholes appropriate for wells with gravel pack envelopes (Roscoe Moss Company 1990).

As in direct rotary drilling, reverse circulation rotary drilling (see Fig. 4-5) also uses a rotating bit to cut through formation, with the key difference being in the direction of flow of the drilling fluid. In reverse circulation drilling, the fluid reservoir remains filled and connected to the

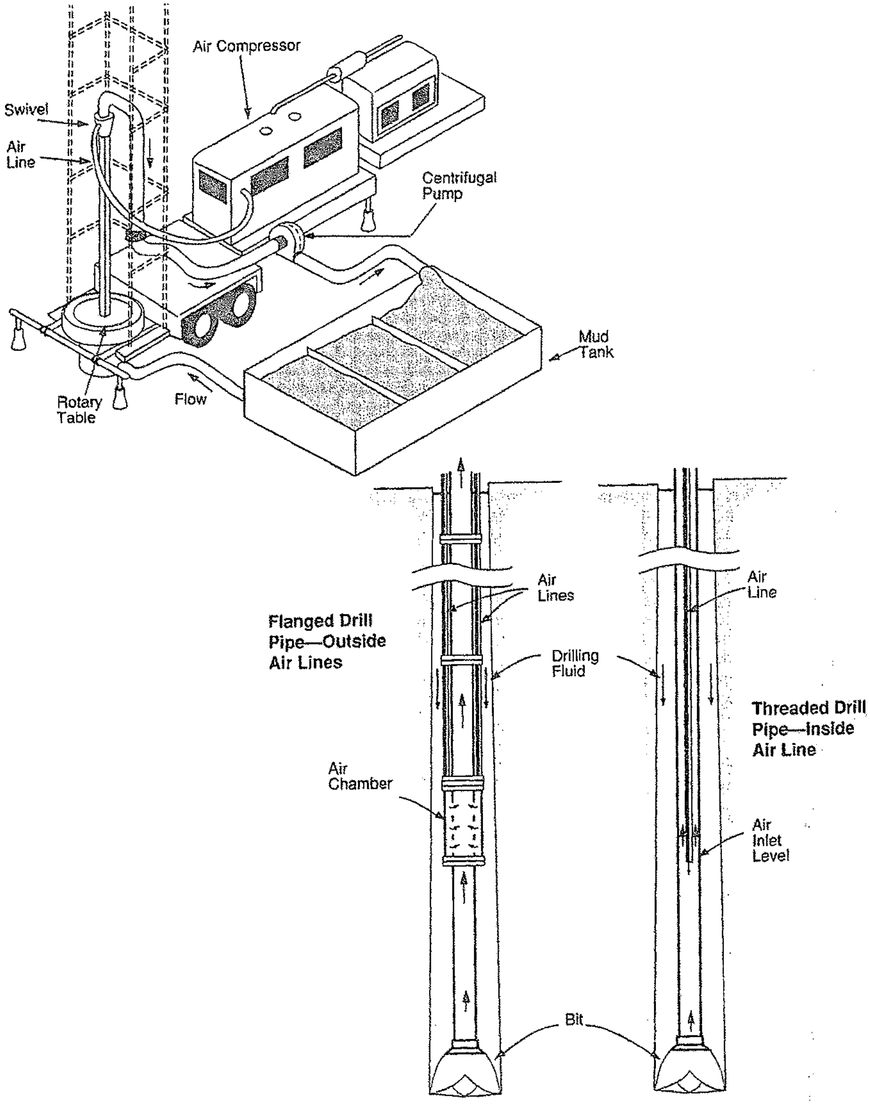

Fig. 4-5. Reverse circulation rotary system components source
Source: Roscoe Moss Company (1990), p. 142; reproduced with permission from Wiley

conductor casing of the borehole by way of a "flow line" (a large diameter hose or pipe). Drilling fluid then flows by gravity through the annular space between the borehole and the drill string and enters the ports in the bit.

A velocity of less than 0.3 m/s (1 ft/s) should be maintained to prevent erosion (or washing out) of the borehole walls due to excessive velocities. Cuttings and fluids are drawn into the interior of the drilling string by airlifting the column of fluid to the surface. The fluid with the cuttings suspended is discharged into large aboveground fluid reservoirs. There, the fluid must remain for a long enough period of time to allow the cuttings to separate from the fluid before it is returned to the borehole. If shaker tables and desanding cones are not used to remove solid materials from the drilling fluid, the baffled reservoirs must be cleaned frequently to maintain volume and the reservoirs' effectiveness in solids removal.

The reverse circulation drilling apparatus is equipped with air compressors to generate the circulation of fluids within the borehole. Pressurized air is pumped into a small diameter pipe, or airline, that hangs within the drill string and bubbles the air to the drilling fluid (Driscoll 2008; Roscoe Moss Company 1990). The air that is forced in the column of fluid causes the column of fluid to become buoyant. This aerated column of fluid will follow the path of least resistance, picking up cuttings with the returning drilling fluid and carrying them to the surface, hence the term *airlifting*.

Some drilling situations require using a drilling fluid system, even with the reverse rotary drilling method. It should be noted that a reverse rotary drilling system that contains only water in the circulation reservoir will develop its own native mud system once the bit begins turning downhole. In formations that contain an abundance of fine-grained materials (i.e., silt and clay), the use of synthetic polymers can be effective in greatly reducing the residency time of the fluid within the circulation reservoir that is necessary in order to separate suspended solids (cuttings) from the liquid drilling fluids.

4.4.6 Other Drilling Methods and Variations

As dictated by differing drilling conditions found throughout the country, many contractors have developed innovative variations of the standard drilling methods to meet the particular needs of their area. A brief discussion of a few of the more well-known drilling methods follows.

4.4.6.1 Bucket Auger Method A bucket auger drilling system consists of either a large-diameter cylindrical bucket that has been fitted on the bottom side with overlapping auger-type cutting blades or a large diameter spiral auger flight. Each type of cutting mechanism is relatively short in length and is approximately 1 m (3.28 ft) in length. The bucket or auger is attached to a kelly that consists of two or more square telescoping lengths of steel. The kelly slides within the center of a circular table and engages a large ring gear, causing the bucket or auger to be rotated. As the bucket or auger cuts into the subsurface materials and deepens the borehole, loosened formation materials are pushed into the bucket or creep up the auger flight. When the full bucket or auger is brought to the surface, it is dumped. As long as the length of the telescoping kelly can accommodate the depth of the borehole, the bucket or auger flight can be brought to the surface where it dumps its load of cuttings without the need to disconnect components. If the auger progresses more deeply than the kelly can extend, drill rods must be included to add length, and these lengths of rod must be removed every time the bucket is brought to the surface to dump cuttings (Driscoll 2008).

The bucket auger drilling method has been used to drill wells up to 76 m (250 ft) in depth in weakly consolidated but stable formations. However, more shallow wells of 16 to 46 m (50 to 75 ft) in depth are more common. In more consolidated formations, the auger blades can be fitted with durable tungsten carbide inserts to grind and cut through harder materials. However, boulders and cobbles must be fished from the borehole by an orange-peel bucket, stone tongs, or a ram's horn tool. The bucket auger drilling method works best in areas of clay deposits, because this is the type of formation that can withstand the excavation without excessive caving, even in areas with high static water levels. When drilling in sandy or loose deposits, water and bentonite gel may be added to maintain an open borehole by increasing the hydrostatic pressure within the borehole and by creating a wall cake to support the borehole walls. When using the bucket auger drilling method in formations that have shallow groundwater, it is typically difficult to maintain an open borehole without the addition of bentonite drilling mud. The bentonite mud helps coat the walls of the borehole and reduces water loss to the formations, keeping the borehole from caving (Driscoll 2008).

4.4.6.2 Dual Tube Methods: Rotary and Percussion A variation on cuttings removal in air rotary and percussion systems is the dual tube method. In this closed circulation system, dual wall drill pipe is used to convey air to the bit where it picks up available cuttings and then lifts them to the surface. Water mist is used as the fluid and passes through the annulus between the walls of the inner and outer pipes, through openings in the bit face, and then up the inner tube, carrying cuttings to the surface. Because water or drilling fluid contacts the walls of the borehole only in the immediate vicinity of the drill bit (where cuttings enter the system), reliable formation samples that are disturbed but unmixed can be collected as drilling progresses. This method is used primary in environmental drilling situations where large cobbles and boulders preclude the standard environmental drilling methods but can be used for municipal water supply, especially in areas with difficult drilling conditions. However, the casing and borehole diameters typically are limited to

150 mm (6 in.), or less. Some contractors are known to carry larger sizes of dual-wall drilling pipe and can accommodate larger borehole and casing diameters.

4.4.6.2.1 Dual-Tube Reverse Air Circulation Method The dual tube (also known as dual wall) reverse air circulation drilling method uses double-walled drill pipe in which the outer wall of the drill pipe is flush-threaded. An airtight double O-ring seal achieves the connections for the inner barrel of the drill string. Short connector sections containing the O-rings slip over the ends of the inner barrel of the drill pipe at each threaded connection of the drill pipe. This completes the continuity of the inner barrel from the drilling bit to the top head drive unit. Within each section of drill pipe, the inner barrel is held in place by centering guides. A top head drive unit provides rotational power to the drill string while a hydraulically operated injection pump is used to introduce water to the stream of air that is being forced down the annular space between the walls of the drill string (see Fig. 4-6).

With the dual wall reverse circulation drilling method, a roller cone bit with intermeshing teeth is used when drilling alluvial or unconsolidated materials, an insert bit (having tungsten carbide chips imbedded in its face and outer ring) is used for denser or more tightly compacted materials, and a down-the-hole hammer is used for well-consolidated materials, such as bedrock. A special drill bit adaptor is fabricated to form a skirt over the body of the bit that catches and directs the cuttings up the inner barrel. This type of bit sub also permits the borehole to be advanced with minimal clearance between the drill string and the borehole wall (typically 1/4 to 1/2 in., maximum). The drill pipe supports the tight borehole, eliminates leakage by the tight fit and allows uncontaminated sampling to occur.

The drilling fluid (consisting of only air and water) flows through the drill string by reverse circulation. All air and fluid is contained between the walls of the drill string and is in contact with formational materials only at the face of the drilling bit. The definition of reverse circulation is that the flow of air and fluid is downward through the annulus (in this case between the inner and outer walls of the drill string rather than in the open borehole) and then upward through the interior of the drill string to be discharged at the surface.

At the face of the drilling bit, loosened rock fragments and groundwater (when present) are picked up by the returning flow of air carried through the inner barrel of the drill string. These materials then are discharged directly to a cyclone separator. The cyclone separator reduces the velocity of the returning air and material so that rock fragments and groundwater drop by gravity from the bottom of the cyclone, through a

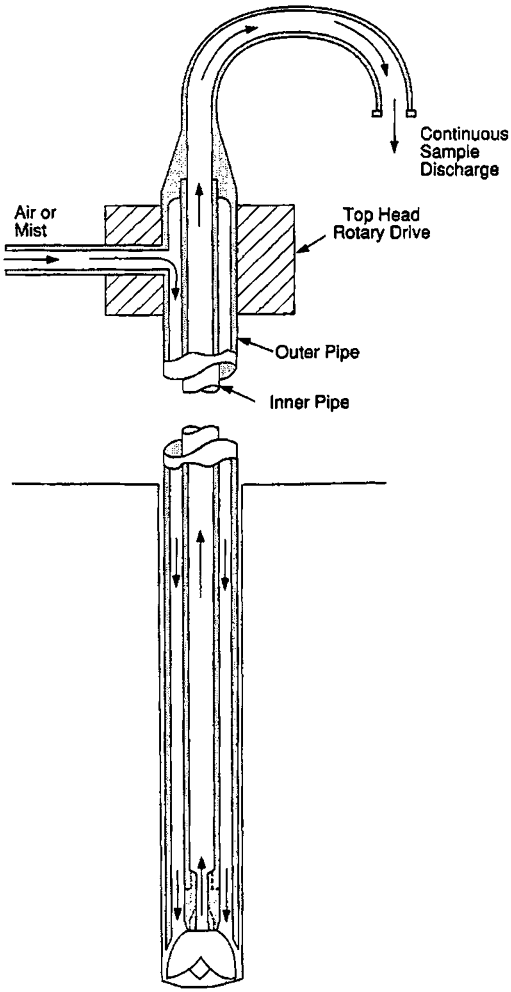

Fig. 4-6. Dual tube reverse air circulation method
Source: Roscoe Moss Company (1990), p. 152; reproduced with permission from Wiley

multilevel sample splitter, into sampling containers or other containment vessels.

Once the rock fragments and groundwater is picked up at the face of the drill bit and begins the journey up the inner barrel, there is no opportunity for mixing with other materials found within the borehole. Thus, the discharged samples are continuous and representative of the materials immediately being drilled at the face of the drilling bit without the risk of sample contamination by materials found in other horizons within the borehole. Formation and water quality samples are nearly immediate as uphole velocities through the inner barrel are nearly 23 m/s.

In situ water samples are collected at discrete-depth intervals by stopping the advancement of the drilling bit, circulating (airlifting) the borehole until any added water has been removed, and collecting a representative water sample directly from the cyclone. Once a water sample has been collected, the top head drive is disconnected from the drill pipe so that water levels can be measured from the interior of the drill string. Drilling is resumed by reattaching the top head drive unit to the drill pipe and returning to drilling.

4.4.6.2.2 Dual-Tube Percussion Drilling Method The dual tube percussion drilling method is a reverse circulation drilling method that typically is used for exploratory drilling, environmental drilling, and the installation of small diameter domestic wells. The drilling method is particularly useful in tough drilling environments, with loose cobbles and boulders occurring throughout the depth of the well, particularly when water and drilling muds as a circulating medium are not allowed. Large cobbles that are 4 to 5 in. in diameter have been known to be discharged at the surface in an intact condition (Layne Christenson Company 2014).

A pile driver that is located on the mast of the drilling rig is used to drive dual wall drill pipe into the ground. The drill pipe is not rotated as it is advanced, as occurs with conventional drilling systems. The dual tube percussion drilling method in particular is suited for unconsolidated formations containing loose soil and rocks. Because the bit is open-faced, lithologic samples are relatively unbroken when they are discharged at the surface. In addition, due to the open design of the bit, undisturbed samples can be obtained from ahead of the drill bit using small diameter split-spoon or Shelby tube sampling devices.

Highly pressurized air is forced into the annular space between the walls of the dual tube drill pipe where it is vented just inside the drill bit. The force of the pressurized air lifts the formation materials from inside the bit, through the inner barrel to the surface in a reverse circulation fashion. At the surface, formation materials are discharged through a cyclone separator, which serves both to contain the discharged material and to slow its velocity as it exits the drill string.

Because the uphole velocities can reach 70 ft/s, the drilling operation is very fast and clean, without side-wall smearing, while providing highly accurate lithologic information. In addition, because there is minimal space between the drill pipe and the borehole wall, in situ groundwater samples either can be airlifted or bailed directly from the borehole through the drill pipe. As well, water levels can be measured at various depth intervals as the borehole is advanced directly through the drill string.

Typically the borehole is drilled and temporarily cased in a single pass (Layne Christenson Company 2014). Angled boreholes up to 30 degrees from vertical are also able to be drilled.

Once the borehole has been drilled to the desired depth, casing and screen materials are installed within the inner barrel of the dual tube drill string. Filter pack material then is added to the annulus through into the inner barrel of the drill string, as are bentonite and cement sealing materials. Because the well is drilled and constructed without the use of drilling fluids, development typically is fairly minimal.

4.4.6.3 Direct Air Rotary Drilling Method In using the direct rotary drilling method, dry air or water mist are all that is necessary to lift the cuttings to the surface, as long as the borehole is stable, and only a small amount of fluid is infiltrating the borehole. The velocity of the air will cool and clean the bit as the borehole is advanced. Large air compressors supply high-pressure air that is pushed through the drill pipe and is discharged through small ports in the face of the drill bit. The cuttings, which are pulverized formation material, are carried up the borehole to the surface by this high-velocity stream of air.

If more difficult drilling conditions are encountered, drilling foam may be used to assist in lifting cuttings from the borehole. By adding small amounts of water and concentrated surfactants (detergents), foam is created. In some cases, other additives, such as polymers and bentonite gel, are used to enhance the foam drilling system. The density of the foam may vary from very stiff like shaving cream to a thin, aerated mud system. The foam adds to the lifting capacity of the "fluid" so that larger cuttings of material can be removed, as well as controlling dust generated by the drilling process. The use of foam also helps to maintain the pressure within the borehole while reducing the loss of air into the formation (Driscoll 2008; Roscoe Moss Company 1990). Additional information regarding the properties of drilling foam can be found in the *Handbook of Ground Water Development* (Roscoe Moss Company, 1990), or in Baroid's *Industrial Drilling Fluids* seminar manual (Baroid 1992).

The "down-the-hole" hammer drilling system uses a pneumatic hammer combined with a bit body suited to hard rock drilling to pulverize formation materials. The hammer operates on compressed air at a pressure of 100 to 110 psi (690 to 758 kPa) to deliver quick rhythmic percussion blows as the bit is rotated to break up the formation, similar to that used with the cable tool method (Driscoll 2008), only much faster. The air that powers the drill bit also provides the lift needed to carry cuttings to the surface. This tool is operated at the end of a standard rotary drill string so that the bit is rotated (at speeds usually from 10 to 30 rpm) as it strikes to produce even penetration and a straight borehole (Roscoe Moss Company 1990). However, if large amounts of water are encountered in the borehole, the down-the-hole hammer bit may be flooded out as the pressure of the incoming water overrides the lifting capacity of the air compressor. Should this happen, the use of alternative drilling methods may be required to advance the borehole.

The downhole hammer is extremely effective at boring smaller-diameter holes (up to 200 mm) in consolidated rock, such as granite and metamorphic rock (Roscoe Moss Company 1990). Because of its rapid removal of cuttings using a high-velocity air jet, the downhole hammer constantly strikes a clean surface, speeding penetration (Driscoll 2008). The alloy steel bit is fitted with tungsten carbide inserts that can be sharpened periodically or replaced when worn. This ensures sharp cutting and grinding surfaces when drilling hard or abrasive materials. These tungsten carbide components and hard facing on the wear points of the bit body also serve to extend the life of the drilling equipment.

Although the initial cost and maintenance of air compressors are high, air rotary drilling methods have many benefits over methods that use water-based drilling fluids. Penetration rates are high (especially with the downhole hammer) due to rapid removal of the cuttings. Air rotary drilling systems can be used in both consolidated and semiconsolidated formations. Because compressed air is used, the aquifer is not contaminated or plugged by drilling fluids, and estimations regarding the yield of a particular formation can be made at any point in the drilling process by temporarily halting the drilling and airlifting a water sample to the surface (Driscoll 2008; Roscoe Moss Company 1990). As the stream of compressed air cools and cleans the bit, it oxidizes the surface of bearings. This oxidized surface acts as lubricant. Water-based fluids are not typically sand-free and so are often abrasive to bearings, causing additional wear and tear on equipment parts, potentially hindering the performance of the drill by decreasing efficiency or causing additional maintenance (Driscoll 2008). Further, the specialized equipment, maintenance of the equipment, and technical expertise needed to monitor and maintain the properties of drilling fluids are unnecessary when using air-drilling systems. Air-drilling methods normally are not suited for unconsolidated materials. However, many drilling contractors have air-drilling systems that are now equipped with mud pumps to drill in unconsolidated overburden while remaining flexible to change over to air rotary drilling when consolidated materials are reached (Driscoll 2008; Strauss et al. 1989).

4.4.6.4 Inverse or Flooded Reverse Method The inverse or flooded reverse method of drilling is based on the reverse circulation rotary system using dual-well drill pipes to introduce air into the drilling fluid system via special air passage tubes built into the drill pipe. As in standard reverse circulation systems, fluid moves down the annulus between the borehole and the drill pipe, enters the drill pipe via ports in the bit, and is conveyed to the surface (Driscoll 2008). This method is beneficial in maintaining borehole stability with induced hydraulic head while transporting cuttings to the surface with a velocity on the order of 23 m/s.

4.4.6.5 Sonic Drilling Method The sonic drilling method is known by several names including rotasonic, rotosonic, sonicore, vibratory, or resonantsonic drilling. Sonic drilling most often is used in the environmental drilling industry as it is a "dry" drilling method, meaning no materials (air, fluid, or additives) are added during drilling. Sonic drilling refers to a dual-cased drilling system that uses high-frequency mechanical vibrations to advance flush-threaded casing while collecting continuous, nearly undisturbed core samples from both unconsolidated and consolidated formations to a maximum depth of 125 m (400 ft). Because casing is advanced at the same time as the core barrel, well construction is accomplished easily within the cased borehole. A top head drive unit contains the hydraulically operated oscillator that generates vibrations with frequencies of 50 to 150 cycles/s. Rotational power can be applied to the drill string when drilling hard formations to distribute the vibrations more effectively and reduce wear on the drill bit face. As the drill bit is advanced, the vibrations cause soil and rock particles to move away from the drill string, permitting fast penetration rates.

Other than the core itself, very few drill cuttings are generated at the surface. Isolated aquifer sampling can take place as the borehole is advanced as the outer casing prevents cross contamination of aquifers and mixing of formation materials. Collection of isolated aquifer samples can be accomplished by either pushing a sampling probe or by installing a 50-mm (2 in.) diameter environmental pump to directly pump a larger sample.

4.4.6.6 Horizontally Directionally Drilled Wells (HDD Wells) Although fairly common in the petroleum industry, directionally drilled wells are not used commonly in municipal or agricultural water supply. These horizontally directionally drilled wells (HDD wells) utilize a mud motor, or shallow entry angle technology, along with sophisticated downhole navigation systems to guide the drill. Using mud motor technology, the well first is drilled vertically and then horizontally. These wells were developed for specialized petroleum industry applications (e.g., to control "blowouts"). The application of HDD technology is in its infancy in the water-well industry; however, there is potential for specialized applications, such as desalination plant intake systems, specialized recharge, or enhancement of a shallow aquifer's saturated thickness. HDD wells may be constructed to extend several thousand feet beneath the ocean floor tapping into salinated aquifers that may provide both feedwater to large-scale desalination plants and pretreatment for seawater reverse osmosis

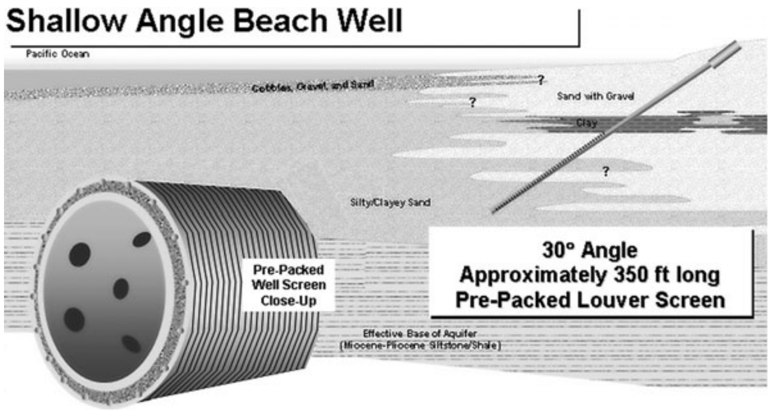

Fig. 4-7. Shallow entry angle HDD well

(SWRO) plants. Horizontal wells may be constructed from 2,000 to 3,000 ft. horizontally at a relatively shallow depths beneath the seabed, which offers a substantial benefit over the approximate 200-ft limitation of current caisson-type hydraulic jacked collector wells (i.e., Ranney Collector Wells), which commonly are used for water supply.

Shallow entry angle wells are drilled typically at angles ranging from approximately 15 to 30 degrees from the horizontal. Special drill rigs are used, which can incline the mast to advance the borehole and casing and screen strings. Shallow entry angle wells are being used for special applications in the water-supply industry, such as for tapping shallow aquifers beneath rivers and, more recently, to supply feedwater to ocean desalination plants.

Fig. 4-7 shows a sketch of a proposed shallow entry angle HDD well near the coast of southern California, which will be used as a feedwater supply for a desalination system.

4.5 GEOPHYSICAL BOREHOLE LOGGING

Geophysical borehole logging includes many methods of gathering additional information from boreholes using geophysical instruments (Barron 1981, Hearst et al. 2000). Geophysical borehole logs normally are conducted in open (uncased) boreholes. However, many types of geophysical borehole logs are designed to be conducted in cased boreholes. The parameters of primary interest in hydrogeology for determining aquifer characteristics are those of hydraulic conductivity and porosity. However, these parameters are impossible to measure directly in the pilot borehole but must wait for the construction, development, and testing of the completed well. Borehole geophysical logs are useful for determining aquifer characteristics, as they provide a graph of the variations in the formation materials measured (i.e., the electrical resistivity, or spontaneous potential). Geophysical borehole logs provide a continuous vertical profile of a borehole that can be used to estimate hydraulic conductivity, porosity, and the occurrence of pore fluids (Hamilton and Myung 1979). Unlike descriptive lithologic logs made by drillers or geologists that can be very subjective, geophysical borehole logs provide a permanent, repeatable record of the borehole properties. These properties can be correlated with geophysical logs from nearby boreholes for stratigraphic interpretation. Fig. 4-8 shows a typical correlation between a long-normal geophysical borehole log and lithology.

Geophysical logging tools are run on a wire line or insulated coaxial cable that is capable of transmitting an electrical current from the tool as it is pulled up through the borehole to the recording instrument that is located at the surface. The instrument at the surface collects and records data regarding the geophysical properties of the formation with respect to depth and line speed as the tool is raised to the surface. The logs are used to evaluate the formations penetrated by the borehole to estimate potential yield of aquifers and water quality variation with depth. These logs are especially cost-effective for high-capacity municipal water wells, where the geophysical borehole logs are used in conjunction with construction-phase testing (such as isolated aquifer zone tests), and they assist the geohydrologist in the placement of the well screens. Although

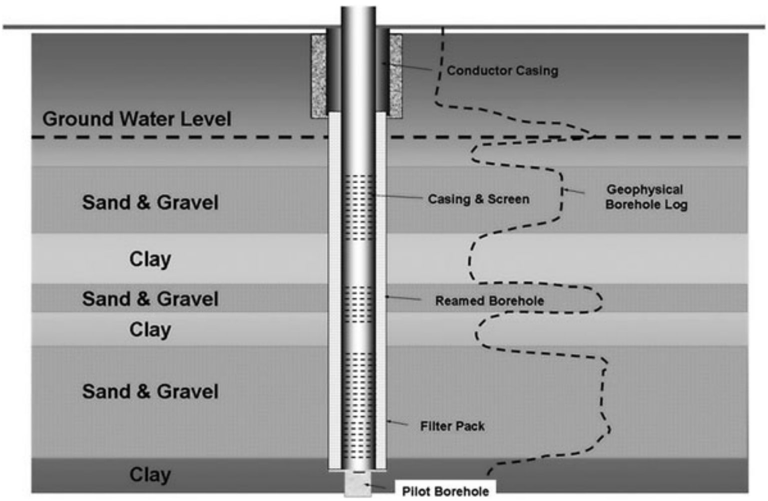

Fig. 4-8. Geophysical borehole log example

there are more than 50 kinds of geophysical logging devices available to the water-well industry (Roscoe Moss Company 1990), the most commonly used logs include electric (resistivity and self-potential [SP]), acoustic (or sonic), Laterolog (focused resistivity), natural gamma ray, induction, caliper, and spinner (flowmeter) surveys.

4.5.1 Geophysical Borehole Logs

The suite of geophysical borehole logs that are included in the typical electric log records the relative character (i.e., sand, silt, or clay), porosity and grain size of the various underground strata penetrated by the boreholes. Electric logs are effective in locating the top and bottom of each formation change. These surveys are performed only in uncased boreholes, as a resistivity log conducted in metallic casing simply will demonstrate the resistivity of the steel. Electric logs are conducted by lowering one or more electrodes into a borehole filled with drilling fluid and forcing an electric current from the electrodes to receiving electrodes that are located at set distances from the source. The receiving electrodes are referenced either to an electrode in the borehole or one located at the surface. A recording instrument located at the surface measures the potential at each measuring electrode away from the main current electrode. The result is a measurement of the resistivity of the formation surrounding the distance between the various electrodes and is provided as a graph of the apparent resistivity (measured in ohm-meters) of all materials located adjacent to the current electrode and the measuring electrode.

A number of factors may mask or change the true properties of the materials in the borehole. Although the resistivity is a measurement of material adjacent to the tool, it is apparent because the values represent the borehole fluid, the fluid that penetrates the near wall, and the formation characteristics. If the drilling fluid in the borehole contains high TDS water with suspended solids (i.e., having low resistivity), the materials in the borehole will appear to be less resistive than they really are due to the current flowing primarily up the borehole. If the fluid in the borehole is water having low total dissolved solids or low total suspended solids (i.e., having a high resistivity), the resulting log more accurately will reflect the true properties of the formational materials, because the current has to flow into the formation. The diameter of the borehole can affect the measurement of the true formation parameters. For example, if the borehole is very large (such as the result of a washout), the electric log tools are influenced more from the surrounding borehole than from the formation. To minimize the effect of resistivity of the drilling fluid on the resulting electric logs, it is important to minimize the diameter of the borehole. Both the salinity and temperature of the water in the pore spaces can affect the apparent resistivity of the formation strongly. Highly saline groundwater has a lower resistivity than fresh groundwater, and warm groundwater has a lower resistivity than cool groundwater.

The electrodes can be arranged in many ways in order to obtain data regarding the true resistivity of the formation material at various distances into the formation and vertical resolutions (identification of thin beds). The farther the electrodes are from each other, the larger the sphere of influence the formation has on the reading (as opposed to the borehole). However, the measurement will average the bed boundaries and decrease the resolution. Inherently there is a trade-off between greater penetration and bed resolution. Electrodes with small vertical spacing will not penetrate deeply into the formation; however, they can determine smaller changes in vertical details.

The following geophysical tools are used the most often in drilling high-capacity municipal water wells.

4.5.1.1 Single-point Resistivity Logs With the single-point resistivity log, an electrode placed in the borehole produces a current that is referenced to a surface electrode. The resulting potential between the two electrodes creates the single-point measurement. This method produces high-resolution (detail) logs but is affected severely by borehole size and borehole fluids. Its reading is calibrated in ohms-meters, however limited in usefulness from one well to the next because of the aforementioned factors. For instance, the same formation may yield different values, because either the hole diameter or the drill fluids are different. The usefulness of the single point resides in its ability to define thin beds, thus giving a detailed picture of interbedded formations.

4.5.1.2 Normal Resistivity Logs (Short Normal and Long Normal) Normal resistivity logs involve sending a constant current out into the formation and having the resulting potential measured as voltage at some distance with another measuring electrode. The depth of the measurement into the formation away from the borehole varies as a function of the spacing between the current (sending) electrode and the measuring (receiving) electrode. The greater the distance between the electrodes, the greater the influence of the formation on the measurement. In the water-well industry, two standard distances are used, 16-in. spacing (referred to as short normal) and 64-in. spacing (referred to as long normal). The short normal is used for shallow readings and the long normal for deeper boreholes.

4.5.1.3 Guard Resistivity (Laterolog) A guard resistivity instrument consists of three electrodes. A current electrode is sandwiched between two guard electrodes. All three electrodes remain at the same potential as the current electrode changes values with respect to the surrounding formation. As the potential between all electrodes remain the same, it enables the current electrode to be shaped into disc-like geometry. This geometry provides excellent bed resolution (usually the length of the current electrode—nominally 4 in.) and deep penetration, because the current is forced laterally from the tool into the formation. As the guard resistivity tool is moved through the borehole, the current will change automatically until the proper balance is reached. This tool is used in conjunction with electric logs for correlation and to define thin strata. Its measurement should be run on the same scale as the electric log and calibrated in a similar manner.

4.5.1.4 Spontaneous Potential (SP) Logs Spontaneous potential (SP) logs measure the electric potential, or difference in voltage, that occurs naturally across changes in the formation. They are nearly always run with the suite of electric logs. Like the resistivity logs, the SP log involves an electrode that is lowered into a borehole attached to a coaxial cable. Another electrode is located at the surface and serves as a reference. However, in the case of the SP log, there are no outside sources of electricity. The instrument records the electrical potential of the formation and is plotted as self-potential in millivolts. The self-potential is generated when a drill bore penetrates clay and sand. If a clean sand is adjacent to two clay layers (one below and one above), excess ions from the clay or sand will move between the beds and set up a potential. There is no absolute scale to the SP, because the interest in measurement is the difference in potential between different zones. If well-defined clay beds are present, a clay baseline can be established on the log with deflection of the SP either positive or negative (moves to the right of clay baseline for positive and left of the line for negative). Because ions flow between sand and clay, one would assume permeability; that is why the SP is known as a permeability log.

The SP log may indicate permeable zones, but variations in the curve must be interpreted with the results of the resistivity logs. Together, these logs make an electric log suite, with the SP curve typically plotted on the left of the graph and the resistivity logs plotted on the right.

The fluctuations in the SP curve tend to become more pronounced at greater depths, because the dissolved minerals (i.e., total dissolved solids) of the water tends to increase with depth, and the solids occurring in the drilling fluids will settle to the bottom of the borehole once circulation is stopped. An SP log should have a known clay baseline in order to be the most useful. Establishing the clay baseline should be the first step in using the log.

4.5.2 Acoustic/Sonic Logs

An acoustic or sonic velocity log involves an acoustic transmitter and one or more receivers, which are lowered into the borehole. Acoustic waves are emitted and propagate to the formation where they are refracted and travel a few inches into the formation. As they propagate along the formation/drill hole wall, they can set up other waves, such as shear waves and secondary waves. These waves are recorded in the full wave train log, often called a variable density log.

The length of time required for the first sound waves (mostly the compressional or p-waves) to return to the receiver are recorded as the travel time, or delta T. Delta T, or travel time, is the difference in time between the arrival of the first waves divided by the distance between receivers, hence the unit of μsec/ft instead of ft/sec.

Formation materials having a shorter travel time (small delta T) will indicate either a higher degree of consolidation or the presence of rigid formations (little water in the pore spaces), whereas a longer travel time (high delta T) indicates the presence of fluid filled pores in the formation.

Acoustic logs can provide a porosity calculation if several parameters are known. However, the full wave train display (VDL, variable density log) can reveal shear waves, indicating shear strength of the formation, along with changes in fluid arrivals that empirically have been demonstrated to indicate permeability. In hard rock formations, acoustic logs have been used to evaluate fractured zones.

4.5.3 Natural Gamma Logs

Some types of formational materials, such as organic clays and shales, emit gamma rays naturally. Typically, organic clays and shales are found to emit large amounts of gamma rays due to their high metal content. When the gamma ray tool is dragged across a formation with high gamma counts, the receiver detects the gamma rays, and they are recorded as the density of gamma particles detected over a given period. Gamma counts typically are found to be lower in clean quartz sands and carbonates, which do not contain detectable levels of radioactive elements. However, granitic and rhyolitic rocks can have very high gamma counts if trace radioactive elements are present. The gamma ray is most useful for defining sediment source changes when used in conjunction with other types of logs.

Gamma rays, like X rays, can penetrate metallic and nonmetallic casing materials easily. Therefore, gamma logs can be performed in cased boreholes and in boreholes that are not fluid filled (dry holes). Natural gamma logs are an available option for logging existing cased wells to gain additional information regarding formation materials.

4.5.4 Induction Logs

Induction logging can be considered the physical opposite of electric logging. Instead of measuring the resistance of a formation, the conductivity is measured. An induction tool consists of a transmitter coil that sends focused electromagnetic waves to create a magnetic field, which is measured by the receiving coils. The coil arrangement in the dual induction is designed to minimize near borehole effects while maximizing the formation contribution to the signal. Induction logs are most effective when the borehole fluid is more resistive than the formation fluid. However, they do have problems when the resistivity of the formation is high due to the low conductivity of the formation (the signal to noise ratio creates unreliable readings).

Unlike the resistivity tools, inductions logs can be run in air-filled boreholes or boreholes cased with PVC. To create a log that is analogous to the commonplace resistivity logs, typically the reciprocal of conductivity is plotted.

4.5.5 Caliper Logs

The caliper log is not a geophysical logging tool per se. However, it physically measures the diameter of the borehole using several spring-loaded arms. These arms remain in physical contact with the sides of the borehole as the tool is brought to the surface. The current is recorded as the average resistance to all the arms and is converted to reflect borehole diameter. It is useful to have the ability to calculate borehole volume, as well as borehole diameter, when running the caliper log.

The caliper log typically is performed in the reamed borehole, prior to construction of the water-supply well in order to estimate the required volumes of filter pack and sealing materials, which will be required to fill the annular space between the borehole wall and the well casing. The caliper log can be useful for identifying enlarged portions of the borehole (washout zones) where the apparent geophysical properties of the formation may be affected by the increased distance between the formation and the caliper tool. In mud filled boreholes, the caliper can be useful in determining swelling clays, zones that have been mined out by drilling, and mud cake across permeable zones. This log often is used in correlation with other logs when run in pilot bores.

4.6 ISOLATED AQUIFER ZONE TESTING

Experience in groundwater basins has shown that contaminants originating at the surface (e.g., nitrate or volatile organic compounds) typically are found in upper water-bearing formations above low-permeability silt and clay layers. To identify aquifer zones containing contaminants in unacceptable concentrations, *aquifer zone testing* can be performed during the construction phase of a new well. The test performed within the pilot borehole results in a vertical variation of water quality (and yield) within aquifer zones. The following summarizes the procedure.

Based on results from both formation sampling during drilling and geophysical borehole logs run on the pilot borehole, representative aquifers are selected within the saturated zone (i.e., between the static water level and bedrock). Typically, in a 1,000-ft borehole, four to six zones may be selected for testing. Working from the lowermost to the uppermost zone, testing is accomplished by attaching a temporary 8-in. diameter 30-ft long well screen to the bottom of the drill pipe. The 30-ft test screen is positioned opposite the zone to be tested, and backfill material is placed to a depth of approximately 10 ft below the test screen. A 10-ft bentonite seal then is placed on top of the fill sealing aquifers below the screen. The annular space between the 8-in. test screen and the 17 ½-in. pilot borehole then is filled with filter pack material to the top of the test screen. Another 10-ft bentonite seal is placed above the filter gravel, completing the isolation process.

The test well is developed then, using the air-lift procedure until the water produced is clean. A high-capacity submersible pump capable of at least 200 gal./min is placed within the 6-in. drill pipe. The test well typically is pumped for approximately 4 to 6 hours during which time measurements are taken as to discharge rate and water level depth to determine aquifer yield. Samples of water quality also are taken and analyzed for particular constituent concentrations in question (e.g., nitrate or volatile organic compounds). Once the test has been completed on a particular zone, the 30-ft test screen is pulled up to the next zone selected for testing and the procedure repeated.

Through the aquifer zone test procedure, vertical variation of water quality is obtained throughout the total depth interval at a particular well site. Based on sample results (yield and water quality), decisions can be made as to an acceptable completion schedule. Zones with unacceptable water quality can be blanked or cemented off to prevent contamination or mixing with potable zones. Fig. 4-9 shows a schematic of a typical aquifer zone testing procedure.

4.7 WATER QUALITY AND YIELD

State standards should be referenced for up-to-date standards for each individual state. However, water quality samples typically are collected during the constant rate pumping test (or as required). Tables 4-2 and 4-3

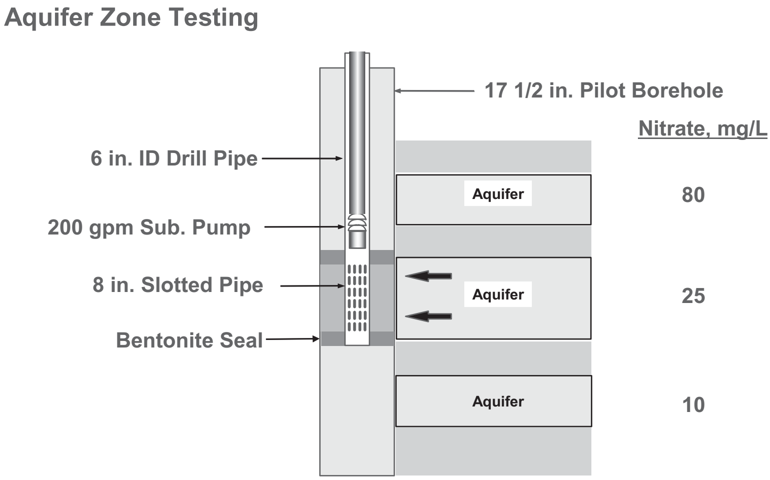

Fig. 4-9. Aquifer zone testing

summarize the constituents of a common Title 22 water quality analysis (APCL 2002) and their maximum contaminant levels (MCLs).

4.8 WELL DESTRUCTION METHODS

Wells that are no longer useful, along with exploration or test holes, must be destroyed because of the risk of contaminating the groundwater, as well as the physical risk of the open borehole to people and animals (California Department of Water Resources 1981, 1991). An abandoned well is defined as one that has been inactive for a period of at least 1 year, unless the owner can prove an intention to use the well again for supply purposes, as an observation well, or as an injection well.

Well owners are required to maintain inactive wells that are intended for future use in such a way that neither the quality of water in the well nor the groundwater that is in contact with the well is impaired. To accomplish this, the top of the well casing and other surface openings must be secured with a locking watertight cover or any other means that will prevent removal of the well cover by unauthorized persons without the use of tools or equipment. The cover must prevent entry of foreign materials, surface water, pollutants, or other contaminants. If the discharge head for a pump that has been installed in the well complies with the aforementioned requirements, it can serve as an approved cover. In addition, all wells must be marked in such a way that they are located easily and are identifiable with a label as a well. All brush, weeds, and other debris must be kept clear of the surrounding area.

Table 4-2. Title 22 Analytical Suite

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
General Physical Properties					
Color	Color unit	1	110.2	2120 B	
Odor	Odor unit	1	140.1	2150 B	
Turbidity	NTU	0.1	180.1	2130 B	GLI Method 2 10133
General Minerals					
Total Alkalinity	mg/L	2	310.1	2320 B	I-1030-85
					ASTM D1067-92B
Bicarbonate	mg/L	2	310.1	2320 B	
Carbonate	mg/L	2	310.1	2321 B	
				2320 B	
Hydroxide	mg/L	2	310.1	2322 B	
Calcium	mg/L	0.2	200.7	3120 B	ASTM D511-93A
			6010	3111 B	ASTM D511-93B
				3500-Ca D	
				3500-Ca B	
Chloride	mg/L	1	300.0	4110 B	ASTM D4327-91
			325.3	4500-Cl- D	ASTM D512-89B
				4500-Cl- B	
Chromium (VI)	mg/L	0.001	6169		

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
Fluoride	mg/L	0.1	300.0	4110 B	380-75WE 129-71W
			340.2	4500-F- B,D	ASTM D4327-97
				4500-F- C	ASTM D1179-93B
				4500-F- E	ASTM D3559-96D
				3113 B	
Magnesium	mg/L	0.1	200.7	3111 B	ASTM D511-93A
			6010	3120 B	ASTM D511-93B
				3500-Mg E	
Nitrate (as N)	mg/L	1	300.0	4110 B	B-1011 601,
			353.2	4500-NO3- F	ASTM D4327-97
				4500-NO3- D	ASTM D3867-90A
				4500-NO3- E	ASTM D3867-90B
Nitrite (as N)	mg/L	0.02	300.0	4110 B	B-1011,
			353.2	4500-NO3- F	ASTM D4327-97
			354.1	4500-NO3- E	ASTM D3867-90A
				4500-NO2- B	ASTM D3867-90B
Total Nitrogen (TKN)	mg/L	0.2	351.3		
pH	pH unit	0.01	150.1	4500-H+ B	ASTM D1293-95
			150.2		
			9040		
Potassium	mg/L	0.4	6010		
			200.7		
Silica	mg/L	1	200.7	4500-Si D	I-1700-85
			370.1	4500-Si E	I-2700-85
				4500-Si F	ASTM D859-95
				3120 B	

Sodium	mg/L	2	200.7 6010	3111 B	
Sulfate	mg/L	2	300.0 375.2 375.4	4110 B 4500-SO4 F 4500-SO4-C,D 4500-SO4 E	ASTM D4327-91 ASTM D516-90
Specific Conductance	umhos/cm	1	120.1		
Total Dissolved Solids	mg/L	10	160.1	2540 C	
Total Hardness	mg/L	2	130.2		
Other Inorganics					
Perchlorate	µg/L	4	314 300.0		ASTM D5475-93 AOAC 991.07
Toluene	mg/L	0.005	502.2 524.2		
Cyanide	mg/L	0.05	335.4 335.2	4500-CN- C 4500-CN- E 4500-CN- G 4500-CN- F	Kelada 01 QuickChem 10-204-00-1-X ASTM D2036-98A ASTM D2036-98B
Bromide	mg/L	0.5	300.0		
Foaming Agents (MBAS)	µg/L	0.1	425.1	5540 C	
Total Organic Carbon	mg/L	1	415.1		
Metals					
Aluminum	mg/L	0.01	200.7 200.8 200.9 6010 B	3120 B 3113 B 3111 D	
Antimony	mg/L	0.006	200.8 200.9 6010 B	3113 B	ASTM D3697-92

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
Arsenic	mg/L	0.002	200.7	3113 B	ASTM D2972-97C
			200.8	3114 B	ASTM D2972-97B
			200.9		
			6010 B		
Barium	mg/L	0.1	200.7	3111 D	
			200.8	3113B	
			6010 B		
Beryllium	mg/L	0.001	200.7	3120 B	ASTM D3645-97B
			200.8	3003 B	
			200.9		
			6010 B		
Cadmium	mg/L	0.001	200.7	3113 B	
			200.8		
			200.9		
			6010 B		
Chromium	mg/L	0.01	200.7	3113 B	
			200.8		
			200.9		
			6010 B		
Copper	mg/L	0.01	200.7	3113 B	ASTM D1688-95C
			200.8	3111 B	ASTM D1688-95A
			200.9	3120 B	
			6010 B		
Iron	mg/L	0.01	200.7	3120 B	
			200.9	3111 B	
			6010 B	3113 B	

Lead	mg/L	0.005	200.8 200.9 6010 B	3113 B	Method 1001, ASTM D3559-96 D
Manganese	mg/L	0.005	200.7 200.8 200.9 6010 B	3120 B 3111 B 3113 B	
Mercury	mg/L	0.001	245.1 245.2 200.8 6010 B 200.7	3112 B	ASTM D3223-97
Nickel	mg/L	0.01	200.7 200.8 200.9 6010 B	3120 B 3111 B 3113 B	
Selenium	mg/L	0.005	200.8 200.9 6010 B 200.7	3114 B 3113 B	ASTM D3859-98A ASTM D3859-98B
Silver	mg/L	0.01	200.7 200.9 6010 B	3120 B 3111 B	
Thallium	mg/L	0.001	200.8 200.9 6010 B 200.7	2550	
Zinc	mg/L	0.05	200.7 200.8 6010 B	3120 B 3111 B	

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
Radiological					
Gross Alpha	pCi/L	1	900.0	302 7110 B 7110 C	R-1120-76
Gross Beta	pCi/L	1	900.0	302 7110 B 7110 C	R-1120-76
Radium 226	pCi/L	0.5	903.0 903.1	7500-Ra C 7500-Ra B 304, 305	R-1141-76 Ra-5 R-1140-76, ASTM D3454-91 ASTM D2460-90
Radium 228	pCi/L	0.5	904.0	7500-Ra D	R-1142-76
Radon 222	pCi/L	20			
Strontium 90	pCi/L	1	905.0	303 7500-Sr B	Sr-01, Sr-02, Sr-04 R-1130-76
Tritium	pCi/L	1	906.0	306 7500-3H B	R-1171-76 ASTM D4107-91
Uranium	pCi/L	1	908.0 908.1	7500-U C 7500-U B	R-1180-76 R-1181-76 R-1182-76 U-02, U-04 ASTM D2907-91 ASTM D3972-90 ASTM D5174-91

Organochlorine Pesticides			
Alachlor	mg/L	0.0005	505
			507
			525.2
			508.1
			551.1
Aldrin	mg/L	0.00002	508
Chlorothalonil	mg/L	0.00002	508
Dieldrin	mg/L	0.00002	508
Endrin	mg/L	0.00002	505
			508
			525.2
			508.1
			551.1
Lindane	mg/L	0.00002	505
			508
			525.2
			508.1
			551.1
Methoxychlor	mg/L	0.001	505
			508
			525.2
			508.1
			551.1
Toxaphene	mg/L	0.001	505
			508
			508.1
			525.2

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
Chlordane	mg/L	0.0001	505		
			508		
			525.2		
			508.1		
Heptachlor	mg/L	0.00001	505		
			508		
			525.2		
			508.1		
			551.1		
Heptachlor epoxide	mg/L	0.00001	505		
			508		
			525.2		
			508.1		
			551.1		
Propachlor	mg/L	0.00002	508		
Polychlorinated Biphenyls (PCBs)	mg/L	0.0005	508A		
			505		
			508		
			508.1		
			525.2		
Organochlorine Herbicides					
2,4-D	mg/L	0.005	515.2		ASTM D5317-93
			555		
			515.1		
			515.3		
			515.4		

2,4,5-TP Silvex	mg/L	0.005	515.2	ASTM D5317-93
			555	
			515.1	
			515.3	
			515.4	
2,4,5-T	mg/L	0.5	515.1	
Bentazon	mg/L	0.5	515.1	
Dalapon	mg/L	0.005	552.1	
			515.1	
			515.3	
			552.2	
			515.4	
Dicamba	mg/L	0.5	515.1	
Dinoseb	mg/L	0.001	515.2	
			555	
			515.1	
			515.3	
			515.4	
Picloram	mg/L	0.001	515.2	
			555	
			515.1	
			515.3	
			515.4	
Pentachlorophenol	mg/L	0.001	515.2.	ASTM D5317-93
			525.2	
			555	
			515.1	
			515.3	
			515.4	

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
N-P Pesticides					
Atrazine	mg/L	0.001	505		Syngenta AG-625
			507		
			525.2		
			508.1		
			551.1		
Molinate	mg/L	0.001	507		ASTM D5475-93
			525.2		AOAC 991.07
Simazine	mg/L	0.001	505		
			507		
			525.2		
			508.1		
			551.1		
Thiobencarb	mg/L	0.001	507		
Butachlor	mg/L	0.001	507		
Diazinon	mg/L	0.001	526		
			507		
Dimethoate	mg/L	0.001	507		
Malathion	mg/L	0.001	507		
Prometryn	mg/L	0.001	507		
Bromacil	mg/L	0.001	507		
Metolachlor	mg/L	0.001	507		
Metribuzin	mg/L	0.001	507		

Fumigants				
Ethylene Dibromide (EDB)	mg/L	0.00002	504.1	
			551.1	
Dibromochloropropane (DBCP)	mg/L	0.00002	504.1	
			551.1	
Carbamates				
Diuron	mg/L	0.005	532	
			531	
Aldicarb	mg/L	0.005	531	
Aldicarb sulfone	mg/L	0.005	531	
Aldicarb sulfoxide	mg/L	0.005	531	
Oxamyl	mg/L	0.005	531.1	6610
			531.2	
Carbofuran	mg/L	0.005	531.1	
			531.2	
Carbaryl	mg/L	0.005	531	
3-Hydroxycarbofuran	mg/L	0.005	531	
Methomyl	mg/L	0.005	531	
Baygon (Propoxur)	mg/L	0.005	531	
Misc. Pesticides				
Glyphosate	mg/L	0.05	547	6651
Endothall	mg/L	0.005	548.1	
Diquat & Paraquat	mg/L	0.005	549.2	
Polynuclear Aromatic Hydrocarbons:				
Acenaphthene	µg/L	NS	550	
Acenaphthylene	µg/L	NS	550	
Anthracene	µg/L	NS	550	
Benz(a)anthracene	µg/L	NS	550	
Benz(a)pyrene	µg/L	NS	550	

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
Benzo(b)fluoranthene	μg/L	NS	550		
Benzo(g,h,i)perylene	μg/L	NS	550		
Benzo(k)fluoranthene	μg/L	NS	550		
Chrysene	μg/L	NS	550		
Dibenz(a,h)anthracene	μg/L	NS	550		
Fluoranthene	μg/L	NS	550		
Fluorene	μg/L	NS	550		
Indeno(1,2,3-cd)pyrene	μg/L	NS	550		
Naphthalene	μg/L	NS	550		
Pheneanthrene	μg/L	NS	550		
Pyrene	μg/L	NS	550		
Semi-Volatile Organic Compounds					
Benzo(a)pyrene	mg/L	0.01	525.2 550 550.1		
Di(2-ethylhexyl)adipate	mg/L	0.01	506 525.2		
Di(2-ethylhexyl)phthalate	mg/L	0.01	506 525.2		
Hexachlorobenzene	mg/L	0.01	505 508 525.2 508.1 551.1		

Hexachlorocyclopentadiene	mg/L	0.01	505
			508
			525.2
			508.1
			551.1
Volatile Organic Compounds			
Benzene	mg/L	0.005	502.2
			524.2
Carbon Tetrachloride	mg/L	0.005	502.2
			524.2
			551.1
1,2-Dichlorobenzene	mg/L	0.005	502.2
			524.2
1,4-Dichlorobenzene	mg/L	0.005	502.2
			524.2
1,1-Dichloroethane	mg/L	0.005	524.2
1,2-Dichloroethane	mg/L	0.005	502.2
			524.2
cis-1,2-Dichloroethene	mg/L	0.005	502.2
			524.2
trans-1,2-Dichloroethene	mg/L	0.005	502.2
			524.2
1,1-Dichloroethene	mg/L	0.005	502.2
			524.2
1,2-Dichloropropane	mg/L	0.005	502.2
			524.2
1,3-Dichloropropene	mg/L	0.005	524.2
Ethylbenzene	mg/L	0.005	502.2
			542.2

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
Methylene Chloride	mg/L	0.005	524.2		
Methyl tert-butyl-ether (MTBE)	mg/L	0.005	502.2 524.2	6200C 6210D 6200B	ASTM D5790-95
Monochlorobenzene	mg/L	0.005	502.2 542.2		
Styrene	mg/L	0.005	502.2 542.2		
1,1,2,2-Tetrachloroethane	mg/L	0.005	524.2		
Tetrachloroethene	mg/L	0.005	502.2 524.2 551.1		
1,2,4-Trichlorobenzene	mg/L	0.005	502.2 524.2		
1,1,1-Trichloroethane	mg/L	0.005	502.2 524.2 551.1		
1,1,2-Trichloroethane	mg/L	0.005	502.2 524.2 551.1		
Trichloroethene	mg/L	0.005	502.2 524.2 551.1		
Trichlorofluoromethane	mg/L	0.005	524.2		

1,1,2-Trichloro-1,2,2-trifluoroethane	mg/L	0.005	524.2
Toluene	mg/L	0.005	502.2 524.2
Vinyl Chloride	mg/L	0.005	502.2 524.2
Xylenes	mg/L	0.005	502.2 524.2
1,3-Dichlorobenzene	mg/L	0.005	524.2
Dibromomethane	mg/L	0.005	524.2
1,1-Dichloropropene	mg/L	0.005	524.2
1,3-Dichloropropane	mg/L	0.005	524.2
Chloromethane	mg/L	0.005	524.2
Bromomethane	mg/L	0.005	524.2
1,2,3-Trichloropropane	mg/L	0.005	524.2
1,1,1,2-Tetrachloroethane	mg/L	0.005	524.2
Chloroethane	mg/L	0.005	524.2
2,2-Dichloropropane	mg/L	0.005	524.2
o-Chlorotoluene	mg/L	0.005	524.2
p-Chlorotoluene	mg/L	0.005	524.2
Bromobenzene	mg/L	0.005	524.2
Dichlorodifluoromethane	mg/L	0.005	524.2
1,2,4-Trimethylbenzene	mg/L	0.005	524.2
1,2,3-Trichlorobenzene	mg/L	0.005	524.2
n-Propylbenzene	mg/L	0.005	524.2
n-Butylbenzene	mg/L	0.005	524.2
Naphthalene	mg/L	0.005	524.2
Hexachlorobutadiene	mg/L	0.005	524.2
1,3,5-Trimethylbenzene	mg/L	0.005	524.2

Continued

Table 4-2. Title 22 Analytical Suite (*Continued*)

Constituent	Units	Detection Limit	EPA Methods	Standard Methods	Other Methods
p-Isopropyltoluene	mg/L	0.005	524.2		
Isopropylbenzene	mg/L	0.005	524.2		
Tert-butylbenzene	mg/L	0.005	524.2		
Sec-butylbenzene	mg/L	0.005	524.2		
Bromochloromethane	mg/L	0.005	524.2		
Bromodichloromethane	mg/L	0.005	524.2		
Bromoform	mg/L	0.005	524.2		
Chlorodibromomethane	mg/L	0.005	524.2		
Chloroform	mg/L	0.005	524.2		
Bacteriological					
Total Coliform MTF	mg/L		1604	9221 B,C	
				9221 D	
				9223	
				9222 B,C	
Fecal Coliform MTF	mg/L			9221 B	
				9221 E	
				9221 D	
				9222 B	
				9222 D	
Heterotrophic Plate Count	mg/L			9215 B	

Table 4-3. State of California and Federal MCLs, by Classification[a]

Constituent	Unit	CDHS[b] MCL	USEPA[c] MCL
Inorganic Chemicals			
Aluminum	mg/L	1 0.2*	0.05 0.2*
Antimony	mg/L	0.006	0.006
Arsenic	mg/L	0.05	0.01
Asbestos	MFL	7	7
Barium	mg/L	1.0	2
Beryllium	mg/L	0.004	0.004
Cadmium	mg/L	0.005	0.005
Chloride	mg/L	250*	250*
Chromium (Total)	mg/L	0.05	0.1
Copper	mg/L	1.3*	1.3 1.0*
Cyanide	mg/L	0.15	0.2
Fluoride	mg/L	2.0	4 2*
Iron	mg/L	0.3*	0.3*
Lead	mg/L	0.015	0.015
Manganese	mg/L	0.05*	0.05*
Mercury	mg/L	0.002	0.002
Nickel	mg/L	0.1	REMANDED
Nitrate	mg/L	(as NO-3) 45	(as N) 10
Nitrate + Nitrite (sum as nitrogen)	mg/L	10	10
Nitrite (as nitrogen)	mg/L	1	1
Selenium	mg/L	0.05	0.05
Silver	mg/L	0.1*	0.10*
Thallium	mg/L	0.002	0.002
Zinc	mg/L	530*	5*
General Physical			
Color	Units	15 15*	15*
Odor	Units	3 3*	3*
Turbidity	Units	5 5*	5
MBAS	mg/L	0.5 0.5*	0.5*
Specific Conductance	micromhos	900*	NA
Total Dissolved Solids (TDS)	mg/L	500*	500*

Continued

Table 4-3. State of California and Federal MCLs, by Classification (*Continued*)

Constituent	Unit	CDHS[b] MCL	USEPA[c] MCL
Volatile Organic Chemicals (VOCs)			
Benzene	mg/L	0.001	0.005
Carbon Tetrachloride	mg/L	0.0005	0.005
1,2-Dichlorobenzene	mg/L	0.6	0.6
1,4-Dichlorobenzene	mg/L	0.005	0.075
1,1-Dichloroethane	mg/L	0.005	NA
1,2-Dichloroethane	mg/L	0.0005	0.005
1,1-Dichloroethylene	mg/L	0.006	0.007
cis-1,2-Dichloroethylene	mg/L	0.006	0.07
trans-1,2-Dichloroethylene	mg/L	0.01	0.1
Dichloromethane	mg/L	0.005	0.005
1,2-Dichloropropane	mg/L	0.005	0.005
1,3-Dichloropropene	mg/L	0.0005	NA
Ethylbenzene	mg/L	0.3	0.7
Methyl-tert-butyl ether (MTBE)	mg/L	0.013 0.005*	NA
Monochlorobenzene	mg/L	0.07	0.1
Styrene	mg/L	0.1	0.1
1,1,2,2-Tetrachloroethane	mg/L	0.001	NA
Tetrachloroethylene	mg/L	0.005	0.005
Toluene	mg/L	0.15	1
1,2,4-Trichlorobenzene	mg/L	0.005	0.07
1,1,1-Trichloroethane	mg/L	0.200	0.200
1,1,2-Trichloroethane	mg/L	0.005	0.005
Trichloroethylene	mg/L	0.005	0.005
Trichlorofluoromethane	mg/L	0.15	NA
1,1,2-Trichloro-1,2,2-trifluoroethane	mg/L	1.2	NA
Vinyl Chloride	mg/L	0.0005	0.002
Xylenes	mg/L	1.750	10
Radiological			
Combined Radium-226 and Radium-228 5	pCi/L	5 pCi/L	5 pCi/L
Gross Alpha Particle Activity (Including Radium-226 but excluding Radon and Uranium)	pCi/L	15	15
Tritium	pCi/L	20,000	20,000
Strontium-90	pCi/L	8	8
Gross Beta Particle Activity		50 pCi/L	dose of 4 millirem/yr

Table 4-3. State of California and Federal MCLs, by Classification (*Continued*)

Constituent	Unit	CDHS[b] MCL	USEPA[c] MCL
Uranium		20 pCi/L	30 µg/L
Synthetic Organic Chemicals (SOCs)			
Alachlor	mg/L	0.002	0.002
Atrazine	mg/L	0.001	0.003
Bentazon	mg/L	0.018	NA
Benzo(a)pyrene	mg/L	0.0002	0.0002
Carbofuran	mg/L	0.018	0.04
Chlordane	mg/L	0.0001	0.002
2,4-D	mg/L	0.07	0.07
Dalapon	mg/L	0.2	0.2
Dibromochloropropane	mg/L	0.0002	0.0002
Di (2-ethylhexyl)adipate	mg/L	0.4	0.4
Di (2-ethylhexyl)phthalate	mg/L	0.004	0.006
Dinoseb	mg/L	0.007	0.007
Diquat	mg/L	0.02	0.02
Endothall	mg/L	0.1	0.1
Endrin	mg/L	0.002	0.002
Ethylene Dibromide (EDB)	mg/L	0.00005	0.00005
Glyphosate	mg/L	0.7	0.7
Heptachlor	mg/L	0.00001	0.0004
Heptachlor Epoxide	mg/L	0.00001	0.0002
Hexachlorobenzene	mg/L	0.001	0.0001
Hexachlorocyclopentadiene	mg/L	0.05	0.05
Lindane	mg/L	0.0002	0.0002
Methoxychlor	mg/L	0.03	0.04
Molinate	mg/L	0.03	NA
Oxamyl	mg/L	0.02	0.2
Pentachlorophenol	mg/L	0.001	0.001
Picloram	mg/L	0.5	0.5
Polychlorinated Biphenyls (PCBs)	mg/L	0.0005	0.0005
Simazine	mg/L	0.004	0.004
Thiobencarb	mg/L	0.07 0.001*	NA
Toxaphene	mg/L	0.003	0.003
2,3,7,8-TCDD (Dioxin)	mg/L	3 × 10 − 8	3 × 10 − 8
2,4,5-TP (Silvex)	mg/L	0.05	0.05

[a]Maximum contaminant levels. Does not include unregulated constituents.
[b]California Department of Health Services, obtained from http://www.dhs.ca.gov/ps/ddwem/chemicals/chemindex.htm
[c]United States Environmental Protection Agency, <http://www.epa.gov/safewater/mcl.html>
*Secondary standard

4.8.1 Destruction of Water Wells

Once a well has been determined to be no longer useful, it must be destroyed to prevent the potential contamination of groundwater by way of the abandoned well casing and to eliminate physical hazards (AWWA 1998). The objective of the destruction process is to restore (as nearly as possible) the subsurface conditions that existed prior to drilling and constructing the well. Any accumulation of oil from oil-lubricated pumps or other contaminants that may interfere with the sealing of the well must be removed. Visual inspection involving the use of a downhole video survey is necessary to assess the current condition of the casing and construction details, as well as the type and amount of debris that may have accumulated within the well. Once the current condition has been assessed, the well casing must be cleared to an appropriate depth as specified by local ordinances. Well clearing is performed by removing undesirable materials and obstructions to ensure that nothing will interfere with filling and sealing the upper portion of the well (see Section 4.3). If pollutants or contaminants are suspected in the well to be destroyed, the local enforcement agency having jurisdiction over water-supply wells must be contacted. In addition, the local enforcement agency having jurisdiction over water wells must be contacted prior to the destruction process to determine requirements for the depth of the seal and for proper disposal of any materials removed. In California, the minimum depth of the sealing material is 6 m (20 ft) below ground surface for wells constructed in unconsolidated materials with an unconfined water table where a static water level within 16 m (50 ft) of the ground surface. The remainder of the well is backfilled using clay, sand, or other suitable inorganic fill or sealing materials. Fig. 4-10 illustrates proper destruction of a water well.

4.8.2 Destruction of Wells Screened in Multiple Aquifers

To keep water from different aquifers from mixing and to isolate aquifers containing contaminated or poor quality waters, impervious material is placed within the screened intervals adjacent to the impaired aquifer(s). In addition, the impervious material must extend at least 3 m (10 ft) above and 3 m (10 ft) below the impaired area. The impervious sealing material may consist of neat cement, sand-cement mixtures, concrete, or hydrated bentonite products.

Wells that are screened in more than one aquifer, or are known to have impaired water quality, require additional destruction measures to ensure that the sealing material fills not only the interior of the casing but also the gravel-filled annular space and any voids that have developed in either the filter pack or the near-well zone within the interval to be sealed. In these cases, it is necessary to puncture or rip the casing and perforated

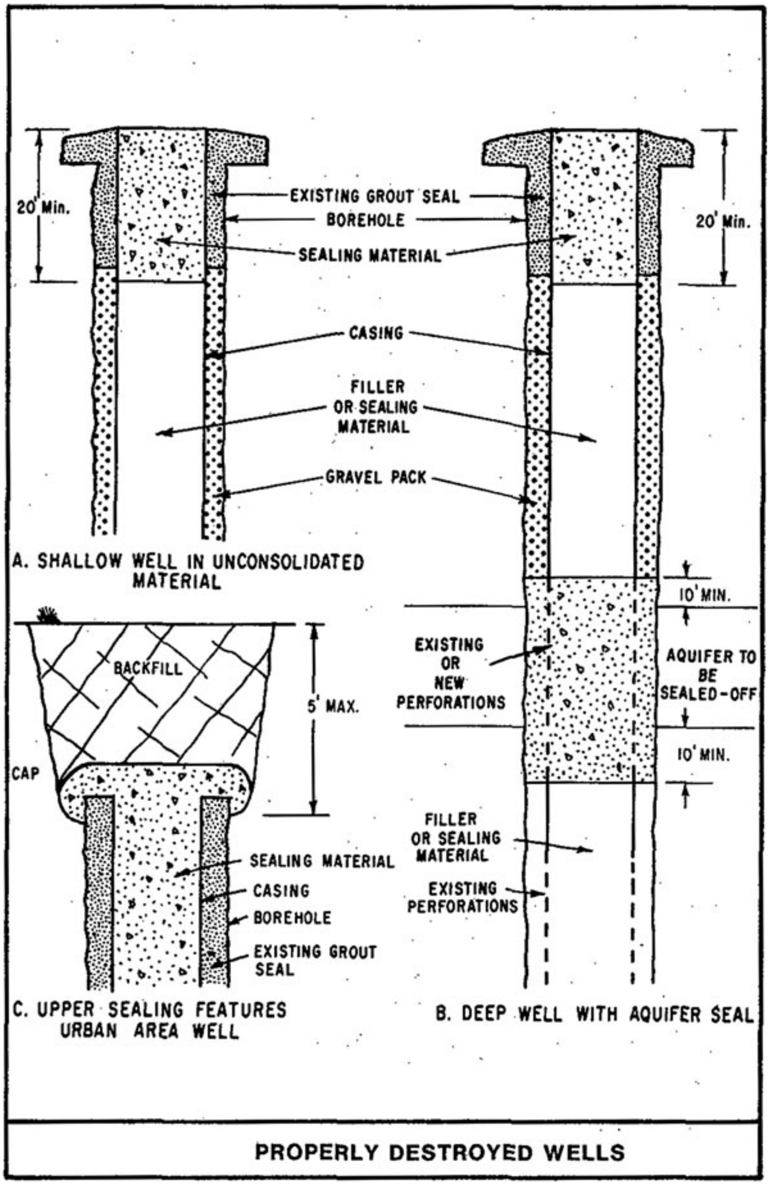

Fig. 4-10. Properly destroyed wells
Source: California Department of Water Resources (1991)

intervals farther. Puncturing of the casing and screen can be performed using either downhole wireline perforators that literally shoot 25 mm diameter holes in the casing using a powerful charge or by using a Mill's knife—a device that uses a retractable vertical blade that operates in a similar manner to a can opener (see Section 4.5.1.2.2 under Cable Tool Drilling). If required by local enforcement agencies, removal of all or a portion of the casing prior to backfilling may be necessary, using cement slurry that is pressurized to force the sealing material into the gravel pack and near-well zone.

If vertical migration of fluids within the well is not a concern, the remainder of the well may be filled with inorganic sealing or filler material (clay, silt, sand, gravel, crushed stone, native soils, etc.) (California Department of Water Resources 1981, 1991) before filling the upper portion of the well using an impervious sealing material. Organic material should not be used in well destruction.

4.8.3 Destruction of Gravel-Pack Envelope Wells

When destroying a well with a gravel envelope, the perforations must be open in the interval to be sealed. If the initial investigations show that the perforations are clogged, additional openings must be made using the Mill's knife or perforations using the downhole wireline perforator. Sealing material then is placed within the casing by pumping through a tremie pipe completely filling the interior of the well adjacent to the zone being sealed. The weight of the cement is nearly twice that of water, so the sealing material may be forced readily into the gravel-filled annular space.

If additional pressure is required, a packer or cementing head may be placed at the surface. The packer may be equipped with a valve that can be closed to maintain pressure until the cement begins to set. Water can be used to pressurize the cement to a predetermined pressure. Once attained, the valve is closed to maintain the pressure level. However, if additional pressure is applied to the column of cement during pumping, the pressure must be maintained for the length of time the cement requires to set.

Samples of the cement mixture should be collected periodically as it is pumped. The sample containers filled with the wet cement mixture should be submerged in a bucket of water and placed out of direct sunlight to simulate downhole conditions. The cement samples should be checked periodically until it is determined that they are sufficiently set before releasing the pressure. Careful record must be kept of both the calculated volume of the well and the actual volume of material placed to verify that bridging has not occurred. The volume placed should equal or exceed the volume of the well taking into consideration the annular space in the case of wells constructed using a gravel envelope.

4.8.4 Placement of Sealing Materials

Placement of the fill or sealing material during well destruction must take place from the bottom of the well, working upward. Materials, such as neat cement, sand-cement grout, or concrete must be pumped into the well through a tremie pipe in one continuous pour. Free-falling the material is not acceptable, because it can separate and become diluted within the borehole as it falls through the standing column of water. In wells having an artesian head that produces a significant amount of flow, special precautions must be implemented to reduce the amount of flow during sealing. In these cases, the casing must be perforated at a depth within the production interval and a packer, or a cementing head must be installed at the top of the casing in order to seal the top of the well around the tremie pipe. The sealing material then is pumped under pressure so that it is forced out into the formation. However, if excessive pressure is used during the placement process, the risk of channeling is increased. Channeling may occur, because cement will follow the path of least resistance, which is typically upward along the casing, migrating out into the formation in only the weakest areas.

4.8.5 Sealing Materials

Acceptable sealing materials must have low permeability. Sealing materials considered suitable include neat cement, sand-cement grout, concrete, and bentonite clay. Local regulatory agencies need to be consulted for information regarding acceptable sealing material. For instance, used drilling mud is not acceptable. Fill materials may consist of a low-permeability inorganic mixture of clay, silt, sand, gravel, and crushed rock. In locations where improvements are planned, the area around the well must be excavated to a depth of at least 1.5 m (5 ft) below ground surface, and the well casing must be cut off and removed to that depth. As the well is filled with the sealing material, it is allowed to spill over the top of the casing, forming a mushroom cap. Once the sealing material has been allowed to set, the excavation should be backfilled using clean soil and compacted to 95% of optimum density.

4.9 MECHANICAL GRADING ANALYSES

In the design of high-capacity water-supply wells, selection of the filter pack and screen slot size is crucial for optimal well performance and efficiency. During the drilling of the pilot borehole, formation samples should be collected at 3-m (10-ft) intervals or more frequently, should formation changes occur, to provide representative samples for sieve analyses and for classification of the geologic formations encountered. Formation samples normally are collected from the sampling trough where solids-laden fluids discharging from the borehole are separated before entering the circulation reservoir. All samples collected in the field should be placed in appropriate containers, such as heavy-duty 1-gal. Ziploc bags that are labeled clearly and stored in a manner to prevent breakage, contamination, or loss.

Dried formation samples are weighed and sifted through a selected series of sieves. The portion retained by each sieve is weighed and recorded (Roscoe Moss Company 1990). Sieve analyses are used to select the filter pack gradation and screen openings and to make estimates of hydraulic conductivity. Additional well screen and filter pack design criteria are found in Chapter 3.

4.10 LITHOLOGIC DESCRIPTIONS OF FORMATION MATERIALS USING UNIFIED SOIL CLASSIFICATION SYSTEM

Samples are classified according to the Unified Soil Classification System (ASTM 2011). Soil samples are divided into coarse-grained soils, fine-grained soils, and highly organic soils. Each group is divided into subgroups, which are further divided as shown in Table 4-4.

Before geophysical logging methods were developed and widely used, lithologic samples were the primary method for obtaining downhole information (Roscoe Moss Company 1990) in boreholes drilled using the rotary drilling methods. Accurate formation sampling continues to be a very important part of designing high-capacity water wells, especially when lithologic samples can be correlated with the results of geophysical borehole surveys (Roscoe Moss Company 1990). For pictures of formation sampling and sieve analysis, see Figs. 4-11 through 4-15.

4.11 PREPARATION FOR WELL COMPLETION

Proper water well design is based on analysis and interpretation of information gathered during the drilling and testing of the pilot borehole. This includes analysis of the geophysical borehole logs, review of the results of isolated aquifer zone testing (particularly in terms of water chemistry), the static and pumping water levels of each of the zones tested, and production rates, as well as review of the lithology and mechanical grading analyses. Once the sieves analyses have been completed, plots are made of the formation materials regarding the percent passing each sieve size before selecting the optimal filter pack for the well.

Table 4-4. Unified Soil Classification System

Categories and Subcategories			Abbreviation	Description
Coarse-Grained Soils (more than 50% retained on a no. 200 Sieve	Gravel (more than 50% of coarse fraction retained on No. 4 sieve)	Clean Gravel	GW	Well-graded gravel, fine to coarse gravel
			GP	Poorly graded gravel
		Gravel with Fines	GM	Silty gravel
			GC	Clayey gravel
	Gravel (less than 50% of coarse fraction retained on No. 4 sieve)	Clean Sand	SW	Well-graded sand, fine to coarse sand
			SP	Poorly graded sand
		Sand with Fines	SM	Silty sand
			SC	Clayey sand
Fine-Grained Soils (less than 50% retained on a no. 200 sieve)	Silt and Clay (liquid limit less than 50	Inorganic	ML	Silt
			CL	Clay
		Organic	OL	Organic silt, organic clay
	Silt and Clay (liquid limit 50 or more)	Inorganic	MH	silt of high plasticity, elastic silt
			CH	Clay of high plasticity, fat clay
		Organic	OH	Organic clay, origin
Highly Organic Soils			PT	Peat

Source: ASTM (2011).

Fig. 4-11. 1-gal. Ziploc bags containing formation samples collected at 10-ft intervals

Fig. 4-12. Ziploc bags and sample trays

Fig. 4-13. Storage of sample trays

Fig. 4-14. Sieve screens

Once the filter pack has been selected, the slot size for the openings in the perforated interval is determined.

The basic rule of well design is that the filter pack is designed to control the formation materials, and the size of the openings in the screens is designed to control the filter pack.

Fig. 4-15. Drying oven

4.11.1 Ream Pilot Borehole to Total Depth

Once the well design has been determined, the pilot borehole is reamed to remove all materials placed during isolated aquifer zone testing and to enlarge the borehole to its final depth and diameter. The same procedures implemented while drilling the pilot borehole and for testing the mud properties (see Section 4.4) should be used while reaming the borehole to its final diameter. As much care as was taken to maintain clean fluids during drilling the pilot borehole should be made during the reaming pass.

4.11.2 Run Caliper Logs

Caliper logs are used to measure the diameter and volume of an open borehole. They are used to verify borehole stability (such as washouts or squeeze zones) and to calculate borehole volumes prior to filter pack installation. A caliper log typically is run following the reaming pass but prior to the installation of the casing and screen. The caliper tool uses two or more arms (preferably three) that move independently and are connected to a precision potentiometer. The movement of the arms is converted to electronic pulses that are sent to the surface to be recorded as changes in borehole diameter (Roscoe Moss Company 1990). Caliper logs can be used to determine the amount of cement or gravel needed to fill the annulus outside the casing and screen (Roscoe Moss Company 1990).

4.12 INSTALLATION OF CASING, SCREEN, AND FILTER PACK

4.12.1 Open Hole Installation Methods

In preparation for construction of the well, tremie pipe is run to within 10 to 12 m (30 to 40 ft) of the bottom of the reamed borehole. The tremie pipe may be suspended temporarily from the conductor casing or in any other manner the operator has available. The gravel feed pipe then is installed to its designed depth and also is suspended temporarily from the conductor casing. More than one gravel feed pipe may be installed, as long as the diameter of the reamed borehole can accommodate all tubes and pipes that are designed for installation in the annulus.

Once the tremie and the gravel feed pipes have been installed, along with any other tubes that are designed for the annular space, the blank casing and screened intervals are suspended over the borehole. Each section of casing or screen either is threaded together or welded to one another in the sequence following their design. Centralizers are attached in appropriate numbers and at appropriate intervals to keep the casing and screen from touching the borehole walls. Also at the appropriate interval, sounding tubes, camera access tubes, and so on are attached to the casing according to the final well completion design. Once all casing and screened sections are in place, the casing is landed on either the conductor casing or the rotary table and is secured prior to pumping filter pack and seals.

4.12.2 Double String Well Installations

Casing and screen may be set in rotary-drilled boreholes using the pullback method if there is a risk of the formation caving or loss of circulation. If the hydrostatic pressure of fluids in the borehole is sufficient to maintain stability, the double-string method can be used to install a high-capacity screened well.

After the borehole is drilled, the casing string is lowered into the hole, and a drillable grout shoe is placed in the bottom of the casing. Then the casing is grouted and the cement allowed to set. Afterward, the casing is cleaned of any grout and the grout shoe drilled out, allowing drilling equipment access to the underlying aquifer. Drilling continues through the casing until reaching the appropriate depth in the producing formation. The borehole is cleaned, and the screen then is lowered through the casing and sealed by an appropriate packer (Roscoe Moss Company 1990).

4.12.3 Single-String Well Installations

The single string method is used in smaller-diameter, rotary-drilled wells. Screens are attached directly to the bottom of the casing, and the entire string is lowered carefully into the hole. Because the length-to-width ratio of this long string of pipe renders it vulnerable to damage and misalignment, use of stabilizers to keep the string centered and out of contact with the borehole walls is common. As the casing and screen are set, the drilling fluids are thinned to allow fluid to enter the screen. To maintain pressure in the casing and prevent collapse, the casing and string may be filled with water as it is lowered into position (Roscoe Moss Company 1990).

4.12.4 Gravel Feed Pipes

The gravel feed pipe is used in gravel pack envelope wells to replenish and monitor the future levels of gravel pack envelopes in the annular space. Gravel feed pipes are 75 to 100 mm (3 or 4 in.) in diameter and are installed from the ground surface to a depth that is approximately 1 to 1.5 m (3 to 5 ft) below the planned depth of the gravel pack (Roscoe Moss Company 1982; Roscoe Moss Company 1990). It is important that the lower end of the gravel feed pipe is installed 1 to 1.5 m (3 to 5 ft) into the filter pack prior to pumping the annular cement seals, if they are required.

4.12.5 Sounding Tubes

Sounding tubes are installed with the well casing and are used to measure water levels manually or to set transducers once the well has been completed. Typically a 50-mm (2-in.) diameter pipe runs from the surface to a predetermined depth, where it enters the well casing. The depth of the connection may be above or below the pump setting; however, in all cases, it should be installed at a depth that will ensure that the lower end will be submerged below the pumping water level (Roscoe Moss Company 1990).

4.12.6 Camera Access Tubes

Larger diameter sounding tubes, up to 100 mm (4 in.) in diameter can accommodate downhole video camera equipment, allowing future video surveys of the well, even when a pump has been installed in the well (Roscoe Moss Company 1990).

To prevent collapse of the well casing at the point of connection, stiffener plates and rings must be used to add strength to the casing in the vicinity of the slot. The opening of the slot should be a minimum of 2.5 m (8 ft) in length. The transition from the camera access tube to the casing must be smooth and free from rough edges. The bottom of the sounding tube should be attached to the casing at depth with a 30-degree angle to the vertical axis of the casing.

4.12.7 Centralizer Installation

Centralizers can be installed as casing is picked up, aligned, and run. For large diameter water wells, centralizers may consist of shaped steel straps measuring approximately 5 cm (2 in.) in width, 6 mm (¼ in.) in thickness, and approximately 90 cm (36 in.) in length and are welded directly to the casing. These shaped straps are bowed outward so that they touch the walls of the borehole, keeping the casing centrally positioned in the borehole as filter pack or grout is pumped into the annular space (Craft et al. 1962). It is critical that centralizers are welded only to blank sections of casing and not to screen sections. Centralizers serve several purposes in keeping the casing from leaning against the borehole walls. These purposes include

- Centering the casing in the borehole and helping to maintain alignment; this also allows for even dispersal of grout and gravel around the casing and screen sections within the annulus,
- Preventing the casing from sticking to the wall cake of borehole walls due to differential pressures, and
- Removing the filter cake from the borehole by scraping the borehole walls.

The position, number, and spacing of the centralizers used in water well construction are a matter of the experience, preference, and judgment of the hydrogeologist, engineer, and contractor involved in the project.

4.12.8 Use of Tremie Pipes

All fluid downhole materials, such as cement or filter pack, must be placed through a tremie pipe to ensure their proper placement at depth through the standing column of water. In addition, the use of tremie pipe helps to prevent bridging of materials and minimizes their separation as they are placed through a standing column of water. To place the downhole materials, the mixtures are pumped down through a length of tube called the tremie pipe or grout pipe, which runs from the surface into the annulus and to the desired depth within the well. As the materials being pumped fill the annulus, the tremie pipe is raised by removing sections of pipe.

4.12.9 Compression Sections

One of the causes of damage to the well casing and well screens in arid and semi-arid regions is ground subsidence due to the depletion of groundwater from the subsurface aquifers. When the pressures of the artesian head and the water table decline unevenly, the well is subjected to pressures that may cause collapse or breaks in the casing. At such breaks, the casing may collapse, one section telescoping into the other in a compression break. Installation of compression sections accommodates these pressures and prevents rupture of the casing (Roscoe Moss Company 1990).

A compression section consists of three approximately 2 m (6 ft) lengths of casing. Two sections that match the diameter and wall thickness of the well casing rest within an outer segment or shell, usually 50 mm (2 in.) greater in diameter than the well casing. The edges of the segments are fitted with beveled steel rings in such a manner that the joints may telescope freely within the shell but are stopped at the ends where the rings are welded in place, serving as a stop to prevent further movement past the maximum length allowed for the extending stroke.

The compression section is positioned within the casing string at depth and after careful evaluation of the formation and its yield to determine where maximum compressional stresses might develop (Roscoe Moss Company 1990). Frequently, the compression section is installed at the bottom of the pump housing casing. However, several compression sections may be installed in a single well in areas of known subsidence (Roscoe Moss Company 1990).

4.12.10 Di-electric Coupling Sections

Piping used in water wells must be treated to provide resistance to corrosion. A topical application of an anticorrosion agent or a seal leaves the possibility of an uncoated area, and any handling of the casing during preparing and installation may remove such treatment. If this happens, a focal point for corrosion may occur. To avoid this, the casing and screen should have anticorrosive properties inherent in the material. Two commonly used corrosion-resistant materials are stainless steel and copper-bearing steel (Roscoe Moss Company 1990). Because the alloys have different physical properties, they may react differently to welding. When welding stainless steel to carbon steel, it has been observed that the "less noble" carbon steel deteriorates more rapidly due to the galvanic action between the dissimilar metals (Roscoe Moss Company 1990; see Section 5.3.3, Chapter 5). Special considerations are taken when joining pipe sections that are composed of different metals. One such method is the use of a di-electric coupling that prevents the potential for corrosion, as opposed to joining dissimilar metals.

Initially a ring of carbon steel is slipped onto the stainless-steel pipe to be joined. The ring of stainless steel is welded to the top of the stainless-steel pipe above the carbon steel ring, and the carbon steel pipe is positioned end to end with the stainless-steel pipe. A wider band of carbon steel then is fitted over the entire seam, overlapping the carbon steel ring and the edge of the carbon steel pipe and completely covering the stainless-steel ring welded to the stainless-steel pipe. This outer ring then is welded to the carbon steel ring and pipe segment, so that like metals are welded to like (Roscoe Moss Company undated).

4.13 INTERAQUIFER SEALS

Following installation of the filter pack material, the annular space between the blank casing and the borehole is filled with a sand-cement slurry of the same makeup as described in Section 4.3.

Following installation of the casing, screen, and filter pack, the annular space between the casing and the borehole may be required to be filled with a sand-cement slurry that meets the requirements of local ordinances. Refer to Section 4.3 for an example.

It is always good practice to use a tremie pipe to place the cement slurry into the annular space positively. Refer to Section 4.12.8 for details.

It is important that no more than two hours are allowed to elapse between the time of addition of water to the cement mixture at the ready mix plant and the pumping of the slurry into the borehole.

Only personnel who are thoroughly trained should operate cementing equipment and specialized tools. The placing of the cement must be performed in such a manner that the casing is entirely sealed against infiltration by water from the surface. When possible, grouting of the blank casing shall be carried out in one continuous operation using a tremie pipe, with the cement mixture being forced by pressure into the annular space to a specific depth. Large hydrostatic forces may be involved, and if necessary, the cementing operation should be allowed a sufficient amount of time following each lift to allow for hydration and consolidation of the column cement.

The cement slurry in the annulus must remain undisturbed for a minimum of 24 h before further work is performed in the well. At completion of grouting, cement must be visible from the surface of the ground between the conductor and the well casing, within approximately 1 m (3 ft) of the ground surface.

4.14 PRINCIPLES OF WELL DEVELOPMENT

Well development is an extremely important part of the post-construction process. Poor practices exercised during well drilling and construction can reduce aquifer permeability and may contaminate the aquifer with drilling fluids. Thorough development can reverse these processes and restore the aquifer to its original condition. It should be noted that well development encompasses any process that maximizes well yield and efficiency and ensures sand- and particle-free water with the highest possible discharge rate and at the highest specific capacity possible.

Objectives of well development (Roscoe Moss Company 1990) are to

- Repair drilling damage to the well, thus restoring the natural hydraulic properties of the well,
- Alter the basic physical characteristics of the aquifer adjacent to the borehole in order to maximize water yield,
- Consolidate and stabilize the gravel pack envelope,
- Remove drilling fluids and debris from screen openings, the filter pack and borehole near-well zone, and
- Create an efficient hydraulic interface between envelope and aquifer.

For naturally developed wells, the objectives are to

- Remove all drilling debris from the aquifer face and formation near-well zone,
- Develop a filter on perforations or screen, and
- Increase productivity by developing zones of high hydraulic conductivity adjacent to the perforations or screen.

Purpose of Well Development Prior to understanding well development, first it is important to understand fundamental relationships that allow water from the aquifer to enter the well. This fundamental principle of well design and development is illustrated in Fig. 4-16. For this principle to be implemented properly, well development must

- Create a filter zone between the aquifer and screen, thereby stabilizing the formation,
- Increase hydraulic conductivity, natural porosity, and permeability in the area adjacent to the well zone,
- Increase effective well radius in naturally developed wells, and
- Remove fine material from the pore space, thus reducing the compactions and intermixing of grain sizes induced during the drilling process (Roscoe Moss Company 1990).

4.14.1 Procedures for Well Development (Gravel Pack Envelope Wells)

Well development consists of dislodging and removing fine-grained material (fines) and drilling fluid from the well and near-well zone until

Fig. 4-16. Fundamental principle of well design and development

predrilling conditions in the aquifer are restored. The procedures and equipment for well development differ on the basis of certain conditions: aquifer characteristics, sand content standards, well design and construction methods, open area and slot configuration, slot size, drilling fluid type, filter pack thickness, and type of formation (Roscoe Moss Company 1990).

Because of the multiple variables previously listed, there are several methods of well development. These methods can be performed alone or in conjunction with others. There are no standard set procedures. According to U.S. Geological Survey (USGS) recommendations, the most effective development methods avoid introducing air, foreign water, or chemicals initially into the well (Lapham et al. 1997).

Although the methods and procedures vary, the following general practices apply in most situations (Lapham et al. 1997):

- Well development begins slowly at very low discharge rates.
- The intensity of the procedure is increased gradually as favorable results are observed and flow is established through the intake portions of the well.
- There is no time limit on well development, which ends only when development objectives have been met. However, development

must progress in a timely manner. (Delays may cause drilling fluids to gel and may impair well development.) It is important to remove drilling fluid from the well immediately after construction.
- Combinations of different development methods may be used to develop the well completely.

Well development can be divided into three stages: predevelopment, initial development, and final development. In these three stages, the methods introduced include airlifting, swabbing, wire-line swabbing, well pumping, well surging, and backwashing. It is imperative to keep records noting time, movement of the gravel envelope, quantity of gravel added, and quantity, type, and gradation of material bailed from the well during all steps of development. The records help to analyze and assess the effectiveness of the work.

4.14.1.1 Predevelopment in Gravel-Pack Envelope Wells Predevelopment occurs during the final stages of well construction when the drilling rig is still at the site. The objective of predevelopment is to minimize formation damage in the well caused by the construction process. It includes careful drilling, fluid control during drilling, timely placement of casing and screen, and fluid conditioning prior to filter pack installation. The importance of each step of predevelopment depends on the drilling procedure and method of filter pack installation.

4.14.1.2 Initial Development Initial development of gravel envelope wells should begin immediately after installation of the filter pack and annular seals, using the drilling rig to airlift and swab the screened interval adequately. The most effective procedures to be used during initial well development are best determined by knowledge of and experience in the area.

The size of the screen opening is chosen to allow a small portion of the filter pack material to pass through it during development. By allowing some of the filter pack material to enter the well, well development is promoted. Favorable progress is seen when the filter pack, or gravel envelope, has been made to “move.” Movement within the filter pack allows fine-grained materials that are trapped within the pore spaces of the filter pack and within the near-well zone to migrate into the well for removal by airlifting or pumping. Situations have been known to occur where the filter pack and near-well zone are so clogged with drilling fluid and cuttings following well construction that no movement can take place. In this case, there are a number of phosphate-free dispersing agents available that, in conjunction with good mechanical development procedures, are successful in breaking down the drilling fluid and assisting the filter pack in beginning the development process.

Once the filter pack has been developed sufficiently with the drilling rig through airlifting and swabbing, and fine sand in the discharge is minimal, initial development may be considered complete. At this point, the fluid being discharged still may show some cloudiness or turbidity caused by colloidal particles (suspended solids), but actual sand or particles that readily settle out of the water column should be at a minimum.

4.14.1.2.1 Swabbing and Airlifting Swabbing and airlifting is the primary activity in the initial stage of development and is performed using a double-disc swab that is located at the bottom of a drill string. The rubber discs of the swabbing tool are spaced approximately 10 ft apart and are separated by a section of perforated pipe. The rubber discs of the swabbing tool should be well supported by steel plates to provide some rigidity and should fit securely into the screen section. As swabbing progresses, airlifting takes place within the interior of the drill string. The swabbing tool actively is lifted and lowered the distance of travel in the mast, starting at the top of the screened interval and working downward. The lifting and lowering action forces fluid in and out of the well screen and into the filter pack, collapsing bridges and filling voids.

The airlifting procedure flushes the filter pack and removes particulate matter by drawing fluid in from the aquifer, which then is removed from the well by the circulating fluid. Once an interval of the well screen has been swabbed and airlifted, the swabbing tool is lowered to the next interval by adding a length of drill pipe. The swabbing and airlifting process is repeated, making upward and additional downward passes through the screen section as necessary until gravel movement in the annulus is no longer observed. If the well has been constructed using gravel feed pipes, the pipes must be flushed with water at this time. The level of the filter pack in the feed pipes should be monitored closely, and additional material should be added as needed.

4.14.1.2.2 Wire-Line Swabbing Unlike drill string swabbing and airlifting, wire-line swabbing utilizes a medium to large cable tool to which the swab is attached. For maximum swabbing effectiveness, the swab must fit tightly in the well with the swab rubbers being no more than 15 mm (1/2 in.) less in diameter than the well casing and screen.

Before wire-line swabbing begins, the well should be cleaned to total depth by running a bailer to the bottom to remove accumulated fill material. Wire-line swabbing begins at the top of the screen and progressively lowers in short intervals of no more than 16 m (50 ft) until it reaches the bottom of the well. At each increment, the swab is pulled up repeatedly with increased velocity and length until it is performing at maximum horsepower and is pulled through the entire screen. Wire-line swabbing does not clean out the well; therefore, the well should be bailed out frequently in order to remove and analyze debris and other material drawn in during the swabbing process.

By observing the amount of material removed during airlifting and swabbing using an Imhoff cone, it is possible to determine areas in the well that may contain voids or need more development time. Voids within the gravel envelope are identified by the presence of fine aquifer material being removed and must be filled quickly before a sand channel develops through the filter pack.

Wire-line swabbing usually is performed only if sand pumping has not driven out enough fine material from the near well zone. In naturally developed wells, swabbing has a greater effect than in a gravel-pack envelope well and, therefore, does not require the swabbing tools to be operated at full power.

4.14.1.2.3 Hydraulic Jetting Jetting requires a high-pressure pump (such as are found on a mud rotary rig), hoses and fittings, threaded and coupled pipe, and a jetting tool. It is necessary to use only clean water in the jetting process. Clean water passes through the screen openings and dislodges debris from the perforations and the filter pack adjacent to the well screen. The jetting procedure should start at the top of the screened interval and proceed slowly down through the screen at a rate of approximately 1 min/0.3 m (1 min/ft) of screen until the fluid returned to the surface in the pump is relatively clear. When the tool reaches the bottom of the screen, it is brought back up at a rate of 1 min/0.3 m (1 min/ft). This process is repeated until the amount of sand and particulate matter in the removed fluid is minimal (<0.5% by volume).

4.14.1.2.4 Mechanical Surging Mechanical surging is performed with a tightly fitting surge block that forces water flow in and out of a screen by operating a plunger up and down in the casing. The surge block is fitted securely into a heavy drill stem and operated with an up-and-down motion that forces the water column to be raised and lowered within the well.

Before surging, the well is bailed out to be certain that water is able to flow back into it.

Starting from the top of the screen below the static water level, the surge block is lowered until it is between 3 and 5 m (10 to 15 ft) below the static water level, yet still above the screen. Similar to well surging with a turbine pump, the initial surging motion is relatively gentle, allowing debris to become dislodged and break up, moving into the well.

As water begins to flow freely in and out of the screen, the surge block gradually is lowered throughout the length of screen, and the force and velocity of the reciprocating motion is increased as the water flows through the length of the screen in a pulsing motion. Accumulated sediment is removed either with a sand pump or a bailer from the bottom of the well. Mechanical surging can be a highly effective method for the development of water wells.

4.14.1.2.5 Overpumping Overpumping is the easiest method of removing particulate matter from a well. Performed with a test pump, it is a process of pumping water into the well at a higher rate than will be pumped from the well when the well is put into production. Although overpumping can be effective, by itself, rarely does it stabilize the aquifer fully. Little additional development occurs in the upper part of the screen, and sand particles may migrate into the filter pack, causing a bridged condition in the well.

4.14.2 Development Methods for Naturally Developed Wells

All methods used to develop gravel pack envelope wells are applicable for natural well development; however, the effects of the development tend to be stronger and do not require as much power from the tools. Because there is no filter pack to control the formation, it is necessary to proceed with caution while slowly increasing the amount of energy expended in developing naturally developed wells. The finer fraction of the formation materials is removed slowly, further leaving coarse-grained particles behind to control fine-grained formation materials in the near-well zone.

4.14.2.1 Sand Pumping Using a Bailer Sand pumping is performed with a scow or large-diameter bailer that is operated with a reciprocating motion opposite the screen. Beginning at the top of the screen and proceeding downward, sand pumping pushes debris into the well. Washing and surging then draws out the debris. Because of the size of the screen aperture, approximately 50% of the formation material typically is allowed to pass into the well. As development progresses, the coarsest-grained materials of the formation form a layer immediately adjacent to the screen, which progressively becomes finer-grained with distance outward from the screen.

4.15 FINAL DEVELOPMENT WITH DEEP WELL TURBINE PUMP (VERTICAL LINE SHAFT)

Final development is contingent on the results of the initial phase of development. Final development is performed with a vertical line shaft turbine test/development pump in place and includes pumping, surging, and backwashing techniques (Roscoe Moss Company 1990).

4.15.1 Well Pumping

Development pumping typically will produce a colored discharge following the relatively clean discharge observed at the end of airlifting and swabbing. Initially during development pumping, the discharge rate must be held constant at very low flow rates while the water column is allowed to clear. Discharge rates, sand content, and water levels should be measured frequently and recorded during the development process. As the discharge clears and remains relatively sand-free (<10 mg/L) the flow rate may be increased slowly in incremental steps. Only when very low amounts of sand are observed can the discharge rate be increased.

When a constant pumping rate and water level are reached, the well is surged and allowed a short time to recover. Recovery occurs in two stages: there is an initial return to a water level often referred to as the 5-min recovery level, and there is a full recovery that occurs when the water level returns to the initial static water level. Once a very high rate of discharge is attained, pumping with surging can be commenced. Pumping and surging are alternated repeatedly and vigorously until the sand content remains at a minimum, and no additional coloration is noticed in the discharge (Lapham et al. 1997).

4.15.2 Well Surging

Surging is performed with a turbine pump and is the process of slowing or stopping the pump to allow the water in the discharge column pipe to flow back into the well. Surges at the beginning of the well pumping phase can be performed by gradually slowing the pump until water level in the well begins to rise. Then the original pump speed is resumed. As well development progresses, the intensity and frequency of the surges increase. Severe surges are performed when the engine clutch is disengaged and the pump backspins as the discharge column pipe are emptied. This creates a faster change in velocity of the water entering the well and a more active washing action. Multiple surges of high intensity should be encouraged only in the final stages of well development (Driscoll 2008).

The variations in water level change the inlet velocity, thereby dislodging the bridges of particles in the aquifer and filter zone, causing fine materials to be pumped into the well.

4.15.3 Well Backwashing

If there is an unanticipated low well production rate after pumping and surging, an additional program of well development should be implemented. Backwashing requires a high-capacity water source in which the water is free of sand and silt. Backwashing is the action of putting an artificial hydraulic head on the well, reversing the flow of water through the screen, and dislodging and breaking up sediment bridges and particles. Reversing the flow of water through the well screen breaks down bridges into the filter pack that may form when water is pumped in only one direction. The backflow breaks down the bridging particles, and the inflow flushes them toward the screen and into the well. Like pumping and surging, backwashing should commence with a relatively low pumping rate and gradually increase in frequency and intensity as long as favorable results are observed (i.e., specific capacity increases, thus the procedure should be continued).

The process called rawhiding can be alternated with backwashing. In rawhiding, a column of water is raised in the well by adding a volume of clean, clear water a noticeable distance above the pumping water level or even above the ground surface (Roscoe Moss Company 1990). After filling the well, the pump is activated to pump off the artificial head quickly. Once the artificial head has been removed, the pump is shut off to allow the well to recover and to increase the hydraulic head on the formation repeatedly. This procedure can be repeated until either improvement is seen in well production (without adding water) or it has been determined that no changes are seen.

4.15.4 Completion of Well Development

Well development should continue until the objectives have been met and the following conditions have been satisfied:

- The quantity of the filter pack material placed in the annulus shall be at least as great as the calculated volume of the annulus.
- There is no further settlement of the filter pack in the gravel feed pipe.
- A test for sand concentration shall be made 20 min after the start of pumping while at maximum drawdown and discharge rate as specified. The sand concentration must not exceed 5 mg/L at that time or for any 2-h cycle thereafter. The sand concentration shall be measured using a centrifugal sand-separating device, such as using a Rossum sand tester.
- There must be no increase in the specific capacity with further development. Fig. 4-17 illustrates well development history.

4.16 PUMPING TESTS

Pumping tests are performed for the purpose of acquiring data from which to calculate certain physical constants of the well and surrounding aquifer. Then these physical constants may be used, for example, to design

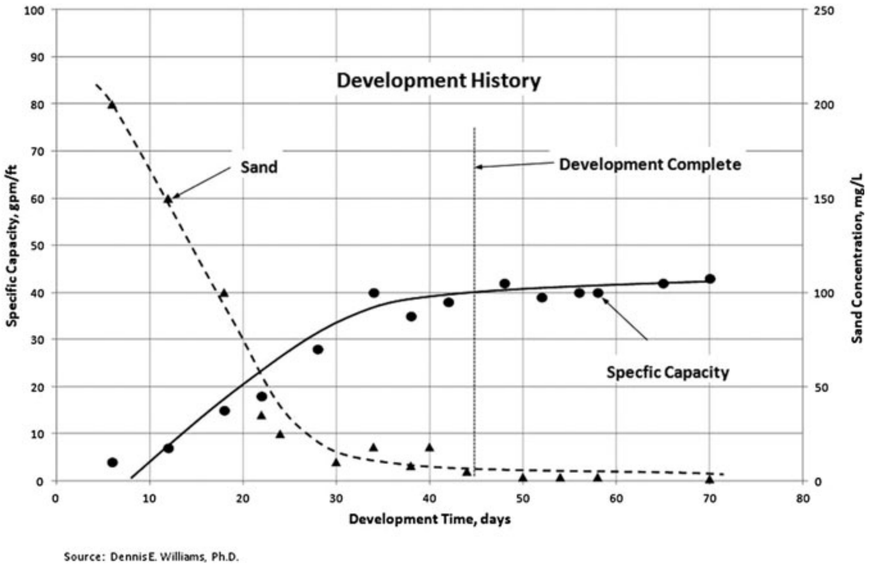

Fig. 4-17. Well development

the maximum safe pumping rate of the well, determine well field spacing, calculate aquifer storage, or determine the rate of movement of contaminants in the groundwater. The two most commonly performed pumping tests are

- Step-drawdown test, and
- Constant rate test with recovery measurements.

4.16.1 Step-Drawdown Tests

Step-drawdown tests generally are performed as the first test on a newly completed production well following final well development. A step-drawdown test involves pumping the well at several discharge rates (e.g., 500 gal./min, 1,000 gal./min, and 1,500 gal./min) and measuring the change in depth to pumping level in the well as time progresses. At least three "discharge steps" are required for the test, with subsequent discharge rates increasing over the previous steps. Data obtained from step-drawdown tests are used to determine well production and drawdown characteristics from which the permanent production pump can be designed.

4.16.2 Constant-Rate Pumping Tests

Following the step-drawdown test, a constant-rate pumping test usually is performed. The purpose of the constant rate test is to verify the design discharge rate estimated from the step-drawdown test and also to measure longer-term drawdown effects on the pumping well and any nearby wells. Data obtained from both the pumping well and nearby wells can be used to calculate aquifer parameters, which then can be used to design spacing between wells, calculate groundwater storage volumes, or determine the rate of movement of groundwater.

In a constant-rate pumping test, the pumping rate is held constant throughout the entire test duration. Two time-dependent cycles of a constant-rate test should be recognized: drawdown and recovery.

The drawdown cycle is the time period between start of pumping and end of pumping. The cycle from the end of pumping to the end of all test measurements is known as the recovery cycle. During the drawdown cycle, water levels decline with time as the cone of depression expands. During recovery, water levels increase as formation water recharges the dewatered area of the cone. Test analysis involves calculation and comparison of data obtained from both cycle periods. In general, data obtained during the recovery period is more reliable due to lack of water-level fluctuations caused by discharge variations.

Interference Measurements Measurement of water-level changes away from the pumping well is known as interference measurements. Unlike measurements obtained in the pumping well, interference measurements contain no turbulent flow losses. As equations for formation parameters do not consider turbulent-flow loss components, interference data are preferred. Multiple interference measurements on observation wells at varying distances and directions from the pumping well provide the most reliable of all test measurements. However, in most practical situations, observation wells generally are limited or missing altogether.

Number and Placement of Observation Wells As a rule, the more observation wells available for measurement during a test, the more reliable the information gained regarding aquifer characteristics. In addition, if the wells are oriented in different directions away from the pumping well, anisotropy of the aquifer can be determined. Ideally then, observation wells should be placed in four quadrants surrounding the well with radial distances ranging from very near (e.g., 3 m) to relatively far (e.g., 300 m) distances. Spacing between the wells should be closer toward the pumping well (where drawdown changes are greatest) and decreasing radially outward.

Use of Existing Wells as Observation Wells There may be one or more existing wells close enough to the pumping well to show measurable interference effects. It is important that the wells chosen for observation are screened in the same aquifer or aquifers, as observation wells completed in different zones will reflect different hydraulic effects, leading to erroneous results.

Drilling New Wells for Use as Observation Wells during a Pumping Test Small diameter observation wells drilled solely for purposes of interference measurements are commonly called *piezometers*. Piezometers measure the head in either confined or unconfined aquifers and should be placed close enough to the pumping well to reflect significant changes in water levels during the test. As the shape of the cone of depression depends on both time and aquifer parameters (i.e., transmissivity and storativity), placement of observation wells should consider both. For example, head changes in unconfined aquifers may be measurable within only relatively short distances from the pumping well (e.g., 15 to 30 m), whereas those in highly confined aquifers may show significant changes hundreds to several thousands of meters away. Further, aquifers having low transmissivities have steep limited cones of depressions contrasted to the broad flat cones seen in highly transmissive formations. Knowledge of the aquifer type, therefore, is important in observation well placement. Also, if hydrologic boundaries are known or suspected, placing observation wells between the boundary and the pumping well may be desirable.

4.16.3 Preparing and Conducting a Pumping Test

The type of pumping test to be performed depends on the test purpose, available resources, and site-specific limitations. For example, in an area containing a single well, it is not possible to conduct a test and calculate aquifer storage parameters. Similarly, observation wells (i.e., nonpumping wells) not screened in the same aquifer as the pumping well cannot provide reliable interference data. In addition, site-specific limitations may affect the type of pumping test that can be performed. These limitations include

- No place to discharge pumped water (i.e., discharge will flood adjacent lands),
- Quality of pumped water not meeting basin discharge requirements,
- Discharge of pumped water affecting environmentally sensitive areas,
- Noise considerations on surrounding homeowners or businesses,
- Lack of available personnel to take measurements during the test, and
- Not being able to take a well off line during critical water demand periods.

Obtaining dependable data from a pumping test, therefore, involves a carefully planned program including consideration of the test purpose, reliability of test results, available staff, and consideration of physical and environmental constraints.

4.16.3.1 Preparation of Well and Pumping Equipment for Testing Before starting the test, it is essential that all test equipment is adequate and in good working order. This includes installation of a properly sized pump with a bowl setting well below the maximum anticipated pumping level. Also, if powered by a gas or diesel engine, there should be enough fuel in the tanks to see the test through. A proper discharge-regulating valve also may be required to control pumping rates, and a reliable and calibrated discharge-measuring device needs to be installed. For water-level measurements, an airline or sounding tube should be installed and properly calibrated prior to starting any test measurements.

4.16.3.1.1 Discharge of Pumped Water Consideration should be given to the amount and quality of water to be discharged during the pumping test and whether discharge will meet NPDES discharge requirements (if they apply). In shallow unconfined aquifers, care should be taken that water does not reenter the aquifer and affect test results. Conveyance of discharge water an adequate distance away from the well may be necessary. A pipeline also may be required. The distance depends on site conditions, but 100 to 150 m would not be unusual. Also, thought should be given to the availability of convenient channels or storm drains. This is especially important in residential areas.

4.16.3.1.2 Personnel Requirements The number of people and responsibility of each person involved with the test depends on the test purpose and duration. For example, tests involving rapidly changing water levels with multiple nearby observation wells require more personnel than periodic measurements at the end of a constant rate test on a single well. Assigning individual responsibilities and performing trial measurements and calculations is best done before the test begins. The pretest measuring period provides an excellent training period to work out logistic and other problems involved with measuring and recording. It may be cost effective in some cases to rent automatic data logging equipment (i.e., MiniTroll or Hermit transducers) to replace a human observer on some wells.

4.16.3.2 Determination of Pump Discharge Rate for Testing

4.16.3.2.1 Determination of Discharge Rates for Step-Drawdown Test Determination of the maximum discharge rate for the test primarily depends on the test being conducted. For the step-drawdown test (usually the first test to be conducted after final development of a new well), the discharge steps are determined based on results from the final development pumping. For example, if during final development, the maximum discharge rates reached 2,500 gal./min with good stabilization, then the three rates for the step-drawdown test might be 750 gal./min, 1,500 gal./min, and 2,200 gal./min. The discharge rates for a step-drawdown test should be reasonably spread out over the maximum range available for the well (as determined during development).

4.16.3.2.2 Determination of Discharge Rate for Constant Rate Test The discharge rate during the constant rate testing should be at the design discharge rate for the well. This may be based on both development pumping and results from the step-drawdown test. The step-drawdown test seldom is performed for a duration sufficient to design the permanent pump and should always be verified with a longer-term, constant-rate test. It is important to keep in mind that development pumping always should be at a rate in excess of the final production rate recommended for the well. A general rule is to develop the well at a rate approximately 50% greater than the permanent design production rate. In other words, if the maximum development pumping reached 2,500 gal./min, then the maximum design production rate should be approximately 1,700 gal./min. However, the final design-pumping rate is still subject to sound engineering judgment and should consider both demand requirements and pumping test results.

4.16.3.3 Essential Measurements and Record Keeping—Time, Depth to Water, and Discharge Rate

4.16.3.3.1 Pretest Measurements Prior to conducting a pumping test, it is important to understand hydrologic influences in the area, which may affect interpretation of test results. These influences include interference effects of nearby pumping wells, as well as atmospheric, tidal, or other pressure changes, which may result in water-level fluctuations during the test. Therefore, trends must be established several days prior to the test with water-level measurements taken preferably twice a day. When the trend is predictable (i.e., not expected to change) the pumping test may commence.

4.16.3.3.2 Test Duration and Time Measurements The question always arises as to how many hours the test should be. The answer depends on the purpose of the test and the hydraulic properties of the aquifer. The cone of depression (i.e., drawdowns) surrounding a pumping well depends on the time (t) since the start of pumping and the distance (r) from the center of the water well.

$$s_w \propto \log\left(\frac{t}{r^2}\right) \tag{4-1}$$

where

s_w = total drawdown in the water well, (ft)
t = clock time, (s)
r = distance in a radial direction from the center of the water well, (ft).

At the beginning of the test, the cone of depression expands rapidly as pumped water comes from the aquifer storage in the immediate vicinity of the well. As pumping continues, the radial expansion of the cone occurs at a decreasing rate as larger volumes of water become available. To the inexperienced observer, this slowing down often is mistaken for steady-state conditions, whereas in actuality the cone of depression will continue to expand until recharge to the cone equals the discharge of the well. When this last condition occurs, the well is said to be in a steady or equilibrium state. In some wells, the condition of equilibrium may be reached within a few hours after start of pumping, whereas in others it may happen after days, weeks, or possibly never.

It is not absolutely necessary to continue the test until steady-state conditions are reached, because nonsteady-state analysis methods are available. However, for design of important facilities (e.g., municipal water-supply wells) the most accurate information is desirable, due to the high cost of such facilities, and pumping until equilibrium conditions are reached is recommended. Also, pumping to equilibrium will reveal the presence of nearby hydrologic boundaries, which may affect long-term operation of the well. Plotting depth to water levels or drawdown versus time on semilogarithmic paper during the test provides an excellent view of changing hydraulic conditions and provides a guide to how much longer the test should continue.

4.16.3.3.3 Time Interval for Measurements Water levels decline or recover most rapidly immediately following a change in pumping rate. For this reason, frequent measurements are required from the first few minutes to as long as several hours after start or stop of pumping. This frequent measuring schedule applies to both the start of each step in a step-drawdown or constant-rate test and immediately after the stop of pumping in a recovery test. Table 4-5 shows a practical range of time intervals for measurement. The time intervals in the table are for the pumping well and nearby piezometers. For observation wells at considerable distances away from the pumped well, the frequency of measurement is not as important.

Table 4-5. Recommended Time Intervals for Field Data Measurement

Time Since Pumping Started or Stopped	Time Interval
0–10 min	2 min
10 min–30 min	5 min
30 min–1 h	10 min
1 h–12 h	30 min
12 h–48 h	1 h

4.16.3.3.4 Measurement of Pump Discharge Rate The discharge rate should be measured accurately and recorded periodically during the test to ensure consistency of pumping. When adjustment is necessary, it is accomplished more accurately by regulating a valve in the discharge pipe than by changing the speed of the pump. Many different types of flow measuring devices are available in the water industry. However, only those most commonly used for pumping tests on water wells are discussed in this manual. Accuracy of measurement is a function of the design of the meter and of the pumping rate. In general, the accuracy should be ±2%.

Propeller Meters A commonly used discharge-measuring device is the propeller meter. Usually placed in a straight section of the discharge pipe (five pipe diameters of straight approach are required to guarantee ±2% accuracy), the meter averages flow through the cross-sectional area of the pipe by counting revolutions of a propeller. The revolutions per time period are related to the velocity of flow through the pipe. Most propeller meters have dials for direct reading of instantaneous discharge, as well as totalizers for cumulative volumes. The meters are calibrated for various pipe sizes and require a full pipe. Both air in the discharge water and sand buildup in the bottom of the meter section affect accuracy. The manufacturer's specifications should be consulted for installation and operational details, as well as for maximum and minimum flow values.

Circular Orifice Weirs A commonly used device to measure discharge during pumping is the circular orifice weir. Flow through the weir is a function of the head above the discharge pipe and the ratio of the pipe to the orifice diameter. Specifically, the equation for flow through an orifice weir with a free discharge is given as follows:

$$Q = C_d A \sqrt{2gh} \tag{4-2a}$$

or,

$$Q = 8.02 C_d A \sqrt{h} \tag{4-2b}$$

where

Q = discharge of water well as measured by the orifice meter, (ft^3/s)
C_d = coefficient of discharge relating orifice diameter to pipe diameter, (dimensionless)
A = cross-sectional area of the orifice opening, (ft^2)
g = gravitational acceleration, (32.174 ft/s^2)
h = hydraulic head as measured in a piezometer tube above an arbitrary datum plane passing through the center of the orifice opening, (ft)
8.02 = dimensional numerical factor = $\sqrt{2g} = \sqrt{2 \times 32.174}$, (ft$^{1/2}$/s).

For field operations or design computational purposes, when it is required to express discharge in gallons per minute, (gal./min), simply multiply the discharge value in cfs or ft^3/s by a factor of 450 gal./min / cfs as follows:

$$Q\,(\text{gal./min}) = 450 \times Q\,(\text{cfs}) \tag{4-2c}$$

For very small discharge rates (<50 gal./min), calculation of discharge can be made from measurements of the time required to fill a container of known volume. Typically, a 1- or 5- gal. bucket is placed under the discharge stream, and discharge is calculated by the time (t) required to fill the bucket. For example

$$Q = \frac{\bar{V}}{t} \tag{4-3}$$

where

Q = discharge of water well in gal./min
$\bar{V}$ = container volume in gallons, (gal.)
t = clock time in minutes to fill the container, (min).

4.16.3.3.5 Measurement to Depth of Water Level Accuracy of depth to water-level measurements during a pumping test should be within 1 mm in observation wells and within 150 mm in the pumping well. Accuracy primarily depends on the measuring device, but the techniques used and the prevailing test conditions sometimes also are added factors that need to be addressed (e.g., very deep wells).

Wetted Tape A simple and reliable method for measuring depth to water is through use of an ordinary tape (preferably made of thin steel with markings in tenths and hundredths of feet). In this method, the approximate depth to water must be known and the lower portion of the tape conditioned with indicator paste, which changes color on contact with water; in most cases, the tape is dried and dirt used to provide the conditioning. The tape is lowered to a predetermined level and held at an even foot mark at the surface reference point. The difference between the reference point reading and the point of water-level contact is the depth to water.

When dedicated sounding tubes are not available, the wetted tape method is seldom used in the pumping well due to surging water levels, cascading water, or pump column leaks.

Electric Sounder A refinement of the steel tape method relies on the electrical conduction of water. A two-conductor electrical wire with internal supporting cable to prevent stretching is lowered into the well. When the water level is reached, an electrical circuit consisting of a buzzer, light, or voltage meter in series with a battery is completed. The conducting wire generally is calibrated in regular intervals (every 1 to 5 ft) and fractional measurements made between the intervals with a tape.

Some electric sounders consist of a one-conductor wire with the second battery lead being grounded to the well casing. These devices also may be equipped with a geophysical type reel containing direct reading depth counters. Like steel tapes, electrical sounders are subject to cascading water or pump column leaks and are most reliable in pumping wells when measuring depth to water in the sounding tubes.

Another technique used for measuring depth to water relies on the pressure-height relationship. Under ordinary fresh-water conditions, 2.31 ft of water exerts a pressure head of 1 lb/sq in. The airline method makes use of this relationship to calculate depth to water from the difference between the bottom depth of the airline and the pressure head required to evacuate the line. This method commonly is used to measure depth to water in the pumping well. Care should be taken to ensure that competent materials (no leaks) are used for the airline and that the line is installed properly and calibrated against an electric sounder or steel tape.

The pressure transducer also makes use of the pressure-height relationship in water. Transducers are placed to a depth below the maximum anticipated lowering of the water level. Changes in the column of water above the transducer result in corresponding changes in electrical output (typically 4 to 20 mA range). Measurement of the output current is equated to depth of water through an appropriate rating curve. Transducers are designed on the basis of the maximum pressure changes expected and produce a reliable and accurate measurement of water levels. Advantages of transducers are that they are interfaced easily to automatic data logging and control devices.

Automatic Water-Level Recorders Continuous water-level recording devices may consist of a float, transducer, or a continuously reading airline (also known as a bubbler). These devices are connected to a recorded output, which may range from light-sensitive film and paper charts to local or remote computer storage. The degree of sophistication of continuous recording devices is limited only by cost, as reliable technology is available to install these devices in a wide range of applications. Advantages are continuous records, computer processing of data, and reduced staff-hour requirements.

4.16.3.3.6 Record Keeping During the Test Information gathered before and during the pumping test should be recorded as a neat and accurate record. A protected or covered clipboard commonly is used to record time, discharge, and depth to water data. In addition to data taken during the test, it is important to note background information regarding the well, pump, and any other information that might be useful during subsequent analysis (e.g., measurement of distances to piezometers, diameters of wells, discharge pipes, etc.). Pumping test forms vary widely in style and format depending on the particular test, but all forms should contain space for essential test measurements.

4.16.4 Analysis of Pumping Test Data

4.16.4.1 Basic Assumptions Used in the Analysis of Pumping Test Data The purpose of a pumping test is to obtain field data, which, when substituted into an equation or set of equations, will yield estimates of well and aquifer properties. As certain assumptions have been used to derive these equations, it is important to observe or control these factors during the test. These assumptions and conditions are as follows:

- The aquifer material is assumed to consist of porous media and with flow velocities being laminar and obeying Darcy's law.
- The aquifer is considered to be homogeneous, isotropic of infinite areal extent, and of constant thickness throughout.
- Water is released from (or added to) internal aquifer storage instantaneously upon change in water level. No storage occurs in the semiconfining layers of leaky aquifers.
- The storage in the well is negligible.

- The pumping well penetrates the entire aquifer and receives water from the entire thickness by horizontal flow.
- The slope of the water table or piezometric surface is assumed to be flat during the test with no natural (or other) recharge occurring that would affect test results.
- The pumping rate is assumed constant throughout the entire period of pumping in a constant-rate test and constant during each discharge step in a variable-rate test.
- Time measurements are referenced to the start of pumping for drawdown tests and to the end of pumping for recovery tests.
- Water levels measured in observation wells are assumed to reflect the same hydraulic conditions encountered in the pumping well aquifer.
- Water-level fluctuations caused by interference from nearby wells, or other causes (e.g., tidal influences) are considered insignificant (or correctable) during the duration of the test.

4.16.4.2 Analysis of Step-Drawdown Test Data For a pumping well fully penetrating the aquifer, the total drawdown in the well is composed of both laminar and turbulent head loss components. Laminar losses generally occur away from the borehole where approach velocities are low, whereas turbulent losses are confined in and around the immediate vicinity of the well screen and within the well bore. The total drawdown in a pumping well at a constant discharge rate may be expressed as (Jacob 1947)

$$s_w = BQ + CQ^2 \tag{4-4}$$

where

s_w = total drawdown measured in the well for a step-drawdown test, (ft)
Q = well discharge rate, (gal./min)
B = formation loss coefficient, (ft/ gal./min)
C = well loss coefficient, (ft/ gal./min^2).

Formation losses are the head losses that are accounted for when the water travels through the bulk mass of the aquifer, damage zone, and gravel pack envelope while moving toward the well. The magnitude of the formation losses can be found from consideration of radial flow into the well and calculated using Jacob's equation.

Well losses are turbulent flow losses that are head losses associated with the flow of water into and through the well screen slots, as well as those losses incurred as the flow moves axially through the well casing

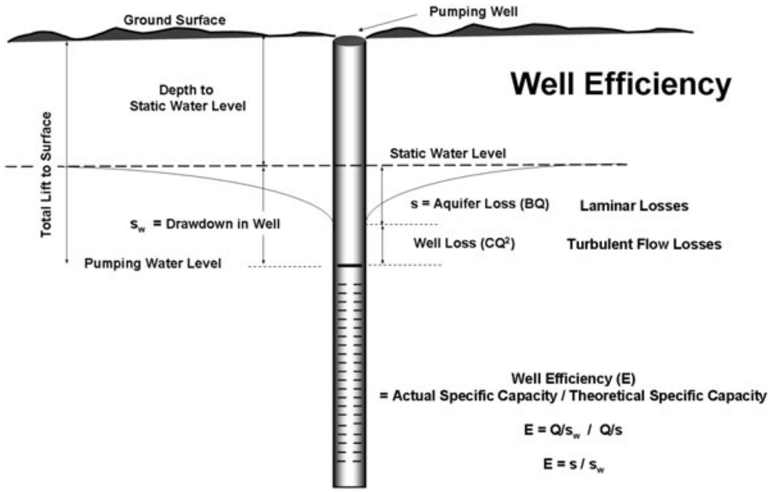

Fig. 4-18. Well efficiency

and wellbore toward the pump intake. These losses vary as the square of the velocity.

Well efficiency, E, for a water well is the ratio of actual specific capacity to the theoretical specific capacity (see Fig. 4-18). Expressed another way, well efficiency (usually expressed as a percentage) is the ratio of the drawdown directly outside the well (i.e., formation loss BQ) to the drawdown as measured in the well, s_w.

$$E = \frac{BQ}{s_w} \times 100\ \% \tag{4-5a}$$

or,

$$E = \frac{100}{1 + \frac{C}{B}Q}\ \% \tag{4-5b}$$

Specific capacity (i.e., yield/drawdown) relationships, well efficiency, and calculations of individual losses may be determined from step-drawdown testing data. The test procedure involves operating the well at multiple discharge rates with each "step" being a fraction of the maximum discharge. At least three steps are needed for most wells. Analysis of the step-drawdown data requires plotting the *specific drawdown*, s_w/Q, for each step. Fig. 4-19 illustrates the procedure.

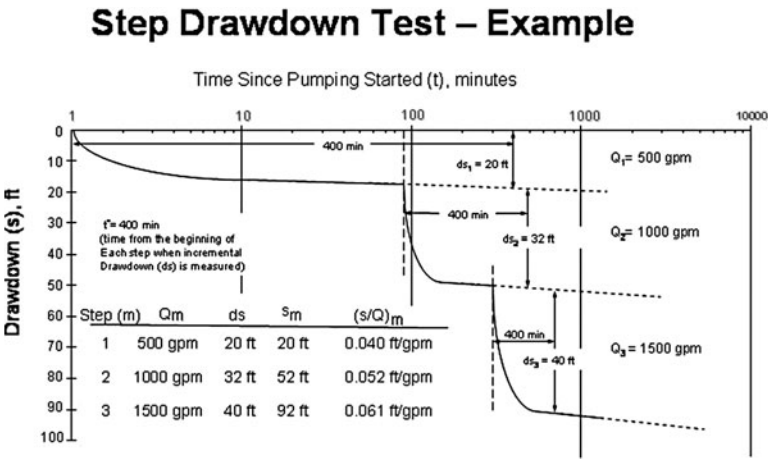

Fig. 4-19. Analysis of step-drawdown test data

Specific drawdown, s_w/Q, *is* obtained by dividing both sides of the drawdown Eq. (4.4) by Q as follows:

$$\frac{s_w}{Q} = B + CQ \tag{4-6}$$

It is obvious from Eq. (4-6) that a plot of specific drawdown (s_w/Q) versus well discharge rate (Q) would plot as a straight line. From the plot, the formation loss coefficient (B) may be determined from the zero discharge intercept of the best-fit straight line of the plot. The slope of the straight line is equal to the well loss coefficient (C). An example of a specific drawdown plot is shown in Fig. 4-20.

Test data on newly developed wells also can provide a *base signature* for the well. Subsequent tests during the operational life then can be compared to the original test as a basis for redevelopment decisions. The step-drawdown test also can be a valuable tool to gauge when development is complete. During the early stages of development, lower specific capacities are associated with high drawdowns in the near-well zone (due to a predominance of fines). As development progresses, these fine-grained materials are removed, and drawdowns decrease, resulting in higher specific capacities. In other words, during the development process, it is common to observe higher specific capacities with higher discharge rates, which is exactly the opposite of a fully developed well. Thus, in a developing well, the slope of the specific drawdown plot versus discharge rate shows a negative value. Plotting of specific drawdown, s_w/Q, versus Q during development, graphically shows the development progress.

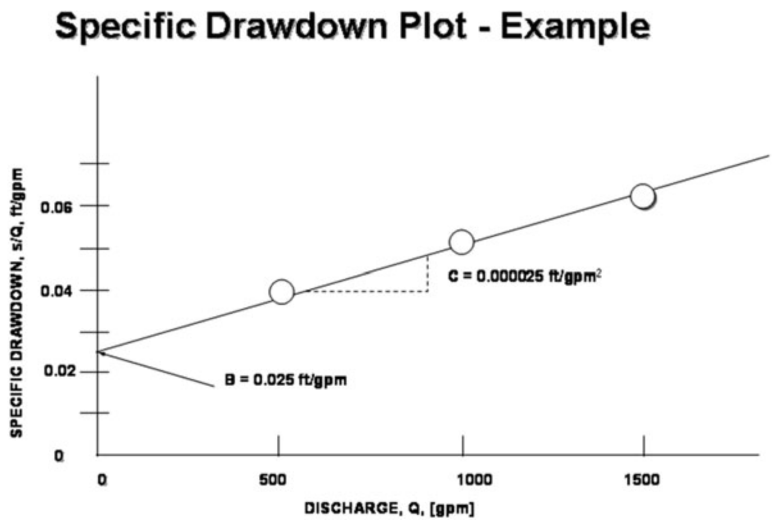

Fig. 4-20. Specific drawdown plot

Development may be considered complete when the slope of the best-fit straight line approaches a positive and constant value.

Based on the formation loss and well loss coefficients as calculated, the specific capacity diagram (Fig. 4-21) may be constructed and used for well design purposes. The following illustrates this concept.

4.16.4.3 Calculation of Aquifer Parameters from Constant Rate Tests Calculation of aquifer parameters from pumping test data is based on analytical solutions of the basic differential equation of groundwater flow, which can be derived from fundamental laws of physics. One of the most widely used solutions of this equation for nonsteady radial flow to artesian wells is the Theis (1935) equation:

$$s_w(r, t) = \frac{114.6Q}{T} W(u) \tag{4-7}$$

where

$s_w(r, t)$ = drawdown at a distance r after time, t, (ft)
t = time since pumping began, (days)
r = radial distance from the center of the pumping well, (ft)
Q = well discharge rate, (gal./min)
T = transmissivity of the aquifer, (gal./day/ft)

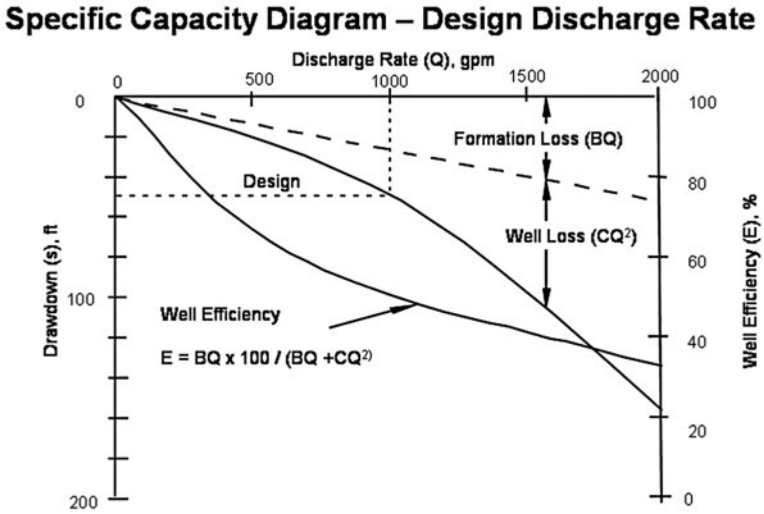

Fig. 4-21. Specific capacity diagram

W(u) = well function of Theis, (dimensionless)
$u = (1.87r^2S)/(Tt)$, (dimensionless)
S = storativity, (dimensionless).

Jacob's approximation to the Theis equation is valid for small values of u (i.e., $u < 0.05$), and may be written as follows (Jacob 1950):

$$s_w(r,t) = \frac{264Q}{T}\log\left(\frac{0.3Tt}{r^2S}\right) \quad (4\text{-}8)$$

Jacob's equation is valid for use for most problems of practical interest, is easier to use than the Theis equation, and involves a simple graphical procedure to calculate transmissivity and storativity. Fig. 4-22 provides an example of how Jacob's equation is used to estimate formation parameters from a constant rate test (Jacob 1950).

Although the assumptions used to derive Jacob's equation apply to confined (i.e., artesian) aquifers only, a correction may be used for unconfined aquifer test data (Jacob 1963). Jacob's correction may be written as $s' = s - (s^2/2D_o)$. When the drawdown (s) is small relative to the saturated thickness (i.e., $s/D_o < 0.25$), the drawdown around a water table well may be analyzed using the artesian well equations provided that drawdown (s), transmissivity (T), and storativity (S) are replaced with $s - (s^2/2D_o)$, KD_0, and θ, respectively (where D_0 = initial saturated aquifer thickness and θ = effective porosity) (Hantush 1964).

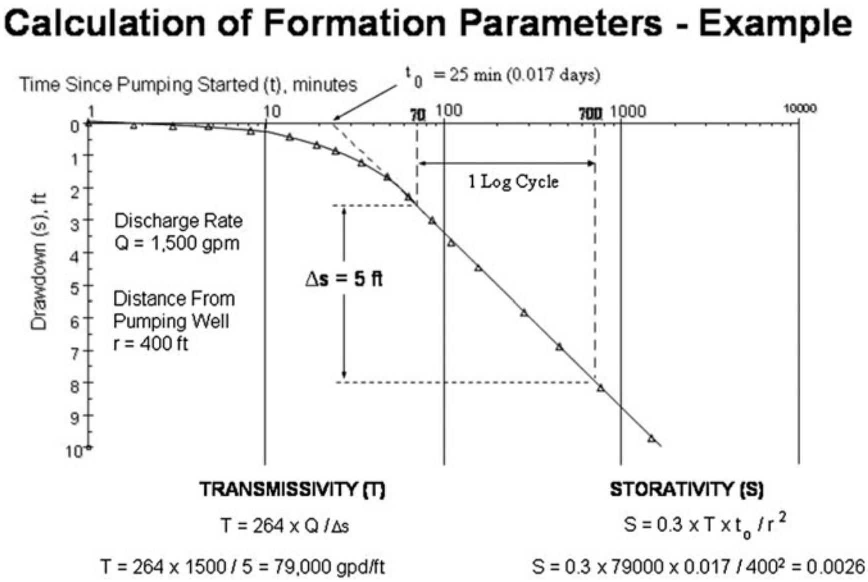

Fig. 4-22. Analysis of constant rate test data

4.17 FLOWMETER (SPINNER) SURVEY

Flowmeter, or spinner surveys, can be used to determine the production rate from any zone in a well (Driscoll 2008). Flowmeter surveys involve a small but very sensitive propeller (flowmeter) that it is moved upward through the screened interval where it is rotated by the water in the well. This rotation causes magnets on the propeller's shaft to generate electric pulses, which then are recorded at the surface as the spinner's rotation rate. From this record, the rate and direction of flow within the borehole can be calculated (see Fig. 4-23).

Flowmeter surveys are performed after the constant rate pumping test and recovery measurements. Typically it is necessary for water levels in the well to have become stabilized under pumping conditions prior to running the spinner survey. At least three down runs at varying line speeds are required to analyze the flow regime fully within the well. By examining the down runs and stop counts (when the flowmeter remains stationary in the well at selected depths for a period of time to collect flow measurements) and knowing the discharge rate of the well during the test, it is possible to determine the percent contribution of each section of screen within the well.

The flowmeter survey is limited in that the water must reach a certain threshold velocity before the impeller will start to rotate. However, past

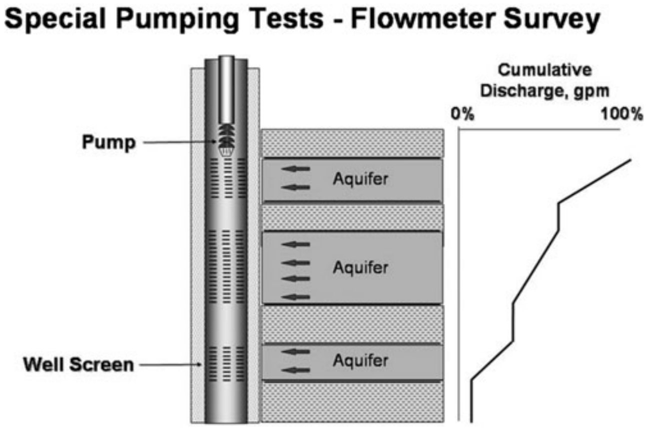

Fig. 4-23. Flowmeter survey

that threshold, the speed of rotation increases linearly with fluid velocity (Roscoe Moss Company 1990). Even for slow velocity areas, the rate may be found by moving the meter at a constant rate before subtracting the known rate from the measured rate.

4.18 COLLECTING WATER QUALITY SAMPLES AT THE END OF THE CONSTANT-RATE TEST

Water quality samples should be collected during and at the end of the constant rate test and should be submitted to an approved laboratory for full Title 22 analysis (APCL 2002), as specified by each state's code of regulations.

4.19 MISCELLANEOUS FINAL TASKS

4.19.1 Removal of Test Pump

At completion of all pump testing, the test pump needs to be removed from the well while the permanent pumping equipment is designed, ordered, and installed.

4.19.2 Video Survey

Downhole video cameras are used to gather information about both open and cased boreholes (Fig. 4-24). In open boreholes, videos record the

Fig. 4-24. Downhole video survey camera

structure of the surrounding formations, as well as any fractures, dipping, or flow channels (Plumley 2000). When used in a cased borehole, videos show the condition of the casing—whether it has been corroded or obstructed (Plumley 2000)—and any lost tools or debris that may be in the borehole (Hamilton and Myung 1979).

The first downhole camera was used in 1947. Today's cameras can take color pictures of all angles within the borehole, and show the current depth footage of the camera superimposed on the picture. Downhole camera can operate at depths as great as 1,500 m (5,000 ft). The video survey is conducted after the test pump has been removed from the well, with the inspection covering the entire length of the casing and screen to serves as the post-construction record of the condition of the casing and screen.

4.19.3 Plumbness and Alignment Surveys

Proper well construction includes two geometric factors: plumbness and alignment. Plumbness refers to the axis of the well relative to the center of the earth and alignment refers to the well's "straightness." Of the two, alignment is more critical. A well that is not plumb may still work for years, but the bearing and shaft may wear out prematurely (Roscoe Moss Company 1990) on a well that is poorly aligned.

Variations in the subsurface material, including faults, boulders, and inclined strata, may alter the plumbness and alignment of a borehole (Driscoll 2008). Although gravity tends to ensure that the hole is drilled vertically, at the same time the variation of materials drilled through tends to deflect the drill bit. The quality of the casing also may affect the alignment; casing that has a casing collar (which is used to facilitate alignment) is more likely to be straight.

Alignment should be checked several times during the drilling of a very deep well, particularly when using the cable tool drilling method. This allows any problem to be corrected as soon as it is discovered. With rotary drilling, alignment is checked at fixed intervals, usually 30 m (100 ft) or more. However, in some cases, alignment is not checked until the well has been completed.

To check the alignment, a tripod with a pulley at the center is set up over the borehole. A circular cage made out of steel wire is attached to a cable and is lowered into the hole. The wire cage should be slightly smaller than the inside diameter of the pump house casing. Two steel rods, set on the casing at right angles to one another, are used to measure the movement of the cable from the center of the well on the east–west and north–south axes. Deviation from the center is measured every 3 m (10 ft) and may be very small, on the order of millimeters or less. The test should be done before the filter pack is placed in the well so that the casing and screen string still can be moved if necessary to correct for plumbness and alignment.

The deviation at any depth from a vertical line centered through the well at the surface may be calculated by the following equation:

$$x = \frac{D(H+h)}{h} \tag{4-10}$$

where

x = deviation of water well at any given depth, (in.)
h = distance from the center of the tripod pulley to the top of the casing, (ft)
H = distance from the top of the casing to the top of the cage, (ft)
D = distance the line moves from the center of the casing, (in.).

Deviations from the vertical (both north–south and east–west) then are plotted to ensure verticality. Standards for plumbness usually allow 152 mm (6 in.) away from plumb for every 30 m (100 ft) of depth. See Fig. 4-25.

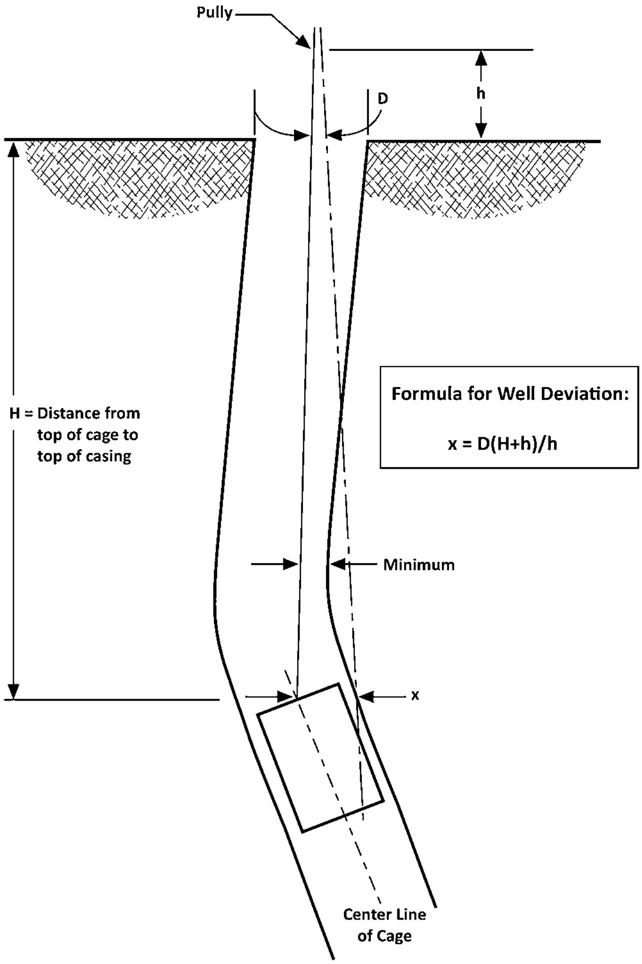

Fig. 4-25. Measurement of deviation of water well

4.19.4 Well Disinfection

A well may require periodic disinfection, especially if there is a chance it has been contaminated by construction, servicing, or maintenance (AWWA 1998). Disinfection of a new well should take place following completion of the pumping tests with all material, including oil, grease, and soil, being removed prior to disinfection. In addition, all pumping test equipment, before it is installed in any well, must be cleaned thoroughly using a strong liquid chlorine solution or sodium hypochlorite as it is being installed. The use of calcium hypochlorite compounds should be discouraged, because they have the potential for forming insoluble precipitate within the well.

For final disinfection of a newly constructed well, prior to removal of the test pump, enough chlorine should be added to the well to produce an initial concentration of at least 100 mg/L of chlorine at pumping. The well then must be pumped to waste for at least 15 min to make certain the concentration of chlorine has returned to an acceptable level (see State Health Services requirements). After the well has been tested and the absence of coliform has been verified, it is safe for public use, after acceptance by the local regulatory agencies.

4.19.5 Well-head Pad Completion

Following construction, development, and testing of the well, the top of the well shall be protected against entrance of surface water or foreign matter by installation of a concrete pedestal with watertight caps or plugs attached to all access pipes that terminate above-ground surface. Typically, state standards require a minimum of a 4 ft × 4 ft × 6 in. thick concrete slab that is constructed around the top of the casing. It is important that the slab is free from cracks or other defects that will affect its watertight nature. The pump pedestal should be poured so that it attaches to any subsurface seals on the outside of the conductor or between the production casing and the conductor. Therefore, prior to pouring the well pad, all soil and poor-quality cement must be removed. If the filter pack extends to the surface, a watertight seal, typically in the form of a welded steel plate, must be installed between the conductor casing and the production casing prior to pouring the pump pedestal.

4.20 FINAL REPORT INCLUDING ANALYSIS

At the conclusion of the well construction activities in the field, a final well report should be provided that summarizes the details of the construction of the well, including

- Progress of well construction and testing and daily field inspection reports,
- Table of well construction details,
- As-built drawings of the completed well design,
- Description of lithologic units and aquifers tapped, including a complete lithologic log as an appendix,
- Digital photos of the formation samples,
- Zone test intervals tested,
- Hourly field water quality results, water level, and discharge rate during zone testing,

- Copies of all geophysical logs, including caliper and spinner surveys,
- Results of sieve analysis, including plots of grain-size distribution curves,
- Well development logs,
- Pumping test data for the step-drawdown test, constant-rate test and recovery measurements,
- Analysis of all pumping test data with a description of the hydraulic characteristics of the aquifers,
- Analytical reports showing water quality results,
- Plumbness and alignment data,
- As-built drawings in an acceptable computerized form for inclusion in the client's GIS mapping system, and
- All other pertinent data, recommendations, and conclusions.

The data should be analyzed after the pumping test is completed and all information, including pretest trends, pumping and observation well time, discharge, and depth to water measurements, has been collected. Steps in the analysis consist of

- Classification and compilation of the data; this includes converting time, discharge and water level data to single units (e.g., min, gal./min/ft, L/s, and m),
- Correcting drawdown data for regional changes in water levels,
- Graphical plotting of data, and
- Calculating well and aquifer parameters from the graphical plots using appropriate equations.

4.21 ACKNOWLEDGMENTS

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CHAPTER 5
CORROSION OF WATER WELLS

Robert G. McLaughlan

5.1 GENERAL

Corrosion is the deterioration of a material, which results from a reaction with its environment. This environment comprises the physical, chemical, and mechanical conditions or surroundings of the material. Although metals and PVC are the most widely used materials for water well casing, there has been an increase in the use of nonferrous materials (e.g., thermoplastic, fiberglass) for use in specialized applications (contaminant remediation or monitoring) and extreme environments. However, this chapter focuses on the corrosion issues related to commonly used water well casing and screen materials (e.g., carbon steel, alloy, stainless steels).

The corrosion of ferrous metals in groundwater may be caused by electrochemical or physical processes. The various types of corrosion that can be generated from contact between water-well components and groundwater include electrochemical, crevice, and galvanic corrosion, as well as stray electrical current or microbial induced corrosion. Physical processes also may corrode metals through fluid or particle effects.

In addition to material selection, the design and operation of the water well will affect the performance of the well.

5.2 THEORY OF CORROSION

5.2.1 Electrode Reactions

The corrosion of metals may be caused by electrochemical processes involving both oxidation and reduction reactions (Fig. 5-1). The corrosion reaction involves oxidation and occurs at the anodic area. An oxidation

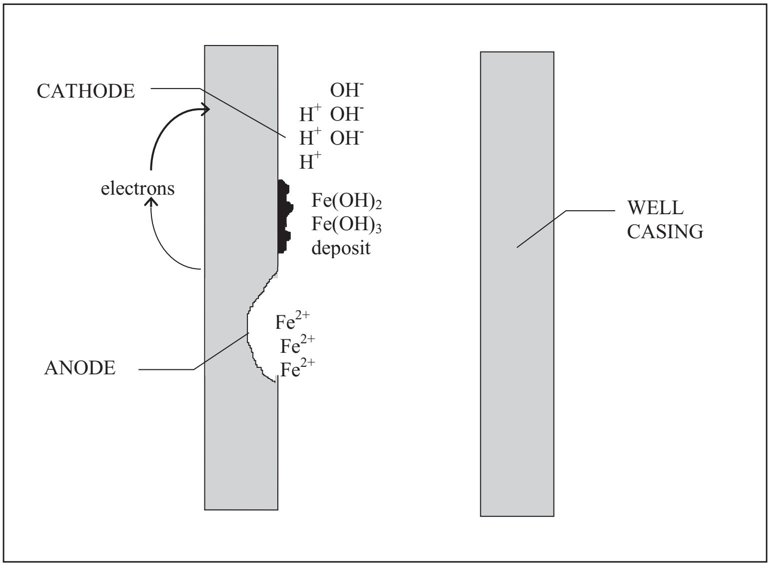

Fig. 5-1. Corrosion processes on a metal surface
Source: McLaughlan (2002)

reaction involves an increase in valence or the extraction of an electron from an ion or atom. Reduction reactions occur in a cathodic region and involve a decrease in valence or the consumption of electrons. For a corrosion cell to exist, the anodic and cathodic areas must be connected so that an electrical circuit is formed. In water wells, water with dissolved ions will allow the transfer of ions to the anodic and cathodic sites, whereas metal surfaces will facilitate electron transfer.

5.2.2 Anode

At the anode, positively charged metal atoms leave the solid surface and go into solution. The oxidation reaction occurring may be generalized as

$$M \leftrightarrow M^{n+} + ne^{-} \tag{5-1}$$

where

M = metal
e^{-} = electron
n = number of electrons.

The value of n depends primarily on the nature of the metal.

5.2.3 Cathode

At the cathode, electrons generated from the anode react with positive ions in the water to preserve solution neutrality. Cathode reactions that can occur during the corrosion of metals are (NACE 1984):

Oxygen reduction (acid solution)

$$O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O \tag{5-2}$$

Oxygen reduction (neutral and alkaline solution)

$$O_2 + 2H_2O + 4e^- \leftrightarrow 4OH^- \tag{5-3}$$

Hydrogen evolution

$$2H^+ + 2e^- \leftrightarrow H_2 \tag{5-4}$$

Metal ion reduction

$$M^{n+} + e^- \leftrightarrow M^{(n-1)+} \tag{5-5}$$

Metal deposition

$$M^{n+} + ne^- \leftrightarrow M \tag{5-6}$$

At the cathode, more than one of these reactions may occur simultaneously.

5.2.4 Passivity

Metals may become passive and lose their chemical reactivity, which enhances their corrosion resistance. This passivity may be due to a thin oxide or adsorbed layer protecting the metal surface. If the passive film is disrupted, strong corrosion cells may operate between the active and passive surfaces of the metal. To maintain the passivity of stainless steel, a low concentration of dissolved oxygen is required.

5.2.5 Polarization

The retardation of electrochemical reactions (polarization) due to protective films may result from a buildup of corrosion products (e.g., $Fe(OH)_3$ or carbonate [CO_3^{2-}]). Other ions (Ca^{2+}, Mg^{2+}) also may precipitate and polarize the surface. These precipitates will decrease the diffusion of O_2 and H_2 at the metal surface and decrease the corrosion rate.

Depolarization involves removing the factors that resist the current. Sulfate-reducing bacteria may depolarize the cathode by utilizing dissolved hydrogen and, therefore, promoting the hydrogen evolution reaction and corrosion (Hamilton 1985).

5.3 TYPES OF CORROSION

5.3.1 Electrochemical Corrosion

Electrochemical corrosion occurs when a concentration cell is formed on the metal surface. A concentration cell is formed when there are differences in the potentials across the metal surface. These differences may be caused by inherent heterogeneity of metal at the microscopic scale due to the presence of impurities and inclusions of metal oxides and sulphides. The thermal and mechanical history of the metal surface due to activities involving welding, abrasion, and strain also may create potential differences across a metal surface.

A deposit or biofilm that does not cover the immersed surface of a metal uniformly also can cause a concentration cell (Fig. 5-2). At the location with the thicker biofilm, oxygen is consumed completely within the biofilm, whereas at the site where the biofilm is thinner, oxygen can penetrate to the surface of the metal and create cathodic depolarization through oxygen reduction. This condition could occur, for example, when a piece of clean pump riser pipe is connected to an older section of pipe (which is covered by deposits) or through the patchy development of

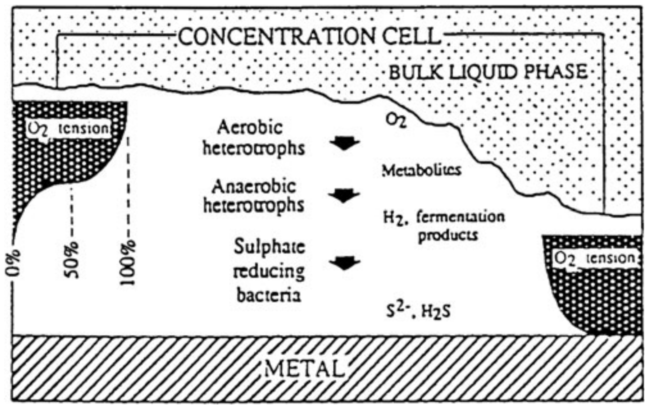

Fig. 5-2. Concentration cell formed under a biofilm
Source: Hamilton (1985); reproduced with permission from Annual Review of Microbiology

biofilms on a pipe surface. Many iron hydroxide deposits within water well environments are likely to contain microorganisms, which can exacerbate electrochemical reactions within the deposit.

The form of the corrosion is influenced by the distribution and potential of the anodic and cathodic areas across the metal surface. Where the areas are microscopic or are dynamic and shift, then the corrosion pits may be uniform across the surface. Where there are large differences in potential between the areas, then the corrosion pit may be small and localized. In water wells, localized pitting may corrode casing rapidly, leading to well failure.

5.3.2 Microbially Influenced Corrosion

Increasingly, microbes are being recognized as playing a role in corrosion in aqueous environments. Although bacteria, fungi, algae, and protozoa can be involved, within water wells it is bacteria that are of primary concern. Whereas potable groundwater aquifers are relatively nutrient poor compared with other environments, various types of bacteria are adapted for the range of environmental conditions found in water wells. The bacteria that can be associated with microbially influenced corrosion in groundwater are iron-oxidizing bacteria, slime-forming bacteria, and sulfate-reducing bacteria.

The iron and manganese oxidizing bacteria gain benefit from converting ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which then can form precipitates. The deposits formed can comprise iron oxyhydroxides, bacteria, particulates, and ions from the groundwater, such as chloride. These biofouling deposits then can create concentration gradients across the surface of the metal leading to localized corrosion. Commonly identified bacteria of this group include stalked bacteria (*Gallionella*) and sheathed bacteria (*Leptothrix*).

The slime-forming bacteria occur in a wide range of conditions from anaerobic through micro-aerobic to aerobic and environments from lakes to wells. These bacteria are characterized by their ability to form extracellular polymers that allow the rapid growth of biofouling deposits on the surfaces. They also play an important role in creating metabolic products used by other bacteria and may oxidize ferrous iron.

Sulfate-reducing bacteria are found widely in soils and water-formed deposits that have anaerobic conditions. They also are implicated in the corrosion of many different types of metals. Sulfate-reducing bacteria gain energy by converting sulphate to sulphide. They utilize dissolved hydrogen (H_2) or organic acids in this process. They can promote corrosion through cathodic depolarization, which involves utilizing dissolved hydrogen evolved at the cathode. The sulphides produced during this process also may be corrosive.

However, these microorganisms often live in a biofilm, which can contain a range of chemical environments that do not occur in the bulk water chemistry. These environments can favor electrochemical corrosive processes, which may not occur in the rest of the groundwater. Within these biofilms a range of conditions promotive of corrosion may occur. Bacteria can convert dissolved organic carbon in the groundwater into fermentation products, such as organic acids. These acids can be corrosive. Any sulfate-reducing bacteria in the biofilm may depolarize the cathode by utilizing dissolved hydrogen. The biofilm can trap dissolved ions, such as chloride, within it. The irregular thickness and conditions within the biofilm may allow concentration cells to form.

5.3.3 Galvanic Corrosion

Galvanic activity occurs when a metal is connected electronically to a dissimilar metal in the presence of an electrolyte. The potential of a metal in solution is related to the energy that is released when the metal corrodes. The corrosion potential of metals can be used to rank them relative to each other in a galvanic series based on their properties in seawater at near ambient conditions (see Fontana and Greene 1985). It is possible the relative order may change in other environments; however, this order is likely to hold for most groundwater.

The materials comprising a particular galvanic group have similar properties, and galvanic corrosion is unlikely if materials within the same group are connected electrically (Fontana and Greene 1985). A corrosion cell can be created when materials of two different corrosion potentials are connected. The farther the two materials are apart from one another in the galvanic series, the greater the risk of galvanic corrosion. Besides, it may be pointed out that there is a difference in the corrosion potential, for example, between a stainless steel in a passive state and an active state. An active state occurs when the passivating film on the surface of the metal has been destroyed. Corrosion cells can be set up on a metal between its active and passive surfaces.

The degree of galvanic corrosion will be influenced by the ratio of the cathodic to anodic areas. As the ratio of cathodic to anodic areas increases, the corrosion rate at the anode increases. So a small section of mild steel when connected to a large section of stainless steel is likely to corrode rapidly.

5.3.4 Erosion Corrosion

Erosion corrosion involves electrochemical corrosion and the mechanical interaction of water and any particles within it and the metal surface.

The corroded metal surface often is characterized by pits or gullies and grooves. Erosion or wear can occur through mechanical abrasion of the metal surface, particularly from entrained particles or the removal of any protective film that exposes fresh surfaces to attack. It can be significant when the flow rate and particle concentrations are above critical thresholds. A practical limit of sand content in pumped water based on submersible pump wear is often around 5 to 8 mg/L.

Cavitation corrosion involves the formation and rapid collapse of gas bubbles in the water. The gas bubbles form in areas of low pressure, which then implode under conditions of high pressure. When this occurs against a metal surface, the localized pressure change can create a damaged surface. Cavitation damage occurs under conditions of highly turbulent flow and is relatively rare in well casings. However, it can occur in groundwater pumps, particularly in and around pump impellers.

5.3.5 Stray Current Corrosion

Currents cause this type of corrosion from electrical equipment using an unintended metallic structure, such as an underground pipeline as a low-resistance pathway. The current will enter the structure at a particular location (which becomes cathodic) and leave the structure at another. Where the current leaves, the structure experiences an anodic reaction, and corrosion occurs. The main sources of stray currents are from direct current (D.C.) electric tractions (e.g., subways, trams, and railway), D.C. industrial devices (e.g., welding machines), high-voltage electrical power transmission lines (mainly direct current), and foreign cathodic protection systems.

5.3.6 Crevice Corrosion

Crevices occur where surfaces are shielded or covered, such as under deposits, gaskets, disbonded coatings, seals, and lap joints or in threaded joints (Kain 1987). Within a crevice, an environment can form that has very different characteristics to the water outside the crevice. The pH may drop to low values (e.g., pH = 1) due to dissolved, iron-forming hydroxides, which increases the hydrogen ion (H^+) concentration and, hence, lowers the pH. Within the crevice the chloride concentration is also higher than that in the water outside the crevice. The chloride ions migrate against the electric current to the pit. The surface outside the crevice will become cathodic. It is difficult to predict the rate of crevice corrosion because of variability in crevice tightness and geometry.

5.4 CORROSIVE PROPERTIES OF WATER

The environment around a metal surface will control the corrosion rate. This includes both the chemical and physical properties of the water.

5.4.1 Dissolved Ions

The corrosion rate generally increases as the salinity of the water increases. High levels of dissolved ions create high conductivity water, which increases the rate of current transfer between different sections of the casing or between the casing and the earth. It also allows anodes and cathodes to operate over long distances, increasing the opportunity for corrosion. Other processes involve dissolved ions (e.g., Cl^-, SO_4^{2-}), which can form acids (e.g., HCl, H_2SO_4) in water causing pitting corrosion, whereas other ions, such as bicarbonate, carbonate, and hydroxide, may decrease the corrosion rate by forming protective scales.

5.4.2 Oxygen

The dissolved oxygen content is recognized as the major factor influencing corrosion rates of carbon steel. In de-aerated conditions, the rate of corrosion of steel is much lower. When oxygen concentrations increase, oxygen reduction occurs at the cathode. This increases corrosion, and an uneven distribution of corrosion products can form on the surface of the metal leading to localized corrosion from concentration cells. In stainless steel, a small amount of oxygen is needed to maintain the passive state and corrosion resistance of the metal, but the surface needs to be kept deposit free to prevent zones of oxygen depletion from forming under the deposit and leading to concentration cells.

5.4.3 Carbon Dioxide

Carbon dioxide is soluble in water and reacts to form a weak acid (H_2CO_3). This can create a pH of less than 6 where an acid attack can predominate. Corrosion by carbon dioxide occurs in water wells, particularly in deep wells, where the effect is exacerbated by elevated water temperatures.

5.4.4 Hydrogen Sulphide

Hydrogen sulfide (H_2S) is recognized as a corrosive agent in the natural gas industry where the water has high temperatures, pressures, and chloride contents. These conditions are unlikely to occur in many potable water-supply wells. However, sulfide inclusions, particularly in older well casings when quality control procedures were not quite so rigorous, are possible. These can act as sources of pit nucleations.

5.4.5 Flow Rate

The flow rate may affect corrosion rates due to influences on the electrochemical reactions or mechanical (erosion) effects. In general, corrosion rates increase with increasing velocities up to a point. Increased flow rates affect electrochemical reactions through increased reductant (e.g., oxygen, hydrogen) supply to the reaction surface (cathode), which promotes corrosion. However, for stainless steels, corrosion also may occur in zones where there is very low flow because some oxygen is needed to maintain the metal in a passive state. Erosion corrosion can occur at higher velocities due to the removal of any protective films on the metal surface, cavitation, or abrasion from particles.

5.4.6 pH

The relationship between pH and corrosion rate reflects a mixture of hydrogen ion (H^+) effects and carbonate equilibrium processes involving carbon dioxide and carbonate. The increased H^+ concentration that occurs at a low pH accelerates the corrosion of most metals. Below a pH of 5, the oxide and hydroxide layers, which can protect a metal surface, tend to dissolve. Both hydrogen evolution and oxygen reduction will occur at the cathode. As the pH increases (>5) the protective oxide and hydroxide scales can form and the corrosion rate decreases. The type of corrosion may change from being uniform when there are no scales to being localized underneath the surface deposits when they form.

5.4.7 Temperature

Temperature can affect the corrosion rate in several ways. Because corrosion often is based on electrochemical reactions, an increase in temperature will increase the corrosion rate. However, as the temperature increases the solubility of oxygen decreases, which may tend to decrease corrosion at the cathode from oxygen reduction. In studies on seawater, a 50% increase in corrosion rates was found as the temperature rose from 7 °C to 29 °C (Roberge 2012).

5.4.8 Deposit Formation

Although thin films on a metal surface may be protective, thick deposits can create concentration cells that are promotive of corrosion. Water quality that is conducive to deposit formation includes those that have a tendency to biofoul and are rich in dissolved iron, carbonates, and sulfides.

5.5 CORROSION OF WATER-WELL SYSTEMS

5.5.1 Corrosion of Well Casings and Screens

It is difficult to observe directly the extent of corrosion in water well casings. However, it is possible to characterize the different environments within a well (Roscoe Moss Company 1990), each with their own factors and processes that control the extent of corrosion in that zone.

5.5.1.1 External Casing Zone The zone of external casing incorporates the outer surface of the well casing in contact with the ground. The corrosiveness in this zone depends on the nature of the soil or sediment in contact with the casing. The extent of soil corrosion has been related to soil resistivity, pH, redox, sulfide content, aeration, and moisture. Soil characteristics that promote corrosion include low resistivity (e.g., clays rather than sands), low pH (<4), reducing conditions (Eh < 100 mV), and the presence of sulfides and moisture. In particular, where soil or sediment layers in contact with the casing have different soil characteristics, then differential concentration cells on the casing can be set up, which accelerates corrosion. This type of corrosion is more often found in soils and sediments in the shallow subsurface rather than at depth. Caution may be needed where reactive sediments are used for backfill or drilling additives are not removed fully from the well. Water wells may be designed with a cement grout at the surface and an inert filter pack to isolate the well casing from subsurface sediments. If this were the case, then the corrosion rate is due to the groundwater and similar to that for the internal surfaces of the well casing.

5.5.1.2 Atmospheric Zone This zone occurs above the static water level. The nature and rate of corrosive attack will be dependent on the nature and composition of any moisture film on the surface of the casing. For iron above a critical humidity level of 60%, a thin moisture film may form on the casing surface, which can absorb atmospheric pollutants (e.g., chlorides) and promote corrosion. Both the number of hours the atmosphere is above the critical humidity and the amount of airborne deposition of contaminants will control the rate of corrosion. This type of corrosion often is negligible compared to other types of well corrosion, because this zone in a well often is relatively isolated from the atmosphere and various sources of contaminants.

5.5.1.3 Splash Zone The splash zone is the internal surface of the casing between the static and pumping water levels. This section of the casing is subject to a periodic wetting cycle caused by changing water levels in a well due to pump operation, as well as humidity. Whenever the pump is turned on, a thin wet film remains on the well casing between the static water level and the pumping level. As the water on the surface of the casing evaporates, any salts within it concentrate, promoting corrosion. The exposed metal surface is likely to dry at different rates causing differential concentration cells. The dewatering of well screens creates conditions that promote corrosion. The well casing also may suffer intense localized corrosion at the water line if the water level remains fixed for long periods. Iron oxide products from corrosion are likely to form in the splash zone to a greater extent than in submerged casing. A concentration cell may form due to differences in the nature and amount of the corrosion products above and below the water line. A laboratory study using high-purity iron found corrosion rates up to three times greater than those observed under continuously immersed conditions (Dunn et al. 2000). Major factors controlling corrosion in this zone are the amount of time that a wet film is present on the casing (related to pump operating schedules and casing surface) and the water chemistry (e.g., salt concentration).

5.5.1.4 Submerged Casing Zone This zone represents the well casing and well screens that are in continuous contact with groundwater. Within this zone different types of corrosion may occur due to material selection, flow conditions, and the changes in the material properties arising from well installation and operation.

Often well screens are made from a different material than the well casing. When dissimilar metals are connected, a galvanic couple is formed, which promotes corrosion. In particular, long sections of stainless-steel screens, which are connected to short sections of mild-steel casing, can cause the mild steel to act as an anode and corrode rapidly. In this situation, the use of stainless-steel casing as spacers is preferred. Welded joints on well screens or between sections of casing also may be areas where corrosion may occur. The metal in the weld seam and those areas affected by heating may have different properties from the surrounding metal.

Well screens also may be vulnerable to corrosion because of their high surface area and exposure to higher flow velocities than other sections of the casing. These higher flow rates may remove any protective film that builds up. The upper limit for screen entrance velocity is 0.46 m/sec (1.5 ft/sec) (AWWA 1997).

Well casings, screens, and riser pipes also are subject to various stresses during installations and well operations. There are axial forces that can pull the casing apart or compress it and radial forces that tend to collapse the casing. Casing fatigue can occur from inadequate well design by suspending or having long lengths of unsupported casing in an open hole. During well construction, the casing may be jacked, driven, or twisted in an effort to make the casing fit the hole. The stresses imposed on the casing can cause it to deform and weaken the casing joints. The sections of fatigued casing also are more vulnerable to corrosion processes. During well operation, iron biofouling deposits often build up on the casing near the pump inlet and on the upper sections of well screens. The buildup of corrosion or biofouling deposits on the surface of the casing may cause localized corrosion. These deposits can create conditions for corrosion by creating concentration cells and microbially influenced corrosion.

If the casing failure is very localized, then the performance of the well may be partially impaired. Small amounts of sand may enter the well increasing pump corrosion. However, if the thickness of the casing is reduced over a larger area, then the risk of massive failure, such as well casing rupture and loss of the pump down the well, increases. The relationship between collapse strength and casing thickness is complex. For a 150 mm and 200 mm casing a reduction in the casing thickness of 25 and 45% result in a reduction in the collapse strength of about 45 and 70%, respectively. How important this is in a particular well depends on the stresses imposed by the water and the strata, as well as the safety margins incorporated into the well design. Detailed information on casing stresses is provided by Roscoe Moss Company (1990).

5.5.2 Corrosion of Pumping Equipment

The pumping equipment includes downhole pump items, the riser pipe used to transmit the pumped water to the surface, and any discharge headwork. Corrosion of this equipment may occur due to material selection, water properties (such as sand and gas content), and changes to material properties during pump installation and maintenance.

The surface of pump impellers can be vulnerable to erosion from particles as well as cavitation. Pump performance is affected by wear on either the leading edge or the outside edge of the impeller. Pumped water can be redirected through the increased impeller clearance resulting in it being pumped again. This leakage reduces the efficiency of the pump. Wear on the impeller surface also can occur through cavitation. This is evidenced at the wellhead by noisy pump operation and fluctuations in both power consumption and water yield. The bearings in submersible pumps are liable to failure from sand pumping, particularly as many impellers are free to float rather than being fixed axially to the pump shaft. The pumps are designed to operate in downthrust with the bearing clearance sufficient to be lubricated by the pumped fluid but exclude abrasive particles. If there is no load during pump startup, the impellers go into upthrust, causing the thrust bearing clearance to increase and allowing very large grains to enter. When the pump stabilizes, the impellers go into downthrust with abrasion of the thrust bearing from the sand grains (Wilson 1990).

Riser pipes, which have threaded joints, are vulnerable to several types of corrosion. When riser pipes are screwed together, the tools used to grip the pipe often roughen up the pipe surface near the joints. This roughens the surface and can initiate corrosion. Any protective coating on the pipe may be damaged. These unprotected areas then become anodic to the protected surfaces. Threaded joints also are liable to crevice corrosion from corrosive groundwater if they are not sealed with a hard setting-jointing compound. Any irregularities in the internal surface of the riser pipe can create the conditions for erosion. In the riser pipe used for line shaft pumps, the shaft centralizers can cause flow restrictions resulting in flow velocities in excess of 20 m/s, which can initiate erosion.

At the wellhead, galvanic corrosion may occur when there is no electrical isolation between dissimilar metals used for the discharge head, ancillary devices (e.g., flowmeters), and the pipeline. Interference current corrosion can occur due to influences of nearby direct current sources with the pipeline or casing.

5.6 PREDICTION OF CORROSION

Estimates of corrosion rates may be used to aid in design processes, such as material selection or for service life estimates.

5.6.1 Scaling Indexes

There have been many attempts to relate corrosion to water quality but no predictors have been found to be universally applicable. Well-known indexes include the Langelier Saturation Index (LSI) and the Ryznar Stability Index (RSI). These indexes are used widely in municipal water system and cooling water system evaluations. These indexes do not measure the corrosivity of steel but are based on the ability of water to precipitate a calcium carbonate film that can act as protective film on the metal surface to protect against generalized corrosion. The use of these indexes to evaluate the corrosivity of metal is limited because they do not account for the following:

1. Microbial factors,
2. Interaction of calcium and carbonate with other compounds in solution (e.g., chelates),

3. Capacity of water to keep producing a scale,
4. Rate at which the scaling reaction will occur, and
5. Effect of dissolved oxygen, chlorides, sulphates, and flow velocity on corrosion.

In some cases these indexes have been developed using empirical data from high-alkalinity water, and caution should be exercised when extrapolating these results to other environments, such as waters with low alkalinity, low pH, and high chloride and sulfate concentrations relative to alkalinity. Another limitation can be whether the chemical analysis of the sample is representative of the water in the localized environments where corrosion often occurs and whether the sample has been collected and analyzed properly. Field-based measurements of water samples are needed.

Pisigan and Singley (1985) found the Langelier Saturation Index was unreliable as a corrosion predictor but may indicate the ability of water to maintain a calcium carbonate deposit. In general, these scaling indexes are useful, because they are easy to calculate and require few analytic inputs, but they can serve only as a guide to understand scaling processes in water. Along with other water quality and geological data these indexes can be used in a weight of evidence approach to evaluate the likelihood of corrosivity of water in a particular environment.

5.6.1.1 Langelier Saturation Index The Langelier Saturation Index (Langelier 1936) may be defined as

$$\mathrm{LSI} = \mathrm{pH} - \mathrm{pH_s} \tag{5-7}$$

where

LSI = Langelier Saturation Index, (dimensionless)
pH = measured (actual) pH of the water, (dimensionless)
$\mathrm{pH_s}$ = pH of the system if saturated with $CaCO_3$ at the measured calcium and alkalinity value, (dimensionless).

The value for $\mathrm{pH_s}$ can be approximated (Faust and Aly 1998) as

$$\mathrm{pH_s} = A + B - \log_{10}\left[\mathrm{Ca^{2+} as\ CaCO_3}\right] - \log_{10}\left[TALK\right] \tag{5-8}$$

where

A = A temperature-dependent constant (see Table 5-1), (dimensionless)
B = A correction factor (see Table 5-2), (dimensionless)

Table 5-1. Constant *A* as a Function of Water Temperature

Water Temperature (°C)	*A*	Water Temperature (°C)	*A*
4	2.1761	18	1.9512
6	2.1422	20	1.9212
8	2.1090	22	1.8916
10	2.0763	25	1.8497
12	2.0442	30	1.7710
14	2.0127	40	1.6409
16	1.9817	50	1.5105

Source: Schock (1984); reproduced with permission from American Water Works Association

Table 5-2. Correction Factor *B* for Various Ionic Strengths and Temperatures

Ionic Strength (I)	TDS (mg/L)	4 °C	16 °C	25 °C	50 °C
0.0000	0	9.70	9.70	9.70	9.70
0.0003	10	9.74	9.74	9.74	9.74
0.0008	30	9.76	9.77	9.77	9.77
0.0013	50	9.78	9.78	9.79	9.79
0.0020	80	9.80	9.80	9.81	9.81
0.0026	100	9.81	9.82	9.82	9.82
0.0038	150	9.84	9.84	9.84	9.85
0.0050	200	9.86	9.86	9.86	9.87
0.0063	250	9.87	9.87	9.88	9.89
0.0075	300	9.89	9.89	9.89	9.90
0.0088	350	9.91	9.90	9.91	9.91
0.0100	400	9.91	9.91	9.92	9.93
0.0125	500	9.91	9.94	9.94	9.95
0.0150	600	9.95	9.95	9.96	9.97
0.0175	700	9.97	9.97	9.97	9.99
0.0200	800	9.98	9.98	9.99	10.00
0.0225	900	9.99	10.00	10.00	10.02
0.0250	1000	10.01	10.01	10.02	10.03

Notes: For calcium analysis reported as mg Ca/L rather than mg $CaCO_3$/L, 0.30 should be subtracted from values of *B* reported here. TDS is estimated by Langelier's approximation $TDS = 2.5 \times 10^5\ LSI$.
Source: Schock (1984); reproduced with permission from American Water Works Association

TALK = Alkalinity expressed in mg/L as $CaCO_3$. For many waters with pH between 6 and 9.5, the $TALK = [HCO_3^-]$ expressed in mg/L as $CaCO_3$ (Faust and Aly 1998).

Generally it is recognized that the LSI may indicate only the corrosive tendency of water within a pH range 6.5 to 9.5 (AWWA 1986). Waters that have a negative LSI are undersaturated, whereby a value of zero is saturated. Waters that have a positive LSI are supersaturated with respect to $CaCO_3$ and may therefore precipitate a carbonate film.

5.6.1.2 Solved Design Example 1 Determine the Langelier Saturation Index, LSI, for the following water analysis:

- pH (measured) = 8.4
- Total Dissolved Solids = TDS = 258 mg/L
- calcium hardness (as $CaCO_3$) = 110 mg/L; to convert to Ca hardness (as $CaCO_3$) from Ca^{2+} (mg/L) then multiply by 2.5
- alkalinity (as $CaCO_3$) = 145 mg/L
- temperature = 12 °C.

Solution From Eq. (5-8)

$$\begin{aligned} pH_s &= A + B - \log_{10}[Ca^{2+} \text{as } CaCO_3] - \log_{10}[TALK] \\ &= 2.05 + 9.87 - 2.04 - 2.16 \\ &= 7.72 \end{aligned}$$

From Eq. (5-7)

$$\begin{aligned} LSI &= pH - pH_s \\ &= 8.4 - 7.72 \\ &= 0.7 \end{aligned}$$

This small value of LSI suggests that the water has a slight tendency toward preciptating a calcium carbonate scale that may be protective against uniform corrosion.

5.6.1.3 Ryznar Stability Index The Ryznar Stability Index (RSI) was derived empirically from scale thickness observed in a municipal water system and the water chemistry. It was defined by Ryznar (1944) as

$$RSI = 2(pH_s) - pH \tag{5-9}$$

where

pH = measured pH of the water, (dimensionless)
pH_s = pH of the system if saturated with $CaCO_3$ at the measured calciumand alkalinity value and can be calculated from Eq. (5-8), (dimensionless).

The Ryznar Stability Index can be interpreted as follows:

RSI << 6 — the tendency to scale increases as the index decreases
RSI > 7 — calcium carbonate formation probably does not lead to a protective corrosion inhibitor film
RSI >> 8 — mild steel corrosion becomes an increasing problem.

These values were verified against field data for incrustation and corrosion in wells (Mogg 1972) and used for guidance on well screen material selection (see Table 5-3).

5.6.2 Corrosion Rate Tests and Data

Where the water well installation environment is characterized adequately (water chemistry, hydraulic conditions), then it may be possible to use historical data or information from other local well installations or even databases to give corrosion data suitable for design purposes. In other environments, it may be necessary to rely on testing more extensively to establish the required corrosion data. These corrosion tests may comprise laboratory, field, and service studies.

Table 5-3. Guidelines for Selecting Well Screen Materials

Well Screen Material	Limits of Ryznar Stability Index for Material
Low-carbon Steel	Between 7.0 and 8.0
Armco Iron	Between 6.5 and 8.0
Silicon Red Brass	Between 6.0 and 8.5
Everdur Bronze	Less than 9.0
Super Nickel	Less than 9.0
Monel 400	Less than 9.5
Type 304 Stainless Steel	Less than 12.0
Type 304 ELC Stainless Steel (Extra Low Carbon)	Less than 15.0
Type 316 Stainless Steel	Less than 15.0
Type 316 Stainless Steel (Extra Low Carbon)	Less than 18.0

Source: Mogg (1972); reproduced with permission from Wiley

5.6.2.1 Laboratory Tests These comprise studies where both the material and the environmental conditions that would occur in the water-well installation have been simplified and controlled. These types of studies are useful particularly for comparative studies of different materials, protective schemes, or environmental variables.

5.6.2.2 Field Tests In these studies, the environmental conditions are more representative of the conditions to which a material would be exposed during service. However, for testing environments within the water well, which are not very accessible (e.g., well screen, sump), some tests may be undertaken at the discharge head, which may have different environmental conditions. These studies utilize test specimens (e.g., metal sections or coupons) of the material of interest rather than actual components. Therefore, environmental conditions that act on the actual component (e.g., stress) may not normally be accounted for in the field test. An example of a field test is described in McLaughlan (2002) and McLaughlan and Stuetz (2004).

The following is a brief description of a downhole coupon test procedure for different metal coupons placed in a water well to determine corrosion tendencies. The procedure utilizes the five most commonly used casing and screen materials.

Field Coupon Testing Downhole coupon testing to determine optimum casing and screen materials should be conducted over at least a 1-year period in a well that is not pumped. It is recommended that three sets of coupons be installed in the well consisting of the following metals:

1. Mild steel,
2. Copper-bearing steel,
3. High strength–low alloy (e.g., Corten),
4. 304 stainless steel, and
5. 316L stainless steel.

The three sets should be submerged in a rack assembly (made out of 316L stainless steel) and each set (i.e., five coupons) should be pulled periodically from the well during the 1-year period. Each sample set should be photographed, the scale removed, and samples weighed and compared against their original weights to calculate the amount of metal lost to corrosion during the period submerged.

5.6.2.3 Service Tests This comprises evaluating the performance of a material in service. It could comprise keeping operational and maintenance records on the water well and reconciling this with a detailed and critical examination of the component of interest at periodic inspections during service or at failure. For pumping equipment, this may entail examination during removal of the equipment from the well. For the well casing, periodic inspections may involve well inspections using downhole closed circuit television cameras (CCTV) or geophysical equipment.

5.6.2.4 Electrochemical Measurement The conventional method of using weight-loss measurement to establish corrosion rates is tedious and may involve difficulties in retrieving specimens during ongoing field monitoring. Electrochemical methods allow the measurement of instantaneous corrosion rates.

5.6.3 Standards

Various standards abound that are relevant, particularly for the design of corrosion control devices and corrosion measurement. These have been developed by NACE and ASTM. Some relevant standard test methods are as follows:

- ASTM D2688-94 (1999) Standard Test Methods for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Methods),
- ASTM G31-72 (2004) Standard Practice for Laboratory Immersion Corrosion Testing of Metals,
- ASTM G44-99 (2013) Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution,
- ASTM G46-94 (2013) Standard Guide for Examination and Evaluation of Pitting Corrosion, and
- NACE TM0169 (2000) Laboratory corrosion testing of metals.

5.6.4 Resources

The Internet provides a vast resource of material that can be useful. Several useful sites are indicated following:

- Corrosion Doctors: http://www.corrosion-doctors.org
- Material Property Data: http://www.matweb.com/search/searchsubcat.asp
- ASTM Standards: http://www.astm.org.

5.7 EVALUATION OF CORROSION RATE DATA

Corrosion data represent unique interactions between a material and its environment. Although some data can be generalized into quantitative relationships, other data may need to be used in an empirical manner because of the complexity of the processes or environmental variables involved. The accuracy of those data in representing the conditions for a specific water-well installation needs careful consideration. This becomes particularly important if the data are collected from a database rather than from site-specific tests at the location where the data will be used. Whereas some types of corrosion data, such as uniform corrosion with specific concentrations of dissolved ions and uniform flow, may be somewhat easier to adapt for another environment, other data, such as crevice corrosion or pitting of stainless steels, may be more difficult. The following factors should be considered (Anderson 1992) in evaluating corrosion data:

- Material involved, including composition, metallurgical condition, surface condition and mechanical properties,
- Environment and the exposure conditions within the environment with particular emphasis on the time dependent environmental conditions at the material/environment interface,
- Corrosion test method used,
- Methods and measurement techniques used to describe these components, and
- Delineation of controlling factors with respect to specific forms of corrosion for the material and environment of interest.

5.7.1 Weight Loss and Penetration Calculations

The most frequently used method of appraising corrosion rate is either weight loss (e.g., $g/m^2/day$) from a test specimen or penetration rate (e.g., mm/year). Conversion factors between these units are available (see Table 5-4).

When interpreting these data, it needs to be recognized that the corrosion rate is not always constant but often decreases in time. Therefore, the rate measured may be unique to that exposure period. Another limitation of this measurement is that it assumes that the corrosion is uniform and occurs evenly over the whole surface of the test specimen. This will not be the case where localized corrosion involves pitting or crevice corrosion.

5.7.2 Exposure Period

There are little published data on long-term corrosion rates in groundwater. Data found generally for mild steel in natural water indicate that the corrosion rate is not constant with time but usually decreases as the length of exposure increases. A long-term, field-based immersion test

Table 5-4. Unit Conversions for Corrosion Rates of Metals

	Factor for Conversion to					
Unit	mdd	g/m²/d	μm/yr	mm/yr	mils/yr	in./yr
mdd	1	0.1	36.5/*d*	0.0365/*d*	1.144/*d*	0.00144/*d*
g/m²/d	10	1	365/*d*	0.365/*d*	14.4/*d*	0.0144/*d*
μm/yr	0.0274*d*	0.00274*d*	1	0.001	0.0394	0.0000394
mm/yr	27.4*d*	2.74*d*	1000	1	39.4	0.0394
mils/yr	0.69*d*	0.069*d*	25.4	0.0254	1	0.001
in./yr	696*d*	69.6*d*	25400	25.4	1000	1

Notes: mdd = milligrams per square decimeter per day; μm/yr = microns per year; $g/m^2/d$ = grams per square meter per day; mils/yr = mils per year; mm/yr = millimeters per year; in./yr = inches per year; *d* = metal density in grams per cubic centimeter, where carbon steel = 7.85 g/cc^3 and Type 316 stainless steel = 8.03 g/cc^3.
Source: Wranglén (1985); reproduced with permission from Springer

using corrosion coupons was undertaken at 24 sites across Australia. The corrosion rate of mild steel at many of the sites ranged between 0.1 to 0.3 mm/year. However, under extreme conditions that rate increased by up to a factor of 3. Stainless steel was found to have minimal corrosion under the same conditions. Galvanized steel was found to offer minimal protection compared with mild steel when the pH was below 7 (McLaughlan and Stuetz 2004). In a field study in seawater, Phull et al. (1997) found that the average corrosion rates were similar at 6 months and 1 year (168 and 172 μm/year), decreasing to 117 μm/year after 3 years and 107 μm/year after 5 years. However, there was no simple trend with time across all test sites studied.

5.8 PROTECTIVE MEASURES FOR CORROSION

The major design choices that can have a significant effect on corrosion within the well are well screen placement, casing, well screen material selection, casing thickness, gravel pack choice, and operational factors that will influence the corrosion rate.

5.8.1 Casing Design

Inappropriate selection of materials or structural design of water wells can lead to the creation of corrosive environments within a water well installation.

One potential area for corrosion is near the joint between the mild-steel casing and stainless-steel screens. In particular, long sections of stainless-steel screens that are connected to a short section of mild-steel casing can cause the more corrosion-resistant stainless steel to act as a cathode and less corrosion-resistant mild steel to act as an anode and thus corrode rapidly. The larger the ratio of the area of the cathode (screen) to the anode (casing), the greater the corrosion rate. Roscoe Moss Company (1990) suggests that the mild-steel section should be at least two times the thickness of the stainless-steel section and its length at least three times its diameter. An alternative approach for short spacers between well screens is to use stainless-steel sections. Welded joints on well screens or between sections of casing are areas where corrosion may occur.

The design of the gravel pack can influence the extent of external casing corrosion from the soil and aquifer. When inappropriate material is used to backfill around the casing, then conditions conducive to soil corrosion may be set up. In these cases, cement should be used to insulate the external surface of the casing.

5.8.2 Material Selection

The selection of ferrous materials for water well construction in potable groundwater is limited when issues related to structural integrity, corrosion resistance, availability, and economics are taken into account. In potentially corrosive environments, it is important to consider well design and material selection, because the well is a permanent structure, and little can be done to change the design or materials after construction.

Mild-steel casing generally is used for the well casing, whereas a choice of mild steel or various stainless steels (type 304 or type 316L) are used for well screens. There are few reported studies about field-based corrosion rates specific to groundwater environments. However, some general corrosion data from other environments can be a useful guide for design purposes. Under long-term immersion in freshwater, the corrosion rate of carbon steel often is stated to be between 0.1 and 0.2 mm/year. Corrosion rates of carbon steel in seawater often are reported in the range of 0.075 to 0.2 mm/year for exposure times of at least 6 months (Phull et al. 1997). Caution must be used with these types of rates as they are averaged over the surface of the metal corrosion coupon. When corrosion is localized in pits, the rates are much higher over a small area and can lead to structural failure earlier than expected based on average or uniform corrosion rates.

Stainless steels are used where a higher degree of corrosion resistance is required. Stainless steels rely on a passivating film for their corrosion resistance. When this passivity is maintained, they exhibit extremely low corrosion rates. However, when it is destroyed, stainless steels will corrode at rates similar to a carbon or low-alloy steel. It is, therefore, important to select an appropriate grade of stainless steel based on its corrosion resistance. In freshwaters (e.g., <600 mg/L TDS) type 304 stainless steel has been found to give excellent results. It has a lower resistance to pitting by chloride ions than type 316L stainless steel because of the lower molybdenum content. In more saline and extreme environments, other materials need to be considered. Forward and Ellis (1994) found that in saline groundwater (e.g., 20,000 mg/L TDS) type 316L stainless steel generally was adequate for pump equipment and screens, whereas the more expensive type 904L stainless was necessary when hydrogen sulfide was present. Zinc-free bronze pumps also can provide good results with the option of coating with epoxy if problems arise.

Nonferrous materials (thermoplastic, fiberglass) are being used increasingly for water-well construction. These are particularly suited for use in corrosive environments where the wells are less than 300 m deep.

5.8.3 Groundwater Well Operating Conditions

The operation of a groundwater well can have a significant effect on the environmental conditions within the well and, hence, the corrosion rate. Frequent pump cycling creates alternate wetting and drying conditions within the splash zone of the casing, which can exacerbate corrosion. Overpumping can increase the flow rates across metal surfaces in the well screen and pump, increase particle migration through the gravel pack, and create turbulence and cavitation. In extreme cases, well screens may be dewatered, which creates oxygenated wet films that promote corrosion.

5.8.4 Protective Coatings

Protective coatings prevent the contact of corrosive waters with a metal surface, but there has been little use of protective coatings on well casings. An abrasion of the coating creates a bare spot ("holiday"), which becomes anodic to the rest of the protected casing. The corrosion rate at this spot is much greater than if there was no protective coating. The coating of only the anodic areas is not recommended due to the possibility of preferential corrosion. The cathodic areas also should be coated. Problems with the abrasion of coatings can occur during casing handling and installation. The surfaces also are vulnerable during well equipment removal and other operations inside the well.

5.8.5 Cathodic Protection

Cathodic protection is used widely in water and oil industries to mitigate the effects of corrosion on pipelines, gas and oil well casings, and storage tanks. However, there have been no widely reported applications to groundwater well casing.

Cathodic protection eliminates the current flow among various parts of a structure. It does this by providing a flow of electrons to a surface and thus creating a cathode, which does not become corroded. The amount of current needed to keep the structure in a protected or cathodic state depends on the environment, such as soil resistivity and casing to soil potential.

There are two sources of cathodic protection current:

- Sacrificial anodes made of zinc, magnesium, or aluminum that can be considered as current drains, and
- Impressed current, where an electric generator creates a direct current (D.C.) positive output to the anode and negative output to the well casing.

Cathodic protection works on surfaces that are in a direct line with the anode. Separate systems are required for external and internal casing surfaces and for intervals of the riser pipe. Incrustation can occur on a cathodic surface, which is a consideration when designing a system for the protection of well screens.

There are difficulties associated with obtaining good electrical contact between sacrificial anodes and internal casing surfaces. Adequate surface preparation is much easier for pump columns. Cathodic protection has found most applications in external casing and storage tank corrosion control.

Protective coatings have been found useful in controlling external corrosion on riser pipes under moderately corrosive conditions. Areas that are particularly vulnerable are around the threaded joints and near the pump-riser pipe connection. When a threaded pump column is screwed together, the riser pipe surface near the joints often is roughened, and the protective coating damaged by the tools used to grip the pipe. Adhesive tapes offer a quick and easy method to coat a pipe and are useful especially around areas that have to be disassembled periodically. The threaded joints should be coated with a hardening thread compound that will exclude water from the joint reducing crevice corrosion. This is important, because once a continuous pathway through the joint into the well is established, then fluid jetting can enlarge the opening rapidly. Coal tar-based products have been used widely as a coating on riser pipes, although there may be problems with the leaching of hydrocarbons into the groundwater. Galvanized steel has a coating of zinc and other coatings that preferentially corrode and then protect the metal underneath. Where highly corrosive conditions occur, then the use of PVC riser pipe or reinforced plastic hoses and the use of submersible pumps is desirable.

5.9 TROUBLESHOOTING FOR WELL CORROSION

5.9.1 Water Quality Indicators

Analysis of pumped water samples can give an indication of the processes occurring within a pumping well. A change in the concentration of specific water quality indicators can be used to indicate whether corrosion processes are operating. The most important water quality indicator is the level of ferrous iron (Fe^{2+}) in the water. Because groundwater can have significant concentrations of Fe^{2+}, it is necessary to establish that the source of dissolved iron is from the corrosion of the casing rather than from the aquifer. This may be established by comparing water samples with other wells from the aquifer and establishing trends through time. Increases in other parameters, such as turbidity, also may be indicative of corrosion. The accuracy of this approach relies on the corrosion products being dislodged by the pumped water and then measured at the discharge head. Very localized corrosion pitting is difficult to detect, whereas more uniform corrosion across a larger surface will produce more corrosion byproducts and may be detected. Corrosion products are most likely to be dislodged during pump startup due to the change in flow rate. However, if the well is subjected to biofouling, then changes in the dissolved iron concentration may be attributable to mobilizing these deposits. Changes in other water quality parameters (e.g., pH, Eh, electrical conductivity, major cations and anions) can indicate corrosion of the well casing has allowed water from different aquifers into the well.

5.9.2 Well Inspection

Well casing cannot be inspected directly; thus, it is necessary to use geophysical methods or a downhole video camera. A downhole video camera provides a visual log of the internal casing condition. Sometimes it can be difficult to obtain good quality logs due to water conditions and the limitations of the video equipment. Although a black and white log may be suitable to identify massive failure of casing, lack of color can make distinguishing between casing scale and casing pits difficult. Color cameras often are preferable.

Turbid water often may occur in corroded or biofouled wells due to the dislodgement of deposits during pump removal. Chemical agents, such as Calgon, may work or the well can be back-flushed with water from the surface. It may even be desirable to brush or chemically treat the casing before the inspection to identify hidden corrosion points. Particular attention during the video inspection should be given to sections of the casing identified as likely to have accelerated corrosion. This can include welded and screw casing joints, mild-steel casing connected to well screens, sections of casing where deposits have formed, pumping water line, well screens, splash zone, and well sump.

5.10 SOLVED DESIGN EXAMPLE 1

The following design example is presented with permission from the City of Ontario, San Bernardino County, CA, and is based on a case study performed for the city by Geoscience Support Services, Inc., Claremont, CA. The material for the design example was summarized by Dennis E. Williams.

5.10.1 Background

A corrosion field test of steels commonly used in well casing and screens has been conducted for the City of Ontario's Well No. 18. The purpose of the testing was to determine the most appropriate material for new wells located within the City of Ontario's boundaries. The test was conducted from May 2003 to May 2004 and consisted of placing metal coupons at a depth of 950 ft (568 ft below the static water level) in Well No. 18 and observing corrosion rates over time. Specifically, the study involved

- Installation of metal coupons in Well No.18,
- Retrieval of the coupons after various exposure times,
- Calculation of corrosion rates from measurements of loss of coupon weights,
- Depth-specific water quality and scale sampling,
- Analysis of water quality and scale for corrosion and microbiological parameters,
- A flowmeter survey to determine variation of vertical flow in the well, and
- A comparison of construction and rehabilitation costs for three different well designs.

5.10.2 History of Well No. 18

Various corrosion-related problems over the years prompted the City of Ontario to evaluate the optimum well casing and screen materials to use for future wells. The City of Ontario's Well No. 18 was selected for this study because it was not in operation (i.e., the pump had been removed). According to the well log, Well No. 18 was originally drilled in 1926 to a depth of 1,035 ft and completed with 20 in. double-wall "stovepipe" casing and perforated with a Mills knife (common construction for cable tool wells of that period).

A video, along with geophysical and flowmeter surveys, were performed by Pacific Surveys of Claremont, CA, in April 2003. The geophysical survey consisted of temperature, fluid resistivity, and fluid electrical conductivity measurements. The temperature survey indicated a steady temperature increase from approximately 71.5°F, at the static water level (382 ft below ground surface [bgs]), to 73.5°F, where flowing water was observed at 550 ft bgs. Fluid electrical conductivity also decreased in this interval.

The video survey showed that some perforations appeared enlarged (possibly as the result of the Mill's knife perforation procedure), and cobbles in the native formation material were observed through the perforation openings. The presence of scale also was observed from 360 ft bgs and increased with depth. Water appeared to be flowing downward between 545 to 549 ft bgs. The presence of flowing water in the well reflects a downward vertical hydraulic gradient (i.e., water is moving from the upper portion of the well to the lower portion). However, the temperature and electrical conductivity gradient in the lower portion of the well indicated stagnant conditions below 700 and 850 ft bgs. This was an important finding, because it is well known that corrosion is more prevalent under stagnant water conditions. Groundwater samples from Well No. 18 showed that the water was a calcium-bicarbonate type.

5.10.3 Downhole Coupon Testing

Coupon testing is a simple in situ (i.e., downhole) method of determining corrosion rates on various types of metals. In this method, a set of metal samples with different chemical compositions (i.e., coupons) were manufactured to specific dimensions (2 in. × 3/4 in. × 1/8 in.), and the initial weights, surface area, and density of the coupons recorded. Coupons can be manufactured with a variety of finishes, including a mill finish or grit-sanded using a 120 grit belt, and with autogenous welds. The coupons were mounted on a stainless-steel rack, separated by Teflon spacers, and submerged in the well for a specified time (i.e., *exposure period*). At the end of each exposure period, coupons were retrieved, grit-sanded (to remove all corroded metal), and weighed to determine the mass of metal lost. The metal loss rate in terms of thickness over time, measured in mils/year (1 mil = 1/1,000 in. = 0.0254 mm), was determined by dividing the mass of metal lost by the density, final surface area of the coupon, and exposure time.

For the downhole coupon testing, four sets of metal coupons were made. Each set consisted of five different steel types. Three sets were placed in the well for the corrosion testing, and one set was used for background or "reference" samples. The metal coupons used in this study were manufactured from five steels commonly used in well casings and

Table 5-5. General Properties of Coupons Used in Well No. 18 Test

Steel Coupon Material	Description
C1010 Mild Steel	A high-strength, high-carbon steel
Copper-Bearing Steel	Provided by the Roscoe Moss Company, Los Angeles
Corten A Steel	A high-strength, low-alloy steel
304 Stainless Steel	A high-chromium, high-manganese steel
316L Stainless Steel	A high-chromium, high-manganese, low-carbon steel

Notes: Copper-bearing steel conforms to ASTM Specification A139, Grade B containing not less than 0.2% copper by ladle analysis.
For Corten A Steel, it should be noted that there are several types of high-strength, low-alloy steels (refer to ASTM standard A606-01). As such, the various types contain different percentages of alloys. For example, type 2 was used in this study. Type 4 contains additional alloying elements and provides a higher level of corrosion resistance.

screens: mild, copper-bearing, high strength–low alloy (Corten A), type 304 stainless, and type 316L stainless. The chemical compositions of the coupon materials are shown in Table 5-5.

All of the coupons except for the copper-bearing steel were manufactured by Metal Samples, Inc. of Munford, AL, and included an autogenous weld. (An autogenous weld is prepared without the use of filler metal.) The second coupon type (copper-bearing steel), was provided by the Roscoe Moss Company, Los Angeles, with a mill finish and brazed acetylene torch weld. Four sets of coupons composed of each of the five alloys were weighed and measured by Metal Samples prior to exposure. Table 5-6 summarizes details of the coupons and testing.

Three sets of metal coupons, each coupon set consisting of five different steel types, were mounted on a stainless steel rack (see Fig. 5-3) and submerged in Ontario Well No. 18 on May 20, 2003, at a depth of 950 ft bgs. The submergence depth was 568 ft below the static water level of 382 ft bgs. This depth was chosen on the basis of the geophysical and video surveys as a location where the water was stagnant and corrosion conditions favorable.

The first set of coupons (identified by number 1a) was removed on August 20, 2003, after an exposure time of 92 days. The first set (reinstalled on December 11, 2003, and identified by the number 1b) was removed on May 27, 2004, after an exposure time of 168 days. (As an added point of measurement and to simulate the effect of servicing and reconditioning wells, the first set of coupons was reinstalled on December 11, 2003, after

Table 5-6. Summary of Coupons Used in Ontario Well No. 18 Corrosion test May 20, 2003 to May 27, 2004

Coupon Set	Identification (ID) Number	Metal Type	Comments
1a	C1010W-1a	Mild Steel	First Sample Set
	1a	Copper-bearing Steel	Installed: May 20, 2003
	CORTAW-1a	High-strength, Low-alloy (Corten)	Removed: August 20, 2003
	304W-1a	304 Stainless Steel	Exposure Time: 92 days
	316LW-1a	316L Stainless Steel	
1b	C1010W-1b	Mild Steel	First Sample Set, Which Was Removed on August 20, 2003 and Reinstalled on December 11, 2003
	1b	Copper-bearing Steel	
	CORTAW-1b	High-strength, Low-alloy (Corten)	Installed: December 11, 2003
	304W-1b	304 Stainless Steel	Removed: May 27, 2004
	316LW-1b	316L Stainless Steel	Exposure Time: 168 days
2	C1010W-2	Mild Steel	Second Sample Set
	2	Copper-bearing Steel	Installed: May 20, 2003
	CORTAW-2	High-strength, Low-alloy (Corten)	Removed: December 11, 2003
	304W-2	304 Stainless Steel	Exposure Time: 205 days
	316LW-2	316L Stainless Steel	
3	C1010W-3	Mild Steel	Third Sample Set
	3	Copper-bearing Steel	Installed: May 20, 2003
	CORTAW-3	High-strength, Low-alloy (Corten)	Removed: May 27, 2004
	304W-3	304 Stainless Steel	Exposure Time: 373 days
	316LW-3	316L Stainless Steel	
4	C1010W-4	Mild Steel	Reference Coupons
	4	Copper-bearing Steel	Never Installed in the well
	CORTAW-4	High-strength, Low-alloy (Corten)	Exposure Time: 0 days
	304W-4	304 Stainless Steel	
	316LW-4	316L Stainless Steel	

Notes: Copper-bearing steel has no formal ID number, is made by California Steel Industries (Fontana, CA), and conforms to ASTM Specification A139, Grade B, containing not less than 0.2% copper by ladle analysis.

Sample set “1a,” which was installed on May 20, 2003, and removed on August 20, 2003, was cleaned and reinstalled on December 11, 2003. After reinstalling, the sample ID designation changed from “1a” to “1b.”

Fig. 5-3. Installing the test coupons in the coupon holder
Source: Courtesy: Dennis E. Williams, Goescience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

being cleaned and measured by Metal Samples. The reinstalled first set of coupons, identified by number 1b, was removed on May 27, 2004, for an exposure time of 168 days.) The second set (identified by the number 2) was removed on December 11, 2003, after and an exposure time of 205 days. The third set (identified by the number 3) was removed on May 27, 2004, after an exposure time of 373 days. A fourth set of coupons (identified by the number 4) was not installed in the well but stored in corrosion-resistant containers for use as a reference set. At removal, each of the coupons was photographed with a binocular microscope and sent to Metal Samples, Inc., for cleaning and measurements. Fig. 5-4 shows the timeline of events surrounding the coupon rack installation and retrieval.

5.10.4 Depth-Specific Water Quality and Scale Sampling

Laboratory results from the sample obtained at 950 ft bgs were consistent with historical samples obtained during operation of this well. The Langlier Index calculated from water quality samples was 0.05 and

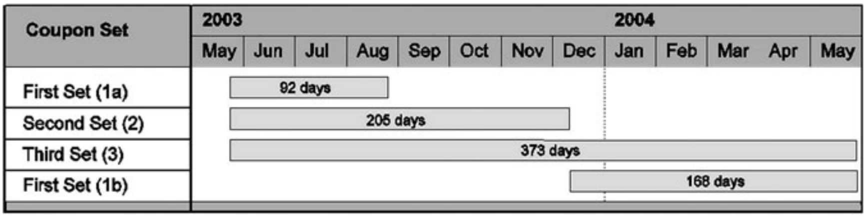

Fig. 5-4. Timeline of coupon testing, City of Ontario Well No. 18
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

the Ryznar Stability Index was 7.43. These values indicate that the groundwater is potentially corrosive, especially for less corrosion-resistant material (e.g., mild steel). Although iron-related and slime-forming bacteria were identified in the groundwater sample, their populations were nonaggressive. Analysis of the scale collected from the well below 800 ft bgs, shows that it is mainly a product of corrosion and is not bacterially mediated or a product of carbonate encrustation.

5.10.5 Flowmeter Survey (Spinner Log)

The flowmeter survey showed downward vertical gradients between approximately 500 ft bgs to 700 ft bgs. However, the amount of flow could not be quantified because of the very low flow velocities. Results from the spinner log indicate that water below 700 ft is stagnant, and the casing below this depth may be more susceptible to increased corrosion when the well is idle for long periods (e.g., months). Note: Wells that stand idle typically require redevelopment when recommencing pumping due to biofouling or scale deposits. Industry experience has shown that wells with regular pumping cycles and an appropriate maintenance program provide high efficiencies for many years without problems. A maintenance program should include periodic testing for well efficiency and comparison against the original value to gauge the degree of production loss. Subsequent improvement of this production loss typically employs both mechanical and chemical redevelopment.

5.10.6 Coupon Test Results

Metal loss rates, mpy (mils/year), as calculated from the coupon tests after an exposure time of 373 days are summarized as follows:

- Mild steel: 2.7256 mpy,
- Corten steel: 2.6894 mpy,

- Copper-bearing steel: 2.2422 mpy,
- 304 stainless steel: 0.0155 mpy, and
- 316L stainless steel: 0.0090 mpy.

where 1 mil/year = 0.001 in./year

Fig. 5-5 summarizes the coupon test period and results for the copper-bearing steel samples. Fig. 5-6 summarizes test results in terms of metal loss rate versus time for five test coupons:

- Mild steel chart code–C1010W,
- Copper-bearing steel,
- High-strength–low alloy (Corten) chart code–CORTAW,
- Type 304 stainless steel chart code–304W, and
- Type 316L stainless steel chart code–316LW.

In general, the less corrosion-resistant alloys experienced significant corrosion, whereas the stainless-steel alloys had very little corrosion. The long-term corrosion resistance can be determined by comparing the corrosion rates of the third set of coupons (exposure time of 373 days). Corrosion rates also decreased over time, most probably due to the buildup of a passive-resistance layer that protects the metal from corrosion to a certain extent.

5.10.7 Cleaning and Reinstalling the First Set of Coupons

As noted earlier, the first set of coupons (labeled 1a) was reinstalled after cleaning by grit-sanding and remeasuring. This was done at the request of the city to simulate the effect of servicing and conditioning of the well. Results show that corrosion rates for the reinstalled sample set (labeled 1b) were lower than the corrosion rates for the first set (1a) and the second (2) even though the second set had a longer exposure time. One explanation is that the "grit" finish applied to the samples after cleaning provided a more corrosion-resistant layer than the original mill finish.

5.10.8 Effect of Metal Loss on Casing Collapse Strength

The long-term metal loss rate can be used to predict the loss of casing collapse strength at any given future time. Multiplying the long-term corrosion rate by a given period of time yields the future thickness and outside diameter of well casing. This information can be used in Timoshenko's equation (see Roscoe Moss Company 1990) for collapse strength of well casing.

Assuming an average useful life expectancy of a municipal well of approximately 30, 60, or 90 years, the long-term corrosion rate from the third set of coupon samples (373 day results) was used to calculate future

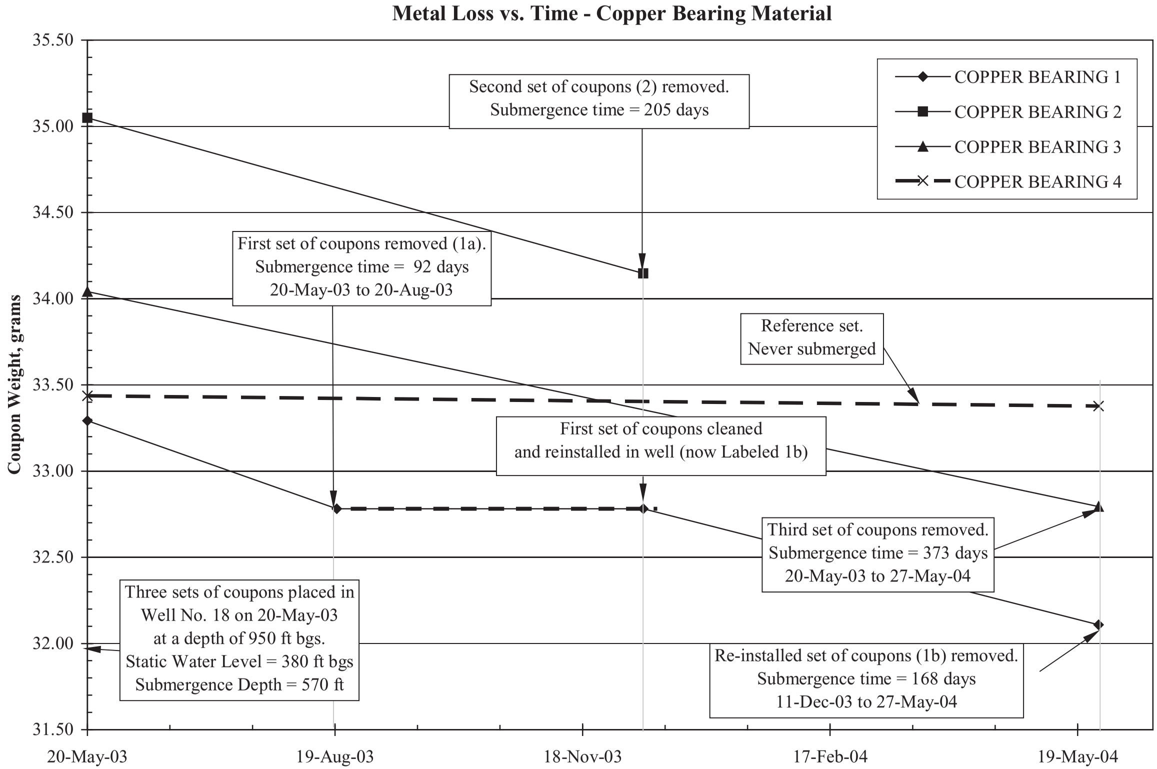

Fig. 5-5. Metal loss versus time for copper-bearing material
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

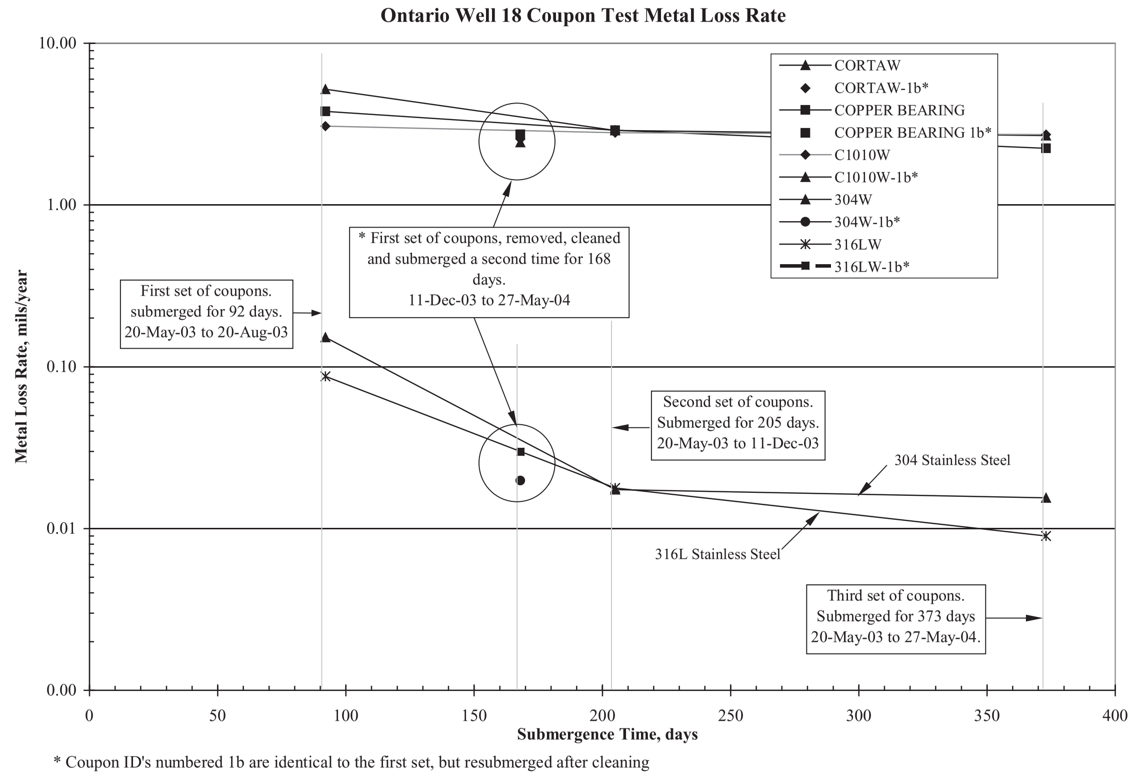

Fig. 5-6. Metal loss versus time, City of Ontario Well No. 18
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

reduction in wall thickness and outside diameter (OD). Table 5-7 shows the initial casing collapse strength for the five metal alloys used in the coupon test and the casing collapse strength after 30, 60, and 90 years of exposure.

As can be seen in the table under the predicted corrosion rates, stainless steel suffered almost no loss of strength, whereas the collapse strength of less corrosion-resistant alloys reduced to 45 to 53% of the original collapse strength after 30 years.

5.10.9 Cost Comparisons for Different Well Design Materials

To make a useful recommendation regarding the selection of casing material, a cost comparison of well construction and maintenance was performed between three different well designs consisting of the following casing and screen material (Fig. 5-7):

1. All copper-bearing blank casing and copper-bearing louvered screen,
2. A combination consisting of copper-bearing blank casing in the upper half of the well and stainless steel louvered screen in the lower half of the well, and
3. All stainless-steel blank casing and stainless-steel louvered screen.

The cost comparison was divided into two sections including initial construction costs and rehabilitation costs and was performed for three time periods after initial construction of the well (30, 60, and 90 years). The future value of construction and rehabilitation costs was calculated on the basis of a 3.0% annual inflation rate (personal communication, Construction Finance Department, IndyMac Bank 2004). The cost comparison parameters and calculations are shown in Table 5-8.

5.10.9.1 Summary of Cost Comparisons The costs of well construction and rehabilitation for each of the three well designs over the 30-, 60-, and 90-year periods were totaled and compared to the all-copper-bearing steel well design (Table 5-9). At the end of the 30-year period, both the combined copper-bearing/stainless steel and all stainless-steel wells cost less than the all-copper-bearing steel well. The difference in cost extended over the 60- and 90-year periods showed that the combined copper-bearing/stainless steel and all-stainless-steel wells cost less than or half as much as the all-copper-bearing steel well. Fig. 5-8 shows the comparisons.

5.10.10 Findings and Design Recommendations

5.10.10.1 Findings Ontario Well No. 18 originally was drilled in 1926 to a depth of 1,035 ft and completed with 20 in. casing (common

Table 5-7. Collapse Strength of Metal Alloys after 30, 60, and 90 years of Exposure

Casing Material	I.D. [inches]	Wall Thickness [inches]	O.D. [inches]	Original Collapse Strength [ft of water]	Long Term Corrosion Rate [mils/year]	Predicted Metal Loss [inches]	Future Wall Thickness [inches]	Future O.D. [inches]	Future Collapse Strength [ft of water]	Percent of Original Collapse Strength
After 30 Years										
C1010W	20	0.3125	20.6250	364	2.7256	0.0818	0.2307	20.5432	163	45%
COPPER BEARING	20	0.3125	20.6250	364	2.2422	0.0673	0.2452	20.5577	192	53%
CORTAW	20	0.3125	20.6250	364	2.6894	0.0807	0.2318	20.5443	165	45%
304W	20	0.3125	20.6250	343	0.0155	0.0005	0.3120	20.6245	341	100%
316LW	20	0.3125	20.6250	343	0.0090	0.0003	0.3122	20.6247	342	100%
After 60 Years										
C1010W	20	0.3125	20.6250	364	2.7256	0.1635	0.1490	20.4615	49	13%
COPPER BEARING	20	0.3125	20.6250	364	2.2422	0.1345	0.1780	20.4905	80	22%
CORTAW	20	0.3125	20.6250	364	2.6894	0.1614	0.1511	20.4636	51	14%
304W	20	0.3125	20.6250	343	0.0155	0.0009	0.3116	20.6241	340	99%
316LW	20	0.3125	20.6250	343	0.0090	0.0005	0.3120	20.6245	341	100%
After 90 Years										
C1010W	20	0.3125	20.6250	364	2.7256	0.2453	0.0672	20.3797	5	1%
COPPER BEARING	20	0.3125	20.6250	364	2.2422	0.2018	0.1107	20.4232	21	6%
CORTAW	20	0.3125	20.6250	364	2.6894	0.2420	0.0705	20.3830	6	2%
304W	20	0.3125	20.6250	343	0.0155	0.0014	0.3111	20.6236	339	99%
316LW	20	0.3125	20.6250	343	0.0090	0.0008	0.3117	20.6242	340	99%

Table 5-8. Summary of Cost Comparison for Three Different Well Designs

Item No.	Cost Description	Units	Casing and Screen Materials: All Copper-Bearing Steel Blank Casing and Screen	Hybrid Copper-Bearing Steel Blank Casing with Stainless Steel Screen[1]		All Stainless Steel Blank Casing and Screen
Well Construction Parameters				**Casing**	**Screen**	
1	Casing Wall Thickness	in.	5/16	3/8	5/16	5/16
2	Casing Inside Diameter	in.	20	20	20	20
3	Casing Outside Diameter	in.	20 5/8	20 3/4	20 5/8	20 5/8
4	Casing Length	ft	1,000	500	500	1,000
5	Perforated Length of Casing	ft	500	0	500	500
6	Casing Weight per Foot	lbs/ft	67.793	81.602	69.380	69.380
7	Total Casing Weight	lbs	67,793	40,801	34,690	69,380
Well Construction Costs						
8	Price of Blank Casing per Pound of Steel	$/lb	$0.96	$0.96	$3.00	$3.00
9	Cost of Blank Casing	$	$65,081	$39,169	$104,070	$208,140
10	Price of Perforations per Foot	$/ft	$50			
11	Cost of Perforations	$	$25,000			
12	Price of Mechanical Connector[1]	$	N/A	$5,000		N/A

Continued

Table 5-8. Summary of Cost Comparison for Three Different Well Designs (*Continued*)

			Casing and Screen Materials		
Item No.	Cost Description	Units	All Copper-Bearing Steel Blank Casing and Screen	Hybrid Copper-Bearing Steel Blank Casing with Stainless Steel Screen[1]	All Stainless Steel Blank Casing and Screen
13	Total Cost of Casing and Screen	$	$90,081	$173,239	$233,140
14	Cost of Well Constuction Minus the Cost of Casing	$	$300,000		
15	Total Cost of Well Construction for One Well [In 2004 Dollars]	$	$390,081	$473,239	$533,140
16	Serviceable Life of Well	years	30	90	90
17	Number of Wells Required to be Drilled Over 30-Year Time Period		1	1	1
18	Total Cost of Well Construction Over 30 Years[2]	$	$390,081	$473,239	$533,140
19	Number of Wells Required to be Drilled Over 60-Year Time Period		2	1	1
20	Total Cost of Well Construction Over 60 Years[2]	$	$1,336,910	$473,239	$533,140
21	Number of Wells Required to be Drilled Over 90-Year Time Period		3	1	1
22	Total Cost of Well Construction Over 90 Years[2]	$	$3,635,112	$473,239	$533,140

Rehabilitation Costs					
23	Present Cost for Rehabilitation	$	$125,000		
24	Service Interval	years	5	10	10
25	Number of Rehabs. Required Over 30 Year Period		5	3	3
26	Total Cost of Rehabilitation Over 30 Year Period[2]	$	$995,131	$697,161	$697,161
27	Number of Rehabs. Required Over 60 Years		10	6	6
28	Total Cost of Rehabilitation Over 60 Years[2]	$	$3,410,575	$2,389,355	$2,389,355
29	Number of Rehabs. Required Over 90 Years		15	8	8
30	Total Cost of Rehabilitation Over 90 Years[2]	$	$9,273,491	$4,709,194	$4,709,194
Total Cost for Well Construction and Rehabilitation					
31	Total Cost Over 30 Years[2]	$	$1,385,212	$1,170,400	$1,230,301
32	Total Cost Over 60 Years[2]	$	$4,747,485	$2,862,594	$2,922,495
33	Total Cost Over 90 Years[2]	$	$12,908,603	$5,182,433	$5,242,334

Notes:
[1]The long-term reliability of the *Hybird Copper-Bearing Blank Casing with Stainless Steel Screen* design is not known.
[2]Dollars adjusted for inflation. Inflation rate used at 3% per year. Standard construction industry inflation rate, based on personal communication, Construction Finance Department, IndyMac Bank, August 24, 2004.

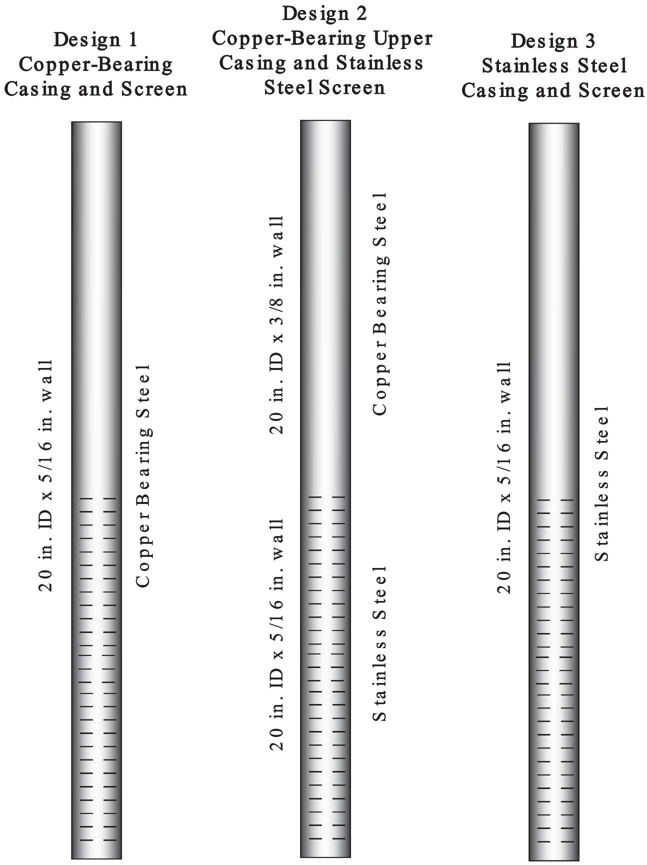

Fig. 5-7. Summary of proposed well designs
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

construction for old cable tool wells). The well was acquired by the City of Ontario in 1963 and used for municipal water supply until 2000. To determine the most appropriate well casing and screen materials for future wells, the City of Ontario commissioned a corrosion investigation, which took place in the city's Well No. 18 between May 2003 and May 2004. The following are major findings from that investigation:

- Total depth at the time of the video log (April 4, 2003) was 1,013 ft bgs. Static water level at the time of the April 4, 2003, survey was 382 ft bgs; the presence of scale was observed at 360 ft bgs and increased with depth, and water appeared to be moving between 545 and 549 ft bgs.

Table 5-9. Summary of Well Construction and Rehabilitation Costs Over Time

Well Design	After 30 Years		After 60 Years		After 90 Years	
	Total Cost	Cost Savings Compared to Design 1	Total Cost	Cost Savings Compared to Design 1	Total Cost	Cost Savings Compared to Design 1
Design 1 - All Copper-Bearing Casing and Screen	$1,385,212	—	$4,747,485	—	$12,908,603	—
Design 2 - Copper-Bearing Casing/ Stainless-Steel Screen	$1,170,400	16%	$2,862,594	40%	$5,182,433	60%
Design 3 - All Stainless-Steel Casing and Screen	$1,230,301	11%	$2,922,495	38%	$5,242,334	59%

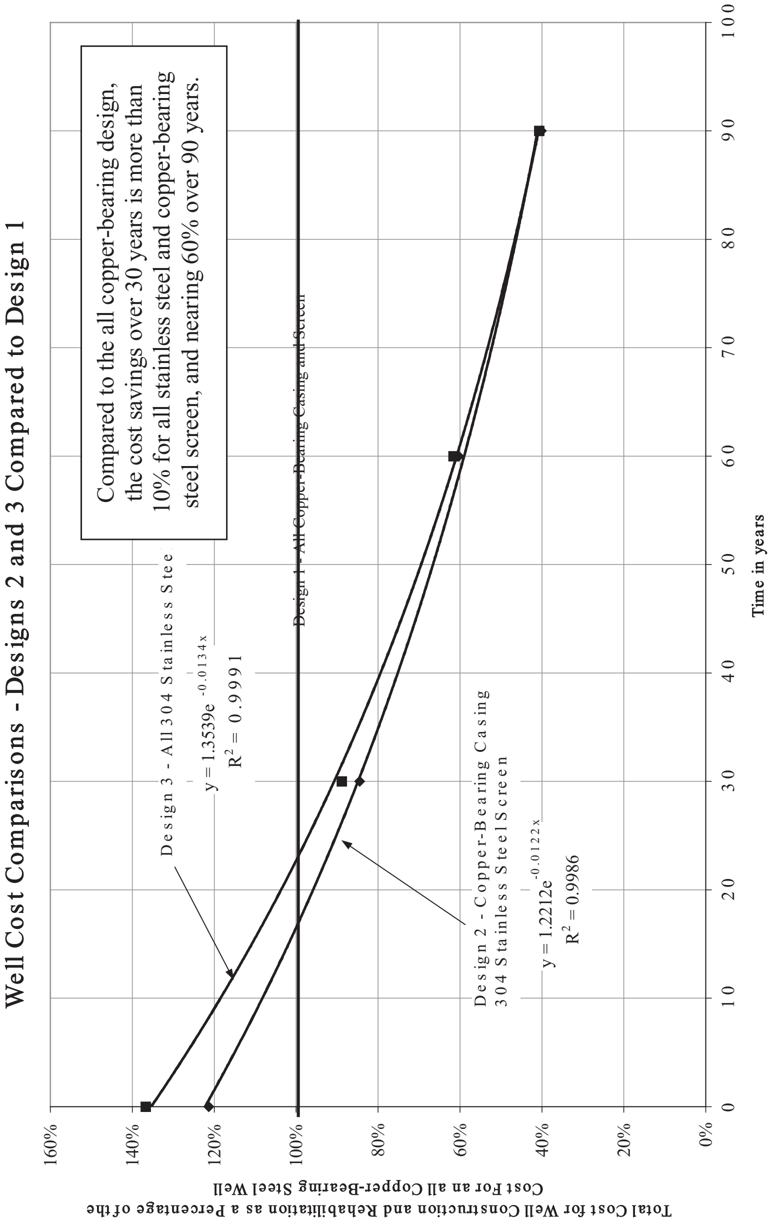

Fig. 5-8. Well cost comparisons
Source: Courtesy: Dennis E. Williams, Geoscience Support Services, Inc., Claremont, CA; reproduced with permission from City of Ontario, CA

- The temperature and electrical conductivity gradient in the lower portion of the well indicated stagnant conditions below 700 to 850 ft bgs; this is supported by the flowmeter survey, which indicated that below 700 ft, water is stagnant and materials below this depth may be more susceptible to increased corrosion when the well is idle for long period (e.g., months).
- A Ryznar Index of approximately 7.5 was measured from water samples reflecting slightly corrosive conditions.
- Analysis of the scale collected from the well below 800 ft shows it to be mainly a product of corrosion and not bacterially mediated or a product of carbonate encrustation.
- Flowmeter survey data indicate downward vertical gradients between approximately 500 ft and 700 ft bgs.
- In general, the less corrosion-resistant alloys experienced significant corrosion, whereas the stainless-steel alloys had very little corrosion:
  - mild steel: 2.7256 mpy,
  - Corten steel: 2.6894 mpy,
  - copper-bearing steel: 2.2422 mpy,
  - 304 stainless steel: 0.0155 mpy, and
  - 316L stainless steel: 0.0090 mpy.
- Cleaning and reinstalling coupons show that corrosion rates for the reinstalled sample set were lower than the corrosion rates for the first set; one explanation is that the “grit” finish applied to the samples after cleaning provided a more corrosion-resistant layer than the original mill finish.
- Under the predicted corrosion rates, stainless steel suffered almost no loss of strength, whereas the collapse strength of less corrosion-resistant alloys reduced to 45 to 53% of the original collapse strength after 30 years.
- After 60 and 90 years, the well construction costs for the copper-bearing/stainless-steel and all-stainless-steel wells were less than half the cost of the all copper-bearing steel design.
- If during the life of the an all-copper-bearing steel well, only one replacement is necessary, then the use of the all-stainless-steel or the copper-bearing/stainless-steel designs are more cost effective.
- Water quality of potential future well sites should be evaluated and the corrosion indexes calculated (i.e., Ryznar Stability Index and Langlier Index).; should the water quality suggest potential for corrosion (as was found in Well No. 18), then the all-stainless-steel design is recommended.
- The relative costs savings using the copper-bearing/stainless-steel design and the all-stainless-steel design are approximately the

same over the all-copper-bearing design. However, due to some uncertainty with the copper-bearing/stainless-steel combination design over the lifetime of the well, the all type 304 stainless-steel casing and screen is recommended.

5.10.10.2 Design Recommendations Primarily based on results from the coupon study and cost comparisons, the city is considering using type 304 stainless steel for future casing and screen materials. This decision was made on the basis of reduced maintenance cost over less corrosion resistant materials and longer life expectancy. These two main factors, combined with the increasing difficulty in acquiring property for new well sites, has shown city planners that the use of a more corrosion-resistant material, such as type 304 stainless steel, is more beneficial on a long-term planning basis.

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CHAPTER 6

INCRUSTATION OF WATER WELLS

John H. Schneiders

6.1 GENERAL

The major loss in production of water wells is due to the blockage of screen openings and flow spaces in the gravel pack or formation. The blockage most often consists of mineral deposits or biological formations referred to as *biofilm*. Primarily, biofilm is a combination of both; however, either singularly or in combination, it can be referred to as *incrustation*. In the water-well industry, incrustation is of extreme importance, because as the flow pathways or pore spaces of the porous medium and the slot openings of the well screen are plugged gradually, water flow is reduced substantially. Naturally, costs escalate to maintain the original level of well production. Often higher capacity pumps are installed to compensate for the lost water volumes or the operating period is lengthened to meet the consumer demand, thus increasing the overall expenditure for electrical power.

6.2 THEORY OF INCRUSTATION

As water flows toward the well, it encounters more surfaces, collides with more ions, crystals, and colloids, and in general becomes more intent to pair with dissimilar charges to form compounds. These compounds eventually form crystals, which are particulate matter too heavy to remain suspended in solution. Eventually falling out of solution, they fall into flow pathways growing larger until the flow path is blocked. This phenomenon can be a uniform mineral precipitation as in the formation of calcite (calcium carbonate), or it can be simply an accumulation of separate crystals held together with clays or organic matter deposited by the flow. The major accumulation, however, which is the truer definition of incrustation, is the attachment of this newly formed crystal to the surface by the adhesive qualities of a polysaccharide material produced by bacteria. The production of this natural polymer (sticky slime) by bacteria is the beginning of the formation or incrustation. All bacteria produce this exopolymer (made outside the cell) to be able to attach to a surface so that it is not swept away by the water current. This attachment serves to form a habitat for the bacteria. Biofilm is the name given to this habitat or collection of bacteria and the polysaccharide exopolymer, and is a place where the bacteria can multiple and live. The sticky polysaccharide is not water soluble and allows for the collection of nutrients. Oxygen diffuses through the surface of the structure for the aerobic organisms, and the water flows through the latticework carrying oxygen and food, and removing waste products, allowing for growth of the biofilm colony. The slime is also a protective mechanism for the bacteria and can be produced in amounts from 30 to 100 times the weight of the organism. The true definition of incrustation then is the combination of mineral and biological deposits formed in a complex matrix. This complex matrix at times also can include natural clays, bentonite, and other colloidal material filtered out of the water flow.

6.3 ANALYSIS OF GROUNDWATER

The analysis of groundwater should cover all the inorganic parameters usually associated with water quality analysis, together with a profile of bacterial activity. Consideration also should be given to the microscopic evaluation to observe sands or silica crystals, clays, and bacteria that are identified more easily. Tables 6-1 and 6-2 are typical commercial laboratory offerings. A laboratory report of these test data provides the practitioner the means to evaluate the potential type and degree of incrustation that maybe found in this well. Inorganic analysis together with the Saturation Index and the oxidation reduction potential (ORP) give values that can be used to determine the probability for certain precipitation reactions. As an example, values for manganese and iron can be used to suggest precipitation of those oxides when certain values are exceeded and especially when oxidation-reduction potential is high and or iron-oxidizing bacteria are present. A negative Saturation Index, along with the moderate levels of calcium, suggests only a limited possibility of calcium carbonate precipitation in the well structure. However, as will be discussed later, certain physical phenomena may increase this probability and could result in considerable buildup of the calcite mineral.

Table 6-1. Water Analysis and Control Report, Well No. 1

	Casing Pumping 3 min* mg/L	**Aquifer Pumping 3-4 hrs**** mg/L
Phenolphthalein alkalinity (as $CaCO_3$)	0	0
Total alkalinity (as $CaCO_3$)	148	172
Hydroxide alkalinity	0	0
Carbonate alkalinity	0	0
Bicarbonate alkalinity	148	172
pH value	7.6	7.8
Chlorides (as Cl)	45	49
TDS (Total Dissolved Solids)	291	297
Conductivity (μS/s)	454	464
Total hardness (as $CaCO_3$)	184	180
Carbonate hardness	148	172
Noncarbonate hardness	36	8
Calcium (as $CaCO_3$)	128	116
Magnesium (as $CaCO_3$)	56	64
Sodium (as Na)	53	66
Potassium (as K)	2.6	3.0
Phosphate (as PO_4^{3-})	0.2	0.3
Iron ferrous (as Fe^{2+})	0.0	0.0
Iron total (as Fe)	0.5	0.4
Copper (as Cu)	0.0	0.0
Tannin/Lignin	0.0	0.0
TOC (Total Organic Carbon)	1.4	0.8
Nitrate (Nitrogen)	0.1	0.1
Sulfate (as SO_4)	0.4	0.6
Silica (as SiO_2)	20	20
Manganese (as Mn)	0.1	0.1
Saturation Index	–0.21	+0.01
Chlorine (as Cl)	0.0	0.0
ORP (Oxidation Reduction Potential)	208 mV	210 mV

*Pump the well (after setting idle 8 to 12 h) in sufficient time to remove the water from the drop pipe and retrieve casing water.

**Pump the well for a sufficient period to remove casing water standing over night and draw water from the aquifer.

Table 6-2. Bacterial Analysis of Well No. 1

	Casing after 3 min	Aquifer pumping 3 to 4 h
Plate count (colonies/ml)	No growth	15
Sulfate-reducing bacteria	Positive	Positive
Anaerobic growth	20%	20%
ATP (cells/ml)	522,500	62,000
Bacterial identification		*Aquaspirillum dispar, Bacillus*
Microscopic	Moderate bacterial activity, moderate amount of crystals, no sheathed or stalked bacteria, no iron oxide	Low bacterial activity, moderate amount of crystals, no sheathed or stalked bacteria noted, no iron oxide

Biological analysis, or more specifically, bacteriological analysis, is important, because it will give information as to the probability of bacterial plugging of the water flow and may give clues as to the infiltration of surface water. Some tests provide a way of quantifying the bacteria present; others do more for the identifying of the specific organism. Tests, such as the simple heterotrophic plate count (HPC), which determines the colony forming units (CFUs) per milliliter, and the test for adenosine triphosphate (ATP) can be used to enumerate the bacteria per milliliter. Both the HPC and ATP tests can be used to quantify bacteria; the questions are what do they do, what do they indicate, and how does a practitioner interpret their presence?

6.3.1 Heterotrophic Plate Count

The HPC count is the number of colonies of bacteria formed on an agar plate after the plate has been streaked with a given amount of the water to be tested. As the water is spread out over the surface of the agar, colonies grow wherever a bacterial cell or group of cells lands. Those colonies observed in a 24-hour period are counted. This count then is reported as CFUs (colony forming units), which gives the number of colonies per milliliter. The count is useful, because it usually is performed the same way in most labs, and if recorded and observed over time, variation in the count can be used as an indication of changes in the well environment.

The fallacy of the tests is that any variation in the procedure can make comparisons almost impossible. In addition, the underlying theory of the plate count revolves around the premise that all bacteria will grow and divide, thus producing a colony to be counted. It also does not take into consideration how many bacteria may land together and the resulting growth counted as one colony. It is believed that one bacterium or 500 bacteria may land together and result in the production of one colony. Also, it is now widely thought in microbiology that fewer than 10% of the bacteria in a water sample may be culturable, and many believe this figure is less than 1%. Nevertheless, many labs do use standard procedures for HPC counts, and if the random nature of growth is accepted, then the tests should reflect the general population change taking place in the well. When growth increases and plugging is expected, the HPC plate should show a numerical increase in the colony count.

6.3.2 Adenosine Triphosphate Determination (ATP)

The ATP count actually determines the amount of adenosine triphosphate that is in a specific water volume after the bacterial cell walls have been lysed. ATP is present only in living cells and in the surrounding water for 15 to 20 s once the cell wall has been lysed. By using the value for the average amount of ATP in a bacterial cell, a count for the live bacteria present can be determined. There are problems with this way of counting bacteria, but it does sidestep many of the errors seen in the counting or quantifying of bacteria in a water sample. It is also one of the most reliable tests used.

6.3.3 Microscopic Observation

There are some benefits to identifying some of the major bacterial populations present. This can be done by various microbial techniques, as well as direct microscopic observation. Whereas microscope work cannot be used to identify many bacteria, it can be used to determine the presence of the iron oxidizing stalked or sheathed bacteria, as well as other branching or filamentous organisms. Knowledge of the presence of any of these organisms should determine some of the parameters of the rehabilitation effort. A microscopic evaluation also can be used to pinpoint iron oxide accumulation, sand infiltration, protozoan presence, and other abnormalities, which can be corrected during rehabilitation. As with any technical report, a professional in this line of work should be consulted for proper evaluation. See also Chapter 8, Sections 8.4 and 8.7 for a discussion of maintenance monitoring and the current research on well monitoring and testing procedures.

6.4 FORMS OF INCRUSTATION

Incrustation or blockage of water flow in a well system takes many forms, but in general, they can be divided into biological blockage, mineral blockage, and physical blockage. Biological blockage usually is slimy and predominately composed of bacterial growth. Mineral blockage is hard and denser, and results from precipitation of the calcium salts, dehydrated ferric iron, manganese oxides, and others. Physical blockage refers to deposits or incrustations that usually are made up of migrating sand or clays being brought into the well zone through overpumping or with the natural movement of water through the aquifer structure.

The soft biological deposits can be observed on all the surface of the well structures, casing, and screens, but for the most part these deposits form blockage when they are found in the gravel pack and immediate formation. Some, particularly the branching bacteria, are known to inhabit the borehole wall. When *Gallionella* (an iron-oxidizing stalked bacteria) deposits first are formed, they often are found in a soft form on or near the screen or intake areas of the well. Later, the iron oxyhydroxide dehydrates (i.e., chemically loses water) forming a very hard matrix usually covering these same openings.

In most cases, blockage is a composite of biological material and minerals either formed as deposits of water constituents, such as calcium and carbonates, or the adhesion of particulate matter, sand, and others. This matrix begins with the formation of sticky, slimy biofilm (from bacterial growth) then matures to a more dense hard form as minerals make up more and more of its mass. Some biomasses, particularly in water with low total dissolved solids, remain primarily organic in nature, but they too begin to grow denser with age and become formidable barriers to water flow.

6.5 CAUSES OF INCRUSTATION

Although there are many reasons for incrustation to form in the water-well systems, the primary cause of incrustation is the quality of the water. Water with high total dissolved solids tends to deposit certain minerals when an environmental change moves the Saturation Index (see Section 5.6.1.1, Chapter 5) to a positive value, resulting in the precipitation of carbonates, sulfates, and others. Changes that move the index to a negative value result in corrosion of the metal well structure, and this phenomenon results in accumulation of iron oxide as incrustation. Reductive reactions also can take place in the aquifer, where minerals containing metals are dissolved and the metal moving toward the well is oxidized and then deposits as iron or manganese oxides.

Bacteria in the water passing through the well set up residence in the form of biofilms, which grow and form biological blockage plugging flow pathways. These same biofilms entrap mineral particles, which further make the incrustation grow in size. Because the well is, in a sense, a giant filter, any particulate or biological entity moving through it is subjected to filtering out and becomes a causal factor blocking the flow path where it is trapped.

6.6 EFFECTS OF VELOCITY, PRESSURE, AND TEMPERATURE CHANGES

The groundwater in most aquifers is balanced chemically and biologically, that is, the Saturation Index is near neutral condition. In this state, a precipitate is not expected to form or to have a deposit dissolved within the confines of a system of aquifers and water wells. Over the period that was taken to form the aquifers, changes did occur as the water moved toward a more balanced state. These changes, which were chemical or biological in nature, were initiated mostly by basic changes in velocity, pressure, and temperature. These same basic phenomena continue to initiate the aforementioned changes as detailed following.

Velocity changes, such as that resulting from overpumping, may initiate dissolution of soft mineral deposits in the aquifer. Whereas these deposits previously had been stable, they are now feeding charged ions (unpaired) into the flow, moving the well toward an unbalanced state. This overpumping or simply the extraction of water from a confined aquifer thus can produce changes resulting in new deposit formation (or the release of carbon dioxide or pressure), which results in degassing of the aquifer.

The pressure changes, or off-gassing, of dissolved gases from the water entering the well also results in changes to the Saturation Index, usually pushing it toward the positive side. A positive Saturation Index brought about by an increase in a specific ion or a rise in the pH can result in precipitation of products, such as calcium carbonate and calcium sulfate.

Temperature changes affect the Saturation Index as well. As the temperature increases, minerals, such as calcium carbonate and calcium sulfate, are less soluble and if they are at or near saturation level, these compounds will precipitate. In addition to the chemical changes, slight variations in temperature can encourage the growth of certain organisms or changes in the bacterial fauna of an aquifer or well environment. The new dominant bacteria may make changes in the pH of the water or may affect the concentration directly of certain minerals present in the system. Examples of direct changes are the reduction or oxidation of iron by the bacteria, resulting in the deposition or the solubilizing of that metal. The soluble iron then moves toward the well, resulting in deposition after oxidation in the well proper, or the familiar red water after oxidation in the distribution system that generates consumer complaints.

6.7 CHEMICAL INCRUSTATION

Chemical incrustation is a form of incrustation usually brought about by a chemical activity or change and, in most cases, results in the mineral form of deposit or blockage. The more common forms of incrustation are calcium salts of carbonates (calcite), sulfates (gypsum), and oxides of both iron and manganese. The Saturation Index is a key determinant of chemical incrustation. For further information, refer to Section 5.6.1, Chapter 5, for scaling indexes.

6.7.1 Carbonate

Carbonate deposits, most notably calcium carbonate and sometimes magnesium and iron, are potential incrustations in a well as determined by the alkalinity, hardness (calcium, magnesium, and iron), total dissolved solids, and pH.

The key to determining the possibility of carbonate formation is the Saturation Index. A positive number indicates the possibility of some carbonate deposits forming in the well system. A negative number may indicate the potential for some corrosion activity. Deposits of carbonate scale can be the primary blockage if pH is >7.5, hardness is >250 mg/L, and alkalinity is >220 mg/L.

6.7.2 Calcium Sulfate (Gypsum)

The potential for the formation of this mineral as blockage in a well is measured by the same parameters as used for carbonates, plus noncarbonate hardness, or sulfates.

If the Saturation Index is positive, indicating the potential for calcite deposits, the noncarbonate hardness is greater than the carbonate hardness, and the sulfate levels are in excess of 100 mg/L, then gypsum or sulfate scale could deposit (especially if there is an increase in the pH). Sulfate deposits could be a major blockage if pH is >7.5, hardness is >250 mg/L, alkalinity is >220 mg/L, and sulfates are >150 mg/L.

6.7.3 Oxides

Oxides are an oxidized form of metals, particularly iron and manganese. Because iron oxide is also a form of corrosion byproducts, understanding of oxide formation potential may require not only knowledge of the existence of iron and manganese levels in the aquifer but also the potential for corrosion in the well. Here again, the Saturation Index is helpful. A negative index reading indicates corrosive water, which could point to corrosion of a carbon steel structure as the source of iron. Iron or manganese concentrations in the aquifer are also a source of possible oxide accumulation as incrustation in the well.

If the Saturation Index is negative and the ORP is below 150 mV, the key to determination is that there is corrosive water in the aquifer, and any metal in the system is subject to releasing ions (most probably iron) into the water to become oxidized to a metal oxide. The accumulation of iron and manganese oxides, which are red (usually iron) or black (usually manganese) from oxidation of the iron and manganese, respectively, found in the aquifer water can result in considerable incrustation. Serious fouling can occur when iron levels are as low as 1.0 mg/L and manganese is 0.1 mg/L or higher in the aquifer water (Schneiders 2001b). Brucite, or magnesium hydroxide, another oxide, may form with the calcite deposits if the magnesium calcium ratio is near 1:1, the alkalinity is greater than 220 mg/L, and the hardness is greater than 250 mg/L.

6.8 PHYSICAL INCRUSTATION

Sands, clays, and particulate matter from the aquifer formations usually are considered in this category as opposed to the minerals precipitated in the water-well systems. Other substances that might fall into this group are bentonite and the synthetic polymers used as drilling mud during well construction. As water moves toward the well, sands and fines may be mobilized by the higher velocity induced by pumping the well. Eventually these fines and sands affect the gravel pack and even enter the casing area. Sand, of course, can damage the pump, resulting in erosion corrosion of pump parts and even screen and slot openings. The resulting larger openings lead to more sand feeding into the well.

Clays also move toward the well, especially if they make up a large part of the formation. Clays, as well as bentonite and synthetic mud left in the well during construction (a major oversight due to incomplete well development), can become part of incrustations, especially in the gravel pack area. These usually are part of a matrix of biological, chemical, and physical entities producing a severe blockage of water flow to the well.

Sand traps are a way of measuring the sand production rate of a well. An increasing production should alert the operator to screen damage or possible infiltration of the gravel pack and the eventual loss of water production. Microscopic examination of water samples drawn from a pumping well often will provide evidence of bentonite, natural clays, or sand accumulating in the well. Of course, proper mud placement and well development during well construction will go a long way toward keeping a clean gravel pack and maintaining good water flow.

6.9 BIOLOGICAL INCRUSTATION

It has been estimated that more than 80% of well blockage is caused to some extent by biological growth. Laboratory work and the experience of many consultants in the field attest to at least this figure. Therefore, the understanding of the role that bacteria play in the well environment and the resulting biological incrustation is important. All bacteria produce what is known as a polysaccharide. These are long-chain polymers used by the bacteria to provide adhesion to surfaces, a means of entrapping nutrients, and as a method of protection. A free-swimming bacterium has a biological need to attach itself to a surface to grow and procreate (Fig. 6-1). After it lands on the surface, it begins to produce the polysaccharide

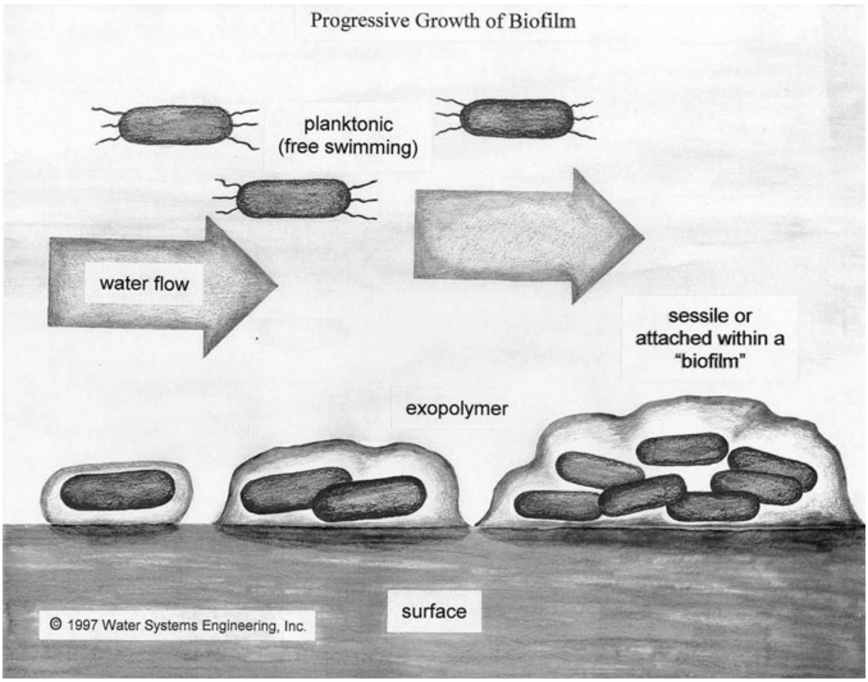

Fig. 6-1. Attachment of free swimming bacteria for the formation of biofilm Source: Schneiders (2003); reproduced with permission from Johnson Screens/A Weatherford Company

material to attach itself. Later, as the cell divides, more exopolymer is produced until many cells live in the formation covered with this protective layer. As discussed earlier, the formation, made up of the slimy polysaccharide and the living bacteria, is known as biofilm.

This is the normal habitat for bacteria and is present wherever there is a surface on which to attach and the presence of water. Biological incrustations or biofilms are the primary reasons most blockage is bacterial. The sticky, slimy biofilm is an ideal place for particulates to attach, and new crystal growth needs a strong attachment for the budding crystal to grow to a mineral deposit.

Biofilms respond to conditions in the well. Increases in oxygen content from aeration due to cascading water often result in excessive growth of certain bacterial populations. Food sources coming into the well with the groundwater may encourage growth and increase biofilms, thus blocking more flow pathways. Velocity increases due to higher pumping rates often result in thicker biofilm as the bacteria produce more exopolymer in an attempt to protect themselves from being pulled into the flow. Each bacterium is capable of producing at least 30 to 100 times its own weight in exopolymer. Fig. 6-2 shows the flow pathways being blocked by the growth

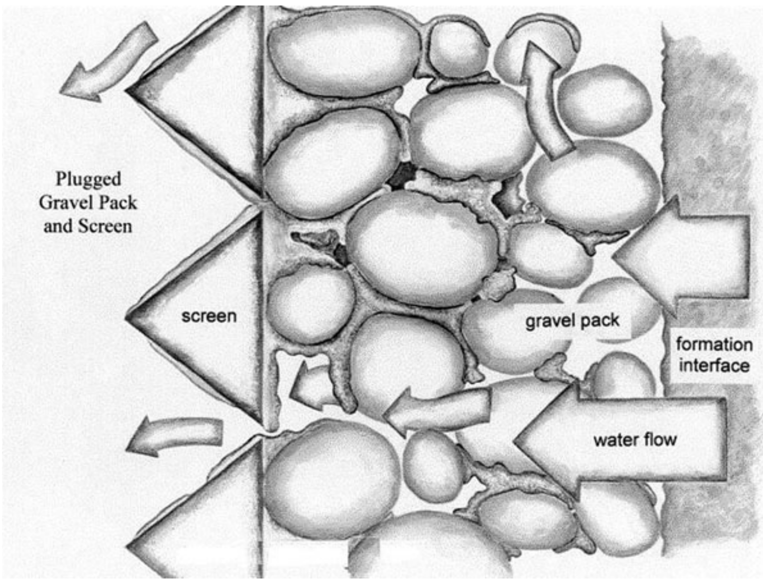

Fig. 6-2. Flow of water from the aquifer formation into the plugged gravel pack and the well screen
Source: Schneiders (2003); reproduced with permission from Johnson Screens/A Weatherford Company

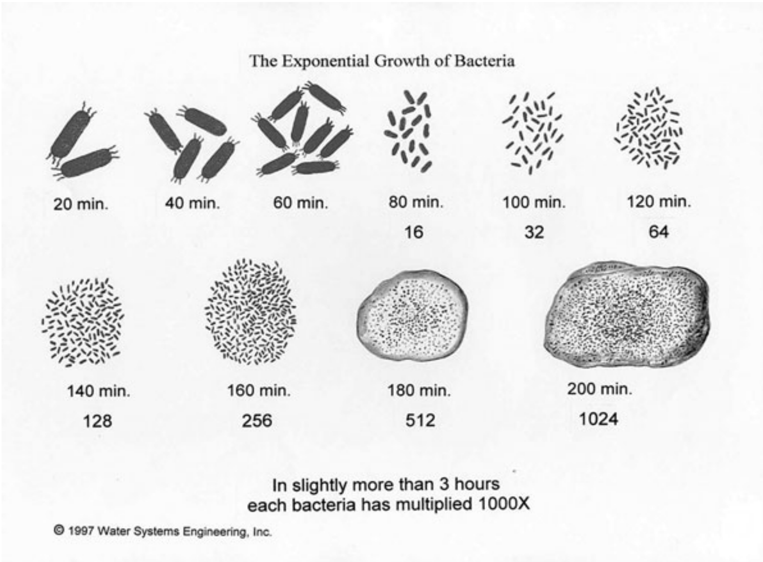

Fig. 6-3. The explosive growth of bacteria
Source: Schneiders (2003); reproduced with permission from Johnson Screens/A Weatherford Company

of biofilm. The exponential growth rates of bacteria (Fig. 6-3) can cause rapid changes in the well environment. Odor and color problems can appear overnight in the water, and often a high-producing well loses capacity rapidly because of the growth of bacteria. Fig. 6-3 indicates that in less than 3 h, each bacterium has multiplied 1,000 times. This figure is based on bacteria doubling every 20 min. The average growth rate of bacteria varies considerably; however, a bacterial population can be expected to double between 20 min and 3 h on average. If all factors were perfect, such as food and byproduct removal, and 50% of the flow pathways were plugged, only one generation of growth would cause the remaining pathways to fill. Although a doubling of the population every 20 min is unlikely, wells that deteriorate over a few weeks can be explained by the fact that doubling the biogrowth quickly produces excessive populations.

This excess population often results in taste and odor problems in the water or measurable slowdown in well production due to pore space blockage. Because most wells are capable of sustaining production with only 50% of the flow pathways open, the capacity being pumped is not limited until the blockage begins to close off the second 50%. It may take many years for the first 50% to become plugged, but the second 50%, or part of it, is closed in considerably less time.

6.10 CHARACTER OF IRON DEPOSITS

Iron deposits are primarily iron oxides. However, some iron carbonates and iron sulfides are formed under certain conditions. In general, they should be considered as chemical incrustations, but the oxidation reaction, which produces the oxide, may be driven either chemically or biologically.

The simplest oxidation of iron is the oxidation of the dissolved ferrous iron, Fe (II), usually entering the well with the aquifer water. Ferrous iron is present in the aquifer from the reduction of iron oxhydroxides coupled with the oxidation of organic matter. The reduction of Fe (III) to Fe (II) is attributed to the bioenergetic activity of the iron-reducing bacteria. Fe (II) also can be present from corrosion of casing or screen. Direct oxidation of steel casings and screens is promoted in the hydrogen rich (acidic) environment in the lower anoxic areas of the well. This environment is also the result of biological activity as the fermentative and sulfate-reducing bacteria are responsible for the low pH of this zone.

Fe (II) from either source is oxidized easily to Fe (III) as the water enters the more aerobic zones in the well, with production of ferric oxide, $Fe_2O_3 \bullet (x)H_2O$, a slick, slimy, very insoluble compound. This viscous, red material covers casings, screens, and other well structures. The chemical dehydration of this material results in a very dense ferric oxide deposit. These deposits form in the more aerobic zones of the well plugging screens and other well flow areas.

Biologically driven Fe (II) oxidation also takes place near the interface of the anoxic/aerobic water, because the iron-oxidizing bacteria are aerobic. The iron oxidizer, *Gallionella ferruginea*, which derives its energy from the oxidation of iron, must operate primarily in this area to satisfy its need for oxygen and the Fe (II) ion, which otherwise would oxidize chemically very quickly as it moves into the oxygen rich water of the aerobic zone.

Iron-oxidizing or iron-related bacteria are divided into two distinct groups, which, in a sense, dictate where deposits will form. The iron bacteria most often responsible for the direct blockage of well screens and gravel packs are the stalk- or sheath-forming bacteria. The most famous of this group is *Gallionella ferruginea*. *Crenothrix*, *Leptothrix*, and *Sphaerotilus* are also common; however, they facilitate the accumulation of ferric (III) oxide by different mechanisms. The other iron-related bacteria usually are grouped in the slime designation and are members of many of the heterotrophic species that inhabit wells. They are ubiquitous in the well system but usually collect more in the aerobic aquifer directly adjacent to the well. Here, where the aquifer formation is much closer, they are able to build biofilms that are more structurally sound, and here they are responsible for accumulation of ferric (III) oxides. In Fig. 6-4 the stalks of

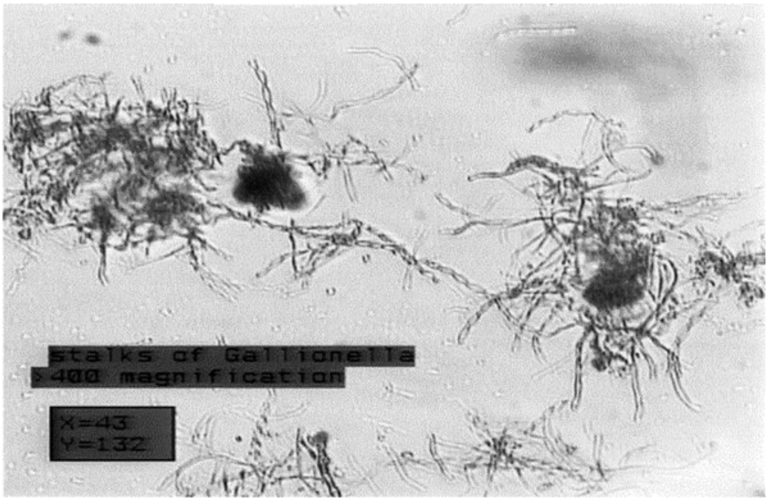

Fig. 6-4. Characteristic twisted stalks of Gallionella ferruginea
Source: Schneiders (2003); reproduced with permission from Johnson Screens/A Weatherford Company

the *Gallionella* are observable. These masses can bridge easily, blocking screens and other well flow areas. The mass formed is made up of the iron oxyhydroxide and bacterial sheaths glued together with the polysaccharide exopolymer of bacterial production. These deposits are soft in the initial stages, but as the iron compounds dehydrate, they become quite dense and are extremely difficult to dislodge. Wire brushing followed by acid treatment is usually the method of choice.

Another iron deposit that is driven bacteriologically is iron sulfide, which often accumulates in wells because of the synergistic anaerobic activity of fermentative bacteria and the sulfate-reducing bacteria. Of course, a source of iron and oxidized sulfur also must be available. Hydrogen, which is present from the metabolic activities of the fermentative anaerobes, usually combines with the reduced sulfur produced by the sulfate-reducing bacteria, resulting in hydrogen sulfide production. When considerable ferrous (II) iron is present, iron sulfide also forms and accumulates in the area. These deposits account for the characteristic black "soup" sometimes found in the well sump or bottom.

6.11 FIELD TESTING OF INCRUSTATION

Although analysis of the well water is far more important in determining the type of blockage that can be present in a plugged well, occasionally samples of incrustation are obtained. Without a complete field laboratory, the analysis usually is restricted to the results of acid dissolution of the incrustation.

Observation first should be made as to the color and density of the deposit sample.

Black: may indicate iron sulfide or a manganese,
Dark to reddish brown: usually indicates ferric (III) iron,
Bright yellow: most probably sulfur and usually seen high up on the drop piping and casing, often above the water level,
Light tan: can be dolomite, a mixture of calcium and magnesium carbonate,
Very light color to white: calcium carbonate, usually seen with other minerals providing additional colors,
Very heavy or dense: usually predominately mineral, or
Very light or low density: considerable biological material present.

Placement of a few drops of hydrochloric acid or muriatic acid on the incrustation may elicit some additional information:

1. Considerable foaming or frothing will indicate a carbonate (calcium, magnesium, or iron).
2. Hydrogen sulfide gas or rotten egg odor indicates iron sulfide present.
3. A strong chlorine odor will indicate the possible presence of manganese dioxide.
4. No effervescent, frothing, or odor usually indicates the presence of iron oxide, calcium sulfate, or silica.

There are a number of simple field tests that can be used to check for iron, sulfate, calcium, and phosphates. If these are available, dissolve a small amount of the deposit in hydrochloric acid using as little acid as possible. Dilute the dissolved material with deionized water to reduce the acid strength and to give sufficient volume for testing. Positive tests for any of the parameters listed here should confirm some of the observations made earlier.

6.12 TIMELY MAINTENANCE

Preventative maintenance on any operating system can save considerable time and costs. Preventative maintenance for water well systems for the most part has been relegated to pump maintenance and occasional observation of casing and screen. Periodic cleaning of the casing and screen, as well as the well bottom, goes a long way toward preventing blockage buildup and water quality loss. The biggest impediment to periodic maintenance cleaning is the need to remove the pump; therefore, any cleaning of the well and its adjacent structure has been limited to scheduling of pump removal and repair. Even then, the necessity for cleaning the well has been understood poorly, because many times the pump has been removed and repaired, and only a token chlorination of the well is carried out to meet the regulatory requirements. This failure to exercise simple cleaning action represents a tremendous loss to maintenance of good well operation.

The incrustation or blockage of water flow to a well occurs over time with the initial blockage formation on or near the screen or in an open borehole well interface where water enters the well bore. This area is subject to mineral incrustation due to precipitation following pH change, as the aquifer water is degassed, or from oxidation as ferrous (II) iron enters the more oxygenated water of the well. Various bacterial activities also encourage deposits in this area. As the deposits occur, water flow is slowed entering the well. The slowing of the water flow permits additional deposition. Bacterial growth, which often precedes mineral deposits, proceeds more abundantly in the channels with slow-moving water. Gradually the blockage moves outward from the well center, becoming denser and more difficult to remove. The gradual formation of the blockage largely depends on the initial formation or deposit. If periodic or "timely cleanings" are scheduled, the more severe and incapacitating blockage can be averted by considering the following. First, learn how often the blockage process (which must occur continually) reaches a point at which cleaning or removal becomes critical before the deeper blockage occurs. Second, because the onset of deeper blockage usually takes place more often than pump maintenance is required, consider how cleaning may be achieved without the cost of pump removal.

Periodic water tests can be used to track potential deposit formation, as well as increases in bacterial growth. In addition, historical records of well field operational data often illuminate the incidence of fouling in well systems. If wells show a loss in specific capacity or a water quality loss on a certain cycle, such as every 6 to 8 years, then cutting the cycle in half is a reasonable schedule to follow. Cleaning at the halfway mark will require far less chemical and mechanical effort then trying to rehabilitate a well that has lost more than 20% of its production. The loss of 10% or more pumping capacity usually indicates movement of the blockage zone farther from the well center.

Light cleaning can be successful in clearing the initial deposits of both mineral and bacteriological incrustations. The difficulty is trying to achieve the cleaning without removing the pump, because this would allow periodic cleanings at less cost and down time. Consequently, cleanings could and would be performed more often. Although the actual design of a light cleaning system is beyond the scope of this chapter, some ideas are presented:

1. Laboratory studies have shown and field use has proven that movement or circulation of chemistry (usually acid and a biodispersant) in the immediate well causes dissolution of the initial deposits of mineral and bacterial origin. These then can be removed by pumping to waste. In some of the more shallow wells, plastic piping has been installed along side the submersed pump up against the casing, where one is fitted to reach to the well bottom, and one is taken to the top of the screen zone; a surface pump is used to circulate a light acid and biodispersant mixture within the well, and when the solution has been circulated for 6 h, it is pumped from the well. The well is pumped to waste until the pH has returned to normal, and then the well can be returned to service.
2. A simpler method is the use of a single pipe to deliver the chemistry into the lower zones of the well with injection of nitrogen gas to facilitate water movement or mechanical agitation to improve cleaning; after 4 to 6 h of cleaning, the cleaner can be pumped from the well using the installed well pump, pumping to waste.
3. In smaller well systems, after addition of the cleaning chemistry, it is often circulated using the well pump by directing the flow back downhole to supply agitation; once cleaning has stopped, the water is pumped to waste and the well returned to standard operation. This method, although supplying some agitation, is limited from reaching the deeper well zones.

Future well design should include the installation of piping or other mechanisms to facilitate the addition of light cleaning chemistry to both the well bottom and the active production zones. This installation also would facilitate the use of disinfection chemicals. See Chapter 8, Section 8.4 for preventative maintenance monitoring methods and records.

6.13 ACID TREATMENT

Acids, particularly mineral acids, are used primarily for the dissolution of mineral deposits or those incrustations that incorporate minerals into the biological matrix. Acids most often used for this are hydrochloric and sulfamic. Phosphoric acid has become more popular due to the food grade availability, handling safety, and the very limited corrosivity of this acid versus hydrochloric and sulfamic. The latter two often are used with inhibitors, but these are never maintained in the cleaning solution during the rehabilitation effort, allowing extensive corrosion to take place once the inhibitor is expended.

Organic acids are used during well cleaning because of their reported effect on the bacterial exopolymer. This activity, however, is overrated and often results in less soluble byproducts being produced. More than 80% of incrustations found in well systems contain heavy concentrations of minerals. The acids generally used for their effect on the biological accumulations are hydroxyacetic and acetic acids. They produce acetates when they are exposed to calcium minerals, such as calcite and to a lesser extent gypsum. These acetate salts have limited solubility and as a result are left in the well system following washout of the acid cleaner. Further, acetates, as well as the organic acids, are both excellent carbon sources for bacterial growth. Citric and hydroxyacetic acids often are used to help solubilize iron deposits when used with a strong mineral acid, such as hydrochloric. Their primary activity is as a chelating agent, which helps hold the iron in solution to be discharged with the cleaner. Citric and hydroxyacetic acids do have some solubilizing effect against the softer iron oxyhydroxide deposits. However, their activity against the denser dehydrated iron oxides is limited even with hydrochloric acid use. Citric and hydroxyacetic acids as well as their deposited salts are an excellent food source for heterotrophic bacteria.

In the last few years the development of dispersants has provided a much more efficient method of improving the dissolution of both iron and biological substance and their removal. Table 6-3 provides some of the basic information concerning the various acids.

Of the three mineral acids most often used for well cleaning, hydrochloric acid is the most universal as a solvent of mineral deposits. It is a very low-cost acid, and it is very corrosive to equipment and human tissue. The acid, hydrogen chloride, is actually a gas, so fumes from the acid solution are dangerous. They can cause deterioration of equipment and electrical wiring when they condense with water vapors on those surfaces. Inhaled, they become corrosive to lung tissue. In addition to the personal safety issues, the acid is very corrosive to steel and, in particular, stainless steel. Inhibited hydrochloric acid or use of inhibitors is often a false protection, as inhibitors have a very short life in a strong acid cleaning operation, leaving the equipment and well structure totally unprotected during the second half of the procedure.

Sulfamic acid is a granular acid and usually is reserved for smaller wells. Its ease of transportation and handling provide a strong chemical for smaller service companies. Use of it for large wells, however, is limited due to the bulk handling and mixing problem required for acid necessary for the larger cleaning operations. Sulfamic acid has a major problem if calcium sulfate is present in the well or if the water contains a high concentration of calcium hardness and sulfates. Sulfamic acid once dissolved

Table 6-3. Characteristics of Common Acids

Characteristic	Sulfamic	Hydrochloric	Phosphoric	Hydroxyacetic	Citric
Appearance	White crystal	Slight yellow liquid	Clear liquid	Clear liquid	White crystal
Formula	HSO_3NH_2	HCl	H_3PO_4	$H_2OHCOOH$	$C_6H_8O_7$
Molecular weight	97.1	36.47	98.0	76.05	192.12
Type	Mineral	Mineral	Mineral	Organic	Organic
Hazardous fumes	None	High	None	Some	None
Relative strength	Strong	Strong	Strong	Weak	Weak
pH @1%	1.2	0.6	1.0	2.6	2.6
Relative reaction time 1 = Fast 10 = Slow	<2	1	2	3–5	4–5
Corrosiveness to:					
• Metals	Moderate	Very high	Slight	Slight	Slight
• Skin	Moderate	Severe	Moderate	Slight	Slight
Reactivity versus:					
• Carbonate scale	Very good	Very good	Very good	Poor-fair	Poor
• Sulfate scale	Good (Initially)	Good-poor	Good-poor	Very poor	Very poor
• Fe/Mn oxides	Fair	Very good	Good	Good/chelates	Chelates
• Biofilm	Poor	Poor	Poor	Moderately good	Poor
Pounds of acid (100%) required to dissolve 1 lb of calcium carbonate	2.0	.73	.65	4.5	4.0

is subject to a hydrolysis reaction, which converts the very soluble sulfamate ion to sulfate, in actuality producing sulfuric acid. Although this is a strong acid, the presence of the sulfate ion prevents any further dissolution of gypsum or other sulfate mineralization and promotes precipitation of these salts when the pH rises, if calcium is present. Therefore, the use of sulfamic acid should be limited to cleaning operations restricted to 6h duration prior to conversion of the acid.

Phosphoric acid will dissolve most or all of the same products as hydrochloric acid, particularly if a strong organic dispersant is used. It is a slower reacting acid; however, it is more available in food grade quality than any other acid. Concentrations usually available are 75 and 85% requiring less volume of acid to be handled and transported. There are no gaseous fumes given off, but sprays or liquid mists are acidic. Corrosion activity against most metals is very limited compared to hydrochloric or sulfamic acid. This acid always should be used with a strong polymeric (nonphosphate) dispersant, as this will prevent the formation of phosphate salts that could enhance bacterial activity if left behind. Numerous testing over time of wells cleaned with this acid, however, have proven this theory unrealistic in actual operation.

The quantity of mineral acid used in well cleaning should be based on the potential for calcite, gypsum, and iron or manganese oxide formation in the particular well. The water analysis will indicate the potential for all or any of the aforementioned and the concentration of acid to be used determined from these analytical results. Table 6-4 gives a listing of some basic parameters that can be used. Carbonates have the highest potential for neutralizing acids downhole; therefore, if present, they are the controlling factor. Calcium sulfate or gypsum and both iron and manganese oxides will require a minimum pH of 2.0 in order to provide reasonable dissolution of the blockage.

Once the concentration of the acid to be used has been determined, the volume of acid must be calculated. The volume of the area to be cleaned is calculated from the standing well volume plus the volume of the gravel

Table 6-4. Quantities of Acid Required for Various Minerals Potential

High carbonate and sulfate potential	10% to 12%
Some carbonate/sulfate or strong iron/manganese	8% to 10%
Moderate mineral potential with no heavy deposits	6% to 8%
No mineral deposit expected, water pH below 7.0	3% to 5%
No alkalinity and pH below 6.0	3%
Recent acid cleaned but using a biodispersant for biogrowth removal	1%

pack times the porosity of the gravel. A rule of thumb is to use 1.5 times the standing well volume. In well systems with unusually large gravel packs or under-reamed gravel packed areas, the actual calculation should be made, because the rule of thumb will not cover the enlarged system. The 1.5 factor also is useful in open borehole wells, as the additional volume aids considerably in penetrating the immediate aquifer surrounding the well bore. This is often the area of severe biological impaction. See Chapter 8, Section 8.3.2, for additional discussion on acids and other chemical usage in wells.

6.14 CHLORINE TREATMENT

Chlorine, or one of its formulations, is the oxidizer of choice for water well disinfection. Technically, it is available as chlorine gas; as 5, 10, 12, and 15% solutions of sodium hypochlorite; and as a powder form as calcium hypochlorite. The powder or granular form has 65 to 70% available chlorine. Chlorine gas usually is not used in well chlorination due to both the safety problem of handling the product and the difficulty in applying a gaseous product to the well environment (Schneiders 1998). Sodium hypochlorite is used widely because of its ease of application due to its liquid state. Calcium hypochlorite finds use due to its high level of chlorine (which reduces cost) and its longer shelf life. Sodium hypochlorite solutions lose 2.5 to 5.0% of their activity for every 30 days of storage.

Chlorine is available as a disinfectant both as the hypochlorite ion and as hypochlorous acid. The hypochlorous acid form is a minimum of 100 times more effective as a disinfectant, particularly against free-swimming (planktonic) bacteria. The pH of the cleaning solution determines the availability of the two forms, which are shown in Fig. 6-5.

When chlorine gas is used, it produces an acid reaction lowering the pH of the water and delivering essentially hypochlorous acid. This can be reversed in highly alkaline waters. Sodium and calcium hypochlorite, however, both have caustic products as part of their formulation, so their use increases the pH of the cleaning solution, and only the hypochlorite ion is formed. Buffering acids can be used to neutralize the causticity of the hypochlorite product and the natural alkalinity of the water to maintain a pH of 6.5. At that point, maximum hypochlorous acid is formed. Because chlorine gas is released if the pH is allowed to fall below 5.0, the reaction must be calculated carefully and watched to prevent the release of the dangerous gas. Several commercial products are available, but only those that take into consideration the alkalinity of the water and the quantity of the hypochlorite product used are worthwhile.

Although well disinfection is absolutely necessary at times, if used to excess, the application can be debilitating to the well system. One of the

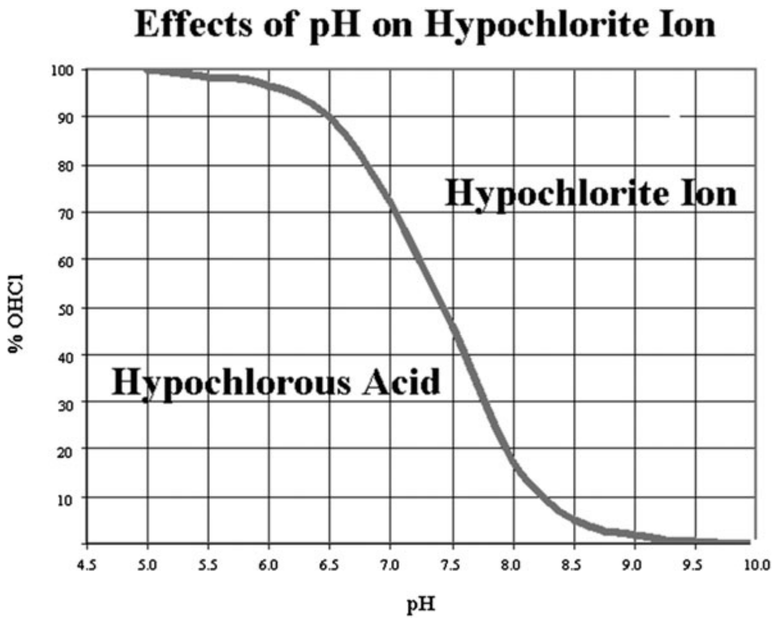

Fig. 6-5. Graphic representation of percentage of hypochlorous acid as a function of pH
Source: Schneiders (2003); reproduced with permission from Johnson Screens/A Weatherford Company

important parameters of the Saturation Index is pH. As the pH rises, carbonates and other minerals begin to precipitate.

The flooding of the well environment with a chlorine solution that will result in a dramatic rise in pH results even more dramatically in the precipitation and placement of insoluble carbonates, sulfates, and oxides in the microstructure or flow spaces of the well. If calcium hypochlorite is used, the reaction takes place even in low-hardness water, because the calcium hypochlorite supplies the calcium necessary for calcite or gypsum deposition. Therefore, the use of pH-controlled chlorination and sodium hypochlorite greatly reduces deposit formation in and around the well.

Chlorine or any strong oxidizing agent will attack the polysaccharide polymers produced by the bacteria (see Fig. 6-6). The attack often leaves insoluble byproducts, which tend to increase the density and decrease the penetration of the bacterial biofilm formation. Continued chlorinating procedures produce or increase the blockage effect of the bacterial slime, particularly in the aquifer formation, where mechanical shear is not available to help dislodge the biological matrix. Using lower levels of chlorine for disinfection can reduce this effect.

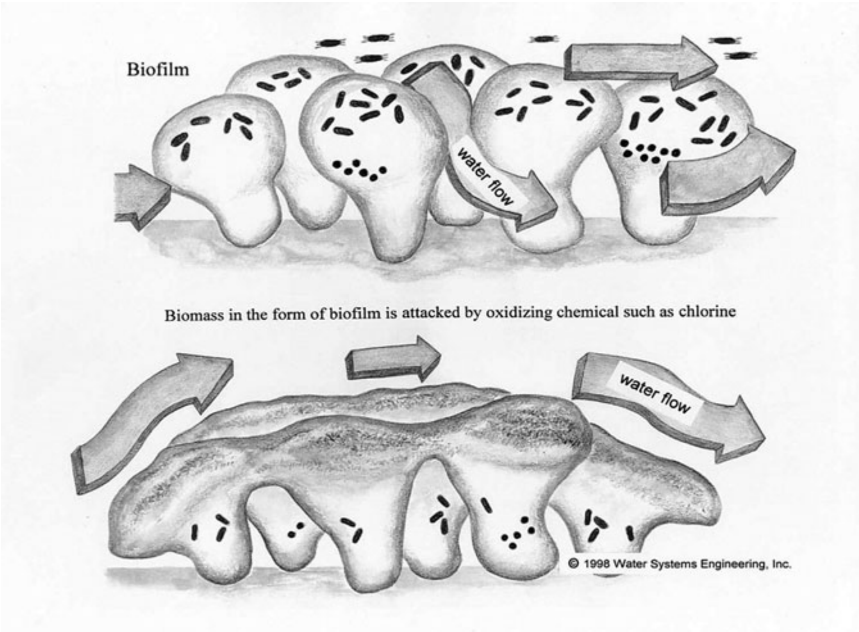

Fig. 6-6. Effects of chlorine on biofilm
Source: Schneiders (2003); reproduced with permission from Johnson Screens/A Weatherford Company

Laboratory tests have shown a higher degree of coliforms removal achieved with chlorine levels between 50 mg/L and 200 mg/L (Schnieders 2001a). The test included treatment of well systems over a wide chlorine dosage of 20 mg/L to 5,000 mg/L. It was perceived that strong oxidation of top layers of the biofilm prevented penetration to the levels where coliforms were residing. The lower levels of available chlorine, together with mechanical activity and adequate time, resulted in better penetration and removal of the coliform contamination.

The pretreatment and method of chlorine application are other factors, which greatly influence the success rate of water well disinfection. The well, not unlike any surface to be disinfected, should have debris removed and surfaces cleaned of incrustation or other hiding places for bacteria. The correct method to disinfect a well is to remove the pump and evacuate all the debris from the well bottom. The well casing and screen areas also should be brushed to remove incrustation. If time is spent evacuating (airlifting or pumping) the well bottom and screen area, the additional development achieved will improve the success rate further.

Once the level of chlorination is selected, the necessary volume should be calculated. Smaller wells often are chlorinated by adding the chlorine solution directly to the well. However, little success is achieved, because the chlorine solution is not dispersed throughout the column. Most often, it never reaches the lowest zone. Larger wells still suffer failure when relatively small volumes of solution are tremied into the various zones. The highest degree of successful chlorination is achieved by preparing a volume of chlorine solution equal to four times the standing well volume (Schnieders 1998). The ideal procedure is to prepare this treatment volume in a blending tank at the selected chlorine level at a pH of 6.5 and tremie the solution into all zones of the well. Place 25% of the volume at the well bottom, 25% at the halfway position in the screen zone, 25% at the top of the screen, and then use the remaining 25% to wash the upper portion of the well. In open borehole wells, equal portions should be placed at the well bottom, a third of the way up the water column, and two thirds of the way up the water column. A portion also should be used to disinfect the upper level of the well. Provisions should be made to disinfect the pump, any removed column piping, and other pieces.

Once the chlorine solution is in place, a surge block or tight-fitting swab should be used to surge the solution, effectively washing most surfaces and forcing the solution out into the gravel pack and formation. Surging should be scheduled for no less than 0.5 min for each foot of casing (below the water line) above and below the screen area. The screen zone should be surged or swabbed at 1.0 min/ft. A jetting device, which recirculates the hypochlorite solution, is usually preferable in open borehole construction to prevent damage to the borehole wall.

Evacuation of the well should be performed using an airlift method or high-capacity pump in order to remove the oxidizing solution and any loosened debris. Begin airlifting or pumping from the well bottom, raising the equipment every 10 to 20 ft once that area is clean. If pump removal is not planned, then the hypochlorite solution should be tremied into place by placing the tremie line alongside the pump. Some method of applying agitation should be devised, such as recirculation of the chemistry downhole with an auxiliary pump or, in smaller well systems, diverting the well discharge back down the well. Most coliforms and other contaminants do or will reside in the bottom portion of the well (many wells are constructed with a sump or dead space) and chlorine must be injected, as well as some mechanical force utilized, to disrupt this area providing contact between the contaminating organisms and the disinfectant chemistry.

6.15 POLYPHOSPHATE TREATMENT

Phosphates are used primarily as silt and clay dispersants during well development. In recent years, the practice has become somewhat controversial, because phosphates stimulate bacterial growth. Originally it was thought that phosphate was removed during the pump out; however, the interaction of phosphates with calcium usually produces insoluble salts, which remain in the well, often resulting in bacterial problems over extended periods. Phosphate chemicals are available in a wide range of products, which are classified as an acid or alkaline product. Determining which product is most effective in a particular area may be difficult and often has been decided by trial and error over time. In formations containing considerable calcium carbonate, potential acidic phosphate products can cause dissolution of those formations with subsequent production of byproducts of limited solubility resulting in formation blockage.

In more recent years, very active polymer solutions have been developed, which have replaced phosphates, especially in large well development. Because of their high activity, polymer use is quite economical. They are usually referred to as mud control agents or SEP polymers applicable for well development. Whereas phosphate products are used at between 0.5 and 2.0% by weight of well volume, the polymer products, which are liquids, are used at 0.2 to 0.4% of well volume. See Chapter 5 for a thorough treatment of well development.

6.16 DESIGN CONSIDERATIONS TO PREVENT WELL FOULING

It has been apparent through the years that mineral or bacterial incrustation results in poor well performance or water quality degradation, yet only a few provisions have been made to design around these problems. Following are examples that need consideration.

6.16.1 Example 1

Earlier in the chapter (Section 6.6) calcium carbonate (calcite) accumulation through carbon dioxide degassing at the well screen–aquifer interface was reviewed. The phenomenon was discussed as the result of overpumping. The degassing takes place because of a drop in the hydrostatic pressure, which then releases the carbon dioxide from solution. Bicarbonates present in the aquifer as a soluble form are carried in proportion to the amount of carbon dioxide in solution, which in turn is determined by the water pressure in the subsurface. A reduction in water pressure due to overpumping, therefore, results in deposition of insoluble carbonates in the gravel pack and more acutely on the surface of the screen, plugging the openings and reducing the yield of the well.

Lehr et al. (1988) showed how application of the Bernoulli equation clearly points to the need for design change to control the phenomenon. The equation dictates that the pressure decreases proportionately to the square of the velocity. As an example, the pressure drop at 2 ft/s is four times greater than the pressure drop at 1 ft/s. As water passes through the screen openings, it accelerates, pressure decreases, and carbon dioxide is released. The deposition of minerals in the slot opening further narrows the water path, resulting in even greater velocity, greater pressure loss with more carbon dioxide release, and more deposits. As the cycle continues, deposition proceeds into the gravel pack, extending the zone of increased velocity and subsequent clogging of the well. At this point considerable loss of yield is evident.

Many high-production wells are designed with screens and gravel packs to improve efficiency. The slot size of the screen, as well as the grain size of the gravel, is determined by a number of factors, one of which should be the water chemistry. Because the presence of hardness (as calcium bicarbonates) in the water reflect the ability of the water to deposit those minerals, their values should be part of the criteria for selecting screen size. By increasing the slot size or open area of the screen, the pressure drop of the water entering the well will be less, reducing the tendency for deposit formation. There are several factors that are reflected in the Saturation Index, thus a carbonate hardness >250 mg/L and a pH ≥7 would be useful criteria for selecting a larger slot size. In addition to slot size, the total open area is reflected in water flow; therefore, the screen type should be considered as well when chemical analysis shows high levels of potential deposits. Louvered, mill slot, or bridge slot screens have open areas that range from approximately 5 to 12%, whereas continuous slot or wire wrapped screens have three times the open area.

6.16.2 Example 2

In recent years, much has been written on the effect of bacteria on well systems. In answer to the question "How can we design a well against this incursion of nature?" we must take into consideration how bacteria thrive within the well. Earlier, biofilms and how they provide habitat for these organisms were discussed. These biofilms require surface area. Consequently all areas within the well could be expected to be covered with a minimum of biofilm and their bacterial inhabitants. This covering is conservative, much like the coating that forms on human teeth, and usually has little effect on water flow. There are some exceptions, such as iron oxidizers, that accumulate along with iron oxide on screen surfaces, which can result in blocked water flow. The large accumulations, however, of bacterial mass occur in two distinct areas of the well, and both areas require consideration during the construction phase. Specific accommodation included in the design phase could eliminate or reduce heavy growth in these areas and the often-ensuing loss of production and or water quality.

The first areas of concern are the formation around the well, the area affected during construction, and the area usually repaired during well development. Damage to the formation indicates compaction and blockage of the flow area and the leaving behind in the aquifer the results of this compaction—the fines, both clay and sediments. The accumulated debris, if left in the aquifer, will slow water flow and reduce yield. It ultimately causes far more damage to the well. The fines left behind result in a tremendous increase in surface area for biofilm development. In addition, the inhibited flow allows earlier establishment of the biology and results in more complete blockage as the biofilms quickly close the gaps between the particulates. This manifestation of the bacterial growth is more harmful to well operation than the accumulation seen on surfaces in other well areas. For this reason, well development is one of the most important operations of well construction and should be defined thoroughly in the specifications and not be sacrificed because of time or budget contraints.

The second major area of bacterial residence in water wells is the well bottom or lower reaches of the well. In this area, anaerobic bacteria thrive. Sulfate-reducing bacteria—a large segment of this group—are well known for their involvement in corrosion and water quality loss. The well bottom often is constructed to form a sump. It is designed as an accumulation area for fines and sands that could enter the well during the initial operational phase. It is thought of as a dead zone, which does not affect the operation of providing high-quality water as the well is operated. Unfortunately, this is not true. As the well ages, the accumulations in the sump increasingly are subject to being drawn into the flow as the sump fills and the debris rises closer to the draw.

Although the sump has some intrinsic value as a wastebasket for sands entering the well, it is really simply a backup for poor well development. Of paramount importance, though, is that it serves as the *accumulation area* for anaerobic bacterial activity. As the well operates, bacteria are taken into the well with the aquifer water. Aerobic bacteria grow where there is plenty of oxygen, and the anaerobes flourish in the lower areas where oxygen is absent or more limited. As wells become constructed with better seals and more attention to securing them from infiltration, less oxygen will be available in the upper zones. Currently, the aerobic bacteria use up the available oxygen and die, leaving their remains to gravitate toward the well bottom. In effect, the aerobic bacterial metabolism removes the oxygen as they descend in the well and furnishes organic debris as food sources for the anaerobic bacteria. This is even more exaggerated if an incident occurs, such as cascading water, which results in an abundance of aerobic bacterial growth resulting in large quantities of organic debris moving toward the well bottom. Wells, sitting idle for a period after construction and before chlorination, are subject to a heavy accumulation of organics in the well bottom and the resulting growth of anaerobic bacteria.

This situation is a perfect scenario for the growth of coliform bacteria, which often inhabit an anaerobic biofilm.

There may be good reasons for the design of wells with sumps. However, within the past 10 years, numerous successful rehabilitation efforts have been carried out in which the well bottom was filled or cemented. This action resulted in the correction of both corrosion and water quality problems that had plagued various communities for years.

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CHAPTER 7

WELLHEAD PROTECTION FOR WATER WELLS

Zohrab Samani and Jorge Garcia

7.1 GENERAL

In Europe, as well as United States, increasing attention is being focused on sanitary protection of public water-supply systems. The Safe Drinking Water Act (SDWA) of 1974 was established by the U.S. Congress for protecting drinking water supplies of public water well systems in the United States Public water well systems are defined as those systems that supply safe and wholesome, potable water to the general public and serving at least 25 or more people. The SDWA defines the minimum standards and regulations for design, construction, and monitoring of public water well systems. The U.S. Environmental Protection Agency (EPA) is the lead government agency in charge of establishing national standards, whereas the individual states are responsible for enforcing such standards within their own respective, individual, territorial jurisdictions. The SDWA provides for establishing a primary set of regulations for the protection of public health and a secondary set of regulations for controlling the dissolved or mixed, harmful substances and microorganisms in the water, as well as taste, odor, and appearance of the drinking water. As a result of the SDWA, any organization planning to provide drinking water to the public must comply with the minimum design standards as defined by the EPA, and monitor and maintain the contaminant levels in the drinking water below a regulated maximum contaminant level (MCL). The SDWA has set MCLs for 83 contaminants deemed harmful to human populations.

In 1986 the SDWA was amended. As part of this amendment, the SDWA mandated that each state develop a wellhead protection program in order to further protect the public water-supply wells from potential contamination. The following sections of this chapter provide, in brief, the necessary design narratives and other related information for the proper establishment of the Wellhead Protection (WHP) program.

7.2 WELLHEAD PROTECTION AND WELLHEAD PROTECTION AREA

Wellhead protection (WHP) means the protection of groundwater from contamination in a specified area, known as the *wellhead protection area* (WHPA), which surrounds a public water-supply well. The WHP program requires that land-use controls be considered as an essential and integral part of a groundwater protection program, prohibiting specific types of commercial, industrial, and agricultural activities in the areas surrounding water well sites as one of a number of protective measures to prevent contamination. Section 1428 of the 1986 Amendment to the SDWA requires that each state adopt a program to protect WHPAs from being contaminated. The amendment further requires that determination of WHPAs should be based on “all reasonably available hydrologic information on groundwater.”

The term WHPA refers to the area around a well that contributes water to the well. SDWA Subsection 1428(E) defines the WHPA as “the surface and subsurface areas surrounding a water well or a wellfield, supplying a public water-supply system, through which contaminants are likely to move toward and reach such a water well or a wellfield.” The WHPA also is called the *zone of contribution* (ZOC). The term ZOC is a more realistic and a fuller definition of the WHPA, because it refers to a three-dimensional volume of an aquifer contributing groundwater to the water well or wellfield rather than its simplistic concept of two-dimensional area. The ZOC is defined differently than the traditional *zone of influence* (ZOI), which is used in the conventional hydrological studies. The ZOI is defined as the cone of depression of a single well or a combination of wells. The ZOI is basically the portion of the aquifer that is affected by the pumping process. The ZOC, conversely, is defined as the entire area that supplies water to the operating wells. Normally, the ZOC includes part of the ZOI, but they never should be considered the same. Fig. 7-1 shows the ZOC and the ZOI for a given hydrological parametric setting. As can be seen in Fig. 7-1, the ZOI of the well is a fixed area, whereas the ZOC is a function of the time-of-travel, which usually is established in the design criteria for the project. For example, if it is required by regulations or simply desired as a protective measure by the facility owner that a water well system be designed on a 10-year time-of-travel basis, then the associated ZOC would be larger than that obtained for a 5-year desired time-of-travel

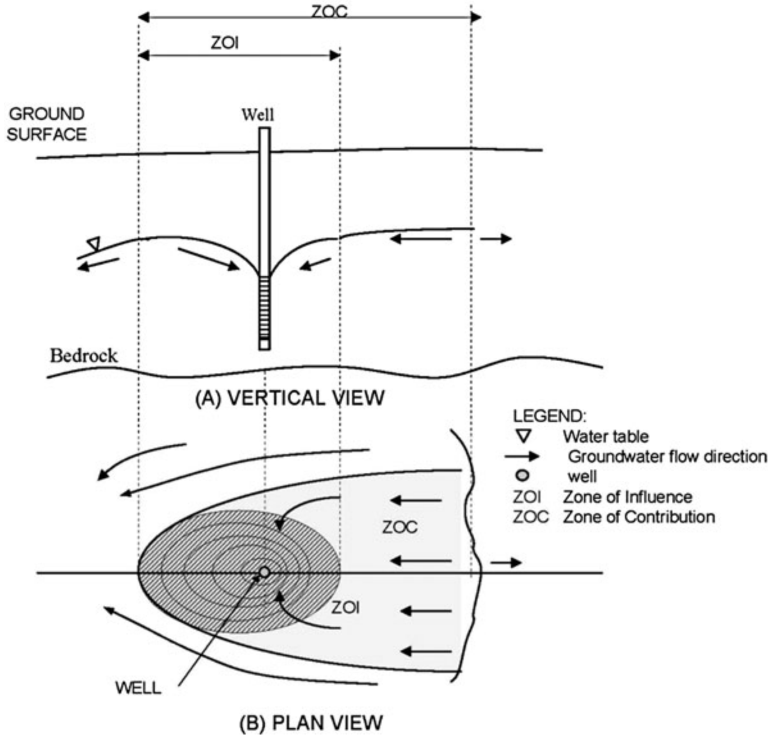


Fig. 7-1. Views of a water well completed in an unconfined aquifer; (A) Vertical view shows the ground surface elevation, cone of depression, well casing, well screen, bed rock elevation, and water table; (B) Plan view indicates the zone of influence (ZOI), zone of contribution (ZOC), groundwater flow direction, pumping well location, and groundwater divide

basis. The time-of-travel is defined as the time required for a contaminant to travel from a distant point of the required ZOC to the water well. Therefore, the longer the set design time-of-travel, the larger the ZOC areal extent would be. The time-of-travel normally is defined by the regulatory agency as the proper design requirement. Fig. 7-1 also shows that the ZOC depends on boundary conditions, as well as on the characteristics of the aquifer formation. The process of developing a WHP program, as guided by the rules and regulations, consists of following five steps in a sequential manner:

1. Formulate a planning committee to initiate and implement a WHPA either for an existing public water well system or for one envisioned in the near or distant future.

2. Delineate the WHPA according to state or federal WHP program requirements and regulatory guidelines.
3. Identify, quantify, and locate possible, potential sources of pollution and contamination, regulated or otherwise, within and adjoining the boundaries of the WHPA.
4. Develop the management and operative strategies and guidelines as mandated by the federal- and state-established rules and regulations for the envisioned WHPA; the complexity, difficulty, and uncertainty of this step will depend on the economic, social, political, and local demographic conditions of the community; management techniques and strategies can range from public speaking, education, seminars, and distribution of printed material to simple permitting guidelines, restrictions, and intricate regulatory, executive orders, and lawful ordinances.
5. Planning, expansion of services, and anticipated construction requirements and their implementations for the future of WHP program and its developmental upgrading should be continued and focused at its best performance; this step involves the long-term protection plan and includes contingency planning for emergency remediation and provisions for alternate public water-supply systems if possible pollution and contamination occurs in the unforeseeable future.

7.3 FUNDAMENTALS OF GROUNDWATER FLOW AND CONTAMINANT TRANSPORT

Contaminant transport in groundwater depends on the velocity of the groundwater flow, concentration gradient of the contaminant, characteristics of the porous medium, and various biological and chemical reactions of the contaminant with the surrounding environment. Zheng (1993) described a three-dimensional transient model in Cartesian coordinates for the transport of contaminants in a porous medium by the following partial differential equation:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right) + \frac{\partial}{\partial x_i}(v_i c) + \frac{q_s}{\theta}c_s + \sum_{k=1}^{k=N} R_k \tag{7-1}$$

where

c = concentration of contaminants, either dissolved or mixed uniformly in groundwater, (M/L^3)
t = time, (T)
x_i = distance along or parallel to the ith Cartesian coordinate axis, (L)

D_{ij} = hydrodynamic dispersion coefficient, (L^2/T)
v_i = seepage velocity or linear pore-water velocity, (L/T)
q_s = volumetric flux of water per unit volume of aquifer, representing both sources (positive) and sinks (negative), (1/T)
c_s = concentration of the sources or sinks, (M/L^3)
θ = effective porosity of a porous medium, (dimensionless)
$\sum_{k=1}^{k=N} R_k$ = first-order reaction term for N number of reactions, (M/L^3).

The second term on the right-hand side of Eq. (7-1) describes advective transport, which refers to the transport of contaminants by the moving water. The advective term describes the transport of a contaminant at the same velocity as that of groundwater (i.e., the pore velocity). For many practical problems concerning contaminant transport in groundwater, the advective term dominates. In developing the boundaries of the WHPA, only the advective term is used to calculate the capture zone around a well. This process generally results in a conservative estimate of the ZOC. The flow of groundwater in a porous medium is governed by the Darcy equation. The Darcy equation in the general *L*-direction in a porous medium may be written as follows:

$$V_L = -K_L \frac{\partial h}{\partial L} \tag{7-2}$$

where

V_L = apparent velocity, bulk velocity, or Darcy velocity in the *L*-direction, (L/T)
K_L = hydraulic conductivity in the *L*-direction, (L/T)
h = hydraulic head or piezometric head, (L)
L = distance in the direction of or along the *L*-axis, (L).

As an example, the *x*-component, V_x, of the general velocity, V_L, can be written as

$$V_x = -K_x \frac{\partial h}{\partial x} \tag{7-3}$$

where

V_x = apparent velocity, bulk velocity, or Darcy velocity in the *x*-direction, (L/T)
K_x = hydraulic conductivity in the *x*-direction, (L/T)
h = hydraulic head or piezometric head, (L)
x = distance in the direction of or along the *x*-axis, (L).

The hydraulic head or the piezometric head, h, in groundwater is defined as

$$h = \frac{p}{\rho g} + z \tag{7-4}$$

where

p = hydrostatic pressure, (M/LT^2)
ρ = density of water, (M/L^3)
g = gravitational acceleration, (L/T^2)
z = vertical distance, (L), from a reference point to a chosen datum.

Of course, Eq. (7-3) represents an apparent velocity in a porous medium and is based on the bulk area. To obtain the actual velocity, seepage velocity, or pore velocity, v_x, in the x-direction, the apparent velocity, V_x, should be divided by the effective porosity, θ, of the porous medium as

$$v_x = \frac{V_x}{\theta} \tag{7-5}$$

Once the actual velocity, v_x, is calculated, then the distance, x, that a contaminant will travel in a given time, t, can be calculated as

$$x = v_x t \tag{7-6}$$

In groundwater flow systems, however, the flow regime is often three-dimensional, especially in the vicinity of a source or sink. The three-dimensional groundwater flow in Cartesian coordinates is defined by McDonald and Harbaugh (1988) as follows:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - W = S_s \frac{\partial h}{\partial t} \tag{7-7}$$

where

K_x, K_y, and K_z = hydraulic conductivity components in the direction of x-, y-, and z-axis, respectively
W = flow rate per unit area per unit length of the sink/source, (1/T)
S_s = specific storage of the porous material, (1/L)
t = time, (T).

Eq. (7-7) can be used to calculate the hydraulic heads and the actual pore velocities in a three-dimensional domain. Utilizing the concepts of Eqs. (7-3), (7-5), and (7-7), the pore velocities for the given porous medium in Cartesian coordinates are given as follows:

$$
\begin{aligned}
v_x(x,y,z) &= -\frac{K_x(x,y,z)}{\theta}\frac{\partial h(x,y,z)}{\partial x} \\
v_y(x,y,z) &= -\frac{K_y(x,y,z)}{\theta}\frac{\partial h(x,y,z)}{\partial y} \\
v_z(x,y,z) &= -\frac{K_z(x,y,z)}{\theta}\frac{\partial h(x,y,z)}{\partial z}
\end{aligned}
\tag{7-8}
$$

The pore velocity equations can be written in an equivalent form as a set of ordinary differential equations as follows:

$$
\begin{aligned}
\frac{dx}{dt} &= v_x(x,y,z,t) \\
\frac{dy}{dt} &= v_y(x,y,z,t) \\
\frac{dz}{dt} &= v_z(x,y,z,t)
\end{aligned}
\tag{7-9}
$$

A pathline of a contaminant particle, $s(t) = s[x(t), y(t), z(t)]$, in the given flow domain is one for which the pore velocity associated with the pathline, $s(t)$, satisfies everywhere the set of Eq. (7-9) along the aforementioned pathline. The pathlines are characteristic curves in a given flow field, which can be calculated by simultaneously solving Eq. (7-9). Several computer programs have been developed to calculate the pathlines for advection transport of contaminants in groundwater. These include the two-dimensional solution by Shafer (1987) and the three-dimensional solution by Zheng (1991).

7.3.1 Solved Design Example 1

Considering the groundwater flow to be one-dimensional, determine the distance, x, that a contaminant would travel in 10 years if the actual flow velocity in the x-direction is given as $v_x = 0.091\,\text{m/d}$.

Solution Here, the actual velocity and pore velocity are considered the same by definition. Applying Eq. (7-6), the required distance, x, is obtained as

$$x = v_x t = (0.091\,\text{m/d})(10\,\text{y})(365\,\text{d/y}) = 334\,\text{m}$$

7.4 DELINEATION METHODS FOR THE WELLHEAD PROTECTION AREA

The EPA (1987) proposed six different methods for delineating the WHPA. The criteria and assumptions used in each method are different. These methods in order of increasing complexity are

1. Arbitrary fixed radius,
2. Calculated fixed radius,
3. Standardized variable shapes,
4. Analytical methods,
5. Hydrogeologic mapping, and
6. Numerical flow/transport models.

7.4.1 Arbitrary Fixed Radius

In this method, the boundary of the WHPA is delineated by drawing a circle of fixed radius around the well. The radius of the circle is established on the basis of various factors, such as administrative policies, economic or social constraints, or professional experience (based on the hydrogeological characteristics of the groundwater formations). For example, the New Mexico Environmental Department has established a 1,000-ft radius around a public water-supply well as a minimum protection area. This radius is approximately equal to a 10-year protection area or zone around an average public water-supply well in New Mexico. The Arbitrary Fixed Radius method is simple to establish and has economic advantages, because it requires a minimum investment in time, money, and staff resources, but it does not take into account site-specific hydrogeological principles necessary to define the WHPA properly.

7.4.2 Calculated Fixed Radius

The calculated fixed radius technique also involves drawing a circle of predetermined specified radius around a well based on the time-of-travel of a contaminant traveling toward the well in a two-dimensional setting. The calculation is based on the volume of water that can be pumped from a well in a specified time period. The time period is chosen on the basis of the desired protection period for a specific well. The equation of interest then can be developed as follows. The volume of water that can be pumped from a well for a period equal to the time-of-travel, t, can be calculated as

$$Q = \frac{\text{Total volume of water pumped}}{\text{Time-of-travel}} = \frac{\pi r^2 b\theta}{t}$$

This equation, when solved for the calculated fixed radius, r, becomes

$$r = \sqrt{\frac{Qt}{\pi\theta b}} \tag{7-10}$$

where

r = calculated fixed radius of the contributing area or zone, (L)
Q = well discharge rate, (L^3/T)
b = effective thickness of the production zone or saturated thickness of the aquifer, (L)
θ = effective porosity of the aquifer, (dimensionless)
t = time-of-travel, (T).

7.4.2.1 Solved Design Example 2

Calculated Fixed Radius: Consider the situation of a municipal well in Las Cruces, NM, which is located in a confined aquifer. The well pumps steadily at the rate of 5,450 m^3/day (1,000 gal./min), and the length of the well screen, which is equal to the saturated thickness of the aquifer is $b = 122$ m. Available literature sources cite the aquifer effective porosity as $\theta = 0.4$. Choosing a travel time of 10 years, determine the radius of the WHPA for the well under consideration.

Solution Substituting the values of the parameters into Eq (7-10) results in the determination of the calculated fixed radius as

$$r = \sqrt{\frac{(5,450 \text{ m/d})(10 \text{ y})(365 \text{ d/y})}{(\pi)(0.4)(122 \text{ m})}} = 360 \text{ m}$$

The 360 m (1,180 ft) calculated fixed radius is close to the arbitrary fixed radius of 303 m (1,000 ft) established by the New Mexico Environmental Department. However, if the period of protection is changed to 20 years, which is the typical life expectancy of a water-supply well in the area, the calculated radius will be 509 m, which is much larger than the arbitrary fixed radius of 303 m.

There are several limitations associated with Eq. (7-10), one being the assumption of a constant pumping rate, which is contrary to the practice of intermittent pumping in the real world. However, if the pumping rate in the example is taken as the average discharge rate for the period of calculation (10 years), then the calculated fixed radius would be reasonable. Another limitation is the fixed thickness of the production zone, which would change due to pumping if the aquifer is unconfined. In this case, the actual thickness of the production zone would be smaller than the initial saturated zone, resulting in underestimation of the ZOC. Eq. (7-10) also assumes that the length of the screen is equal to the thickness of the production zone, which may or may not be true. In cases where the length of screen is less than the saturated thickness of the aquifer, the length of the screen can be used as effective saturated thickness for a conservative estimation of WHPA radius.

7.4.3 Standardized Variable Shapes

The standardized variable shapes method uses analytical models to produce standardized shapes of the WHPA using representative hydrological criteria, time-of-travel, and hydrogeological boundaries. Various standardized shapes are calculated for different sets of hydrological conditions. Of course, various shapes of the WHPA are possible for each given set of conditions; however, this methodology uses quite a few generalized forms. Therefore, the most suitable form is chosen for each well by determining how closely that form matches the hydrogeological and pumping conditions of the well. Once the appropriate standardized form is determined, the so-called form can be oriented around the wellhead by aligning the shape in a manner that parallels the direction of flow of groundwater.

Once the shape is oriented, the upgradient portion of the WHPA is extended either to the flow boundary or to a specified time-of-travel boundary (Fig. 7-2). The upgradient extension of the WHPA can be determined using the time-of-travel equation (Fabian and Summers 1991).

The advantages of using the standardized variable shapes method are that this method requires little actual field data and can be implemented easily once the forms are calculated. Also, this method provides a more realistic delineation of the WHPA than either the arbitrary fixed radius or the calculated fixed radius method with only a minor increase in cost.

Again, once the standardized variable shapes are developed, the necessary, required information includes the pumping rate of the well, type of aquifer material, and direction of groundwater flow. The disadvantages of the method include the potential for introducing inaccuracies in the determination of WHPA with variable hydrogeological conditions.

7.4.4 Analytical Methods

The WHPA can be determined using analytical methods based on equations that describe groundwater flow and contaminant transport phenomena. For example, equations, such as those listed by Todd and Mays (2004), are based on the concept of uniform groundwater flow and are used to define the ZOC to a pumping well in a sloping water table (Fig. 7-3). Site-specific hydrogeologic data are required as input and include

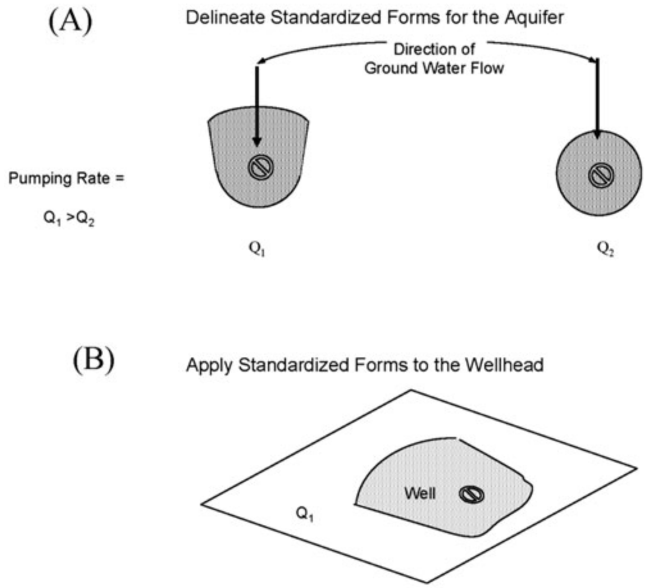


Fig. 7-2. Delineation of (A) standardized variable shapes, and (B) their application to wells of similar pumping rates and hydrological parameters

hydraulic conductivity, transmissivity, hydraulic gradient, pumping rate, and saturated zone thickness. Once this information is obtained, the following equations can be used to define the WHPA for a specific well as follows. The downgradient divide, X_L, is calculated from Eq. (7-11) as

$$X_L = -\frac{Q}{2\pi Kbi} \tag{7-11}$$

where

Q = pumping rate, (L^3/T)
K = hydraulic conductivity, (L/T)
b = length of the screened interval of the well or saturated thickness, (L)
i = hydraulic gradient of groundwater (L/L).

The limit of the flow boundary in y-direction, Y_L, is defined as

$$Y_L = \pm\frac{Q}{2Kbi} \tag{7-12}$$

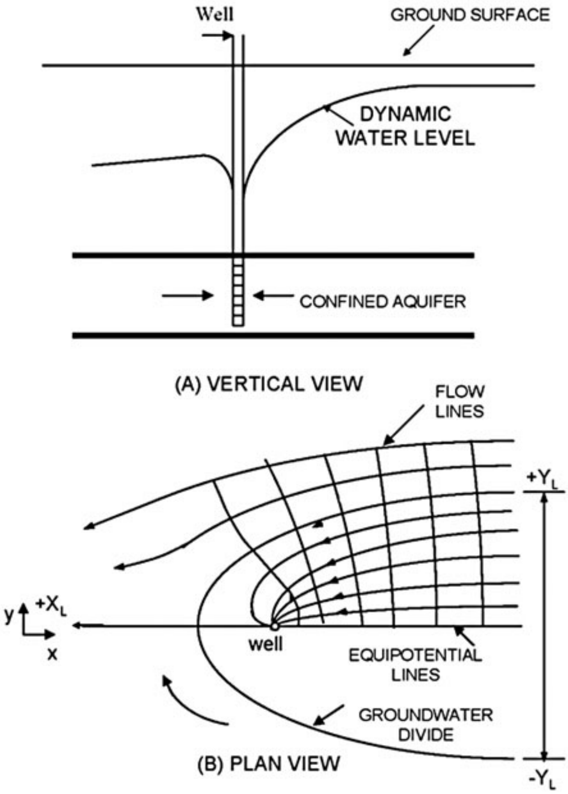


Fig. 7-3. Views of a water well completed in a confined aquifer; (A) Vertical view shows the ground surface elevation, piezometric surface, confined aquifer, well casing, and well screen; (B) Plan view indicates a partial flow net of streamlines and equipotential lines, pumping well, limits of ground water entering well, and groundwater divide

and the flow boundary defining the ZOC is given (EPA 1987) by

$$\frac{y}{x} = -\tan\left(\frac{y}{-X_L}\right) \tag{7-13}$$

Eqs. (7-11) through (7-13) define the ZOC around a well, but the upgradient boundary of the ZOC can extend a very large distance. To avoid such an unrealistic upgradient boundary, the EPA (1987) introduced an approach to calculate the upgradient boundary using the time-of-travel. Time-of-travel is estimated for the aquifer using the concept of the pore velocity equation. The pore velocity depends on the regional groundwater gradient and the local gradient at the vicinity of the pumping well. The distance, s, traveled during the time-of-travel, t, is calculated from the following equation:

$$s = v_r t + v_p t \tag{7-14}$$

where

s = distance the groundwater would travel in time, t, (L)
t = time-of-travel, (T)
v_r = regional groundwater velocity, (L/T)
v_p = velocity in the vicinity of the pumping well, (L/T).

On the basis of these equations, the menu-driven computer model called T-O-T was developed by Fabian and Summers (1991) to calculate the WHPA for a single pumping well. The model uses an iterative algorithm to calculate time-of-travel. The program uses the EPA-recommended criteria and methods to delineate WHPA, assuming ideal uniform conditions.

7.4.4.1 Solved Design Example 3 Consider the same aquifer as was described previously in Section 7.4.2.1, Solved Design Example 2, with $Q = 5{,}450\ \mathrm{m^3/d}$, $K = 5.45\ \mathrm{m/d}$, $b = 121\ \mathrm{m}$, and $i = -0.003$. Determine the downstream extension of the WHPA, X_L, and the maximum half width of the flow zone, Y_L.

Solution Using Eqs. (7-11) and (7-12), the downstream extension of the WHPA, X_L, and the maximum half width of the flow zone, Y_L, can be calculated as

$$X_L = -\frac{5{,}450\ \mathrm{m^3/d}}{2\pi(5.45\ \mathrm{m/d})(122\ \mathrm{m})(-0.003)} = 435\ \mathrm{m}$$

$$Y_L = \pm\frac{5{,}450\ \mathrm{m^3/d}}{2(5.45\ \mathrm{m/d})(122\ \mathrm{m})(-0.003)} = \pm 1{,}366\ \mathrm{m}$$

7.4.5 Hydrogeologic Mapping

This method uses geologic, geophysical, and dye tracing techniques to map flow boundaries and time-of-travel criteria. To determine flow boundaries, geological studies of the aquifer are undertaken to characterize the rock for the purpose of identifying permeable or impermeable boundaries. Geophysical investigations are used to determine the thickness and extent of unconfined aquifers. The groundwater hydrologic divide can be used to define the flow boundaries as well. Of course, hydrologic divides can be determined by mapping groundwater contours.

Moreover, this method can be used to delineate the WHPA for karst formations. Hydrogeologic mapping is well suited to conditions dominated by near-surface boundaries, which are found in glacial and alluvial aquifers with high pore velocities. Besides, it is suitable for highly anisotropic aquifers, such as fractured rocks and conduit flow in karst formations.

This delineation technique requires expertise in geological sciences and ability to make judgments on what constitutes flow boundaries. This method may prove expensive if hydrologic information is limited and direct field investigation becomes necessary.

7.4.6 Numerical Flow/Transport Models

Analytical methods are based on several assumptions. These assumptions include homogeneous and isotropic formations, two-dimensional flow, and simplified boundary conditions. Analytical methods also ignore the effect of temporal variation of pumping rates and other hydrological features, which may have significant effect on the shape and extent of the WHPA. For example, the arbitrary fixed radius method defines the WHPA by drawing an arbitrary circle around a well. The radius of the circle may depend on various factors, such as distance to the nearest source of contaminant and the number of years of desired protection. The cost, as well as the level of protection and its legal and environmental implication, determines the method that is used to delineate the WHPA and the input parameters used in each method. The most accurate delineation of WHPA is only possible through numerical modeling of groundwater flow and contaminant transport. Numerical modeling is the most expensive and time-consuming method. The accuracy of the modeling depends on the availability and accuracy of detailed hydrologic and geologic data. Numerical methods do make it possible to account for complex geologic and hydrologic boundaries, heterogeneous characteristics of the water bearing formation, and temporal variation of the pumping rates. Another important feature of the numerical models is the ability to simulate groundwater flow and contaminant transport in a three-dimensional domain.

Groundwater flow in the vicinity of a well may or may not be two-dimensional, depending on the geological characteristic of the aquifer and the well geometry. In addition to the assumption of two-dimensional flow in the first four methods, other assumptions include homogeneous and isotropic aquifer, infinitely extended boundaries, and fully penetrated and fully screened wells. These assumptions may overestimate the extent of the WHPA and, thus, increase cost without the benefit of increased protection. Conversely, the simplified methods may underestimate the extent of the WHPA and thus reduce the level of protection. Ramanarayanan et al. (1992) demonstrate that analytical methods underestimate the WHPA in comparison to numerical models, the latter of which better account for hydrologic features and temporal variation of pumping rates.

Several computer models have been developed to simulate the groundwater flow and contaminant transport. MODFLOW (McDonald and Harbaugh 1988), developed and maintained by the U.S. Geological Survey, can be used to simulate groundwater flow in a three-dimensional domain. MODFLOW can be coupled with other models, such as MT3D (Zheng 1993) or PATH3D (Zheng 1991), to simulate the contaminant transport around a single or multiple wells. Whereas MT3D can account for advection, dispersion, and chemical reaction of the contaminant, PATH3D accounts only for advection, thus resulting in a conservative estimate of the WHPA. Models such as MT3D can be used to develop contingency plans in case of a contaminant spill within the WHPA.

7.5 A CASE STUDY

Ten water-supply wells installed by the City of Las Cruces in the southern part of New Mexico were chosen for this case study. The City of Las Cruces WHP program was comprised of three phases:

1. Wellhead delineation,
2. Field assessment and contaminant inventory, and
3. Implementation.

7.5.1 Wellhead Delineation

The following describes the process of developing a wellhead protection program for the City of Las Cruces in southern New Mexico. The pumping rates from the wells ranged from 5,450 m^3/day (1,000 gal./min.) to 11,000 m^3/day (2,016 gal./min.). WHPAs were delineated for 10- and 20-year times-of-travel for the sake of comparison. The WHPAs for the 10 wells were delineated using the simplified EPA (1987) method. These results were compared with those obtained from more detailed three-dimensional interpretation of wellhead protection using a combination of a MODFLOW (McDonald and Harbaugh 1988) groundwater flow model and a PATH3D (Zheng 1991) particle-tracking model.

7.5.1.1 Hydrologic Models Both MODFLOW (McDonald and Harbaugh 1988) and PATH3D (Zheng 1991) were used to define the

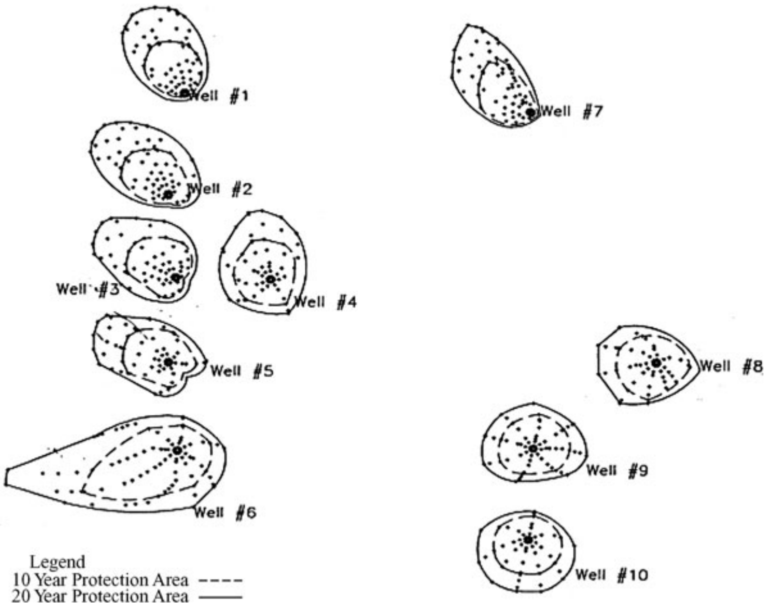


Fig. 7-4. Wellhead protection areas for 10 wells supplying the City of Las Cruces, New Mexico

10- and 20-year WHPAs around the 10 water-supply wells for the City of Las Cruces. These wells are located in the unconfined aquifer of the East Mesa formation. The water table in the aquifer is located at 120 m below the ground surface. The bedrock, or so-called bottom of the aquifer, is located at 300 m below the ground surface. The delineated areas were defined by backward tracing of particles placed in the wells for specified periods.

Fig. 7-4 shows the resulting two-dimensional views of the WHPAs produced by numerical modeling. The configuration of the delineated WHPA around each well depends on the hydrologic and geologic parameters surrounding the well. Using an arbitrary circle of 30 m (1,000 ft) around each well closely approximates the extreme boundaries of the 10-year protection zone in all the wells with the exception of Well No. 6 in which the pumping rate was higher than the average. From a practical point of view, however, protecting odd-shaped areas (such as those shown in Fig. 7-1) is difficult using circles alone, and the use of other shapes (such as rectangles or squares) might be necessary, because they better represent the delineated WHPA and conform to the land use planning in the area.

Theoretically speaking, the WHPAs presented in Fig. 7-4 represent 10 years and 20 years of protection, respectively. In reality, however, particles may reach the well sooner due to the presence of hydrologic or geological boundaries. For example, the delineated 20-year WHPA around Well No. 7 in Fig. 7-4 corresponds to a 20-year particle travel time on the northwest direction and only a 2-year travel time on the southeast direction. This is due to the presence of a geologic boundary in the southeast direction, which results in a shorter travel time. In this case, it is impossible to define a 20-year protection area around this well because of variable hydrogeologic characteristics surrounding the well. But a 2-year WHPA is possible and can be defined quite conveniently. In the case of Well No. 7, the protection area corresponding to shorter travel time implies a higher protection requirement in one side of the delineation zone compared to the other side, thus resulting in different economic and environmental implications, which would require more monitoring and priority given to the area corresponding to shorter travel time.

7.5.1.2 Vertical Contaminant Transport An important factor, which is often ignored in determining WHPA, is the potential for vertical transport of contaminants. The vertical hydraulic gradient is considerably smaller than horizontal gradient. This implies that defining the WHPA on the basis of horizontal contaminant transport alone will overestimate the extent of the WHPA significantly, resulting in costly overprotection of the well. This is especially true where the well screen is below the water table. Fig. 7-5 shows horizontal and vertical cross sections of a numerically-simulated contaminant plume for a well in the City of Las Cruces. In Fig. 7-5, the contaminant has traveled 1,300 m horizontally within 20 years while it has traveled only 3 m vertically within the same period. In this well the screen is 100 m below the water table, thus requiring a long time for the contaminant to reach the screen. The scenario could be different if the well were fully screened and subject to contamination introduced at the water table. Fig. 7-5 shows also that even within the same well, the magnitudes of horizontal and vertical contaminant transport vary depending on direction.

Fig. 7-5 shows not only the importance of vertical transport analysis but also the effect of well configuration on the economic and environmental implications of the WHPA. In general, the configuration of WHPA depends on duration of protection, hydrogeological characteristics of the aquifer, and well design and configuration. Well design can have a significant effect on the protection of a water well. Fig. 7-6 shows a water-supply well for the City of Las Cruces. The well is drilled in a two-layer aquifer where a 250 ft (76 m) unconfined upper aquifer is underlain by a confined lower aquifer. The well is screened partially, only in the lower aquifer. Further, the upper aquifer is separated from the lower aquifer by a clay aquitard. In this case, the clay layer effectively prevents the transport of any surface-borne contaminant from reaching the well screen, even if the contaminant were to be introduced within the WHPA. The initial

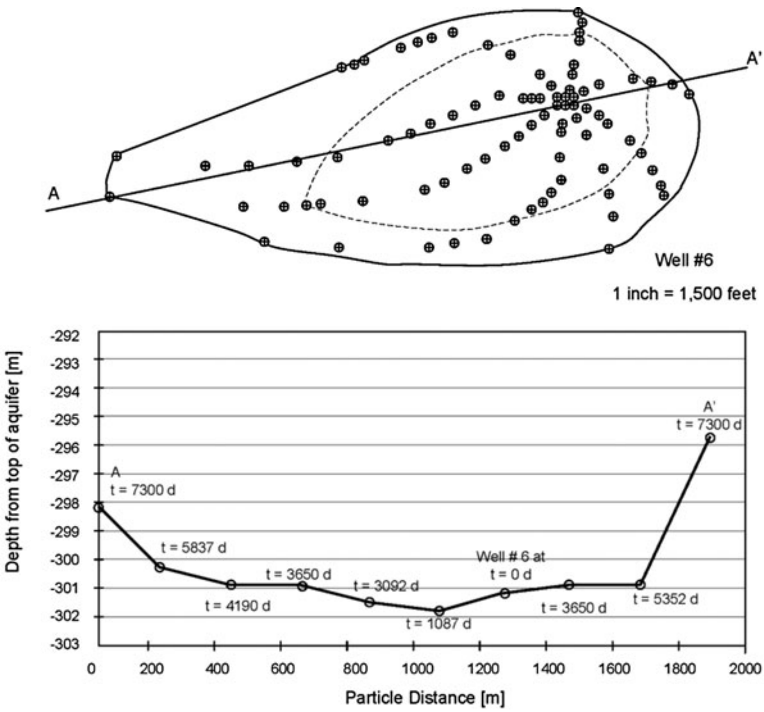


Fig. 7-5. Comparison of horizontal and vertical contaminant transport for correct delineation of the WHPA

borehole is grouted to prevent short circuiting, and there is an additional hydraulic buffer zone of 240 ft (73 m) above the screen. A WHPA defined for this under any of the aforementioned methods would be overly conservative.

7.5.1.3 Comparison with Analytical Method WHPA is a modular, semi-analytical groundwater flow model recommended by the EPA (1987) to generate wellhead protection areas. This model was used to generate the 20-year protection area for Well No. 6, and its results were compared with the wellhead protection zone defined using PATH3D (Fig. 7-7). The first noticeable difference is the shape of each wellhead protection area. The WHPA model produces a more uniform shape due to the homogeneity assumption of the model. The PATH3D results shows a larger and more realistic shape taking into account the hydrogeological variability around the well. The numerical models generally result in a more realistic delineation of the WHPA; however, within a given hydrologic model, the results may vary depending on the input parameters. For example, large

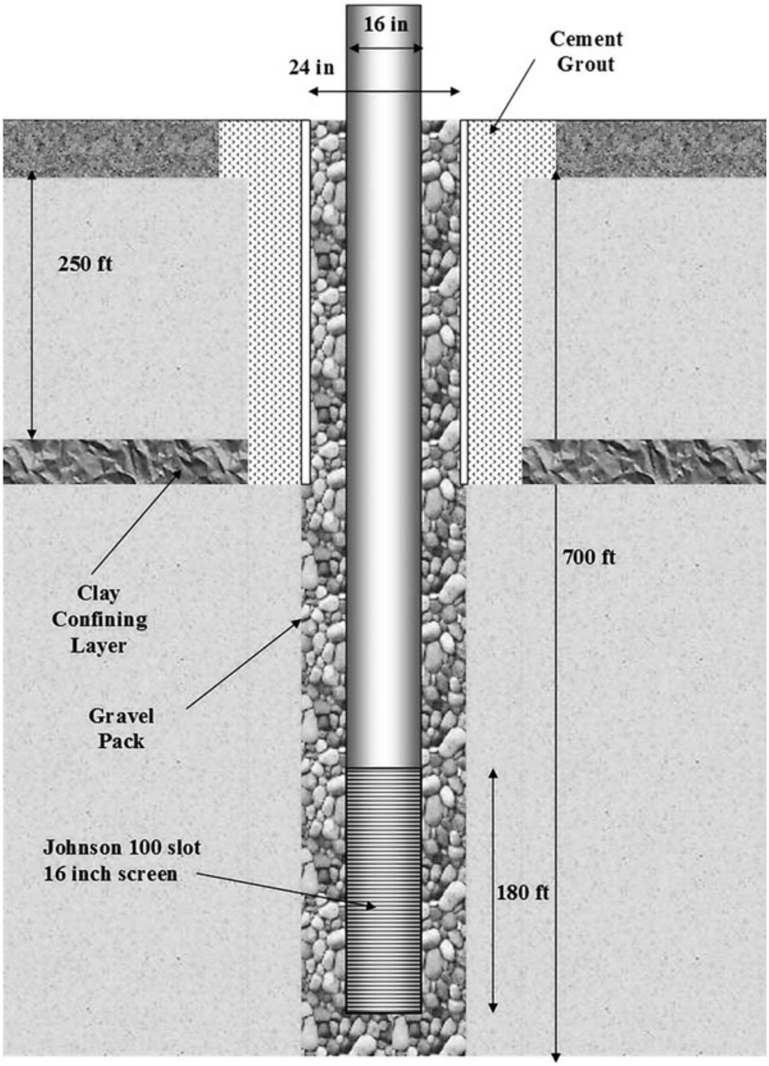
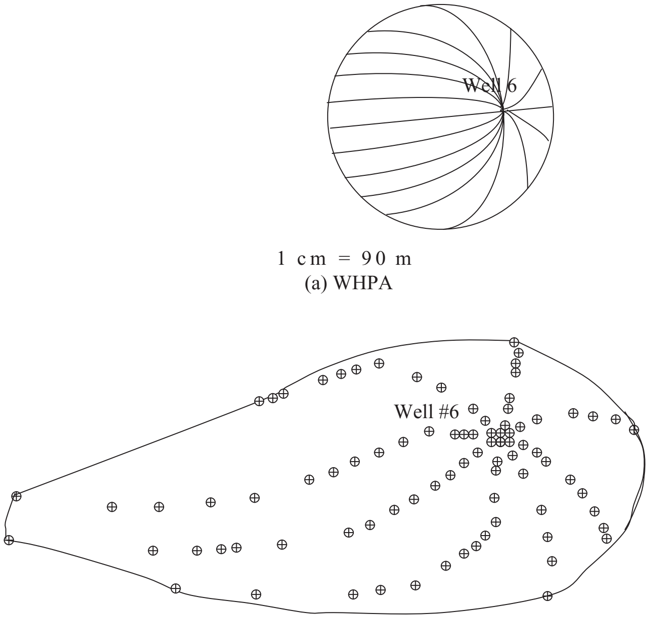


Fig. 7-6. Vertical cross section of a water supply well (Well 58, Las Cruces, New Mexico)

grid sizes used in numerical models may underestimate hydraulic gradients and consequently overestimate the WHPA. Conversely, numerical models generally are more accurate, but they require more expertise and data. Hence, the use of numerical models may increase the initial cost of delineating the WHPA but may generate cost savings when implementing the WHP program.



1 cm = 90 m
(a) WHPA

1 cm = 180 mm
(b) Path3D

Fig. 7-7. (A) Delineation of the 20-year wellhead protection area using the WHPA computer model assuming homogeneous conditions; (B) Delineation of the 20-year wellhead protection area using the PATH3D numerical model: Direction of flow is from right to left in both cases

7.5.2 Field Assessment and Contaminant Inventory

Once WHPAs were identified, a survey team assessed the areas and surveyed the potential contaminants within the delineated zones. The EPA has identified 111 potential sources of contaminants that could result in contamination of a water-supply well. The existing sources within the delineated wellhead protection zones were compared against the EPA list to identify potential contaminants. Fig. 7-8 shows a typical list of contaminant inventory for a water-supply well in the area.

7.5.3 Implementation

At completion of wellhead delineation and contaminant inventory for each well, steps were taken to secure the wellhead protection zones by fencing, and a land-use plan was developed to protect the wellhead areas from potential contamination. The land-use plan would supplement the

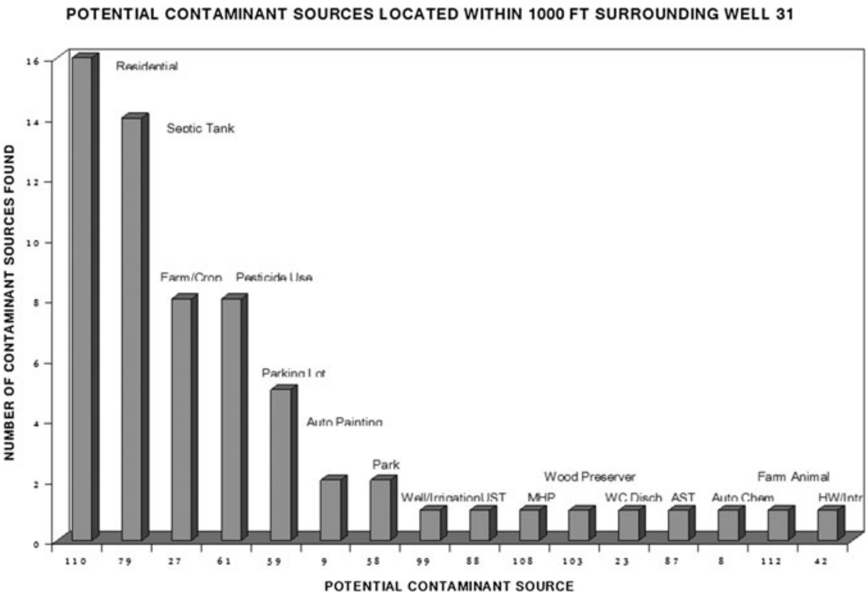


Fig. 7-8. Contaminant inventory for a water supply well (AST = above ground storage tank; HW = highway; MHP = mobile home park; UST = underground storage tank; and WC = discharge to water course)

existing urban planning and land-use program for the community. In addition to the contaminant inventory on the ground surface, the groundwater quality within the wellhead areas was evaluated. In cases where the vadose zone or the groundwater within the ZOC was contaminated already, contaminant transport modeling was used to evaluate the economic and technical feasibilities of remediating and rehabilitating the system.

7.6 SUMMARY

The existing methodologies for delineating a WHPA have been described and compared. Currently, there are no precise techniques available to define the areas around public water-supply wells in a satisfactory manner. The type of methodology used to delineate a WHPA has legal, economic, and environmental implications during the implementation phase of the program. In general the method selected for use for delineating a WHPA should take into account the level and urgency of protection, hydrogeologic characteristics of the groundwater, well configuration, and long-term legal and economic implications of the project.

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CHAPTER 8

MAINTENANCE OF WATER WELLS

Stuart A. Smith

8.1 GENERAL

Water wells, like other mechanical structures or equipment, are called on to operate in harsh natural environments and are subject to loss of performance due to the mechanisms described in the preceding chapters. Degradation of natural performance of water-well systems due to clogging and corrosion mechanisms is aggravated by design limitations and due to less than optimal well construction and development.

The effective maintenance of water-well performance, efficiency, and integrity depend on adopting a multitrack approach of optimal design and construction, a practice of regular maintenance, and prudent operation within the limits of the well and aquifer capacity. Diligent and effective maintenance and vigilant operation can make up for shortcomings in design and construction. This chapter is concerned mostly with water wells; however, it is equally relevant to the maintenance of other types of wells (e.g., monitoring and injection) and related hydraulic structures, such as radial collector wells and the toe drains of dams.

8.2 CAUSES OF WELL PERFORMANCE: PROBLEMS AND FAILURES

An important step in implementing well maintenance is to understand what performance degradation or failure modes are possible. The range of specific possibilities is large and site-specific. Well system problems have a number of identified causes (Driscoll 2008; Borch et al. 1993; Alford et al. 2000; Smith and Comeskey 2009) that often work together to produce conditions encountered at the well sites.

8.2.1 Decline and Failure of Water Wells: Viewing Wells as Systems

A common problem in predicting or assessing causes of well performance decline is attempting to define the problem too narrowly. For example, is it a well problem or aquifer problem? Wells and their performance must be understood as interdependent with conditions in the aquifer in which the well is developed (see Chapters 3 and 4), and well maintenance planning necessarily involves awareness and consideration of many of the issues discussed elsewhere in this manual.

Ideally, a well is designed for specific local aquifer conditions. The intake is designed to access the proper aquifer interval, and if screened, designed to retain the correct particle sizes while permitting water to enter at the optimal velocity and rate. Possible ways in which this harmonious relationship may never be realized include changes in the aquifer conditions (e.g., regional or local water level decline) or a design or installation that provides less than the most efficient possible contact with the aquifer (as discussed elsewhere in this manual).

Well performance expressions, such as specific capacity (volume of output per unit drawdown), depend on both the well's hydraulic conditions and aquifer hydrologic parameters (see Chapters 3 and 4). A reduction in transmissivity (an aquifer-scale property) reduces specific capacity (a well calculation).

A third factor is the mechanical efficiency of the water withdrawal and transmittal system (typically a pump and piping with appurtenances). Pumps themselves ideally are designed and installed for a given set of well performance and head relationships. They also are subject to clogging, wear and tear, and corrosion. Pump discharge lines are subject to clogging and corrosion (see also Chapters 5 and 6).

8.2.2 Types of Well Performance Decline and Failure and their Causes

Table 8-1 is a summary of problems associated with wells and causes of these problems, offered for the purpose of categorizing them for discussion. As the table illustrates, symptoms may have multiple and sometimes interactive causes. Detailed discussions of causes are available from a number of sources, including Driscoll 2008, Smith and Comeskey (2009), Smith and Comeskey (2011), and elsewhere in this manual. A developing theme through the 1980s and 1990s reflected in this literature was that the total range of causes (not just one cause) should be addressed in well maintenance planning.

Table 8-1. Definitions of Poor Well Performance and Causes

Problems	Causes
Sand/Silt Pumping: Pump and equipment wear and plugging	Inadequate screen and filter-pack selection or installation, incomplete development, screen corrosion, collapse of filter pack due to washout resulting from excessive filter pack vertical velocity, presence of sand or silt in fractures intercepted by well completed open-hole, incomplete casing bottom seat (casing-screen break) or casing-screen break due to settlement, ground movement, or poor installation. Pumping in excess of gravel pack and system capacity (oversized pump, pipe breakage, lowered pumping head, etc.).
Silt/Clay Infiltration: Filter clogging, sample turbidity	Inadequate well casing seals, infiltration through filter pack, "mud seams" in rock, inadequate development, casing-screen break due to settlement, ground movement, or poor installation. Formation material may be so fine that engineered solutions are inadequate.
Pumping Water Level Decline: Reduced yields, increased oxidation, well interference, impaired pump performance	Area or regional water level declines, pumping in excess of sustainable aquifer capacity, well interference, or well plugging or incrustation. Sometimes a regional decline will be exaggerated at a well due to plugging.
Lower (or Insufficient) Yield: Unsatisfactory system performance	Dewatering or caving in of a major water-bearing zone, pump wear or malfunction, incrustation, plugging, corrosion and perforation of discharge lines, or increased total dynamic head (TDH) in water delivery or treatment system.
Complete Loss of Production: Failure of system	Most typically pump failure. Also loss of well production due to dewatering, plugging, or collapse.

Continued

Table 8-1. Definitions of Poor Well Performance and Causes (*Continued*)

Problems	Causes
Chemical Incrustation: Increased drawdown, reduced output	Deposition of saturated dissolved solids, usually high Ca, Mg carbonate and sulfate salts or iron oxides, or Fe(II) sulfides. May occur at chemical feed points (e.g., feeding caustic soda to raise pH into a Ca-rich water).
Biofouling Plugging: Increased drawdown, reduced output, alteration of samples, clogging of filters and lines	Microbial oxidation and precipitation of Fe, Mn, and S (sometimes other redox-changing metals that are low solubility when oxidized) with associated growth and slime production. Often associated with simultaneous chemical incrustation and corrosion. Associated problem: well "filter effect": samples and pumped water are not necessarily representative of the aquifer. Often works simultaneously with other problems such as silting.
Pump/well Corrosion: Loss of performance, sanding or turbidity	Natural aggressive water quality, including H_2S, NaCl-type waters, biofouling and electrolysis due to stray currents. Aggravated by poor engineered material selection.
Well Structural Failure: Well loss and abandonment	Tectonic ground shifting, ground subsidence, failure of unsupported casing in caves or unstable rock due to poor grout support, casing or screen corrosion and collapse, casing insufficient, or local site operations.

Source: Data from Borch et al. (1993); Alford et al. (2000).

8.3 PREVENTIVE MATERIAL, DESIGN, AND TREATMENT CHOICES TO AVOID WELL PERFORMANCE DECLINE AND FAILURE

Maintenance of well performance and the prevention of the failure of components depend on good design and proper materials, regular inspection, repair, and treatment of well systems, and early warning detection of symptoms of problems, made systematic by effective record keeping. In this regard, wells are no different than other mechanical or even biological systems. Unfortunately, wells, as a class of engineered structures, seem to suffer historically on both counts. In facility design and project management, there is a tendency to put less engineering effort into wells than in other parts of a facility and not always to pursue quality over price in construction and materials. Further, it is easy for operators of wells to miss necessary symptoms of well performance decline, particularly if wells are not equipped to permit symptom detection.

Material selection and design to prevent or mitigate corrosion are considered in Section 8.3.1, and prevention of incrustation (or encrustation) in Section 8.3.2, as well as in Chapter 5. Optimizing well performance through design and careful execution of the installation plays an important role in preventing a variety of modes of well deterioration. Material selection is crucial in preventing or slowing down the rates of corrosion. Maximizing hydraulic efficiency reduces the effects of clogging mechanisms, for example. Finally, early-warning monitoring for deterioration is considered in Section 8.4, as well as in Chapters 5 and 6, and extensively in Smith and Comeskey (2009).

8.3.1 Prevention of Corrosion

Corrosion prevention in wells (in contrast to water distribution systems, for example) is almost entirely dependent on preventive material selection and not the treatment. A number of mechanisms for metallic corrosion are at work, including

1. Mechanical erosion in well screens, at pump intakes, and within discharge piping,
2. Stress-related cracking,
3. Electrochemical corrosion (cathodic depolarization, differential aeration, etc.), and
4. Biocorrosion (microorganisms inducing or sustaining corrosion mechanisms).

Additionally, plastic and fiberglass resin materials also “corrode” under circumstances where solvents that attack resins are present, as in product recovery wells. Prevention involves obtaining an adequate understanding of potential corrosion mechanisms, specifying and installing materials suitable for the environment, and eliminating aggravating conditions (notably stray or induced electrical currents in metal components).

Choosing corrosion-resistant materials obviously can slow the deterioration of well components and results in longer service life and fewer service interruptions. Corrosion- and deterioration-resistant materials limit recurrence of preventable problems, making the success of the full range of maintenance actions more likely.

The process of identifying potential corrosion mechanisms is difficult but rewarding in long-term asset preservation. One common mistake is oversimplification. Langelier, Ryznar, and chloride-corrosion indexes commonly are calculated and used to make a determination of relative corrosive or incrusting tendencies of waters on metals. Langelier and Ryznar indexes are based on carbonate chemistry and do not account for sulfide or biological corrosion inducing conditions. It is common for groundwater to have a positive (incrusting) Langelier Index for corrosion of metals to occur.

Groundwater containing chloride or with very low dissolved mineral contents (often found in granite) is routinely corrosive. Groundwater with low bulk redox potential (e.g., favoring sulfide reduction) is typically corrosive. Detection of sulfide, hydrogen or methane in groundwater should trigger selection for materials that are resistant to anaerobic corrosion. The contrasting condition (very high redox potential) typically is absent in groundwater.

Another complicating factor is the abundance of discreet microenvironments on the surfaces of well components. Corrosion is observed to occur preferentially adjacent to contacts between formation units with differing bulk redox potentials (e.g., between a carbonaceous shale and a sandstone) and even on casing pipe where biofilms are established within grout.

Biological activity in groundwater and on well component surfaces induce, sustain, and concentrate corrosion activity where materials might pacify under sterile conditions (e.g., Characklis et al. 1988), principally by sustaining contrasting microenvironments and electrochemical cells. It is essential that potential biologically influenced corrosion mechanisms (which include sulfide generation) be identified prior to the selection of well and pump materials. This should be done periodically as groundwater quality and microbial ecology changes over time.

A further complicating factor in wells is corrosion due to contact between metals with differing electron potentials, such as between bronze impellers and cast iron bowls in pumps, with high-conductivity water as the conductor in the cell. A subset of this contributor is electron flow between altered and unaltered metal of the same composition. Welded, threaded, or otherwise stressed metal (such as at pipe joints) is more prone to corrosion than less-altered metal (such as the middle of a pipe joint).

Once potential mechanisms of corrosion are understood, materials can be chosen to provide good service in the well environment. The U.S. Army Corps of Engineers (1999) provides general information on material compatibility. The National Ground Water Association (NGWA) (1998) provides extensive guidance on well casing and screen material selection and installation.

Specific to well equipment, PVC casing, for example, is corrosion resistant under a wide range of water-well circumstances and is suitable for most water-well applications if properly selected and installed. Metal casings are available where plastic or fiberglass casings are not suitable. Mild- or high-carbon steel is often the material of choice due to its tendency to pacify evenly except under biocorrosion attack.

Often stainless steel is specified to resist corrosion. In particular, well screens are routinely specified in stainless steel. Screens are available in mild- or galvanized-steel materials; however, punch-slot louver screens are the only type for which mild steel is recommended, and any protective effect of galvanizing typically is defeated by the metallurgical complexity of screens. Well screen fabrication results in inevitable alteration of the metal use, either mechanically (bending, punching), thermally (welding), or both. Stainless steel in welded, wire-wound screens historically has a reliable service record.

A common mistake in stainless-steel specification is selection of an alloy type not suitable for low redox potential in the well's environment. Passivation of type 304 stainless steels (like high-carbon steel alloys) depends on the formation of an oxide coating on the metal surface. In groundwater containing unreacted sulfides or depositing ferrous sulfide, these oxides are stripped, leaving the metal unprotected against corrosion. Weld joints are another point of vulnerability. One spectacular example (others are available in the literature) was the specification of type 304 stainless steel for deep, long screen intervals in wells of Libya's Great Manmade River Project Sarir wellfields. A large percentage of these (made by a major manufacturer under established quality control) experienced failure of rods at weld points. At least a contributing factor was the occurrence of low-Eh sulfide groundwater resulting from the presence of sulfate-reducing bacteria.

In some environments, no stainless steel is suitable, because stainless alloys (including type 316, usually considered impervious) also are subject to erosion if electrochemical gradients are induced. Monitoring wells at a major facility serving U.S. government energy needs, constructed of type 316 stainless steel and encased in bentonite grout and mild steel isolation casings, experienced wide-scale corrosion of the stainless-steel casings within 6 years, including some instances of penetration at seams in the fabricated pipe. Intact installations (monitoring well, grout, and isolation casing) exhibited measurable electrical current between the casings. Grout samples, when cultured, were found to contain sulfate-reducing and heterotrophic acid-producing bacteria. When immobilized anaerobic biofilms containing such microflora are formed on pipe surfaces, the corrosion resistance of high-Ni/Cr alloys is defeated locally.

Notable product developments (approaching 30 years in service) include the widespread availability of all-stainless-steel and stainless-and-plastic pumps, high-quality rigid plastic pump discharge (drop) pipe with lockable connections, and flexible discharge hose (specifically designed for well pump use) composed of reliable, high-strength, corrosion-resistant material that permits easy pump service. Relatively smooth pump interior surfaces and corrosion resistance increases intervals between pump service events, as well as reduces discharge head loss.

Pump motor and discharge-end product lines can seem to have a remarkable sameness in a competitive market. Conversely, pumps may be marketed for "environmental duty," which may not be superior to other products for aggressive groundwater pumping applications. Some considerations are as follows.

1. Pump end material selection:
   - A material designation of "stainless steel" includes a range of corrosion-resisting alloys. Some do well in anaerobic environments typical of high-organic-carbon water (e.g., type 316 and better), and some do not (type 304).
   - Welding and stamping alters the corrosion-resisting characteristics of stainless-steel alloys so that the manufactured product may not match the resistance of the unaltered alloy. In some cases, a cast stainless bowl selection may be superior.
   - Although versatile, stainless steel may not suit every situation. In some high-chloride, biocorrosive environments, only high-silicon bronze or plastics may provide suitable service life. At higher temperatures or higher radiological activity, some plastics degrade at unacceptable rates. In addition to bowl and impeller materials, selections of bearing materials and designs are factors in selection.
2. Pump end hydraulic efficiency: Higher-efficiency pump ends are recommended. Pump impeller bowl designs and numbers of stages should be matched to the operating head conditions.
3. Achieving a balance of equipment features: As exact matches to conditions and ideals may not be possible; any pump choice is likely to be a balance of features.

8.3.2 Prevention of Encrustation and Well Fouling

Well incrustation and well fouling (including biofouling) result from a complex interaction of the physical-chemical characteristics of pumped groundwater (temperature, pH, Eh, mineral, and metal content), pressure changes in the well, occurrence of biofouling microflora (virtually ubiquitous), well material composition, and well use (see also Chapter 6). Prevention or mitigation of well incrustation and fouling depend on

- Knowledge of groundwater physical, chemical, and biological characteristics, used in preventive design and resulting from maintenance monitoring,
- Preventative design: Reducing intake pressure loss (e.g., reducing screen entrance velocity), reducing corrosion potential (corrosion results in deposition of oxidized products), reducing exposure to encrusting groundwater if possible, and planning for treatment; employing the design-optimizing recommendations elsewhere in this publication is sufficient for this purpose,
- Maintenance monitoring for indications of fouling and performance effects, as discussed in the following section, and
- Preventive treatment in some instances; usually this is conducted when there is a history of performance decline in nearby wells, which appears to be inevitable due to water quality conditions and conducted if indicators from maintenance monitoring predict that performance or undesirable effects on water quality will occur.

Chemical treatment in a preventive mode is a major aspect of maintenance of well and fluid system performance. As well rehabilitation (treatment conducted in reaction to performance decline) has advanced, many product choices have come onto the market. Chemical choices in well treatment can be made on the basis of incomplete information or vendor sales literature—not always the most objective or complete source of information. Also, there is still debate about chemical choices due to the still-incomplete knowledge of performance in actual practice. It is crucial that personnel engaged in the planning of well system operations and maintenance (O&M) become as well acquainted as possible with the features of chemical choices, both for effectiveness and safety.

Listings of chemicals and summaries of their uses are available in numerous industry publications. Detailed information for well treatment is provided in Borch et al. (1993), ADITC (1997), and Smith and Comeskey (2009), and some recommendations in Chapter 6 apply to maintenance. Alford et al. (2000) provide detailed guidance specifically for maintenance treatment. This should be considered as distinct from rehabilitation applications, with which there are some differences in chemical choices and application. Chemical choices should depend on educated evaluations of effectiveness, cost-effectiveness, and reactivity:

1. Effectiveness: The chemical solution chosen should be suitable for dispersing the developing clogging materials.

2. Cost-effectiveness: Cost is frequently cited as an issue in choices made as to whether to use chemicals and electing which ones and how much to use. A better comparison is cost-effectiveness (which factors in results).
   (a) Three factors affect the market price of chemical products used in well cleaning:
      - Actual process and shipping costs,
      - Premiums for purity and standard certification, and
      - Degree of commercial exclusivity (particularly with proprietary products).
   (b) In terms of effectiveness, a more expensive chemical may provide a higher performance return than a low-cost product, and, therefore, is more cost-effective. Among the following acids, for example, organic-based and more concentrated products are more expensive than inorganic acids, primarily due to process costs. However, their effectiveness against biofouling and relative handling safety tend to outweigh the actual material cost differential.
3. Reactivity with constituents of contaminated groundwater is an issue in remediation and monitoring well maintenance, and if reactive compounds are present in groundwater, chemical choices should be evaluated carefully, including the use of hydrochloric acid in high-sulfide groundwater.

O&M management benefits from taking a long-view approach to O&M cost-effectiveness calculations, in other words, to consider cost effectiveness on a life cycle cost basis. Available research (Sutherland et al. 1993) in water-supply applications indicates that even aggressive preventive maintenance (PM) is cost effective compared to losses in efficiency, equipment repair and well failure (Section 8.5). The upfront cost of design, materials and installation, maintenance monitoring (Section 8.4), and treatment (Section 8.3.2) can be minor compared to the cost of operating in a deteriorated state.

The following are summaries of chemical purposes and effects, safety, handling, and effectiveness features.

Acids Acids are used to dissolve hard incrusting materials, including Fe and Mn oxides and carbonate deposits. The selection is complicated, relatively, site-specific, and not unanimous among experts. Tables 8-2 and 8-3 are summaries of the compounds recommended and not recommended by the U.S. Army Corps of Engineers for preventive well maintenance use (Alford et al. 2000) to prevent or slow clogging.

Proper handling, mixing, and use instructions for personnel (and preferably supervision by knowledgeable people) is crucial to success and

Table 8-2. Acid Effectiveness, Safety and Handling—Recommended Compounds

Acid	Effectiveness	Safety and Handling
Acetic acid	Excellent biocide and biofilm dispersing acid. Acidizing to pH < 2 with sulfamic acid recommended (rapidly loses acid power without). Use food or good industrial grade. Relatively safe to handle.	Safety: Use gloves, splash protection, and respirator at barrel end. Does not require placarding for shipment. Handling: These solutions freeze at working ambient temperatures: glacial at 10–13 °C, 84% at 4–5 °C, 15% (working solution) ~0 °C.
Glycolic acid	Very similar to acetic: more products with NSF 61 ratings, less odor, higher acid power than acetic.	Handling and physical properties similar to acetic. Can use about 1/2 to 2/3 as much.
Sulfamic acid	Relatively effective against carbonate scales, and as an acid enhancer for acetic and glycolic acid.	Safety: Relative safe to transport and handle (solid, avoid dust inhalation). Use gloves, dust mask and goggles. Provide proper ventilation. Circulate during mixing. Handling: Solid, less aggressive than HCl (Table 8-3). Not effective alone against biofouling or metal oxides.
Other organic acids	For example, oxalic and citric acids. Useful as chelating agents. Oxalic acid also effective as primary acidizer in low-Ca water. Often form insoluble precipitates in high-Ca waters.	Safety and Handling: Depends on form (typically granular solids), safe to transport.

Source: Data from Alford et al. (2000).

Table 8-3. Common Well Cleaning Chemicals—Not Recommended for Maintenance

Chemical	Effectiveness	Safety and Handling
Muriatic acid (HCl)	Powerful for removing mineral and inorganic metal oxide scale. Relatively ineffective against biofouling and deleterious to stainless steel. Quality is a problem, with cadmium and other impurities often present in industrial grades, although NSF 61 certified solutions are available. NOT RECOMMENDED for maintenance treatments.	WARNING: Extremely hazardous to handle. Volatile liquid: Requires respiratory and splash protection; DO NOT mix with chlorine; use inhibitors for metal but note that some industrial and organic inhibitors should not be used in potable water.
Phosphoric acid	A strong food grade quality acid, readily available, 75%, in 55 gal drums and 12–15 gal containers. Effective against metal and mineral hydroxides. Somewhat effective against biofouling, but no more so than some other mixtures. Can leave phosphate residue behind for bacteria. NOT RECOMMENDED for maintenance treatments.	WARNING: Extremely hazardous to handle. Full breathing mask and splash protection required. Adequate ventilation a must.

Source: Data from Alford et al. (2000).

avoiding long-term damage. This chapter alone and associated chapters should not be considered a sole source of well cleaning and maintenance information.

Note: A thorough review of this text and available literature and presentations on the topic will reveal differences in opinion on chemical choices. Those made in this chapter pertain to well maintenance, as opposed to rehabilitation. Future work may change the conclusions of this and other chapters in the manual.

Biocides These agents are used in an attempt to reduce bacterial populations. In water-supply well cleaning (maintenance or rehabilitation), this is not a primary objective (Borch et al. 1993; Alford et al. 2000, Smith and Comeskey 2009). Of these, chlorine compounds are most commonly recommended for well PM treatment, although peroxide compounds have some limited application (Alford et al. 2000). Most typically chlorine is used in the sodium (Na) or calcium (Ca) hypochlorite form (AWWA 2010). Na hypochlorite is liquid and more likely to retain solubility in high-TDS solutions than Ca-hypochlorite compounds.

One procedure used to limit and remove biological incrustation is the so-called shock chlorine treatment. Procedures for shock chlorination and bacteriological testing for the disinfection of wells for potable water service are described by AWWA (2013). Well cleaning (maintenance and rehabilitation) is not standardized but methods are prescribed in Chapter 6 and elsewhere in the literature (Borch et al. 1993; Smith and Comeskey 2009). Concentrations as high as 500 mg/L of chlorine (often higher) often are specified for rehabilitative applications of shock chlorination, but lower values, properly mixed to favor the hypochlorous acid ion form in solution, are more effective (see Chapter 6). Chlorine is a powerful oxidant that reacts with reductive organic compounds, causing chemical alteration to more difficult-to-treat forms or potentially explosive situations.

In some cases, water heated to the scalding range (around 54°C) is sufficient for PM treatment without chemicals at least in the short term. Heat propagates from the application source but typically accumulates in the well structure due to the poor thermal conductivity of soil materials. Heat actually can enhance growth away from the thermal shock zone, as well as cause drying and shrinking clays, such as bentonite grout. Using heat alone is also very inefficient in terms of fuel or power to generate thermal energy. The best approach to using heat is in a process, such as the blended chemical heat treatment method (described following) with a wise selection of chemicals.

Sequestration In well treatment, these compounds are used most properly in low concentrations in chemical blends as aids in acidizing mixtures to retain biofilm and metal oxide components in solution for removal, once they are dissolved and dispersed in the water column. Examples are various polyphosphates, pyrophosphates, and polyacrylamide-based compounds. In addition, acetic acid and citric acid, and some proprietary acid formulations also have related chelating properties.

- Phosphate-containing compounds are the most controversial of this class of compounds. USACE guidance is that these compounds are not recommended for PM treatment (Alford et al. 2000). Residuals of the compounds themselves (higher molecular weight [MW] polymers) and breakdown products (low-MW pyrophosphate and orthophosphate or P) remain behind in the formation (attached to clays). The presence of an enhanced P resource induces enhanced biofilm development, often at the edge of development influence. The recommended practice of chlorinating during and after the use of polyphosphates actually may increase P residues. Chemists involved in their development in turn contend that newer liquid compounds do not leave P residues.

- Polyacrylamide and similar polyelectrolytes provide the desired effects of dispersing clogging deposits and clay/silt buildup without being P sources. Microorganisms do not attack these compounds readily. They should be handled, used, and ultimately disposed of according to manufacturers', suppliers', and material safety data sheet (MSDS) instructions.

The chemicals mentioned are all reactive to some degree and pose risks to skin, mucous membranes, and other soft tissues of humans, and potentially to the environment if handled improperly. They should be used only by trained personnel familiar with their safe use and who are equipped with proper respiratory and skin protection. MSDS and other safety information must be reviewed by all personnel involved (mandatory). No well maintenance or rehabilitation project should employ personnel or contractors in well cleaning who cannot clearly demonstrate competence in relevant chemical knowledge (including knowledge of mixing and application).

Typically, no one chemical type will address all incrustation and biofouling removal, suspension, dispersal, and repression needs. Blending strategies can permit more effective removal of multiple problems or treat a single difficult problem more effectively (Smith and Comeskey 2009). The exact blend of chemicals for a particular well field situation is determined on the basis of an analysis of the needs for cleaning the clogging materials present and groundwater quality. Also, it should be emphasized that all chemical mixtures are far more effective with adequate mechanical mixing and development and should be specified based on an adequate analysis of the problem.

8.3.3 Development in Preventive Maintenance Well Treatment

Well development, which is the mechanical agitation of fluids in a well intended to improve hydraulic conductivity, is also important in well rehabilitation or redevelopment (Chapter 6) for best results. The necessary procedures (which also pertain to Chapters 6 and 8) are discussed in Chapter 4 and its sources.

PM well treatments often are conducted using passive dosage of chemicals and sometimes with mild surging with the installed well pump. NGWA (2002) reinforced advice and experience that chemicals (in that case, chlorine) should be mixed by agitation in the well column. PM treatments also may require agitation to provide sufficient chemical contact with developing clogs in the formation material. Thus, they can resemble light- or short-duration rehabilitation treatments. In some cases, redevelopment may be sufficient on its own or the only treatment permitted. Where possible, very light chemical treatments augmented by redevelopment are preferred over high chemical doses and insufficient redevelopment.

8.4 PREVENTIVE MAINTENANCE, MONITORING METHODS, AND RECORDS

The previously described problems (Section 8.2) can be prevented and mitigated by effective O&M (Section 8.3), but to do so requires valid information on the environment, hydrology, and material performance of the well system produced through a process known as maintenance monitoring. The ideal working methodology is to detect deteriorating effects in time to prevent problems or soon enough to employ the most effective countermeasures. This maintenance monitoring system should include valid information on well construction, dimensions, and hydraulics, including history; aquifer environment and hydrology; and material performance of the well system.

8.4.1 Information to be Collected for Preventive Maintenance Monitoring

Table 8-4 (modified from Alford et al. 2000) is a summary of useful information to collect about wells for both troubleshooting and predicting problems in PM. A detailed discussion of the use of these methods is provided in Alford et al. (2000).

In a PM monitoring program (in contrast with a troubleshooting analysis), system water and quality and performance monitoring are compared over time to establish trends. To the information in Table 8-4 should be added additional information about the wellfield environment useful in interpreting trends (see Table 8-5).

Table 8-5 provides a troubleshooting summary guide for well maintenance. It is based on the prevention-mitigation matrix drafted for Borch et al. (1993). Refer to descriptions in Tables 8-1 and 8-4 of problems and well monitoring methods discussed. Additional information helps in interpreting trends. In preventive maintenance, once a problem, such as

Table 8-4. Summary of Recommended Preventive Maintenance Monitoring Parameters

Category	Monitoring Parameter
Hydraulic	Flow and drawdown for specific capacity (level rise in injection wells).
	Total amount of pumping time and quantity pumped per year.
	Periodic step-tests for well and pump efficiency, and linear and nonlinear loss estimates.
	Power and fuel consumption for pump efficiency.
Physicochemical	Total and ferric iron, and total manganese (and other metals as indicated) looking for changes due to deterioration.
	Important cations (Ca, Mg, Na) and anions as identified, including sulfides, sulfates, carbonates, and bicarbonates.
	pH, conductivity, and redox potential (Eh) where possible (instrument readings may be replaced by checking ratios of Fe [total] to Fe^{2+} [soluble]).
	Turbidity or total suspended solids calculation of product water.
	Calculation of corrosion/incrustation potential using a consistent method—as a piece of information and not as a predictor.
Microbial	Total Fe/Mn-related bacteria (IRB), sulfur-reducing bacteria (SRB), slime-forming and other microbial types of maintenance concern as indicated.
Visual/physical	Pump and other equipment inspection for deterioration.
	Borehole TV for casing and screen deterioration.

Source: Data from Alford et al. (2000).

a tendency to biocorrosion, is identified, the same choice of parameter monitoring can be employed.

To make use of such information over time the following must be done:

- A maintenance system must have organized and accessible records.
- Information collection should start with the project design phase and continue throughout the working life of the extraction and injection system.
- Records must be reviewed regularly by qualified personnel.

Table 8-5. Summary of Troubleshooting Guide for Well Maintenance

Problem (Refer to Tables 8-1 and 8-4)	Review Area-Regional Ground Water Conditions	Review Design and Construction Records	Conduct Downhole TV Inspection	Check SWL and PWL and Review Histories	Conduct Step Tests and Review History	Test for Biofouling Parameters and Review Records	Test for Physical-Chemical Parameters and Review Records	Test Pump Mechanical Condition and Performance and Changes in Head Relationships	Check for Power Malfunction
Sand/Silt Pumping		•		•	•				
Silt/Clay Infiltration		•	•	•	•				
Pumping Water Level Decline	•	•	•	•	•	•	•	•	
Lower (or Insufficient) Yield	•	•			•			•	•
Complete Loss of Production		•						•	•
Chemical Incrustation	•	•				•	•		
Biofouling Plugging	•	•	•			•	•		
Pump/well Corrosion	•	•	•		•	•	•	•	
Well Structural Failure	•	•	•	•					

Source: Data from Borch et al. (1993); Alford et al. (2000).

In general, maintenance monitoring approaches should be tried and reviewed over time and adjusted based on experience. They must be implemented as part of a systematic maintenance program involving

- Institutional commitment,
- Having a goal of deterioration prevention,
- Systematic monitoring as part of site maintenance procedures, and

- Employing a method of evaluation to determine what maintenance actions are necessary.

In any case, monitoring approaches and responses need to be site-specific and likely will require adjustment during implementation.

Too often the significance and central importance of data are overlooked in the context of the scope of the whole project. What may seem to be minor clerical details to those responsible for a project's overall management can be important later in site operations.

A minimum of baseline data on each well are needed to assess and interpret the well's performance through time. Data trends are more reliable if data collection is incorporated into the project plan at the onset. There is a tendency to omit maintenance planning, data gathering, and repair costs when bids are higher than budgeted or to fund these tasks inadequately as costs are adjusted to available funds during project management. Budgets to fund facility water activities themselves can be unrealistic in this regard in not considering the real costs of maintenance adequately (Section 8.5).

Although Table 8-4 lists a range of useful parameters, it is helpful to consider microbial biocorrosion and biofouling analyses specifically. Standards for biofouling analysis (e.g., *Standard Methods for the Examination of Water and Wastewater*, Section 9240, APHA-AWWA-WEF 2012) are only recently catching up to the state of the art (Smith and Comeskey 2009). McLaughlan et al. (1993) note that there is no set protocol for MIC analysis in wells. This remains the case to some degree (see also Chapter 5). Smith (1996) and Smith and Comeskey (2009; 2011) provide a framework for a PM biofouling monitoring methodology.

BART tube methods (Droycon Bioconcepts, Inc., Regina, Saskatchewan) described in Cullimore (2007) and Section 9240 and field-evaluated by Smith (1992) permit field collection and inoculation into dehydrated media to form a culture broth that can be observed for speed and type of reaction. These patterns can be linked to the occurrence of certain microbial consortia (Cullimore 2007) and are useful in qualitative biofouling assessment. A similar methodology has been developed independently and is in use regionally (Gariboglio and Smith 1993, Section 9240), and some also use modifications of other Section 9240 media. These systems have performance advantages over using heterotrophic plate count as a microbial indicator. Alternatively, ATP luminescence and microbial genetic identification is employed in characterizing biofilm composition and activity (see Chapter 6).

Biofilm and solids samples can be examined by light microscopy for evidence of morphologically distinct microflora, such as stalked or filamentous iron bacteria, and solids morphology. They also can be analyzed for mineral and elemental content. These are more typically troubleshooting rather than PM monitoring methods. The absence of "iron bacteria" structures should not be interpreted as conclusively indicating an absence of such microflora.

8.4.2 Records and Software for Preventive Maintenance Monitoring

Records for well maintenance are essential. It is impossible for a manager to remember all data and other information effectively, such as procedures, and personnel turnover requires that records be available if successors are to understand the history of a well or wellfield. Maintenance monitoring assumes that records of data will be kept in order to establish trends (Section 8.4.1). Records may be entirely analog and consist of hard copy files. For many, this is the most effective and foolproof system. However, facilities of all kinds increasingly are employing computer software to manage maintenance. A variety of options are available.

A large fraction of maintenance information can be managed using off-the-shelf database and spreadsheet systems, such as those found in commercially available integrated office software packages. Databases, such as Microsoft Access or Lotus Approach, can store any desired data used in well maintenance, as well as costs and budgeting analysis conducted with spreadsheets. A scheduling program can provide a way to prompt maintenance exercises, as can an analog wipeboard.

A small selection of software packages are available that integrate data management, scheduling, and work order generation. Those marketed for the water and wastewater market (e.g., AllMax Software, Inc., Kenton, OH) provide a one-platform solution if that is desired. Triggers, such as a floor for specific capacity for a specific well, can be set to start a well treatment work order. Software for similar facilities, such as refineries, also can be adapted. Maintenance of wellfields is not conceptually different than other complex facilities subject to environmental degradation.

Supervisory control and data acquisition (SCADA) systems that automatically collect data, such as water levels and flows from wells, are highly useful in providing trend information with relatively little effort. For many well fields (especially widely dispersed systems or those with eight or more wells) SCADA is cost effective compared with manually checking drawdown and flow. It is important to note that sensors have to be maintained and calibrated against manual measurements, or the data collected may be invalid and therefore useless or misleading. Such systems benefit from expert design that best incorporate features (such as specific capacity alarms) that fit the hydrogeology and engineering performance of the system.

It is important to note that hard copy files (invoices, specifications, videos, etc.) are a necessary adjunct to software-housed data records unless very sophisticated archival software systems are employed. Finally, it is more important to have a deliberate systematic means of collecting, storing, accessing, and assessing data than a sophisticated means. Accuracy and assessment are crucial; a large body of data that is inaccurate or with large gaps that no one can interpret is useless.

8.5 SCHEDULE OF WELL MAINTENANCE ACTIVITIES

A maintenance schedule should be based on the principle of establishing a data baseline and then settling into less-frequent (or more intense) PM activity if conditions warrant. Table 8-6 is a summary recommendation for first-year maintenance activity frequency for a valuable well, such as one for a municipal water supply.

Maintenance (including monitoring) intervals can be reduced as trends are established. Typically, on wells performing adequately, the frequency of physicochemical and biofouling parameter testing can drop to quarterly if little change in conditions is noticeable after one year. Table 8-7 summarizes a post-first-year PM schedule.

Actual schedules and parameter lists should be developed in a site-specific way. Some wells and wellfields are relatively trouble free or so well known that a few parameters need to be monitored (flow and drawdown are absolute minimum choices to establish specific capacity). At the other end of the continuum are wells subject to intense chemical and biological attack, such as those involved in management of groundwater contamination. These may require either intense monitoring or frequent treatment.

Water Systems Council (1987; 2001) provides detailed troubleshooting guides for well pumps and their motors and pressure systems. Schedules of PM treatments should be established on the basis of site-specific knowledge of clogging conditions.

8.6 ECONOMICS OF WELL MAINTENANCE

The primary obstacle to initiating a robust program of well maintenance is the perceived cost involved. Going from a regime of little or no maintenance monitoring in an established system does involve some cost in personnel time, equipment, materials, and expert assistance from time to time. Beyond the value judgment that maintenance of existing assets is a virtue, justifying these investments requires some form of cost–benefit analysis. Most analyses of cost–benefit are made in a "first world" economic context, in which budgets may be tight but the resources are available to replace fixtures, such as wells, if necessary. In developing or

Table 8-6. First Year Preventive Maintenance Monitoring Schedule

Inspection Task	Frequency
Physical inspection	
Borehole color video	Initially, then at pump service intervals
Surface facility inspection: Inspect and clean equipment as needed.	Monthly or whenever visited
Examination of pulled components	As needed (at least test pump if not pulling it annually)
Hydraulic performance	
Well discharge (volume rate and pressure)	Weekly (recommend installation of automated data collection)
Drawdown	Weekly (recommend installation of automated data collection)
Conduct graphical analysis.	Monthly
Specific capacity test (well hydraulic performance).	Annually
Pump performance: Conduct 5-step “pump” test, compare to “nominal” data.	At least annually or at recommended shorter intervals in pump service is severe (*Q/s* and pump test can be a single operation)
Electrical (power)	
System and motor V, A, ϕ, Ω	Weekly. Recommend installation of current monitors with alarms
Physicochemistry	
Inorganic parameters and pH, mV, Eh, and temperature	At well start-up and monthly using on-site instruments (calibrated)
Suspended particulate matter (sand, silt, clay)	At well testing then quarterly
Turbidity (adds colloidal)	In-line monitors (continuous)
Biofouling microbial component	
BART analyses: Wide suite (IRB, SRB, SLYM, DN) or suitable alternative	At well start-up for baseline, then monthly
Biofilm flow cell for microscopy	Quarterly for baseline then annually
Treatments and service	
Well hydraulic improvement and pumping systems	As testing indicates *Q/s* drops below 90% or pumping system degrades
Instrumentation calibration	In accordance with recommend procedures

Source: Data from Alford et al. (2000).

Table 8-7. Long-term Preventive Maintenance Monitoring Schedule

Inspection task	Frequency
Physical inspection	
Borehole color video	At pump service intervals Concentrate on screen and other stress points.
Surface facility inspection: Inspect and clean as needed at sampling points.	Quarterly or each visit
Examination of pulled components	As needed (at least test pump if not pulling it annually)
Hydraulic performance	
Well discharge (flow rate and pressure)	Weekly (recommend installation of automated data collection)
Drawdown	Weekly (recommend installation of automated data collection)
Conduct graphical analysis	Quarterly
Specific capacity test (well hydraulic performance)	Annually or at recommended shorter intervals
Pump performance: Conduct 5-step "pump" test of centrifugal pumps and similar wear analysis of positive displacement pumps, compare to "nominal" data.	At least annually or at recommended shorter intervals in pump service is severe (Q/s and pump test can be a single operation)
Electrical (power)	
System and motor V, A, ϕ, Ω	Weekly (recommend installation of current monitors with alarms)
Physicochemistry	
Inorganic parameters	At least quarterly using project on-site instruments (calibrated)
Suspended particulate matter (sand, silt, clay)	Manually at well testing then quarterly
Turbidity (adds colloidal)	In-line monitors (continuous)
Biofouling microbial component	
BART analyses: Wide suite (IRB, SRB, SLYM, DN) or alternative	Quarterly until patterns develop then focus on types that change.
Biofilm flow cell for microscopy	Annually on selected wells
Treatments and service	
Well hydraulic improvement and pumping systems	As testing indicates Q/s drops below 90% or pumping system degrades

Source: Data from Alford et al. (2000).

redeveloping economies, replacement of assets once installed may be very difficult. In this case, maintenance is mandatory if the well, for example, is to continue functioning, and budgeting must reflect available funds only and not whether maintenance is more or less costly than permitting the well to deteriorate then replacing it.

Helweg et al. (1983) and Chapter 3 set forth cost-calculation and cost–benefit analyses that provide a means to compare costs of operation under varying head and efficiency conditions, taking into consideration costs of power. The cost-calculation equation can be used to establish optimal specific capacity targets to provide needed volumes of water under various constraints and to calculate cost of operation over time. Calculating estimated costs of operation under differing efficiencies also could be used to calculate the "payback period" for well maintenance efforts. An example calculation is included in AWWA (2003).

Cost–benefit also can be calculated and may be strictly economic or have a mixture of quantifiable and semi- or nonquantifiable characteristics. Helweg et al. (1983), Jordan (1998), AWWA (2003), and Chapter 3 of this manual provide examples of such cost–benefit calculations. Benefit (B) can be defined in a variety of ways, including more water available for sale in a year, reduced costs to supply water, or avoiding having to turn to a high-cost alternative, such as purchased water, new wellfield, or surface water. In establishing "B" in justifying maintenance costs (C), the very high "C" of alternatives, such as importing water or surface water treatment, is certainly an issue in comparisons. An example of one such calculation is provided in the SWWI (2000) and economic analysis of wellfield operations is further discussed in Smith and Comeskey (2009).

Although strict cost–benefit balances are valuable, the U.S. Bureau of Reclamation (USBR) (1992), in addressing the economic analysis of maintenance, recommends that such analyses include factors beyond mere economic return. In the case of the USBR's Closed Basin project, which manages 170 wells supplying water to the Rio Grande under the U.S.–Mexico Rio Grande Compact, reliable water output meeting its target was identified as a "nonquantitative" benefit. As reliable yields are not a sure possibility due to a long-term well deterioration, the expense of enhanced well maintenance could be considered justifiable whether or not a dollar value could be placed on produced water; however, an attempt to establish such a "B" was recommended (Ground Water Science 2000).

Benefits that are difficult to quantify on the surface may be calculated by assigning economic value if monetary values can be placed on benefits using available methods in water economic value (e.g., Young and Gray 1972). In the case of the Closed Basin project, it was recommended that a monetary value should be placed on the water pumped into the Rio Grande, using some value, such as dollars per unit of water (typically acre-feet in the United States) available to upstream Colorado irrigators or potential downstream customers, such as the City of El Paso (switching to surface water).

Sutherland et al. (1993; 1996) offer a methodology specific to justifying maintenance monitoring costs versus reacting blindly to well deterioration. This spreadsheet-based method compares costs over a period of years (up to 20). Two variations exist: one employing representative costs, and using actual costs if they are known. Both total differences and annual comparisons can be made. Generally, both life cycle and annual variability in costs are lower for utilities employing routine maintenance monitoring for well-deteriorating parameters. Regardless of the cost differential, the predictability of maintenance costs has many advantages when compared to reacting to well deterioration in a crisis-management manner.

8.7 THE FUTURE: FIELD AND LABORATORY RESEARCH ON WELL MAINTENANCE

Field and laboratory research relevant to well maintenance has been ongoing since about 1980. In the time since then, simple field-usable biofouling and biocorrosion analysis methods have been developed (e.g., BART and MAG testing tubes and sampling innovations) and described (Smith 1992; Gariboglio and Smith 1993; McLaughlan et al. 1993; Cullimore 2007; Smith and Comeskey 2009), and virtually all the objective analysis of rehabilitation results conducted since 1960 (e.g., Borch et al. 1993; SWWI 2000; Smith and Comeskey 2009). Updated summaries of sources and current research may be found at Ground Water Science (2012a). Additionally, the SWWI of the Canadian Prairie Farm Rehabilitation Administration presently is assessing the effects of treatment chemicals and application methods under field and laboratory conditions.

It is important for engineers and managers making decisions about well and groundwater system maintenance and improvements to consult a range of sources of information, preferably current. Due to the fast-moving nature of this research, it is probably most fruitful to supplement text sources by periodically researching websites devoted to well maintenance and well rehabilitation to learn about latest developments. Experience with specific well fields will be the final filter in decision-making processes.

8.8 SOLVED DESIGN EXAMPLE 1

The Department of Public Works and Utilities (DPWU) of the City of Elkhart, Indiana State, IN, owns and operates South Wellfield consisting of Wells 1, 2, and 3. Due to clogging, the performance level of the three

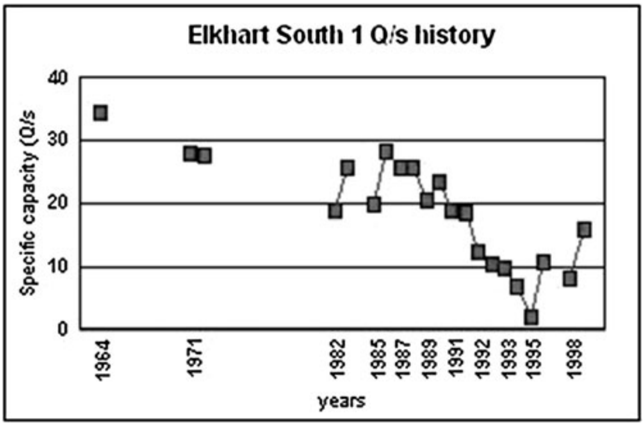

Fig. 8-1. Elkhart South Wellfield specific capacity history (1964–2000) Source: Ground Water Science (2012b); reproduced with permission from Smith-Comeskey Ground Water Science LLC

wells had been decreasing steadily. The graphic expression of specific capacity as a function of time for Well 1 is shown in Fig. 8-1. (Ground Water Science 2012b).

Solution Note that nothing is entirely "solved" in well maintenance and rehabilitation. Such efforts are like those intended to slow physiological aging. They buy time and improve results. Also like public and private health efforts, the process rarely is implemented perfectly. These two examples are close to being models of plan implementation.

Well Rehabilitation in South Wellfield of Elkhart, Indiana Elkhart's South Wellfield, one of three operated by the city's DPWU, is developed in the glacio-fluvial outwash Yellow Creek tributary of the St. Joseph River aquifer. This wellfield is developed with three high-capacity screened "gravel wall" wells to date and supplies a conventional aeration/pressure-filtration water treatment plant. Over time, these wells have experienced performance decline, adversely affecting the economy of the plant and its operations, with periodic attempts to restore production capacity.

This example illustrates the importance of

- Evaluating and understanding a wellfield's history and hydrogeology as part of well rehabilitation planning,
- Setting goals based on cost-effectiveness targets for well rehabilitation,

- Employing appropriate well cleaning techniques (and especially sufficient well development) in rehabilitation, and
- Objectively measuring results using step testing.

An Evaluation of Well Performance History Wells in the South Wellfield have experienced a decline in performance since at least 1971, when the first rehabilitation was conducted on Well No. 1 (the northern-most of three). Each of the wells was treated several times. A review of the treatment history since 1971 showed that despite repeated treatments, a pattern of continual decline in specific capacity (yield per drawdown *Q/s*) was evident. However, this decline was reversed somewhat by rehabilitation events. From the outset, the problem was attributed to "iron bacteria" and treated for such periodically. In 1998 Smith-Comeskey Ground Water Science confirmed a biofouling cause.

Well No. 1, having the lowest initial specific capacity of the three (35 gal./min/ft), declined below the optimal pumping economics point most quickly. Rehabilitation was first attempted 6 years after completion with no improvement, and the well was permitted to decline in performance to uneconomical levels before a series of treatments from 1981 to 1989 kept specific capacity in the mid- to upper 20 gal./min/ft range. Treatment effectiveness then fell off rapidly, with specific capacity falling to as low as 2 gal./min/ft, until the well effectively was abandoned in 1995. Table 8-8 summarizes treatments in Well No. 1.

Wells No. 2 and No. 3, with higher initial specific capacities (51.2 gal./min/ft and 88.6 gal/min/ft, respectively), appeared to decline in performance more slowly. Well No. 2 was not rehabilitated until 21 years after original construction and specific capacity had fallen to 63% of original output. Well No. 3 had a similar history but was permitted to drop to less than 40% of original *Q/s* in 14 years. Table 8-9 summarizes Wells No. 2 and No. 3 results.

Contributing Factors in Well Performance Decline in the South Wellfield An analysis of the history of treatment performance and well performance decline in these wells shows several contributing factors as discussed following.

The Aquifer and Well Conditions Have Clogging Potential The working mechanisms are a combination of fine sediment migrating from the glaciofluvial formation (mixed particle sizes) and biofouling. Fine sediment migrates toward the well. Biofouling forms theoretically in a cylindrical band from the depth into the formation where iron oxidizes to the screen face. Whereas biofouling does reduce hydraulic conductivity, it clogs more effectively as it traps in-migrating particles.

Table 8-8. Treatment History of Well No. 1 (1971–1995)

Date	Treatment	Before *Q/s*	After *Q/s*
Dec. 1971	acidization (A-6), phosphate (P-6, B-6), surging	28	27.9
Sept. 1982	acidization (A-6), phosphate (P-6, B-6) with HTH, surging	18.9	26
Sept. 1985	phosphate (P-6) with HCl acidization and A-6, surging	20	28.3
Dec. 1987	P6 + HTH, light acidization, alternating, surging	26	26
Nov. 1989	phosphate and acidization, chlorine and wetting agent. phosphate + wetting agent, surging	20.7	23.7
Oct. 1991	phosphate with Cl_2, wetting agent, acidization alternating, surging	19.1	18.6
Mar. 1992	surged and caustic soda added	12.5	10.65
1993	Sonar Jet treatment	10	7
1995	Aquafreed treatment	2	11

Notes: *Q/s* = specific capacity (yield Q in gal./min per drawdown s in feet). Original *Q/s* = 34.6. In Sept. 1982, treatments typically included alternating treatment chemical types and surging. Several 100 lb of chemical typically used.
Source: Smith-Comesky Ground Water Science (2007); reproduced with permission from Smith-Comeskey Ground Water Science LLC

The Wells were Permitted to Decline in Performance Below the Point Where Full Performance Recovery was Not Possible Below about 75 to 85% of original or target specific capacity, it requires a great amount of development energy to restore performance, and most especially to remove nutrients and residual debris to slow the return to well decline after cleaning.

Notably, Elkhart's wellfield operations team from the mid 1980s to early 1990s had a well maintenance monitoring and treatment plan in place that could have halted decline earlier. However, this plan was permitted to lapse for several reasons. This kind of intermittent well maintenance history is more the rule than the exception in wellfield management.

Choices of Treatment Methods in the Past Affected the Present Prior to 1998, phosphate-containing surfactant compounds were used in each treatment in large quantities. These were selected with the best of intentions on the basis of information provided by chemical suppliers and

Table 8-9. Treatment Histories of Wells No. 2 and No. 3 (1987–1991)

Date	Treatment	Before *Q/s*	After *Q/s*	% original *Q/s*
	Well No. 2			
1987	acidization, phosphate, surging	34	44	86
1991	acidization, phosphate, surging	33	41[a]	80
	Well No. 3			
1987	acidization, phosphate, surging	34	62.5	71
1991	acidization, phosphate, surging	48	65.6[b]	74

[a]*Q/s* for 898 gal./min
[b]*Q/s* for 932 gal./min
Source: Smith-Comesky Ground Water Science (2007); reproduced with permission from Smith-Comeskey Ground Water Science LLC

short-term (<10 years) experience in wellfields (including Elkhart's) that showed good initial results. However, phosphorus-containing surfactants are suspected of ultimately being counterproductive in well rehabilitation use due to residual phosphate (a limited nutrient in groundwater) left behind. P is adsorbed into clays by cation exchange and available for bacteria to use in metabolism and cell growth and development.

A condition commonly observed in sand-and-gravel wells treated repeatedly over time using phosphorus-containing compounds is a change in the type of biofouling present. It is transformed from a low-biomass filamentous form toward a bulkier, slimy type of biomass that is more difficult to remove using conventional rehabilitation methods. This change results in an acceleration of the performance decay in such wellfields. The change from short-term success to long-term acceleration of decline seems to be illustrated by the *Q/s* history graph supplied by Peerless Midwest for Well No. 1. Successes in the 1980s were followed by rapid declines in performance persisting to the present.

Evidence of a possible change in biofouling in the DPWU South Wellfield was provided by a review of color downhole videos performed on Well No. 1. In the past the problem was described as "iron bacteria" (filamentous iron-related biofouling), whereas recent videos showed a more gray, flocculent, slimy growth. Tests performed by Smith-Comeskey Ground Water Science in 1998 using BART methods (Droycon Bioconcepts) and microscopy confirmed potential for intense slimy growth.

Insufficient or Inappropriate Well Redevelopment Methods were Used Redevelopment methods that are "good enough" for many wells may not be adequate for difficult wells. A Sonar-Jet treatment (acoustic shock-wave development), conducted in 1993, resulted a large decline in specific capacity when attempted. This probably was due to shock wave force pushing abundant soft debris and fine sediment back to the outside boundary of the gravel pack.

An Aqua Freed treatment (injecting liquid and gaseous carbon dioxide) was attempted in 1995 and *Q/s* was improved from about 2 gal./min/ft to the already low 1992 value around 11 gal./min/ft). However, it is likely that with the accumulated and impacted sediment-biofouling buildup in the near-well formation, the injection force of this treatment also may have added to proposed compaction problem in the gravel pack. In any case, conditions in the well at that time probably limited the effectiveness of this treatment.

1998 Treatments Because the wells appeared to be fundamentally sound and the cost of rehabilitation to restore performance was favorable compared to new construction, the team recommended rehabilitation over either well reconstruction or abandonment and new construction. Target yields and specific capacities were calculated based on pumping goals (production needed and maximum drawdown) and power efficiency (using Helweg et al.'s 1983 formulas).

On the basis of the analysis of causes, a Blended Chemical Heat Treatment (BCHT) program was recommended to break through the expected clogging material and restore performance. The BCHT process (which employs a mixture of chemicals, heated upon injection) has a history of effectiveness on difficult well clogs promoted by the slime-forming biofouling, similar to that detected in the South Wellfield tests.

In this case, the treatment comprised a combination of acetic acid (amended to reduce pH to <2) and nonphosphate polyelectrolyte (ARCCsperse CB-4 and PM-30, ARCC, Daytona Beach, FL), jetted in at 180°F (at the nozzle), with a program of extensive mechanical development using double surge block and airlift pumping. This program was used on both Wells No.1 and No. 3.

Because of cost differences and as a comparison, Well No. 2 was treated with hydrochloric acid, calcium hypochlorite, and development. Phosphate-containing compounds were not used in any treatments, replaced as surfactants by the ARCCsperse products.

Well No. 1 Well No. 1 was in extremely poor shape prior to cleaning (*Q/s* = 8.2 gal./min/ft at 402 gal./min). After the initial chemical charge with minimal development, specific capacity fell to 5 gal./min/ft. This probably was due to development action collapsing clogging material against the screen, but it resulted in some short-term hand wringing. Surging and airlift began a recovery over 1 week to 16.1 gal./min/ft at 737 gal./min, an economically viable level of performance for 1 million gal./day, based on calculations. Although not the target result, the well then could pump 737 gal./min with 45 ft of drawdown instead of 402 gal./min (maximum) with more than 70 ft of drawdown. Our assessment was that the result was neither at its potential nor complete.

The effectiveness of development was hindered by a delay in commencement of development after chemical loading due to scheduling (under BCHT, development is most effective when commenced while the solution is still hot), some stoppage in development subsequently due to mechanical problems and process "choke points," and (initially) the effectiveness of development with the tools at hand.

Wells No. 2 and No. 3 Well No. 3 provided the most effective immediate response to the BCHT approach. After one chemical treatment pass and 3 days of development, *Q/s* was restored to 55 gal./min/ft at 770 gal./min from 15.6 gal./min/ft at 686 gal./min. *Q/s* reached 61.3 gal./min/ft on July 23, 1998, when a large amount of silica sand was pumped in. The screen was repaired, reducing *Q/s* somewhat. Overall, performance was restored to somewhat less than 1987 post-treatment levels by the end of treatments in 1998.

Well No. 2 was treated differently by the well service contractor, Peerless Midwest, using hydrochloric acid, alternating with an alkaline (soda) and chlorine steps, with 3 days development. Success in immediate redevelopment response here also was evident in increased specific capacity: from 22.8 gal./min/ft at 800 gal./min to 38.7 gal./min/ft at 1,002 gal./min.

Comparing the effectiveness of the two chemical regimes will require evaluation over time. In wells where the clogging is not compacted, as in Well No. 2, various chemical treatments can have similar results. History with aggressive biofouling well environments shows that the benefits of both BCHT (and the amended acetic acid chemical choice) and effective redevelopment come with delayed decline in performance after rehabilitation rather than in obvious immediate effects.

Rehabilitation Follow Up The Elkhart experience clearly shows what happens when wells are permitted to decline in performance. Long-term effectiveness of these treatments in the South Wellfield will depend on follow up by the Elkhart DPWU. Because of other pressing issues, a fully developed maintenance program in this wellfield is still in development. A resumption in performance decline can be expected to continue.

Acknowledgments The support, assistance and contributions of the Greeley and Hansen Indianapolis Office (Stan Diamond), Allen Comeskey, CPG (Smith-Comeskey), George Alford (ARCC, Inc.), and the management and personnel of Peerless-Midwest and the Elkhart DPWU are greatly appreciated.

8.9 SOLVED DESIGN EXAMPLE 2

The Tate-Monroe Water Association (TMWA) owns and operates the New Richmond Wellfield in Clermont County, OH. Determine a maintenance-rehabilitation solution for the wellfield. It is located adjacent to the north bank of the Ohio River in the Ohio River Valley. This example comes from Smith-Comeskey Ground Water Science (2007), from seminar notes case history.

Solution This example illustrates evaluating and understanding a wellfield's history and hydrogeology as part of well rehabilitation planning, employing appropriate well cleaning techniques (and especially sufficient well development) in rehabilitation, objectively measuring results using step testing, and especially demonstrating an example of a maintenance program involving routine well cleaning over a relatively long period.

The TMWA New Richmond wellfield is developed adjacent to the north bank of the Ohio River in Ohio River Valley alluvial terrace deposits over essentially impermeable Ordovician limestone-shale bedrock. This stratified alluvial aquifer is considered to be in hydraulic contact with the river channel. This behavior is reflected in the response of the static water level to recorded river stage.

Aquifer Influence on Design Notably, the aquifer thickness constricted available screen length, and aquifer stratification (with interbedded clays and silts) dictated a gravel-packed well construction design to avoid multiple screen slot opening sizes. "Naturally developed" wells (without gravel packs) commonly are constructed in similar alluvial aquifer situations, but using gravel pack allows for more margin for error.

Maintenance Activities TMWA has been very diligent in implementing a rational well maintenance program since the mid 1990s, when its personnel began regularly recording data and chlorinating wells.

Causes of Well Problems

1. *Biofouling*: The occurrence and influence of biofouling has been well demonstrated in this wellfield. Testing shows active biofilm

formation capable of causing well clogging and the aeration-filtration system slime buildup and corrosion problems experienced.

2. *In-migration of fines*: The wells are screened in units that consist of mixed particle sizes, from clay through silt and sand to gravel. In all the wells, there appears to be a significant fraction of fine particles in the screened units. Ideally, these were developed out satisfactorily during original construction. However, mechanical well development has a limited radius of influence (<12 in.). Over the years, pumping close to 0.5 million gal./day per well caused fine particles from further out to migrate toward the well (see Chapter 3). Without biofouling development, these would come into the screen and out. Redevelopment over time appears to have been unsuccessful in eliminating this zone, probably located at the gravel pack–aquifer formation interface.
3. *Aquifer chemical quality*: Although mildly encrusting in balance, the overall low ionic strength does not suggest a tendency toward carbonate encrustation. Both iron and manganese concentrations in pumped water samples are low. Manganese consistently is higher than iron. As iron greatly exceeds manganese occurrence in formation materials, this pattern suggests that oxidized iron is filtered out in the formation. Redox potential data support this idea. Biofilm capture in the aquifer is the likely mechanism.
4. *Overall aquifer and wellfield aging*: Older wells show reduced response to well cleaning when compared to newer wells. Step drawdown test analysis results indicate that there is increased formation loss since historical tests.

Well Performance History and Responses to Problems

Specific Capacity and Performance History Comparisons of specific capacities (*Q/s*) as recorded over 1997 and 1998, and as compared to original or historical *Q/s* are tabulated in Table 8-10.

Well Rehabilitation History Maintenance records are kept for most of the wells, showing well cleaning and maintenance chlorination incidents. In general the reduced performance of wells as compared to their original condition, ongoing biofouling deposits in the raw water system, and erratic pump, motor, and electrical component performance suggests that the current maintenance system, although sufficiently thought out, requires continuous improvement to prevent wellfield decline.

In the 1999–2000 period, a specification for well cleaning that utilizes blended acetic or glycolic acid and nonphosphorus polymers, combined with effective well redevelopment, was implemented. The performing well contractor was trained and implemented the program effectively. Results appeared to be good, with stabilizing *Q/s* values, and evidence of

Table 8-10. Comparison of Average 1998 to Original Specific Capacity Values

Well	Av. 1998 *Q/s*[a]	Original *Q/s*	% original
1	23.96	34	70.47
2	14.96	25	59.84
3	16.97	22.7	74.76
4	17.6	21.32	82.55
5	18.09	25.66	70.5
6	15.46	24.6	62.85
7	16.74	24.2	69.17
8	23.27	31.2	74.58
9	31.61[b]	30.41	103.93
12	28.61	30	95.37

[a]*Q/s* = specific capacity in gpm/ft drawdown.
[b]As low as 16 gal./min/ft prior to cleaning in 1998.

removing previously untouched material. Newer wells (No. 9 and No. 12) return to original conditions. The wellfield appears to be manageable with a routine sequence of budgeted treatments.

To test results better, Smith-Comeskey Ground Water Science observed and analyzed well cleaning conducted in 2003 by H-D Water Services on several wells representing phases of the wellfield's development. The focus of the 2003 study was to provide a systematic analysis of step-drawdown pumping tests of the wells before and after cleaning.

Well *Q/s* Results Well No. 7 test results were illustrative (Fig. 8-2). In this case, valid, original step test analysis is available, which is not the case for all wells.

The slopes of the post-cleaning lines (middle two lines) indicate that the turbulent loss is reduced to a near-original level. Aquifer loss remains higher. The treatment apparently brought in a lot of material, necessitating a second cleaning. When cultured in the lab, the gravel pack developed out and collected in June 2003 contained culturable iron-related bacteria.

Moving Forward With the availability of historic information sufficient for trend analysis, it is possible to provide specific plans for well pumping rates and cleaning intervals. Also, it is evident where improvements in the treatment and evaluation process can be made.

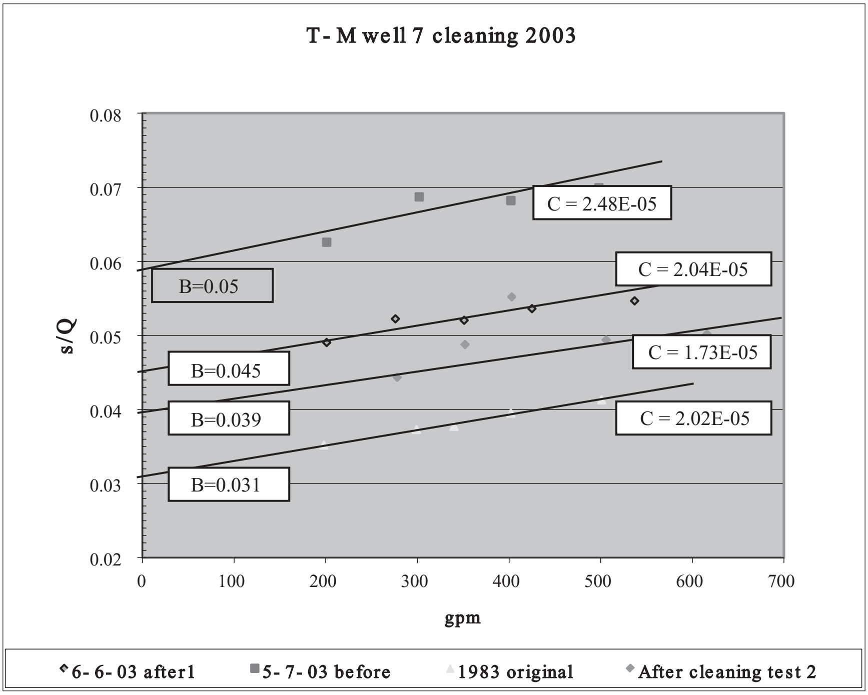

Fig. 8-2. Well No. 7 step-drawdown test, Hantush-Bieschenk analysis Source: Smith-Comeskey Ground Water Science (2007). Reproduced with permission from Smith-Comeskey Ground Water Science LLC.

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APPENDIX A

EXAMPLE OF A WATER-WELL SYSTEM DESIGN

Dennis E. Williams

A.1 GENERAL

A.1.1 Background

Appendix A provides an example of a complete evaluation of construction of a high-capacity municipal water supply well in an alluvial groundwater basin in southern California. Specifically, the example is from the Chino Basin within the City of Ontario's service area. This appendix includes material on the well siting analysis, well design, well construction and testing, well equipping, and well operation and maintenance.

A.1.2 Well Site Investigation

This appendix presents a hydrogeologic analysis along with recommendations for the location of two high-capacity groundwater production wells (to be designated Wells No. 40 and No. 41) for the City of Ontario's Public Works Agency (California). Ontario needs additional wells to help make up its current maximum daily water demand deficit. Six potential well sites have been identified by Ontario for consideration. The objective of this evaluation was to select two of the six sites that have the greatest geohydrological potential to yield 3,000 gal./min to a well installed at that location.

In addition to production potential, other factors considered in the site selection process were acceptable water quality (including proximity to potential sources of contamination), potential interference with existing groundwater pumpers, and California Department of Health Services (DHS) requirements. The scope of work to achieve the objective included

- Developing a hydrogeologic basemap on which to plot and evaluate data,
- Analyzing specific capacity test data, long-term pumping test data, and pumping records,
- Evaluating water quality data,
- Evaluating potential sources of contamination based on regulatory records, and
- Evaluating potential capture of existing contaminant plumes using a capture-zone model.

A.1.3 Location of Potential Well Sites

The locations of the six potential well sites selected for consideration by Ontario are shown in Fig. A-1. The sites are summarized as follows:

Site 1. Reservoir No. 7 site at Campus Avenue and 8th Street in the City of Upland, Lot 637—Parcel No. 1046551 12 for 13th Street Pressure Zone;

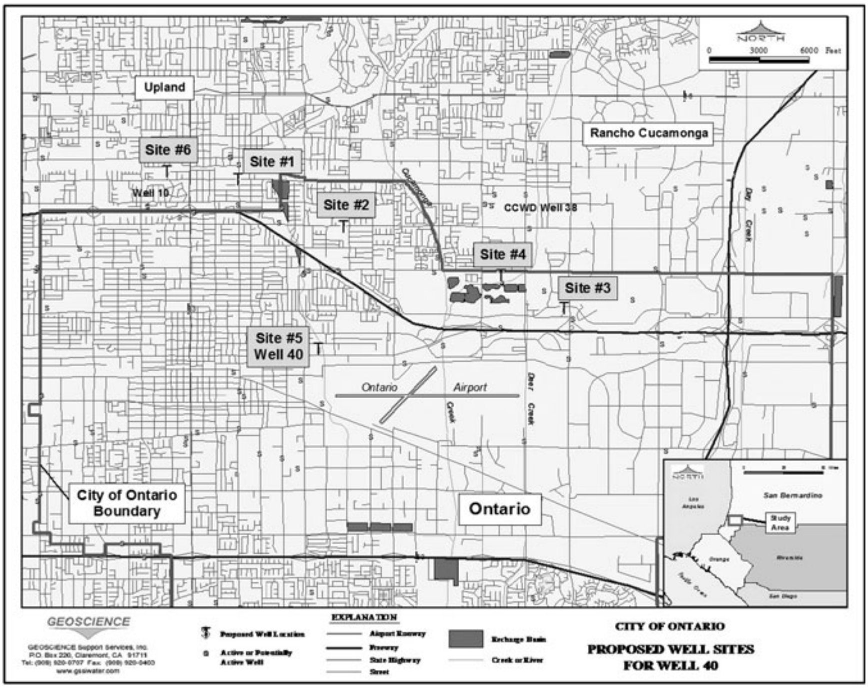


Fig. A-1. Locations of the six potential well sites selected for consideration by Ontario

Site 2. Vineyard Park at 1530 E. 6th Street and Baker Avenue in the City of Ontario, Assessor's Parcel Nos. 108 291 13, 108 291 14, and 210 021 12 for either 13th Street Pressure Zone or 8th Street Pressure Zone;

Site 3. A vacant lot between Lotus Avenue and Haven Avenue north of Shelby in the City of Ontario, Parcel Nos. 0210 182 16 and 0210 182 17 revised Assessor's Map Par. 4 lot 63 for 8th Street Pressure Zone;

Site 4. Current Well No. 19 site near Cucamonga Guasti Regional Park (owner is County of San Bernardino, CA);

Site 5. A vacant land for 8th Street Pressure Zone well at 1331 E. Holt Blvd, west of Imperial Avenue on the north side of Holt Blvd. Next to the flood control channel (City owns the land, Parcel No. 110 061 15); and

Site 6. Fern Reservoir Park at 395 West 8th Street in the City of Upland, CA.

A.1.4 Sources of Data

Data used in the analysis of the six potential well sites were obtained from multiple sources. The primary sources and the types of data provided by them are summarized as follows:

- *City of Ontario, 2001*: Updated groundwater levels, specific capacity data, driller's logs, geophysical logs, well completion data, water quality data, and production data for their wells.
- *Wildermuth, 2000 (TIN/TDS Database)*: Well locations, well completion data, groundwater level data, water quality data, and information on geology including basin boundaries and locations of alluvial faults (groundwater barriers).
- *CBWM, 2001*: Well status, groundwater levels, specific capacity data, and groundwater production data.
- *California Department of Water Resources (DWR)*: Driller's logs.
- California Division of Mines and Geology, 1986: Detailed surface geology.

A.2 HYDROGEOLOGY

A.2.1 Hydrogeologic Setting

The proposed well sites are located in the northern portion of the Chino Basin of southern California (see Fig. A-1). The Chino Basin is a structural depression located between the San Gabriel Mountains to the north and the Chino and La Sierra Hills to the south. The proposed well sites are located near the base of the San Gabriel Mountains, which are part of the Transverse Ranges geomorphic province and are composed primarily of granitic and metamorphic rocks.

Weathering of the mountains surrounding the Chino Basin has resulted in the deposition of alluvial sediments that have filled the basin. Where these sediments are saturated in the subsurface, they form the basin's aquifers.

A.2.2 Bedrock

Surface exposures of bedrock occur approximately 4 to 5 mi north of the proposed well sites. The bedrock consists primarily of Cretaceous granitic rock and metasedimentary rock of unknown age (see Fig. A-2). In the area of the proposed well sites, the depth to bedrock ranges from approximately 950 ft below ground surface (ft bgs) in the vicinity of Site No. 2 to approximately 1,300 ft bgs in the vicinity of Site No. 5 (see Fig. A-3).

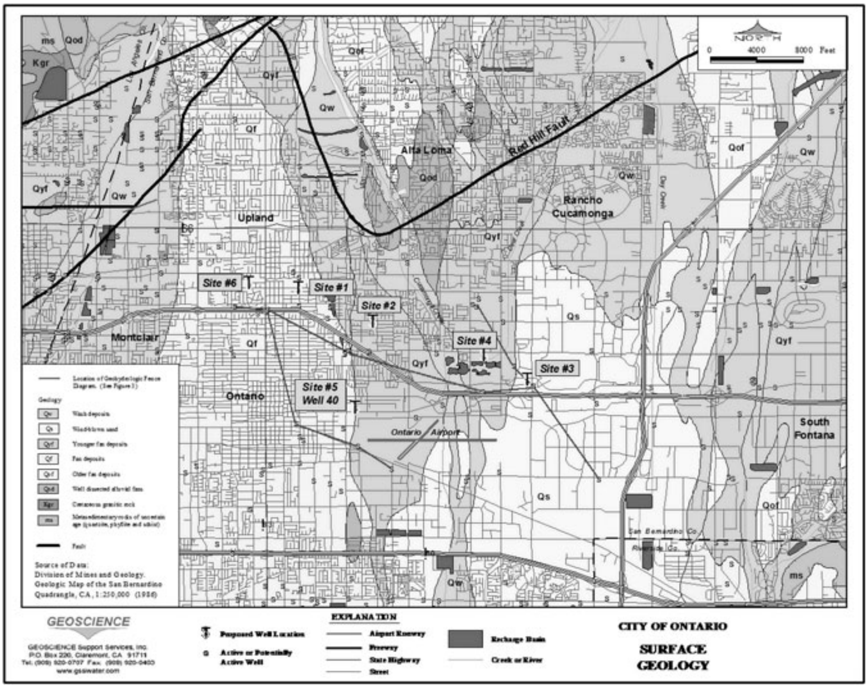


Fig. A-2. Bedrock characteristics of the Chino Basin

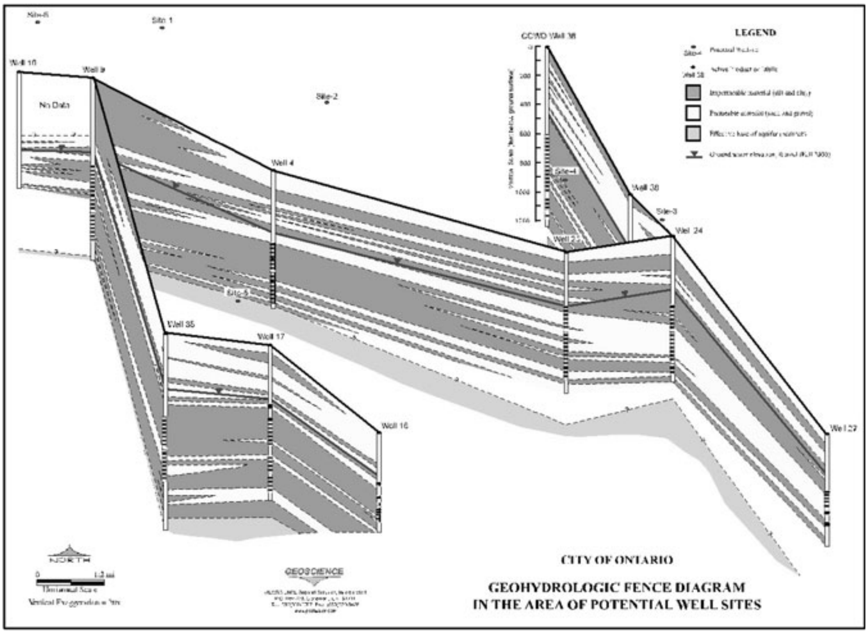


Fig. A-3. Hydrogeologic fence diagram in the area of potential well sites

A.2.3 Alluvium

Surface exposures of the alluvial sediments are quaternary in age and have been grouped into alluvial wash deposits (youngest) and alluvial fan deposits of various ages (see Fig. A-3). Evaluation of driller's and geophysical borehole logs from the wells in the Ontario area indicate the subsurface alluvial sediments consist of alternating layers of sand, gravel, silt and clay in varying proportions. The thickest sequences of sand and gravel (aquifer material) occur in the vicinity of Ontario Wells No. 24 and No. 25, located near proposed Site No. 4.

A.3 GROUNDWATER

A.3.1 Groundwater Level

The groundwater level in the vicinity of the proposed well sites is relatively deep, ranging from approximately 350 to 500 ft bgs. Potential production aquifers consist primarily of permeable sands and gravels. As with all alluvial basins, complex water-bearing zones consisting of interlayered sands, gravels, silts, and clays comprise the aquifer system of the

Ontario area. The water-bearing zones have been grouped into two general aquifer systems: an upper system that is generally unconfined to semiconfined, and a lower system that is generally semiconfined to confined.

A.3.2 Aquifer Parameters

Specific capacity data from pumping tests on Ontario wells and other wells in the area of the proposed well sites were analyzed. Specific capacities in the area range from approximately 10 to 100 gal./min/ft. Higher specific capacities generally are associated with wells that are deeper and with longer perforation intervals (e.g., screen). Aquifer transmissivity in the vicinity of the proposed well sites is estimated to range from approximately 50,000 to 300,000 gallons per day per foot (gpd/ft).

A.3.3 Groundwater Flow

Groundwater in the vicinity of the proposed well sites flows from the northeast to the southwest at a gradient that ranges from approximately 15 to 40 ft/mi (0.003 to 0.0076 ft/ft; see Fig. A-4). Flattening of the gradient

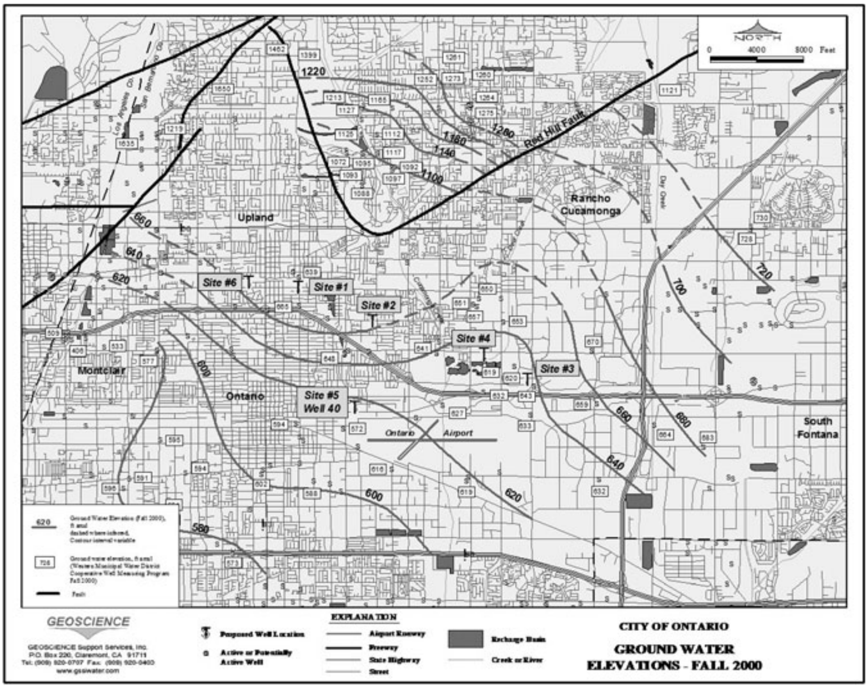


Fig. A-4. Groundwater elevations for six potential well sites, City of Ontario in the area between the Ontario Airport and Guasti Regional Park appears to be a result of groundwater pumping in the area. Static groundwater elevations at Well No. 19, which has a period of record starting in 1927, have declined approximately 160 ft since records first were kept. Static groundwater levels at Wells No. 19 and No. 24 have declined substantially since the early 1990s, despite the relative abundance of precipitation during that time. Groundwater elevations at Well No. 4 declined steadily between approximately 1920 and 1980 but have been recovering since. Groundwater elevations have been steady, relatively (with a few exceptions), at Wells No. 9 and No. 17, which have periods of records that extend from the early 1960s to the present.

A.3.4 Groundwater Contamination

Native groundwater in the Ontario area is a calcium-bicarbonate type with total dissolved solids (TDS) concentrations ranging from approximately 200 to 300 milligrams per liter (mg/L). Point sources of contamination include specific sites where contaminants have been released to the subsurface from an underground storage tank (UST) or a localized surface spill. Locations of point source sites were obtained from the Regional Water Quality Control Board's (RWQCB) GeoTracker database (http://geotracker.swrcb.ca.gov) and are plotted in Fig. A-5. The extent of known groundwater contamination plumes, based on the Chino Basin Watermaster's (CBWM) Optimum Basin Management Plan also are shown in Fig. A-5.

The primary risk to the proposed well sites is from vertical migration of contaminants from shallow aquifer zones through the impermeable layers and into the deeper aquifer system. The proposed wells would be completed in the deeper aquifer system. The primary upgradient concern is the former Upland sanitary landfill, located closest to potential Well Site No. 1. On the basis of the Chino Basin Watermaster Optimum Basin Management Plan, volatile organic compounds (VOCs) have been detected in groundwater from three monitoring wells in the vicinity of the landfill. The VOCs detected above their respective maximum contaminant levels (MCLs) include perchloroethene (PCE), trichloroethene (TCE), dichlorodifluoromethane, and vinyl chloride.

The primary nonpoint source of groundwater contamination in the Ontario area is agricultural activity, which has resulted in widespread nitrate effects to the groundwater from nitrogen-based fertilizers applied to crops and citrus orchards. In the area of the potential well sites, residual nitrate in the groundwater is a result of historical agricultural practices, since the area has been almost completely urbanized.

Nitrate concentrations exceeding the MCL of 45 mg/L occur in Ontario wells that are near to or north of Interstate 10. Most of these wells are old

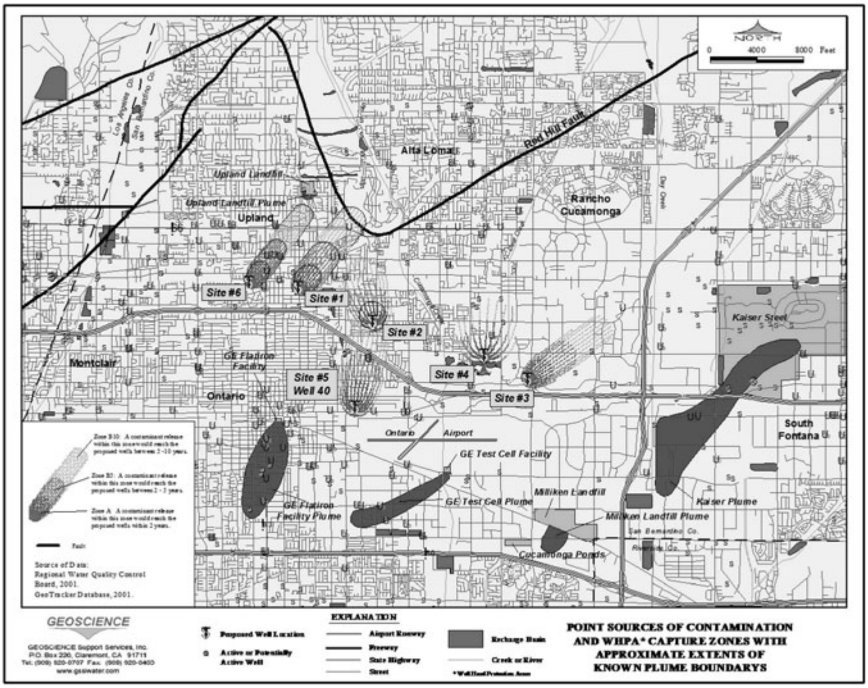


Fig. A-5. Groundwater contamination plumes, Chino Basin, Ontario

and, in the case of Wells No. 18 and No. 19, have shallow perforated intervals. New wells in the areas (e.g., proposed well sites No. 1 and No. 2) will have to be screened in the deeper aquifers to avoid high nitrate concentrations.

A.4 WELL SITE CHARACTERISTICS

A.4.1 Well Site Selection Criteria

The six potential well sites were evaluated on the basis of the following criteria:

- Groundwater production potential,
- Groundwater quality,
- Potential for interference with existing production wells, and
- Ability to comply with California DHS requirements.

A.4.2 Production Potential

Production potential of each potential well site was evaluated on the basis of the current operational pumping rate of the closest existing Ontario wells; specific capacity data from the closest wells; lithologic characteristics of the aquifer sediments from driller's logs; and, where possible, geophysical logs of nearby wells; and depth to the base of effective aquifer sediments (generally bedrock).

A.4.3 Groundwater Quality

Groundwater quality relative to nitrate (from nonpoint sources) was evaluated at each potential well site on the basis of consideration of screened interval and nitrate concentrations in nearby wells. Each well site also was evaluated with respect to potential for contamination from point sources by evaluating its hydrogeologic relationship (i.e., upgradient, downgradient, crossgradient, etc.) to the contamination source or mapped plume. Final consideration of contamination potential was conducted using the U.S. Environmental Protection Agency's (EPA) wellhead protection area (WHPA) model.

A.4.4 Interference Issues

The potential for wells at each proposed well site to interfere with existing production wells was evaluated by plotting existing active production wells on the same map and comparing the distance to the proposed site. Also considered were regional drawdown trends that may suggest over production of these areas.

A.4.5 Compliance with DHS Requirements

The California DHS requires each new well site to comply with its Drinking Water Source Assessment and Protection Program (DWSAP). The DWSAP is a permit that evaluates the potential for contamination from area land use and is related closely to the issue of water quality evaluation described in Section A3.4. As such, potential to comply with DWSAP guidelines was evaluated in the context of groundwater quality and potential contamination sites using the EPA's WHPA model (see Fig. A-5).

A.4.6 Well Site Ranking

Given the siting criteria discussed, the six potential well sites were ranked as shown in Table A-1.

Table A-1. Ranking Criteria for Well Sites

Potential Well Site	Ranking Criteria: Production Potential	Groundwater Quality	Low Interference with Existing Production Wells	Compliance with DHS Requirements	Total Points	Site Ranking
Weighting Factor	(10)	(8)	(6)	(4)	—	—
	Criteria Points (1–10)					
Site No. 1 (8th and Campus)	7	6	2	6	**154**	**6**
Site No. 2 (Vineyard Park)	8	8	8	8	**224**	**1**
Site No. 3 (Lotus—Haven)	9	8	3	8	**204**	**5**
Site No. 4 (Guasti Park)	8	7	7	7	**206**	**4**
Site No. 5 (Holt St.)	8	7	9	7	**218**	**2**
Site No. 6 (Fern Reservoir Park)	8	6	9	6	**206**	**3**

The four siting criteria (production potential, groundwater quality, etc.) were given a weighting factor of 0 to 10 (10 being highest). For example, production potential was considered the most important factor and, thus, was given a weight of 10. The six potential well sites then were assessed individually as to their respective site-specific criteria on a scale of 0 to 10 (10 being the highest). The product of the site-specific criteria times the weight factor then was summed cumulatively for all four ranking criteria to arrive at the total points.

A.4.7 Selection of Site No. 5 (Holt St.) For Construction of Well No. 40

Site No. 5 (Rank = 2), located at 1331 East Holt Street in Ontario, was selected as the first site for a new well (subsequently labeled Well No. 40). However, due to land acquisition issues, the actual site of Well No. 40 is slightly to the east of Site No. 5 (see Fig. A-1).

A.5 TECHNICAL ASPECTS OF WATER WELLS

A.5.1 Well Design, Construction, and Testing

Well No. 40, located in the vicinity of Holt Street and Grove Avenue (see Fig. A-1), was drilled using the reverse circulation drilling method by Beylik Drilling Company of La Habra, CA. A 48-in. diameter conductor borehole was drilled to a depth of 50 ft using a bucket auger rig. The 36-in. outside diameter (OD) surface conductor casing was installed to 50 ft bgs and cemented in place from the ground surface to a depth of 49 ft. The 17 ½-in. diameter pilot borehole was drilled to a total depth of 1,220 ft bgs. Geophysical logs then were run in the open borehole. The borehole was reamed to 30 in. from 50 to 1,102 ft bgs. Alluvial materials penetrated during drilling consisted primarily of varying amounts of coarse- to fine-grained sand, fine-grained gravel, broken cobbles, and interbedded layers of silt and clay. Bedrock was not found in the borehole.

A.5.2 Well Construction

The drilling contractor for Ontario Well No. 40 was Beylik Drilling, Inc. Drilling and construction of the well began on October 31, 2002. Development and testing was completed on February 6, 2003, and the final video survey was completed on March 18, 2003.

A.5.3 Conductor Casing Installation and Pilot Borehole Drilling

A 48-in. diameter conductor borehole was drilled on October 31, 2002, to a depth of 50 ft using a bucket auger rig. A 36-in. OD by 3/8-in. wall mild steel conductor casing was installed on October 31, 2002, to 50 ft bgs and was cemented in place from a depth of 50 ft to ground surface. Below the bottom of the conductor casing, a 17½-in. diameter pilot hole was drilled using a reverse circulation rotary drilling rig. Drilling of the pilot borehole began on November 5, 2002, and was advanced to a final depth of 1,220 ft by November 12, 2002.

Formation materials encountered during pilot borehole drilling consisted primarily of varying amounts of coarse- to fine-grained sand, fine-grained gravel, broken cobbles, and interbedded layers of silt and clay.

A.6 GEOPHYSICAL LOGGING AND AQUIFER ZONE TESTING

Upon reaching the final depth of the 17 ½-in. pilot borehole at 1,220 ft bgs, fluids in the borehole were circulated for an adequate amount of time to stabilize the borehole before removing the drilling string. A suite of geophysical borehole logs then were run by Pacific Surveys, Inc., of Claremont, CA, on November 12, 2002, and included the following:

- 16-in. and 64-in. normal resistivity with point resistance,
- Spontaneous potential (SP),
- Focused guard resistivity (Laterolog),
- Acoustic (sonic),
- Gamma ray,
- Caliper (following reaming on December 4, 2002), and
- Spinner survey (February 6, 2003).

Fig. A-6 shows the geophysical borehole logs and lithology.

A.6.1 Aquifer Zone Testing for Yield and Water Quality

From examination of the formation samples and analysis of the geophysical logs, three intervals (1,030 to 1,050 ft, 610 to 630 ft, and 510 to 530 ft bgs) were selected for isolated zone testing. The purpose of isolated zone testing is to determine both yield and water quality from the potential completion interval(s) before determining the final design of the well. Isolated aquifer zone testing was performed from November 12 to November 21, 2002.

A.6.2 Aquifer Zone Testing Procedure

Prior to zone testing, the open 17 ½-in. pilot borehole was backfilled with gravel and bentonite to the bottom of the zone to be tested. A 20-ft section of perforated pipe (mill-slotted) was attached to the drill string

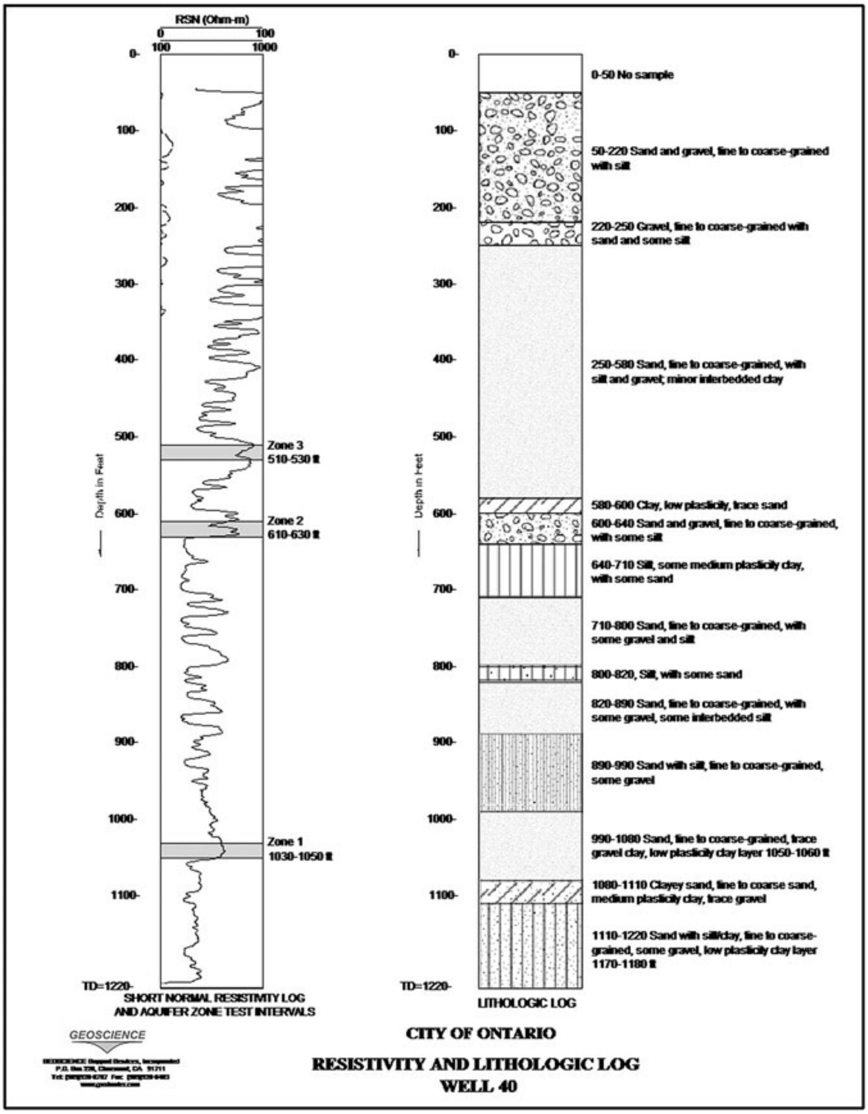


Fig. A-6. Geophysical borehole logs and lithology for Well 40, City of Ontario

and installed in the pilot borehole within the target zone to be tested. Filter pack material then was added to the annular space between the 17 ½-in. borehole and the zone test tool (perforated pipe), until the tool was covered by at least 10 ft of material. A second bentonite seal was placed to isolate the zone from the rest of the borehole. The bentonite seals were allowed to hydrate for a specified amount of time before airlifting of the isolated zone began.

The test zone was developed by airlifting the temporary "well" until the fluid being discharged remained acceptably clean and clear, and the integrity of the seal had been verified. Verification of the seal for zone testing is determined when water levels occurring in the annulus remain stable and predictable, allowing for losses to the formation above the top seal, and is different than the water level measured inside the zone testing tools (i.e., the drill pipe), whether the zone is being actively pumped or is at rest. If the seal was not holding, more bentonite or cuttings were added to the annulus and were allowed to hydrate before continuing development.

Once the water airlifted from the zone was observed to be clean and clear, and it was determined that the seal was holding, the temporary well again was airlifted for several additional hours. This additional airlifting was to ensure that only formation water from the isolated zone was being produced and that the water was not contaminated by the fluids used during drilling. During this time, periodic measurements were made of field water quality parameters, water levels, and rates of discharge.

At the end of continuous airlifting, samples were collected from each zone for water quality analysis. The water quality samples were then delivered by City of Ontario personnel to Babcock & Sons Laboratory in Riverside, CA, for water quality analyses. The zone test tools were removed from the borehole after the zone test for cleaning and inspection. This process was repeated for each of the three zones tested.

The zone test procedure is summarized as follows:

1. The 17 ½-in. pilot borehole was backfilled with gravel to approximately 10 ft below the zone selected for testing. A bentonite seal was placed on top of the backfill material.
2. A 20-ft long mill-slotted section of pipe was placed opposite the zone to be tested.
3. Filter pack material was placed in the annular space between the perforated tool and the borehole to approximately 10 ft above the top of the tool.
4. Ten ft of bentonite material was placed on top of the filter pack material to complete the zone isolation process and was allowed to hydrate.
5. The temporary well was developed by airlifting, and the integrity of the seal was verified.
6. Following airlift development, each isolated zone was pumped using a high-capacity submersible pump for several hours. Rates ranged from approximately 20 to 200 gal./min.

7. Water levels and discharge rates were measured and recorded periodically. Water samples were collected to determine the water chemistry for each zone tested.

A.6.3 Results of the Aquifer Zone Testing

Water quality analyses were performed for each zone and included general mineral, general physical, and inorganic analyses, as well as regulated and unregulated organic analyses. Results show that the total dissolved solids (TDS) concentrations for Zone No. 1 through No. 3 ranged from 190 to 250 milligrams per liter (mg/L), well below the recommended secondary MCL of 500 mg/L. Iron and manganese concentrations from Zone No. 1 (900 micrograms per liter [μg/L]) exceeded the maximum contaminant levels (MCLs) of 300 μg/L, and 50 μg/L, respectively. However, it is likely that the high concentrations are a reflection of the turbidity of the sample and not natural aquifer conditions. The turbidity of the sample from Zone No. 1 was 6.9 NTUs, which indicates some suspended sediment remained in the sample at the time of analysis.

A summary of selected water quality analytical parameters is presented in Table A-2.

A.7 DESIGN ASPECTS OF WATER WELLS

A.7.1 Well Design

Based on review of the pilot borehole geophysical borehole logs, drill cuttings, and sieve analyses (see Figs. A-6 and A-7) and in consideration of the water quality data, the casing and screen schedule in Table A-3 was designed.

A.7.2 Reaming Pilot Borehole, Caliper Log, Gravel Feed Pipes and Sounding Tube

The 17 ½-in. diameter pilot borehole was enlarged to 30 in. in diameter from 50 ft to a depth of 1,090 ft. This design allows for 20 ft of extra borehole (i.e., "rat hole"); in case a small amount of fill accumulates during the casing and screen installation. A caliper log was run in the reamed borehole. Prior to installing the casing and screen, two 3-in. diameter gravel feed pipes were installed, each to 355 ft bgs, for the purpose of adding filter pack material (gravel pack) during development and in the future as needed. Additionally, a 2-in. diameter sounding tube was installed from ground surface, connecting to the 20 in. ID blank casing at

Table A-2. Summary of Water Quality Results—Aquifer Zone Testing

		Zone No.			
		1	2	3	
Depth Interval	**[ft, bgs]**	1,030–1,050	610–630	510–530	**MCL or Action Level**
Apparent Color (Unfiltered)	[color units]	15	<3.0	<3.0	15[2]
Odor Threshold @ 60 °C	[TON]	<1	<1	<1	3[2]
pH	[std. units]	8.0	8.0	7.8	6.5–8.5[2]
Arsenic	[μg/L]	2.7	<2.0	<2.0	50[1]
Chromium (VI)	[μg/L]	Not analyzed	2.3	1.7	50[1]
Fluoride	[mg/L]	0.3	0.4	0.4	2.0[1]
Iron	[μg/L]	900	170	140	300[2]
Manganese	[μg/L]	52	11	20	50[2]
Nitrate (as NO_3)	[mg/L]	<0.45	4.95	26.6	45[1]
Perchlorate	[μg/L]	<4.0	<4.0	<4.0	4[3]
Total Filterable Residue @ 180 °C, TDS	[mg/L]	190	200	250	1,000[2]
Volatile Organic Chemicals (EPA Method 524.4)	[μg/L]	Not analyzed	NA[4]	ND[5]	Varies with compound

[1]California Department of Health Services (DHS) Primary Maximum Contaminant Levels (MCL)
[2]California DHS Secondary Maximum Contaminant Levels
[3]California DHS Recommended Action Levels for Unregulated Chemicals Requiring Monitoring
[4]Data not available as of the submittal of this report
[5]None of the individual constituents within the method were detected above their respective detection limits

Table A-3. Casing and Screen Schedule, City of Ontario Well No. 40

Interval (ft bgs)	Borehole Diameter (in.)	Casing Diameter (in.)	Wall Thickness (in.)	Screen Slot Size (in.)	Material Type
0–50	48	36 OD	3/8	—	Conductor Casing (ASTM A139 Grade B Steel)
0–355	Annulus (2 each)	3	sch 40	—	2 ea. Gravel Feed Pipes (ASTM A53, Grade B steel)
0–496	Annulus	2	sch 40	—	Sounding Tube (ASTM A53, Grade B steel)
0–345	Annulus	—	—	—	Sanitary Seal (10.5 Sack Sand-Cement Slurry)
345–350	Annulus	—	—	—	Fine Sand Layer
350–1,090	Annulus	—	—	—	Custom 4 × 12 Tacna Filter Pack Material
0–500	30	20 ID	3/8	—	Blank Casing (Copper-Bearing Steel)
500–630	30	20 ID	5/16	3/32 (0.094)	Ful-Flo Louvered Screen (Copper-Bearing Steel)
630–705	30	20 ID	5/16	—	Blank Casing (Copper-Bearing Steel)
705–1,050	30	20 ID	5/16	3/32 (0.094)	Ful-Flo Louvered Screen (Copper-Bearing Steel)
1,050–1,070	30	20 ID	5/16	—	Blank Casing w/End Plate (Copper-Bearing Steel)

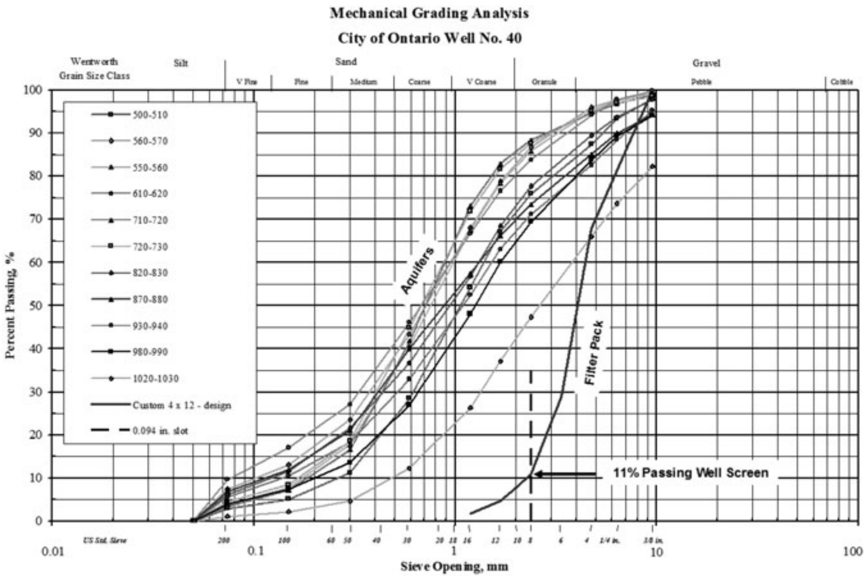


Fig. A-7. Mechanical grading analysis, Well 40, City of Ontario

a depth of 496 ft. The sounding tube is used for the purpose of obtaining accurate water level measurements while pumping the well, or for installation of a transducer.

A.7.3 Filter Pack and Slot Size Selection

Mechanical grading analyses (i.e., sieve analyses) were performed on formation samples from ten selected intervals below 500 ft (see Fig. A-7). Based on the results of these sieve analyses, the recommended filter pack gradation along with sand migration and permeability information are summarized in Table A-4. The recommended size of openings for the entire screened interval is 3/32 (0.094) in., which will allow approximately 11% of the filter pack (gravel pack) material to pass.

A.7.4 Well Completion

Well No. 40 was completed to a total depth of 1,070 ft bgs using 20-in. inside diameter (ID) copper-bearing steel casing and louvered well screen (see Fig. A-8). Well screen consisting of 20-in. ID by 5/16-in. wall copper-bearing steel Ful-Flo horizontal louver well screen was installed from 500

Table A-4. Well Screen/Filter Pack Design Parameters

Well Screen/Filter Pack Design Parameters City of Ontario Well No. 40

Design Criteria	Depth [ft]	Formula (D = Filter Pack) (d = Aquifer)	Value	Recommended Value
Pack/Aquifer Ratio (Finest Zone)	710–720	D_{50}/d_{50}	5.7	4 to 6
Terzaghi Migration Factor (Finest Zone)	710–720	D_{15}/d_{85}	1.3	less than or equal to 4
Terzaghi Permeability Factor (Coarsest Zone)	1020–1030	D_{15}/d_{15}	4	greater than or equal to 4
Screen Slot [in.]	—	—	0.094	—
Percent Filter Pack Passing Screen Slot	—	—	11	10% to 20%
Uniformity Coefficient of Filter Pack	—	$C_u = D_{60}/D_{10}$	2.0	—

Custom 4 × 12—design

U.S. Standard Sieve Size	Opening [in.]	Opening [mm]	Cumulative % Retained	Cumulative % Passing
3/8 in.	0.375	9.53	0.0	100.0
4	0.187	4.75	32.1	67.9
6	0.132	3.36	71.0	29.0
8	0.094	2.38	89.1	10.9
10	0.079	2.00	92.3	7.7
12	0.066	1.68	95.3	4.7
16	0.047	1.19	98.3	1.7

to 630 ft, and 705 to 1,050 ft. The openings in the screen measured 3/32 in. Copper-bearing steel blank casing (20-in. ID by 5/16-in. wall) was installed from ground surface to 500 ft, and 630 to 705 ft. Additionally, 20-in. ID by 5/16-in. wall copper-bearing steel blank casing was installed from 1,050 to 1,070 ft bgs with an end plate to serve as a sediment trap below the screened section. A total of 475 ft of well screen and 595 ft of blank casing were installed.

Tacna Sand & Gravel 4 × 12 custom blend filter pack material was installed from 355 to 1,1020 ft bgs, between the 30-in. diameter borehole and the 20-in. ID casing and screen. A layer of fine transition sand was placed from 343 to 350 ft bgs to prevent the cement, when pumped, from invading the upper portion of the filter pack. An annular seal consisting of a 10.3 sack cement mixture was pumped through a tremie pipe from 343 ft depth to the ground surface, and acts as a deep sanitary seal for the well. Fig. A-8 and Table A-5 summarize the well construction details.

A.8 PUMPING TESTS

A flowmeter (or spinner) survey was conducted by Pacific Surveys, Inc., on February 6, 2003, at an average discharge rate of 2,984 gal./min. Results of the spinner survey down-runs indicate that at this discharge rate the majority (59%) of flow into the well occurs within the upper perforated interval (500 to 630 ft). The lower perforated interval (705 to 1,050 ft) accounts for 41% of flow into the well (see Fig. A-9).

Both step drawdown and 24-h constant rate pumping tests were run on the well. The pumping tests have established that the designed discharge rate for the well is approximately 3,000 gal./min. Short-term pumping of this well (i.e., one day of continuous pumping) is expected to result in 46.2 ft of drawdown and a specific capacity of 65 gal./min/ft. Long-term pumping of this well (extrapolated to 1 year of continuous pumping) was estimated to result in 54 ft of drawdown (see Figs. A-10, A-11, and A-12).

Calculations using the information obtained from the step drawdown and 24-h constant rate pumping tests indicate a well efficiency of 93% and an aquifer transmissivity of 240,000 gpd/ft.

On the basis of the information collected during the pumping tests, the recommended discharge rate and pump setting for well No. 40 are listed in Table A-6.

At the end of the 24-h constant rate pumping test, water samples were collected from the completed well by a Geoscience employee for Title 22 water quality analysis. Babcock & Sons Laboratory of Riverside, CA, performed these analyses. The laboratory reported a total dissolved solids

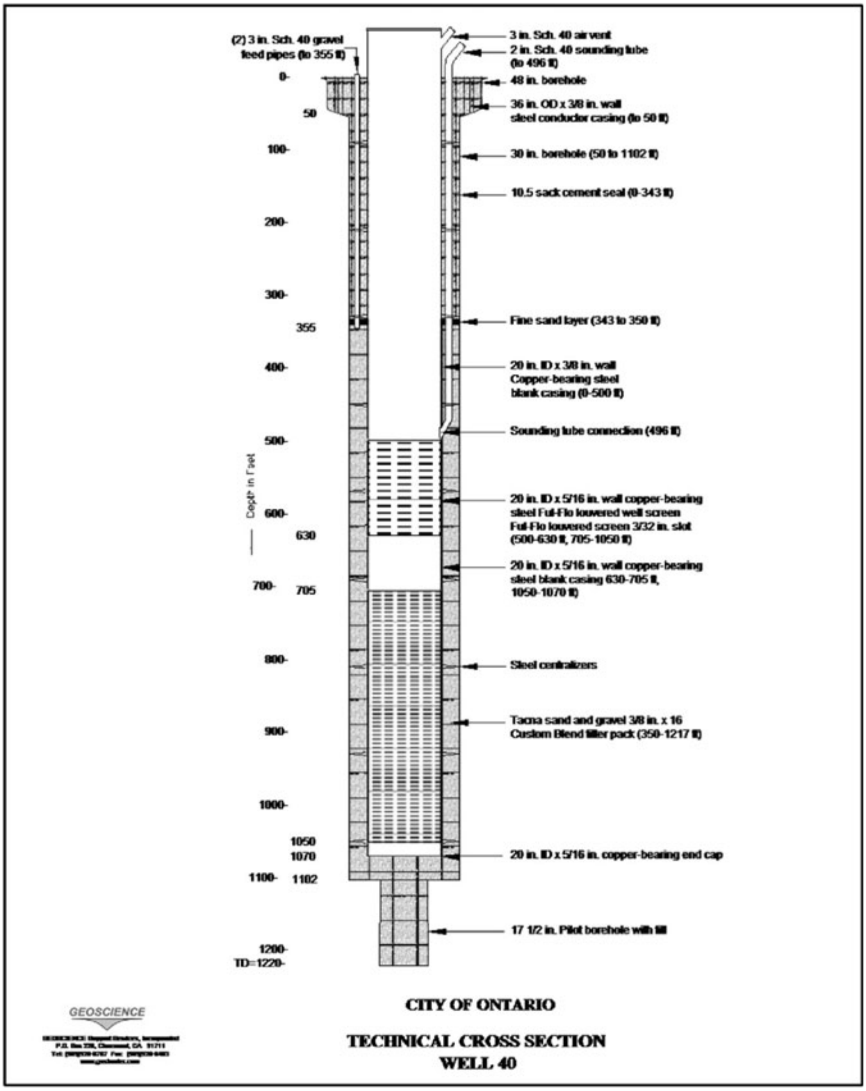


Fig. A-8. Technical cross section of boring for Well 40, City of Ontario

Table A-5. Summary of Well Construction Details, City of Ontario Well 40

Summary of Well Construction Details City of Ontario Well 40		
General Information		
Owner Well Name: Well 40	Latitude: 34° 3.78′ North	Hydrologic Unit: Chino Hydrogeologic Basin
State Well Number:	Longitude: 117° 5.05′ West	Geological Setting: Alluvium
Well Owner: City of Ontario	Land Surface Elevation: ~980 ft amsl	Use of Water: Municipal
Owner Address: 1425 South Bon View Ave. Ontario, CA 91761	Well Location: 1331 East Holt Street	
Drilling Equipment		
Drilling Rig Type: Reverse Circulation Rotary	Fluid Reservoir Type: Above-Ground Tank	
Pilot Borehole Bit Size/Type: 17 1/2-in.	Fluid Additives: None	
Reamed Borehole Bit Size: 30-in.	Method of Sample Recovery: Sample Collection Box	
Conductor Casing and Sanitary Seal		
Conductor Casing OD: 36-in.	Conductor Borehole Diameter: 48-in.	Sanitary Seal Depth: 49 ft
Wall Thickness: 3/8-in.	Start Date of Conductor Borehole: 31-Oct-02	Composition of Sanitary Seal: 10.5 sack sand cement slurry
Casing Length: 50 ft	Completion Date of Conductor Borehole: 31-Oct-02	Date of Seal Placement: 31-Oct-02
Casing Material: A139 Grade B Steel	Date Conductor Casing Set: 31-Oct-02	Witness of Seal Placement: San Bernardino Co. Inspector

Borehole Drilling and Logging			
Pilot Borehole Diameter: 17-1/2 in.	Reamed Borehole Diameter: 30-in.	Geophysical Logs Run: 12-Nov-02	
Start Date of Pilot Borehole: 05-Nov-02	Start Date of Borehole Reaming: 22-Nov-02	16-in./64-in. Normal Resistivity	Laterolog Gamma-Ray
Completion Date of Pilot Borehole: 12-Nov-02	Completion Date of Borehole Reaming: 03-Dec-02	Spontaneous Potential (SP) Acoustic (Sonic)	Caliper (04-Dec-02)
Total Depth of Pilot Borehole: 1,220 ft	Total Depth of Reamed Borehole: 1,102 ft	Flowmeter (Spinner; 06-Feb-03)	
Casing, Screen, Filter Pack and Annular Seals			
Start Date of Casing and Screen Install.: 04-Dec-02	Date of Completion of Casing & Screen Install: 04-Dec-02	Completed Depth: 1,070 ft	
Casing ID: 20-in.	Screen ID: 20-in.	Filter Pack: Tacna Custom Blend (355–1,090 ft)	
Casing Wall Thickness: 3/8-in. (0–500 ft)	Screen Wall Thickness: 5/16-in.	Method of Placement: Fluid circulation through tremie pipe	
Casing Wall Thickness: 5/16-in. (500–1,070 ft)	Screen Type: RMC Ful-Flo Louvers with 3/32-in. openings	Start Date of Filter Pack Placement: 05-Dec-02	
Casing Type: Roscoe Moss spirally welded	Screen Material: Copper-bearing steel	Completion Date of Filter Pack Placement: 06-Dec-02	
Casing Material: Copper-bearing steel	Screened Intervals: 500–630, 705–1,050 ft	Annular Seals: 0 to 343 ft 10.3 sack cement with 2% $CaCl_2$ 343 to 350 ft (fine sand) 06-Dec-02	
Cased Intervals: 0–500, 630–705, 1,050–1,070 ft	Gravel Feed Pipe Size & Length: 2 ea. 3-in. Sch40, 0–355 ft		
Sounding Tube Size & Length: 2-in. Sch40, 0–496 ft			

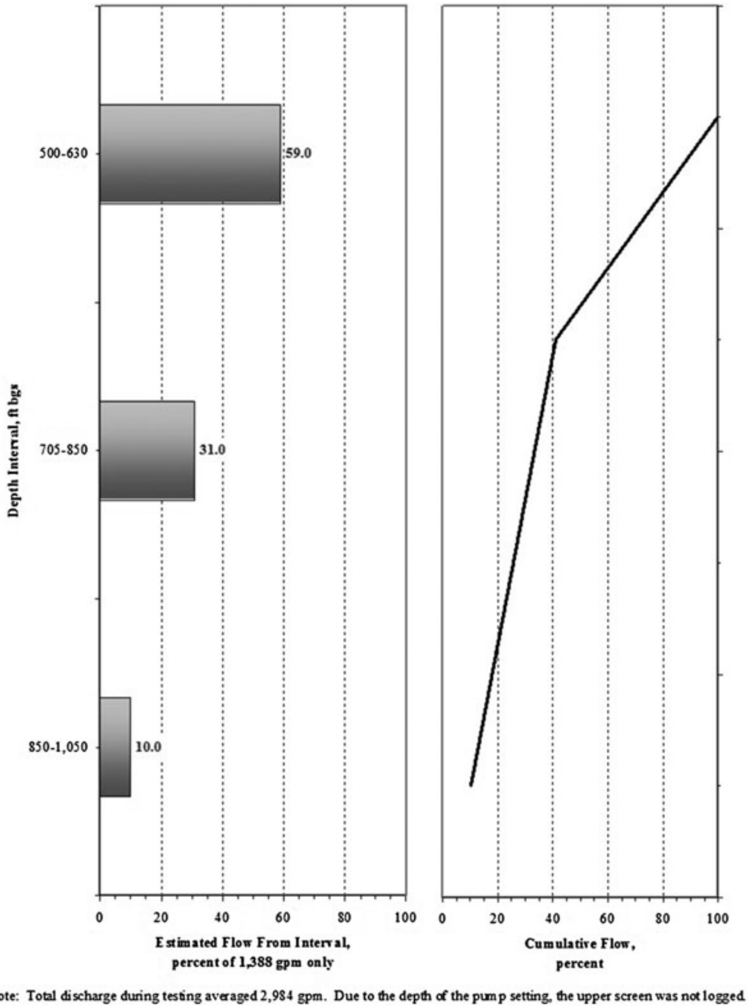


Fig. A-9. Flowmeter survey of Well 40, City of Ontario

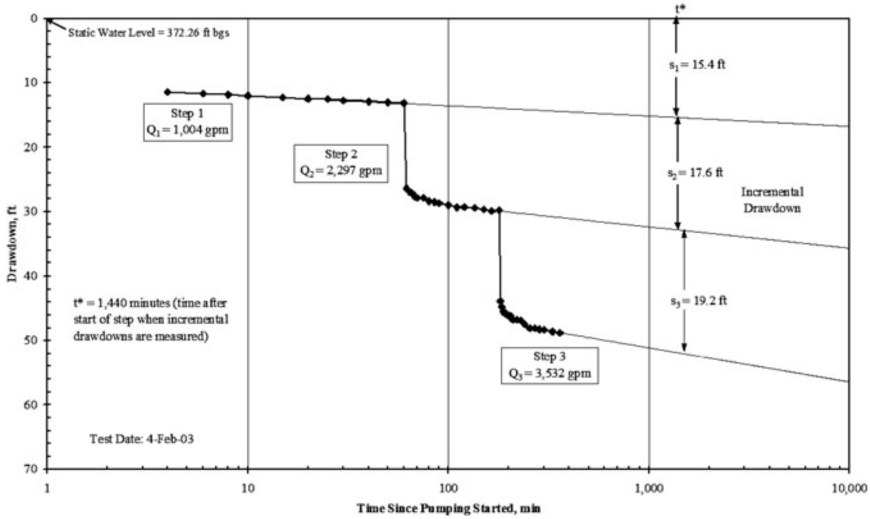


Fig. A-10. Step drawdown test, Well 40, City of Ontario

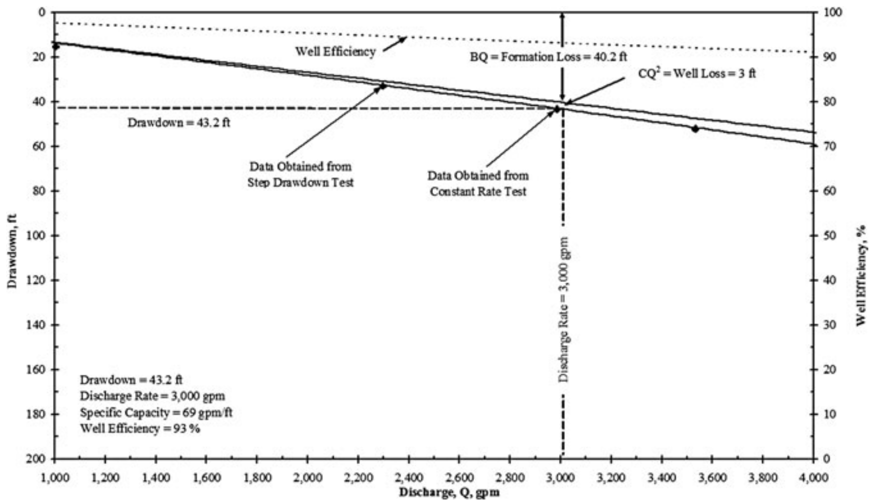


Fig. A-11. Specific capacity and well efficiency graph, Well 40, City of Ontario

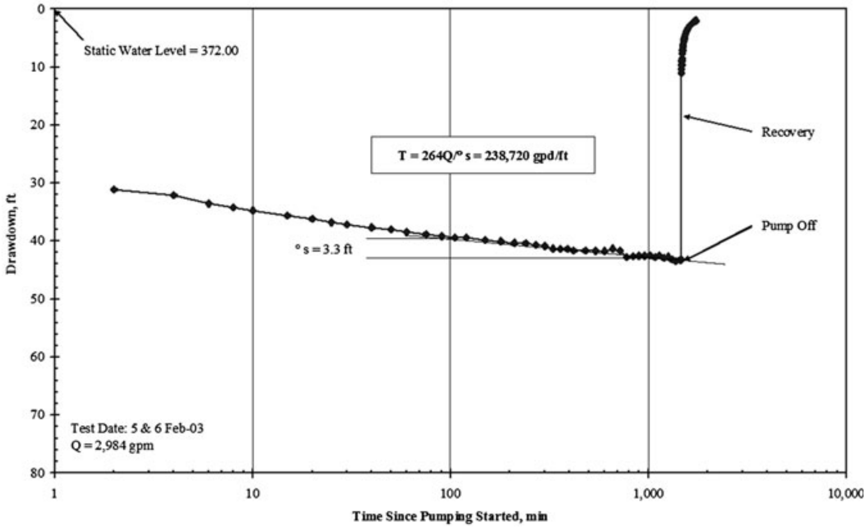


Fig. A-12. 24-hour constant rate pumping test, Well 40, City of Ontario

Table A-6. Recommended Design Parameters, City of Ontario Well No. 40

Parameters	Short Term	Long Term*
Design Pumping Rate	3,000 gpm	3,000 gpm
Design Drawdown	46 ft	54 ft
Design Well Efficiency	95%	NA
Pump Setting	640 ft bgs	640 ft bgs
Static Water Level Depth	272 ft bgs	272 ft bgs
Total Lift to Surface	318 ft	426 ft

*Extrapolated using water level data from the step drawdown and constant rate pumping tests

(TDS) concentration of 240 mg/L. This value is well below the California EPA's recommended drinking water standard of 500 mg/L. The nitrate (as NO_3) concentration was 15 µg/L, which is below the current MCL of 45 µg/L. All other constituents that have been reported are below their specified MCLs. Fig. A-13 shows a trilinear diagram of completed water quality, as well as water quality for the three zone tests.

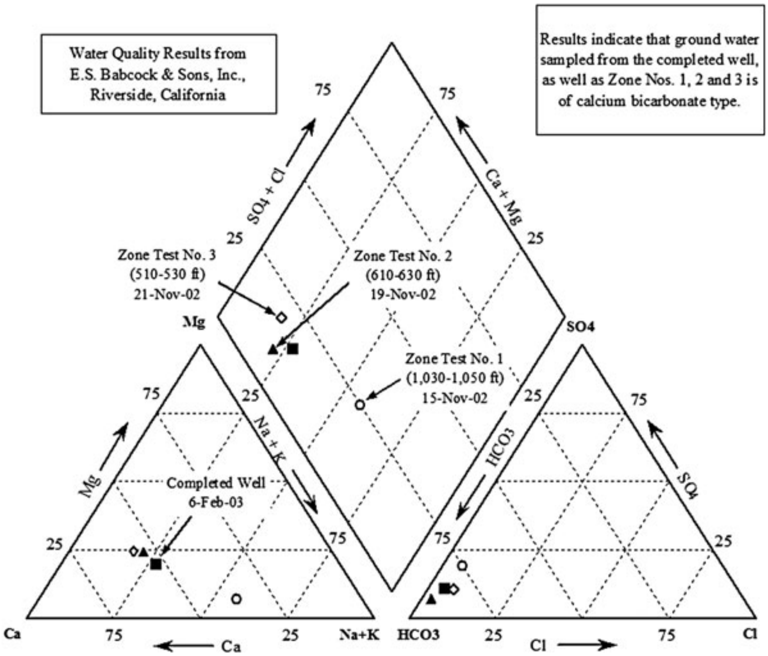


Fig. A-13. Trilinear diagram of aquifer zone test and completed wellwater quality data, Well 40, City of Ontario

A.9 VIDEO SURVEY, PLUMBNESS, AND ALIGNMENT

After well completion, a downhole video survey was conducted as a permanent record of the post-construction condition of the well. The results of the plumbness and alignment survey showed that the well did not exceed the specified limit of 6 in. per 100 ft of well depth. At 640 ft bgs (i.e., the recommended pump setting) the deviation from vertical was found to be 7.5 in. in the north–west plane and 0 in. in the south–east plane. The maximum deviation in the north–west and south–east planes was approximately 10 in. and 0 in., respectively, at a depth of 840 ft.

A.10 WELL EQUIPPING, OPERATION, AND MAINTENANCE

After the well was completed and tested, the pumping plant was designed by Albert A. Webb and Associates of Riverside, CA. Well Pumping Plant No. 40 was equipped with a vertical turbine type unit, operating at 1,770 rpm designed for a capacity of 3,000 gal./min. The unit

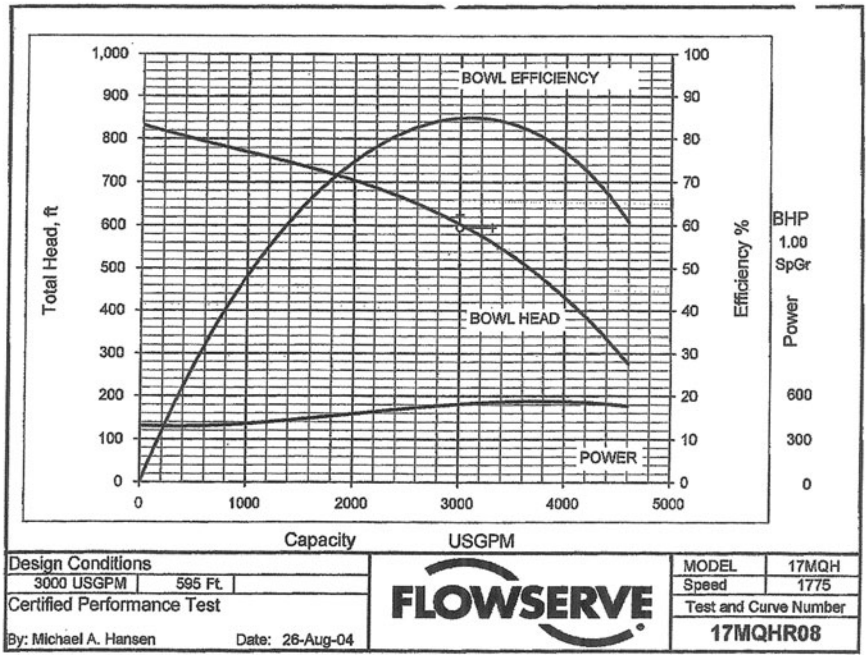


Fig. A-14. Head capacity test, Well 40, City of Ontario
Source: Courtesy of Albert A. Webb Associates

has a cast iron surface discharge head and 12-in. diameter column piping. The pump discharge head and motor are installed on a reinforced concrete pier. The total piping head (exclusive of pump losses) is estimated to be 783 ft. Utilizing a 12-in. inside diameter column piping, a 2 3/16-in. minimum diameter line shaft and a 3 ½-in. minimum diameter oil tube, the estimated column and discharge head loss is approximately 22 ft. The Total Dynamic Head (TDH) is approximately 805 ft. Based on a field pump efficiency of 80%, (at the mid-design point), the brake horse power (bhp) is approximately 763-hp plus shaft horsepower loss (estimated at 17 hp), providing a motor horsepower requirement of 780 hp. The pump driver is an 800 hp, 480-volt vertical hollowshaft, premium efficiency electric motor. An electronic water level monitoring system is installed with the pumping unit.

In addition, an emergency standby generator is installed as part of the completed pumping plant. A 1000 kW standby diesel generator supplies the 800 hp motor load together with the auxiliary electrical loads.

PUMP MATERIALS SPECIFICATIONS		
PART NAME	MATERIAL DESCRIPTION	
	Common Name	ASTM No.
DISCHARGE HEAD		
Fabricated Head	Steel	A36-GR D/A53-GR B
Packing Box	Cast Iron	A48-CL30
Packing	Graphite Fiberglass	Graphite Fiberglass
BASEPLATE		
Baseplate	Steel	A36-GR D
COLUMN ASSEMBLY		
Pipe	Steel	A53-GR B
Lineshaft	C-1045 Steel	A108-GR 1045
Enclosed Lineshaft		
Enclosing Tube	Steel	A120-76
Lineshaft Bearing	Bronze	B505-C84400
Tube Stabilizer Threaded	Rubber	Buna-N
BOWL ASSEMBLY		
Bowl (Case)	Cast Iron	A48-CL30
Bolts for Flanged Bowl Construction	316 S.S.	A193-GR B8M-CL1
Impeller	Bronze	B584-C90300
Collet	316 S.S.	A269-TYPE 316
Bowl Bearings	Bronze	B505-C84400
Protecting Collar	Bronze	B505-C84400
Grease Plug	Iron	A197
Pump Shaft	416 S.S.	A582-Type 416
Lineshaft Coupling	416 S.S.	A582-Type 416
Suction Strainer	316 S.S.	316 S.S.

Fig. A-15. Pump materials specifications, Well 40, City of Ontario
Source: Courtesy of Albert A. Webb Associates

The head-capacity curve and pumping unit and pipeline specifications are shown in Figs. A-14–A-16. The detailed site layout and pumping plant building are shown in Figs. A-17 and A-18.

Under normal circumstances the well will be operated as required to meet system demands. Periodically, variable rate discharge testing will be done to evaluate well efficiency and compare with the original values. When the well efficiency declines warrant rehabilitation, the well will be taken out of service, video logged, and a mechanical and possibly a chemical rehabilitation program developed.

A.11 ACKNOWLEDGMENTS

The author is greatly indebted to the City of Ontario, CA, for granting permission related to the material appearing in Appendix A. Also, the author is appreciative to Albert A. Webb Associates, Riverside, CA, for additional contributing materials used in this appendix.

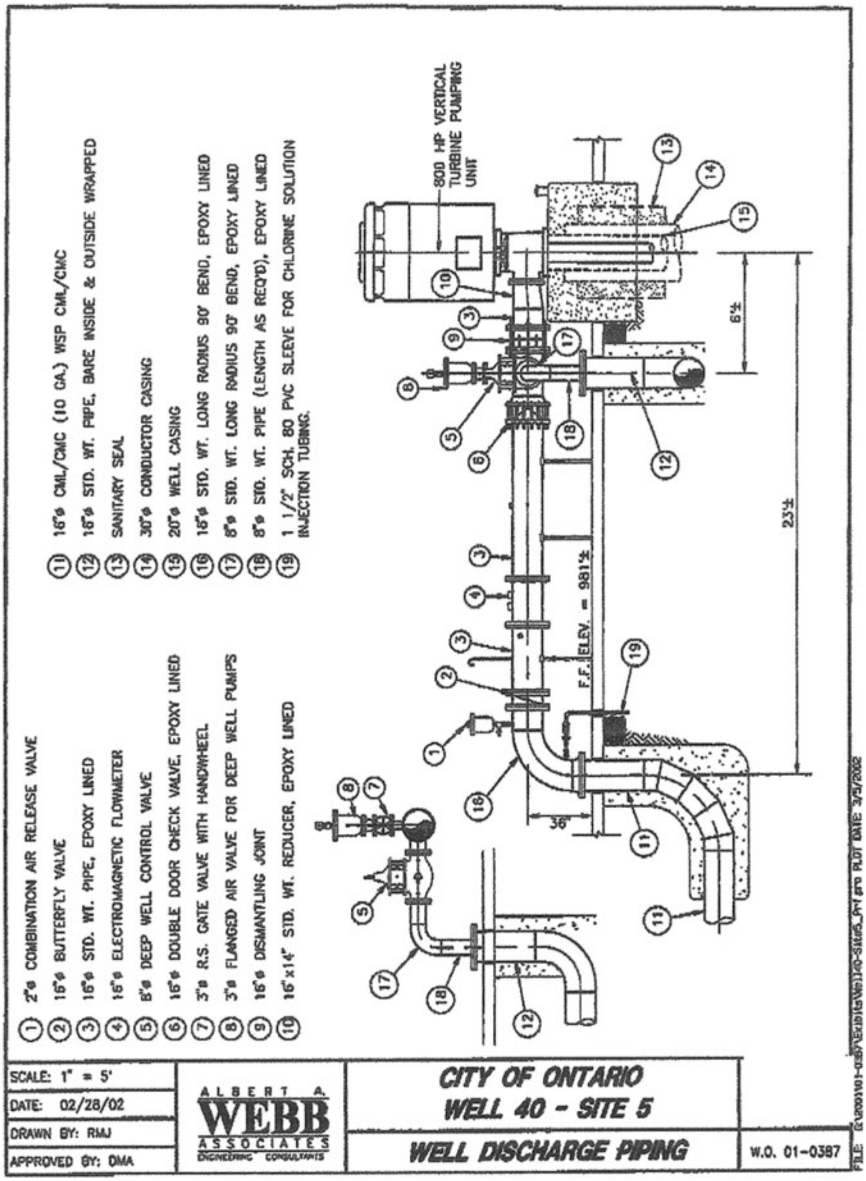


Fig. A-16. Well discharge piping diagram, Well 40, City of Ontario
Source: Courtesy of Albert A. Webb Associates

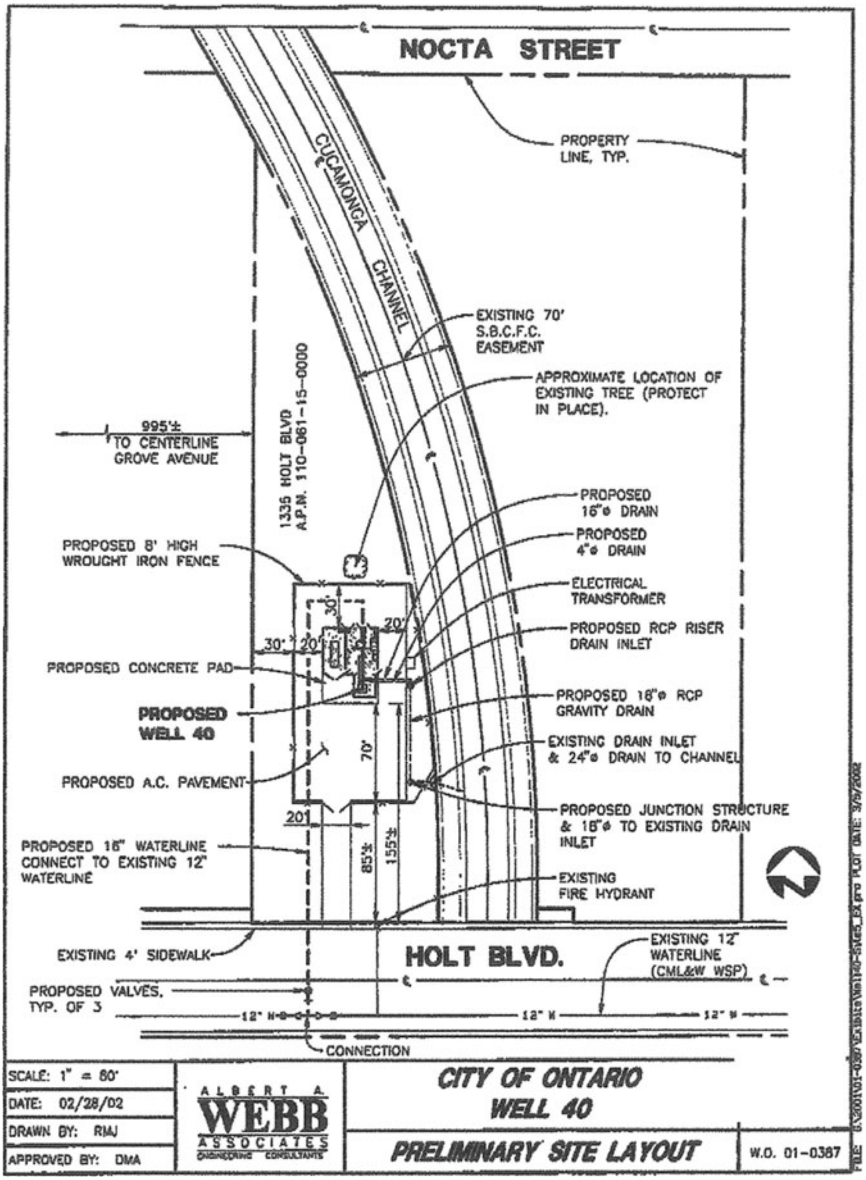


Fig. A-17. Preliminary site layout, Well 40, City of Ontario
Source: Courtesy of Albert A. Webb Associates

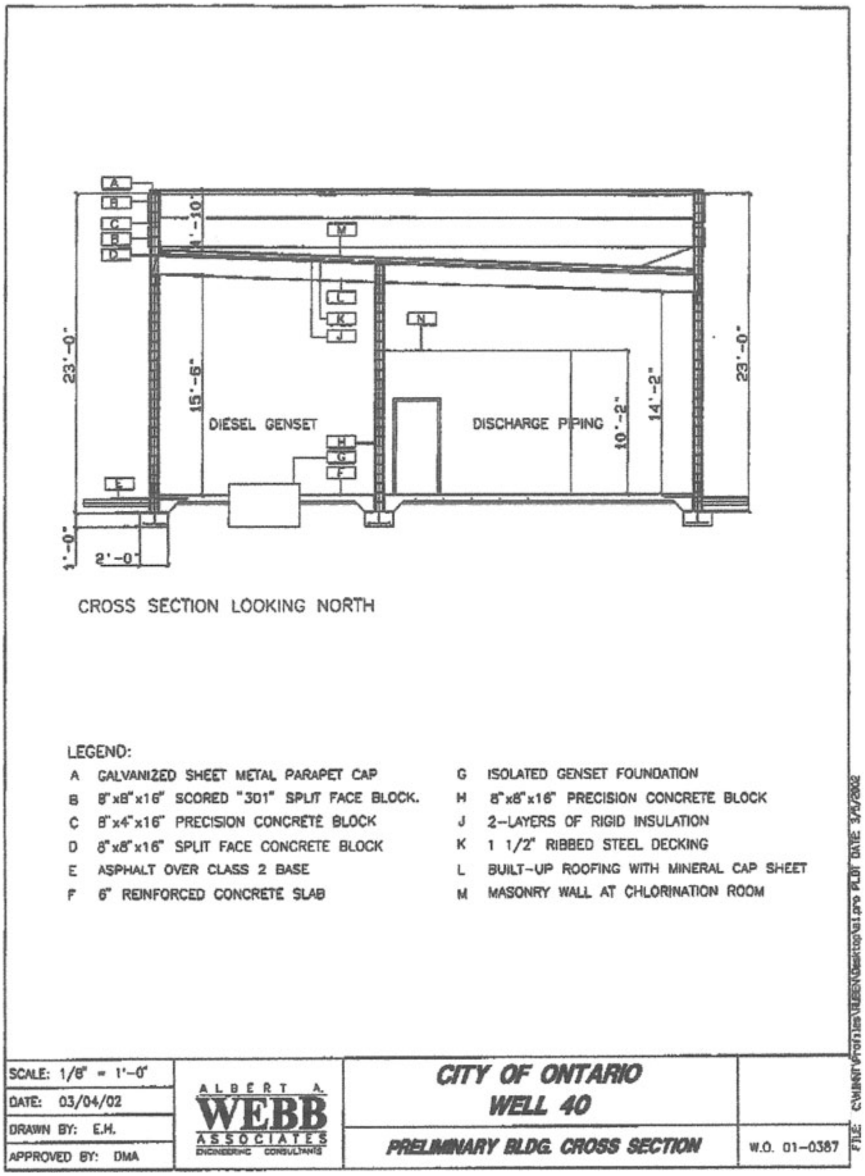


Fig. A-18. Preliminary building cross section, Well 40, City of Ontario
Source: Courtesy of Albert A. Webb Associates

APPENDIX B

TECHNICAL SPECIFICATIONS FOR DRILLING, CONSTRUCTING, AND TESTING OF WATER WELLS

Dennis E. Williams

B.1 GENERAL

B.1.1 Purpose and Scope

The purpose of this document is to provide technical specifications for the construction, development, and testing of one production water well. [Well name] is to be drilled at a site owned by [Owner/client] located at ____________. Fig. B-1 shows the general location of the well site while Fig. B-2 shows a more detailed location of the well. [Owner/client] will use the well for municipal water supply. The details of construction, completion, and testing of [Well name] are shown on Fig. B-3, which shall be constructed as specified herein.

These specifications have been prepared based on the most recent information available regarding site conditions, drilling methods, and materials to be used. However, should the contractor take exception to any part of these specifications or well design and is not prepared to follow the specifications as included herein, the contractor shall notify the owner or the owner's representative in writing before mobilizing to the project site.

The scope of the work encompassed by these specifications consists of furnishing all plant, labor, equipment, appliances, and materials in addition to performing all operations in connection with the drilling, sampling, constructing, developing, and testing of the well.

A mandatory pre-bid meeting will be held at the time and date specified in the notice inviting bids. The mandatory pre-bid meeting will allow potential bidders the opportunity to view the site and ask questions. Well completion reports and lithologic logs for nearby wells are included in Attachment B8.1 of these technical specifications.

The well shall be drilled using a reverse rotary drilling rig and shall be completed in two passes (the flooded reverse drilling method is not acceptable). The first pass (pilot borehole) shall be made using a 444.5 mm (17 ½ in.) diameter bit. The second pass will enlarge the pilot borehole to its final diameter down to a depth specified by the hydrogeologist. The hydrogeologist will provide final well construction details to the contractor following review of mechanical grading analyses, isolated aquifer zone test results and geophysical borehole logs. All work is to be completed, and in strict accordance with these specifications and the attached drawings unless otherwise modified by the hydrogeologist. The preliminary plans for the completion and testing of the well are shown in Fig. B-3 and shall be modified as necessary following completion of drilling the pilot borehole, geophysical logging and isolated aquifer zone testing.

Based on other production wells in the area of similar construction, the anticipated production capacity is approximately ___liters per minute (L/min) (____ gallons per minute [gal./min]).

Activities at the site shall be 24 h per day from Monday through Saturday, with work taking place on Sunday only if strictly required.

B.1.2 Definitions

- **Owner:** ______________________________
- **County:** ______________________________
- **Engineer:** ______________________________

Hydrogeologist: ______________________________

Certified Analytical Laboratory: ____________________

Standard Specifications:

American Society for Testing and Materials (ASTM). (2008). D4050-96 (2002): *Standard test method (field procedure) for withdrawal and injection well tests for determining hydraulic properties of aquifer systems*, ATSM International, West Conshohocken, PA.

American Water Works Association (AWWA). (2006). *Standard for Water Wells (AWWA A100-97)*, AWWA, Denver.

California Department of Water Resources (CDWR). (1981). “Water Well Standards: State of California” (Bulletin 74–81) < http://www.water.ca.gov//pubs/groundwater/water_well_standards__bulletin_74-81_/ca_well_standards_bulletin74-81_1981.pdf> (Jan. 2, 2014).

CDRW “California Well Standards” (Bulletin 74–90) < http://www.water.ca.gov/pubs/groundwater/water_well_standards__bulletin_74-90_/ca_well_standards_bulletin74-90_1991.pdf> (Jan. 2, 2014).

Note: For global usage, specifications of local jurisdictions would override the specifications detailed in this technical specification.

B.1.3 Location, Depth, and Well Dimensions

The planned well will be located at ______. The conceptual well completion diagram is shown in Figure B-3.

The contractor shall drill the well at the location indicated on the attached location maps (see Figs. B-1 and B- 2). [Owner/client] will mark the exact field location of the well prior to mobilization. For the purpose of these specifications and bidding, the contractor may assume an approximate total pilot borehole depth of ___ m (___ ft) below ground surface (bgs) and an approximate well completion depth of ___ m bgs (___ ft bgs) based on current geologic cross sections. The contractor shall satisfy himself or herself by personal investigation of all local conditions affecting the work. Neither information contained in this section, nor that derived from maps or plans, or from the owner, the owner's representatives or employees, shall relieve the contractor from any responsibility either specified herein, or from fulfilling any and all terms and requirements of the contractor's contract.

Prior to drilling the pilot borehole, a ___ mm outside diameter (OD) mild steel conductor casing with ____ mm wall thickness shall be installed within a ___ mm diameter borehole to a minimum depth of ___ m bgs.

The borehole for the well itself shall be drilled using at least two separate drilling passes. The first pass, or pilot borehole, shall be drilled using a 444.5 mm (17 ½ in.) diameter drill bit to an estimated maximum depth of _____ m bgs. Once the drilling, sampling, geophysical borehole logging, and isolated aquifer zone testing are completed, the pilot borehole shall be enlarged (reamed) to a diameter of ___ mm from ___ m bgs (bottom of conductor casing) to a depth of ______ m bgs. However, the final completion depth and borehole diameters shall be as specified by the hydrogeologists based on the formation samples, geophysical borehole logs, and the results of the isolated aquifer zone tests.

The final completion design will be issued in a separate letter following receipt of zone testing water quality analyses. The contractor should plan on a minimum of 1 week of shutdown time from the completion of zone testing to the receipt of the well design letter. Under no circumstances shall the contractor begin the reaming pass prior to receiving the well design. Well materials consisting of __ mm inside diameter (ID) with ___ mm wall thickness copper-bearing steel casing and ____ mm ID with ____ mm wall thickness copper-bearing steel horizontal louvered screen shall be used for the construction of the well.

The well dimensions and completion depth are as shown on the technical cross section (see Fig. B-3) and shall be as specified herein. However, any of the various depths indicated herein may be increased or decreased by the hydrogeologist in accordance with formations encountered during drilling and based on the results of geophysical borehole logging. In the event that drilling is authorized or ordered to a depth shallower or deeper than specified herein, a corresponding adjustment shall be made to the appropriate bid item cost within the contract.

B.1.4 Local Conditions—Hydrogeology

Note: This section should include a description of local hydrogeology and information on nearby wells as required in the contract specifications.

B.1.5 Permits, Certification, Laws, and Ordinances

The contractor shall, at contractor expense, procure all necessary permits, certificates, and licenses required by law for the execution of his or her work. The contractor shall comply with all federal, state, and local laws, ordinances, or rules and regulations relating to the performance of the work.

The contractor shall be required to obtain necessary permits from such regulatory agencies including the State Department of Transportation, county department of transportation, county flood control, and city agencies for discharge of water during the various testing phases.

B.1.6 NPDES Requirements

Attachment B8.2 contains the general National Pollutant Discharge Elimination System (NPDES) permit for ground water dewatering operations as required by the Regional Water Quality Control Board (RWQCB). The owner shall provide a renewed general NPDES permit prior to the start of drilling. The contractor shall comply with all conditions and requirements of the approved general NPDES permit and shall be responsible for all costs of meeting these conditions and requirements. These conditions and requirements include, but are not limited to, the following:

- RWQCB notification 5 days prior to start of construction;
- Procurement of the necessary paperwork and forms;
- Collection of water samples during the first 30 min of discharge;
- Testing of water for water quality parameters, such as total suspended solids (TSS), total dissolved solids (TDS), color, etc.; and
- Filing of the required reports.

The contractor must comply with the requirements of the [owner/client]'s general discharge permit (see Attachment B8.2).

B.1.7 Boundary of Work

The owner will provide land or rights-of-way for the work specified in this contract and will make suitable provisions for ingress and egress. The contractor shall not enter on or occupy with personnel, tools, equipment, or material, any ground outside the specified area of the property of the owner without the written consent of the owner of such ground. Other contractors and employees or agents of the owner may for any necessary purposes enter upon the work site and premises used by the contractor.

B.1.8 Protection of Site and Disposal of Wastewater and Drilling Mud

Due to the proximity of the proposed well to a local drainage, drilling activities shall be conducted in such a way as to prevent the introduction of pollutants to the ground surface during construction. Accordingly, any equipment or materials brought to the project area must be managed in accordance with the following procedures:

- Drip pans will be used to catch leaks and residual material in hoses and spigots under all stationary equipment. The drip pans will be checked daily and emptied as needed by reusing the substance or disposing of it properly at the contractor's expense.
- Hazardous materials spills will be contained immediately using sand, dirt, or absorbent materials. Such spills will be cleaned up promptly along with the contaminant material and will be disposed of properly at the contractor's expense.
- Outdoor storage of all oils, solvents, cleaners, and other liquid materials shall be within secondary containment. The area should be covered, as necessary, to prevent storm water accumulation in the containment.
- Bentonite, cement, and any other powdered product shall be stored on pallets and away from any drainage path. The storage area should be covered and protected, if necessary, to prevent pollution runoff by wind or storm water.
- Chemicals, bagged material, or drums shall be stored on pallets within secondary containment.

Waste products generated during the drilling/construction work must be managed in accordance with the following procedures:

- Containerized waste will not be allowed to overflow. Any waste that requires storage in containers shall be removed from the project area on a regular basis and disposed of at an approved facility at the contractor's expense.

- Cleaning of the drilling rig, cement/bentonite mixtures, tremie pipe, and any other equipment shall be conducted within a fully contained area or outside the project area in a place approved by [owner/client].
- Waste bentonite or cement must be removed from the project area prior to completion of the work.

The use and maintenance of drilling rigs and support vehicles shall be in accordance with the following procedures:

- Fueling of vehicles and equipment will be performed on site at designated areas. During fueling operations, drip pans will be used to catch leaks. "Topping off" of fuel tanks is not allowed.
- Maintenance of vehicles will be performed within designated areas to be approved by [owner/client]. Drip pans will be used during maintenance activities to catch any leaks.
- Daily inspections of drilling rigs and support vehicles and equipment will be made to check for leaks. Any leaks detected shall be fixed immediately.
- All contractor employees and subcontractors shall be educated in the proper handling and storage of construction materials used during the project.
- Small spills shall be soaked up using absorbent materials and disposed of properly at the contractor's expense. Washing down or burial of spills is not allowed.
- Steam cleaning of the drilling rig and support equipment must be within a designated area, to be approved by [owner/client]. The cleaning area shall be bermed or otherwise contained to prevent runoff to storm drains. All wastewater generated from cleaning equipment must be containerized and disposed of at the contractor's expense. Any soap used during cleaning must be phosphate-free and biodegradable.

Except as otherwise provided herein, the contractor shall protect all pipelines, trees, and, as much as possible, shrubbery during the progress of the work. At completion of the work, the contractor shall restore the site to its original condition. The contractor shall use best industry practices for the protection of the well site during work activities and shall take whatever measures are necessary to ensure that work activities do not affect surrounding areas.

Disposal of drilling cuttings and excess drilling fluid shall be by spreading once the drilling rig has been demobilized. The contractor shall not allow fluids to flow either off the site, into nearby creek beds, or onto improved roadways. Disposal of drilling fluid or water extracted from the borehole shall comply with the general NPDES permit requirements as stated in Section B.1.6, NPDES Requirements. If necessary, to avoid runoff and nuisance due to excess fluids, the contractor may be required to contain fluids and drill cuttings in roll-off bins or similar containers.

Disposal of wastewater or water pumped from the well shall comply with the general NPDES permit requirements as stated in Section B.1.6, NPDES Requirements. All costs incurred in the disposal of drill cuttings and other water, as well as pumped and wastewater, shall be at the contractor's expense.

The contractor shall investigate and obtain any and all permits required (e.g., flood control and city encroachment) for the disposal of wastewater and drill cuttings resulting from the well drilling, construction and development activities. [Owner/client] shall approve the location and method of disposal, as determined by the contractor. Prior to disposal, wastewater shall be pumped into a series of covered and locked temporary holding tanks that have been placed on the site. Water pumped from these tanks shall be conducted to a place determined by the contractor and approved by [owner/client], where it will be possible to dispose of water (that meets the required NPDES provisions) without damage to property or the creation of a nuisance.

During the drilling process it is anticipated that high-turbidity fluids will be discharged from the circulation reservoirs at the drilling rig to a series of 80,000 L (21,000 gal.) Baker tanks located on the site. The Baker tanks shall be the enclosed style with locking covers. All ladders shall be removed from access by the public at all times when not in use by the contractor. From the Baker tanks, clean fluids that meet NPDES discharge requirements will be pumped to the unnamed drainage located on the eastern side of the site.

All costs incurred in the disposal of wastewater and drill cuttings removed from the borehole shall be at the contractor's expense. For further details regarding disposal of cuttings see Section B.2.4, Testing and Disposal of Drill Cuttings.

B.1.9 Site Security

The contractor shall make adequate provision for the protection of the work area and the borehole/well against fire, theft, and vandalism, and also for the protection of the public against exposure to injury.

Where sound barriers are not used, the contractor shall enclose the work site with a chain-link fence including a gate and a lock. The fence, gate, and lock shall be adequate to protect the work and temporary facilities against acts of theft, trespass, violence, or vandalism. In locations where the probability of such acts of theft and vandalism is reasonably expected, this fencing requirement shall be enforced to include the enclosure of all equipment, well construction materials, temporary offices, and storage areas. The contractor shall bear the responsibility for protection of equipment and material on the worksite.

To prevent intrusion by unauthorized persons, temporary openings and gates in existing fences shall be protected. During night hours, weekends, holidays, and other times when no work is being performed at the site, the contractor shall provide temporary closures or guard service to protect the site. All openings in the enclosure shall be closed when not immediately in use.

B.1.10 Source of Water

[Owner/client] will provide the contractor with a water source that is within a reasonable distance to the drilling site. It shall be the contractor's responsibility to provide and maintain at the contractor's own expense all water supply connections for use for construction and domestic consumption. The contractor shall install and maintain all necessary supply connections and piping only at locations and in manners as approved by [owner/client]. All water shall be metered and carefully conserved. Before final acceptance of the well, all temporary connections and piping installed by the contractor shall be removed.

B.1.11 Noise Control

Operations shall be performed in a manner to minimize unnecessary noise generation and minimize disturbance to persons living or working nearby and to the general public, while meeting all applicable noise abatement ordinances. Standards generally mandate that "facility-related noise, as projected to any portion of any surrounding property containing a 'habitable dwelling, hospital, school, library or nursing home' must not exceed the following worst-case noise levels:"

- Between the hours of 10 p.m. to 7 a.m. (nighttime standard): 45 decibels—10-min noise equivalent level ("leq").
- Between 7 a.m. and 10 p.m. (daytime standard): 65 decibels—10-min leq.

The cost of noise control measures shall be included in the contractor's bid price, and the measures to be used in noise suppression shall include (but are not limited to)

- Equipping all internal combustion engines with critical residential silencers (mufflers),

- Shielding noise-producing equipment from nearby areas of human occupancy by erecting padded sound curtains of at least 7.3 m (24 ft) in height that completely surround the work site (the sound curtains shall extend to the ground surface in all places and shall not have any gaps between panels and the ground surface) and by locating equipment in positions which will direct the greatest noise emissions away from these areas,
- Wrapping the mast with padded sound blankets (which will additionally shield nearby residences from nighttime lighting), and
- Conducting operations in the most effective manner that will minimize noise generation, while being consistent with the prosecution of the contract in a timely and economic manner.

In the event that unacceptable noise levels persist, [owner/client] shall direct the contractor to cease operations until appropriate mitigation measures are implemented and acceptable noise levels are obtained, at no additional cost to [owner/client].

B.1.12 Dust Control

To control dust at the site, the contractor shall take whatever steps, procedures, or means as are required to prevent abnormal dust conditions from being caused by its operations in connection with the execution of the work, or on any unpaved road or surface that the contractor or any of the subcontractors are using for excavation or fill areas, demolition operations, or other activities.

Dust control at the well site shall be accomplished by dampening with water, providing a cover of gravel (or other acceptable material) on the active working areas of the site, modification of operations, or any other means acceptable to agencies having jurisdiction.

B.1.13 Hours of Work

A hydrogeologist will be onsite during the various phases of drilling and reaming, zone testing, construction, development, and aquifer testing. Work shall be continuous (24 h per day, 6 days per week, unless other working arrangements are made) from the start of the drilling of the pilot borehole to the placement of the casing, screen, filter pack material, and annular seals. Continuous drilling shall minimize both the risk of borehole collapse and the time that the formations are in contact with the drilling fluid. Noise effect to the residents of the neighborhood shall be kept to a minimum at all times, and mandated noise levels (see Section B.1.11, Noise Control) shall be strictly enforced.

No work shall be performed on major holidays, during the week of Thanksgiving, or the time period from Christmas Eve to New Year's Day.

B.1.14 Site Communications

The contractor shall have at the drilling site at all times means for communicating (i.e., cellular telephones and pagers) between all workers at the site, their office, and the hydrogeologist (two-way radios are not an acceptable form of communication). The telephone numbers of such devices shall be provided to the hydrogeologist before the start of the work so that the contractor's personnel are available at all times for status updates. Telephones with a vibrating mode shall be made available to crew members so that the incoming calls may be heard above the noise at the worksite.

Emergency (24 h/day) telephone numbers of all key contractor personnel involved with the project shall be provided to the hydrogeologist at the time of the preconstruction meeting.

B.1.15 Competent Personnel

The contractor shall employ only sober, competent, and experienced workers for the execution of the work, and all such work shall be performed under the direct supervision of an experienced well driller satisfactory to the hydrogeologist. During periods of standby or waiting, the contractor must provide trained and experienced onsite staff, approved by the hydrogeologist, to monitor and maintain the fluid levels in the borehole to protect the borehole from intrusion.

B.1.16 Abandoned Boreholes

Those boreholes that the contractor abandons before reaching the specified depth because of defective workmanship, unsuitable materials introduced to the borehole, or faulty equipment will be considered "lost" boreholes and will not be paid for by [owner/client]. If a borehole is lost, the contractor shall drill another hole to the specified depth, adjacent to the lost borehole (the exact location to be specified by [owner/client]). No payment will be made for subsequent moving, setting up installation of conductor casing, or drilling of the borehole.

All lost boreholes shall be backfilled with bentonite or a bentonite-cement mixture, and the casing shall be removed to a depth of at least ___ m belowground surface, as per ____ County requirements. The site shall be cleaned and restored as directed by the [owner/client]. No payment will be made for the backfilling, removal of casing, site cleaning, or restoration of lost holes.

B.1.17 Cleaning Up and Cleanliness of Worksite

Throughout the entire drilling, construction, development and testing process, the contractor shall maintain site cleanliness and neatness and shall not allow dirt, debris, waste, or rubbish to accumulate. The contractor shall provide adequate trash receptacles at the job site to ensure proper housekeeping of the site is maintained on a daily basis. The contractor is responsible for disposal of all trash generated by workers or subcontractors at the site. A waste disposal bin of sufficient size, equipped with a locking cover, shall be located at the worksite at all times. The trash receptacle shall be emptied weekly, or as necessary, during the progress of work and the completion of the work. The cost of all disposal shall be borne by the contractor.

Care shall be taken to prevent the spilling of either fluids or solid materials on any city streets over which hauling is being done. If any such spillage occurs or debris is deposited on city streets due to the contractor's activities, it shall be removed immediately and cleaned up at the contractor's expense.

B.1.18 Site Sanitation Facilities

The contractor shall provide all necessary sanitary facilities (i.e., privy accommodations) within the fenced area for the use of his employees at the worksite. These facilities shall be maintained and cleaned at least twice per week and kept in a sanitary condition (i.e., well-stocked with an adequate supply of toilet paper, etc.). A portable hand-washing sink attached to a small holding tank for clean water and a soap dispenser shall be provided as a part of the sanitary facility.

The contractor shall provide for contractor employees an adequate supply of clean, potable drinking water.

The contractor shall obey and enforce such sanitary regulations as may be prescribed by the State Department of Health and other government entities having jurisdiction.

At the completion of work, the contractor shall remove all rubbish, excess materials, temporary structures, and equipment from the site and shall leave the site in a neat and presentable condition as approved by [owner/client].

B.1.19 Nighttime Security

Site security in the form of temporary enclosures or guard service shall be provided during all nonworking hours. The site shall be kept lit at night; however, the light shall be shielded so as to avoid creating a nuisance to nearby residents.

B.1.20 Contractor's Health and Safety Plan

The contractor shall provide a site-specific health and safety plan (HASP) for the work specified herein. It shall be solely the contractor's responsibility to conduct daily safety meetings at the worksite and to enforce all standard health and safety practices at the worksite. No hazardous materials are believed to exist at the project site; therefore, working conditions requiring U.S. Occupational Safety and Health Administration (OSHA) Level D for personal protection equipment (PPE) can be assumed.

B.1.21 Construction Inspection

The contractor will be required to contact the hydrogeologists at various stages of construction for the purpose of job inspection. The contractor will perform no work until the hydrogeologist has made such an inspection. A list of the required inspections is shown following, and an inspection checklist is included in these specifications. The contractor will notify the hydrogeologist at least 24 h prior to each of the required inspections to assure that a representative will be available to conduct the inspection.

The following is a list of required inspection items. Inspection and approval of each item by the hydrogeologist is required before proceeding to a subsequent stage of the project. These required inspection items include, but are not limited to, the following:

1. Mobilization
   Equipment (drilling equipment and accessories), geolograph, sound wall, and sanitary facilities
2. Construction materials
   Drilling fluid additives
   Casings and screens
   Filter pack
   Annular seals
3. Conductor casing installation
   Grouting
4. Pilot and reamed borehole drilling
   Mud properties
   Deviation surveys
   Geophysical borehole logs
   Caliper log
5. Zone testing
   Verification of seal
   Static and pumping water levels
   Turbidity measurements
   Water quality sampling

6. Construction process
   Casing assembly installation
   Filter pack and sealing materials
7. Well development
   Development tools
   Pumping equipment
   Discharge assembly
8. Well testing
   Sand tests
   Pumping tests
   Spinner survey
   Plumbness and alignment tests
9. Final
   Video inspection
   Final disinfection
   Wellhead construction security
   Site clean up

B.2 DRILLING METHOD AND EQUIPMENT

The contractor shall provide a reverse circulation drilling unit, complete with all tools, accessories, power, lighting, water, and any other necessary equipment for the completion of the work (the flooded reverse drilling method is not acceptable). The contractor shall provide experienced onsite personnel necessary to conduct an efficient and safe drilling operation. Prior to the beginning of drilling operations, all equipment supplied by the contractor shall be certified by the contractor to be suitable for the specified drilling operation. The replacement of any equipment later found to be unsuitable shall be at the contractor's expense.

All equipment intended for use in the drilling, construction, development, and testing of the well shall be inspected by the hydrogeologist prior to mobilization at the site to ensure that the equipment intended for use is adequate and acceptable for the work.

All "pipe dope" used in the performance of the work must comply with environmental standards and shall be inert. A materials safety data sheet (MSDS) for all controlled materials used in the performance of the work shall be provided to the hydrogeologist prior to the start of the work.

B.2.1 Selected Method and Equipment for Drilling

The well shall be drilled by the reverse circulation drilling method and shall be artificially filter packed using modern-day technology for drilling, construction, materials, and development (the flooded reverse drilling method is not acceptable). The use of drilling equipment having flanged drill pipe with external air lines will not be accepted.

The contractor shall furnish, with the contractor's bid, a complete list of equipment that is proposed to be used in the performance of the work. After award of the contract, the work shall not proceed until the hydrogeologist approves the proposed construction method and is satisfied that the listed equipment is adequate for the work and will be at the site when needed. The contractor must provide for an uninterrupted course of work operations (during the hours allowed) from the time drilling is commenced, to completion of development and final testing. All equipment must be in good working condition and approved by the hydrogeologist.

The list of equipment accompanying the bid shall include the following:

- Rated maximum safe mast, substructure, and draw-works capacity (the minimum acceptable working capacity of the mast and draw-works shall be 68,000 kg (150,000 lb),
- Approximate mast height,
- Total available rig horsepower,
- Available rotary table horsepower,
- Available draw-works horsepower,
- Type and capacity of portable fluid reservoirs,
- Type and size of required shale shakers and desanding/desilting equipment,
- Type and size of air compressor,
- Pump curve for the submersible pump to be used during zone testing,
- Pump curve for the line shaft turbine test pump to be used for well development and testing, and
- Type and size of all zone testing tools to be used.

The contractor shall also submit a proposed drilling program including

- Type or types of drill bits,
- Diameter, total length, and number of drill collars (including total weight),
- Size and type of drill pipe (the use of flanged drill pipe will not be accepted),
- Rotary speeds,
- Fluid circulation rate,
- Specifications for proposed drilling fluid compounds and/or additives, if necessary,

- Air compressor size to be used for initial development by airlifting and swabbing, and
- Specifications and drawings for tools to be used for initial development by airlifting and swabbing.

The rig shall be equipped with the following operating accessory equipment:

- Weight indicator,
- Approved equipment for measuring mud properties,
- Sample collection box, or approved method of collecting formation samples (as shown on Fig. B-4),
- Two-pen recording hydrogeolograph (string weight and footage rate), or other approved real-time drilling rate indicator, and
- Totco or equivalent drift indicator, or other approved deviation survey equipment.

No delays or work stoppages will be tolerated. The contractor shall be held responsible and payment may be withheld for damages done to the well due to any cause of negligence or faulty operation.

B.2.2 Circulation Reservoirs—Portable Fluid Tanks

The contractor shall provide adequate baffled drilling fluid reservoirs with solids control equipment in the form of shale shakers and desanders/ desilters. Such equipment will allow the removal of drill cuttings from the fluid before recirculation to the borehole. The consistency of the drilling fluid shall be such that fine drill cuttings and sand will settle out in the reservoir. In addition to using a shaker table, desilters and desanders, the drilling fluid reservoir shall be cleaned frequently to minimize the potential for excessive sand content of the return fluid. The use of in-the-ground pits will not be accepted. The contractor shall provide a sample collection box, or other such approved device, for the collection of representative formation samples (see Fig. B-4).

B.2.3 Drilling Fluid—Reverse Circulation Drilling Method

Unless otherwise approved by the hydrogeologist, water alone shall be employed as the circulating medium. If drilling additives are used, the materials used shall be manufactured by Baroid, or a manufacturer approved by the hydrogeologist. If "loss of circulation" or other drilling problems require the addition of bentonite gel or loss of circulation materials (LCM), such material may be added only with the prior approval of the hydrogeologist. Procedures must be adopted to ensure the removal of these additives during the development process.

If any drilling additives are used in the circulating medium, the time of day and depth of the borehole shall be recorded on the driller's daily log, and a strict accounting shall be kept of the materials used. In addition, whether or not drilling additives are used, the sand content, viscosity, and weight of the drilling fluid shall be measured and recorded a minimum of every 4 h during drilling or circulation of the borehole (both pilot and reaming pass). The sand content of the fluid returning to the borehole shall be maintained at less than 1% (by volume) at all times.

In the event that drilling additives are used, the contractor shall maintain careful mud control. The contractor shall record a continuous log of mud weight, funnel viscosity, 30-min water loss, wall cake thickness, pH, and sand content. Fluid checks shall be taken at a minimum of every 4 h during drilling, whenever conditions appear to have changed, or if difficulties arise. The contractor shall provide the hydrogeologist with an updated list of all products and the quantity of each product that is delivered to the site. The contractor shall record the type, time, and quantity of each product as it is used.

Drilling fluid additives, if approved for use, shall have such properties as to be adequate to form a thin but effective filter cake to coat the walls of the borehole to prevent water loss, to support the borehole wall to prevent caving, and to permit the recovery of representative samples of drill cuttings (formation materials). If there is a conflict between adjusting the drilling fluid properties for the ease of drilling or maintaining the proper drilling fluid properties for the protection of the aquifer, the protection of the aquifer shall prevail. The contractor shall make every effort to prevent the penetration of mud filtrate into the potential aquifers to be screened.

The circulating fluid shall not exceed the following parameters at any time:

- Weight—1.02 to 1.08 kg/L (8.5 to 9.0 lb/gal.) normal range. 1.14 kg/L (9.5 lb/gal.), maximum
- Funnel viscosity—29 to 35 s normal range. 38 s, maximum
- 30-min water loss—15 cubic cm, maximum
- Filter cake—1.59 mm (2/32 in.), maximum
- Sand content of fluid entering borehole—less than 1% by volume, maximum
- pH—7.0 to 9.0 units.

Depending on borehole conditions during drilling, and if directed by the hydrogeologist, the drilling fluid shall be thinned after the well borehole has been reamed and before the caliper log is run, until it has the following properties:

1. Weight—1.02 kg per liter (8.5 lb/gal.), maximum
2. Funnel viscosity—29 s, maximum
3. Sand content of fluid entering the borehole—less than 1% by volume, maximum.

The contractor shall measure and record drilling fluid properties at a maximum of 4-h intervals, with approved on site equipment, to demonstrate compliance with drilling fluid requirements.

In the event that the contractor cannot attain these properties during any phase of the drilling process or if the contractor does not maintain proper drilling fluid control to the satisfaction of the hydrogeologist during drilling, reaming, casing, and gravel packing, the contractor shall, at contractor's own expense, obtain the services of an approved qualified drilling fluid engineer (who is not an employee of the contractor), to assist in performing all the necessary operations needed to bring the drilling fluid under proper control.

In the event that the specified drilling fluid properties are violated within the formation to be screened, or if loss of circulation materials are used, the contractor shall, at contractor's own expense, obtain the services of a qualified drilling fluid engineer to develop a chemical treatment program (using dispersing agents) to be used in conjunction with the well development process to remove these materials from the aquifer.

B.2.4 Testing and Disposal of Drill Cuttings

All soil cuttings and fluids generated during the drilling and geophysical logging process shall be contained in the immediate area of the borehole. Although contaminated soils are not anticipated, if soil cuttings show indications of contamination (staining or odor), they shall be stored in ANSI-approved 208.2-L steel drums until lab analysis can be obtained to verify the nature and concentration of the contamination. The owner and hydrogeologist must be notified immediately upon discovery of potentially contaminated soils. The contractor will be required to stop work if so instructed by the owner or hydrogeologist to accommodate laboratory analysis, if needed, of the potentially contaminated soils. At the completion of drilling and geophysical logging, uncontaminated soil cuttings shall be spread out in the immediate vicinity of the borehole site and compacted to prevent erosion and runoff.

B.2.5 Drilling Problems

If fluid loss is noticed while drilling, immediate action should be taken. Maintaining a stable, open borehole during geophysical logging and testing may mean carrying the filtrate loss at a level lower than would be required normally. Solids control equipment will be required to minimize the loss of circulation, stuck pipe, and slow penetration rates (e.g., shale shaker with desanders/desilters). In addition to the solids control equipment, adequate fluid reservoir volume is recommended to help control the buildup of solids.

All contractors are required to make themselves aware of local drilling conditions and are required to be prepared with the proper drilling bits and necessary associated equipment. The contractor will not be compensated for lost holes or lost time due to "twisting off" or "hard rock" conditions encountered downhole.

B.2.6 Records—Driller's Log and Samples

The contractor shall keep an accurate (and legible) up-to-date log of work operations at all times on a standard American Petroleum Institute (API) form with fields for the activities performed and materials used during each shift of drilling, well construction, and development. In addition to drilling rate, the contractor shall record the type, character, and depth of materials encountered, thickness of strata, water level depths, and any additional information that may be helpful in interpreting the drilling log (e.g., fluid loss or gain). All measurements for depths shall be referenced to existing ground surface at the well site. At completion of drilling, copies of the drilling rate chart (i.e., hydrogeolograph), driller's formation log, and other pertinent notes shall be furnished to the hydrogeologist.

Samples of drill cuttings will be obtained by the contractor under the supervision of the hydrogeologist, for each 10 ft (3.05 m) interval of drilling, placed in large heavy-duty plastic Ziploc bags (i.e., 3.8 L [1 gal.] sized freezer bags) and appropriately labeled with indelible black ink with the owner's name, well number, and the top and bottom of the depth interval sampled. When the character of the drill cuttings indicates changes in formation, samples shall be taken at shorter intervals. The contractor shall obtain formation samples from a formation sampling device approved by the hydrogeologist. An accurate depth record and tally of all tubing, drill pipe, casing, and screen in the hole, stored on the pipe rack, or stacked in the derrick shall be kept current at all times.

A properly installed and correctly working two-pen recorder shall be operating on the drilling site at all times. (Records must be shown as proof that the two-pen recorder has been calibrated in the 30 days prior to the start of the work. The manufacturer of the equipment may be Geolograph, Martin-Decker, or Totco, or as otherwise approved.) The two-pen recorder shall continuously record both the drill string weight and the footage rate, and shall be maintained in working condition from the start of drilling the pilot borehole through the completion of casing installation. The recorder charts shall be changed every 12 h or every 24 h, depending on the type of clock and strip chart used. Adequate numbers of pens and charts shall be made available on the site at all times, as shall a backup clock mechanism. The driller shall note on the strip chart the time and depth of each connection, as well as any formation changes, drilling problems, rig repairs, bit changes or other delays and activities, including zone sampling.

B.3 WELL CONSTRUCTION SEQUENCE

The well shall be constructed using the reverse rotary drilling method (the flooded reverse drilling method is not acceptable). Prior to the beginning of the drilling operation, all equipment supplied by the contractor shall be inspected by the hydrogeologist to be suitable for the specified drilling operation. The replacement of any equipment later found to be unsuitable shall be at the contractor's expense.

The construction sequence of the well shall include but shall not be limited to the following:

1. Mobilizing a reverse rotary drilling rig (the flooded reverse drilling method is not acceptable) and its associated equipment at the well site (including reservoirs for fluid containment, solids control equipment, and sound barriers for noise control),
2. Drilling, installing and cementing a 914.4 mm (36 in.) OD conductor casing to a minimum depth of 15.24 m bgs (50 ft bgs) within a 1219.2 mm (48 in.) diameter borehole (or as specified by the DHS), to serve as the sanitary seal,
3. Drilling and sampling the 444.5 mm (17 ½ in.) diameter pilot borehole to a total estimated depth of ___ m bgs, with deviation surveys being performed every 30.48 m (100 ft),
4. Conditioning and cleaning the borehole, as necessary, prior to running the geophysical borehole logs, as specified,
5. Performing isolated aquifer zone testing, as described herein, on an estimated four zones within the pilot borehole,
6. Enlarging the pilot borehole from 444.5 mm (17 ½ in.) to 711.2 mm (28 in.) from 15.24 m bgs (50 ft bgs) to the completion depth, as directed by the hydrogeologist,
7. Performing a caliper survey on the enlarged borehole less than 8 hours prior to the installation of the casing and screen,
8. Installing 457.2 mm (18 in.) ID copper-bearing casing and louvered well screen in the reamed borehole, with centralizers, gravel feed pipe, and sounding tube,
9. Installing an artificial filter pack in the annular space between the casing or screen and the borehole wall,

10. Installing a layer of fine sand above the filter pack material in the space between the casing and the borehole wall,
11. Installing a cement seal above the fine sand layer in the space between the casing and the borehole wall. Install fill material (filter pack or equivalent) above the cement seal to the ground surface,
12. Performing initial development by airlifting and swabbing from between packers,
13. Removing fill material from the blank casing below the screened interval,
14. Demobilizing the drilling rig and associated drilling equipment,
15. Mobilizing the test pump and support equipment,
16. Installing a deep well turbine test pump with a variable speed engine,
17. Performing final development using a deep well turbine test pump,
18. Performing well and aquifer tests (including step-drawdown, constant-rate, and recovery tests, as well as conducting a spinner survey),
19. Collecting water quality samples as per Title 22 (California Code of Regulations) analysis (by a hydrogeologist),
20. Removing the test pump from the well,
21. Performing plumbness and alignment surveys in the well,
22. Bailing the well to remove sediments that have accumulated during test pumping,
23. Performing a "dual-cam" video survey on the well,
24. Disinfecting the well using a sodium hypochlorite solution and securing the well against entry, then
25. Demobilizing all equipment, including site cleanup, restoration, and wellhead completion.

B.3.1 Drilling, Installation, and Cementing of Conductor Casing

The contractor shall drill and install the conductor casing using drilling methods approved by the hydrogeologist, as circumstances may require. A 1219.2 mm (48 in.) diameter borehole shall be drilled to a depth of 15.24 m (50 ft bgs).

The conductor casing shall have an outside diameter of 914.4 mm (36 in.) with a wall thickness of 7.94 mm (5/16 in.). The conductor casing shall be manufactured in accordance with ASTM Specifications No. A139 Grade B. The conductor casing will provide near-surface borehole stability, will conduct drilling fluids and cuttings safely to the surface, and will serve as a sanitary seal.

1. Requirements for hydrostatic testing shall be waived.
2. The steel from which the casing is manufactured shall be low-carbon (mild) steel.

Following installation of the conductor casing, the annular space between the 914.4 mm (36 in.) diameter conductor casing and the 1219.2 mm (48 in.) borehole shall be filled with 10.3 sack sand-cement slurry. The cement shall be a sand-cement grout mixture consisting of 331.17 kg per cu m (968 lb/cu yard) of Type II cement (ASTM C150-95 Standard Specification for Portland cement) and 662.35 kg of washed sand (1,936 lb/cu yard), to create a volume of 1 cu m of material. Approximately 180 L of water per cu m (63 gal./cu yard) shall be added, with a maximum of 188.25 L/cu m (66 gal./cu yard) allowed, if necessary, to make the mixture more fluid for pumping. Care must be taken to avoid segregation of the grout mix by the addition of excessive quantities of water. The weight of the mixture shall be approximately 2,180 kg/cu m (136 lb/cu ft).

A maximum of 2% by weight of bentonite, and 2% by weight of calcium chloride may be added to condition the slurry for a fluid mix and to accelerate the setup time for the cement. The addition of bentonite will reduce shrinkage and cracking of the cement; however, if used, it shall be added to the water first and shall be allowed to hydrate a minimum of 10 min prior to the introduction of the cement to the mixture.

In no case shall more than 2 h elapse from the time of addition of water to the mixture at the ready mix plant, to time of pumping the slurry downhole.

B.3.2 Drilling the Pilot Borehole

A pilot borehole shall be drilled from the bottom of the conductor casing to an estimated depth of ____ m bgs. Formation samples shall be collected at 3.05-m (10-ft) intervals, or less, in order to provide representative samples for sieve analyses, and for classification of the geologic formations encountered. The diameter of the pilot borehole shall be 444.5 mm (17-½ in.). The hydrogeologist will be on site during the drilling process to determine the depth of the hole, based on the drill cuttings and the lithologic log. The contractor shall take all measures necessary to protect all portions of the pilot borehole from caving or raveling. The contractor shall protect the formation samples from being lost, destroyed, or contaminated with foreign debris during construction of the well.

Deviation surveys will be conducted at 30.48 m (100 ft) intervals using a Totco drift indicator, or approved equal, while drilling the pilot borehole. Three-degree (3°) targets shall be used. A maximum deviation of 1/2° from vertical per 30.48 m (100 ft) will be allowed. If this amount is exceeded, the contractor will be required to correct the deviation at that time. If the deviation is not corrected, the borehole will be abandoned and will be redrilled at the contractor's expense. As representative samples of the formation are required, lithologic samples shall not be collected after the cuttings have passed the shaker table.

During drilling of the pilot borehole, procedures for collecting formation samples and keeping records as previously specified shall be strictly followed. The contractor shall provide a sampling device that will be approved by the hydrogeologist to collect lithologic samples that are representative of both the fine- and coarse-grained fractions of the formation.

At each change of formation and at 3.05 m (10 ft) intervals between changes in formation, the contractor shall collect a large, representative sample of the interval of new formation material from the sampling trough, label, and preserve each sample in a clear, heavy-duty, freezer-type, 1 gal. Ziploc plastic bag. Each sample bag shall be labeled clearly with indelible black ink to indicate the depth interval of the collected sample, owner's name, and well number, and shall be stored in a manner to prevent breakage, contamination or loss. All sample bags shall be furnished by the contractor and become the property of [owner/client].

B.3.3 Geophysical Borehole Logs

At completion of the pilot borehole, a suite of geophysical borehole logs shall be run on the entire depth of the pilot borehole by a company mutually selected by the hydrogeologist, engineer and [owner/client]. The cost of the geophysical logs shall be borne by the contractor. There will be no additional payment for either rig time or standby time while the logging is being performed or while the contractor is waiting on a subcontractor.

The following suite of geophysical borehole logs shall be run:

- Electric logs consisting of 406.4 mm (16 in.) short-normal and 1625.6 mm (64 in.) long-normal resistivity,
- Spontaneous potential (SP),
- Laterolog 3 (focused resistivity log),
- Natural gamma ray,
- Acoustic (sonic) log sonic porosity and variable density log (VDL), and
- Caliper with borehole volume calculation (following reaming).

The aforementioned logs shall have appended to them such information as necessary for proper interpretation of the log (e.g., resistivity of the mud and mud filtrate, surface and bottom borehole temperatures, etc.). The logs shall be scaled appropriately to the formations logged to allow for adequate definition of the subsurface strata. The horizontal scale for the plot of the spontaneous potential log shall be capable of being displayed in the range from at least 5 to 20 millivolts/in., as specified by the hydrogeologist. The horizontal scale for the plot of each of the resistivity logs (40.64 cm [16-in.] and 162.56 cm [64-in.] normal or guard) shall be capable of being displayed in the range from at least 25 to 50 ohm-meters/in., as specified by the hydrogeologist. A vertical scale of 2.4 m/1 cm (20 ft/in.) is specified.

The geophysical logs shall become the property of [owner/client] at the time that logging is completed. The logs shall be run in the presence of the hydrogeologist. The logs shall be provided to the hydrogeologist for interpretation immediately after completion. The contractor shall provide the hydrogeologist with six copies of each log in the field and one reproducible original. In addition, the contractor shall provide the hydrogeologist with electronic copies of each log in a format suitable for inclusion into an AutoCAD drawing file (e.g., dxf or dwg file), as well as ASCII file format.

If the logging tools fail to descend to the desired depth, the contractor, at contractor's expense, shall clean and condition the borehole in order to permit the logging tools to descend to total depth. Standby time will not be paid for nor additional cleaning and conditioning of the hole as necessary to enable logging operations to proceed.

B.3.4 Aquifer Zone Testing for Yield and Water Quality

To determine water quality, as well as estimated groundwater yield at the well site, it will be necessary to perform up to four isolated aquifer zone tests in the pilot borehole. Aquifer zone testing consists of isolating a specific aquifer zone (after drilling the pilot borehole) for testing for both yield and water quality.

The procedure to be used for aquifer zone testing in each pilot borehole is as follows:

- Based on analysis of the formation samples collected during drilling and the geophysical borehole logs, the hydrogeologist will select the four zones from within the saturated interval for isolated zone testing. (The saturated interval is defined as the formations found between the static water level and bottom of the borehole.)
- Prior to construction of the first (deepest) zone test interval, the contractor shall submit to the hydrogeologist for approval samples of the filter pack material to be used to complete the zone test interval and the sealing material, which will be used to seal above and below the zone test interval.
- Backfill material shall be placed in the pilot borehole to a depth of approximately 3.05 m (10 ft) below the first (or deepest) zone tested. The top of the backfill material shall be "tagged" and recorded to verify its depth. The depth measurement shall be recorded in the Driller's Daily Report.

- A 3.05 m (10 ft) seal consisting of Baroid bentonite products (or as otherwise approved by the hydrogeologist) shall be placed on top of the backfill material. (This seal is necessary to isolate aquifers occurring below the zone selected for testing.) The top of the seal shall be tagged and recorded.
- Isolated zone testing shall be accomplished by attaching an 203.2 mm (8 in.) diameter by a 6.1-m (20-ft) long piece of mill-slotted pipe to the bottom of the 177.8 mm (7 in.) ID threaded drill pipe. (The use of "pump column pipe," or other such thin-walled materials having nontapered threads shall not be accepted for use during zone testing.) This 6.1-m (20-ft) section of "screen" will be placed opposite the zone selected for testing. The annular space between the 203.2 mm (8 in.) section of slotted pipe and the 444.5 mm (17 ½ in.) pilot borehole then shall be backfilled using the filter pack material approved by the hydrogeologist. The filter pack material shall be brought to a minimum of 3.05 m (10 ft) above the top of the slotted screen section. The top of the filter pack material shall be tagged and recorded.
- A second 3.05 m (10 ft) seal consisting of Baroid bentonite products (or as otherwise approved by the hydrogeologist) shall be placed on top of the filter pack material. The bentonite seal shall be allowed to hydrate for at least 1 h, completing the isolation process. The top of the upper seal shall be tagged and recorded.
- Each isolated zone shall be developed initially by airlifting until the water produced from the zone is clean and clear, and the integrity of the seal has been verified by the hydrogeologist. Verification of the seal for zone testing shall be determined when the water level in the annulus is remaining stable and is predictable (allowing for losses to the formation) and is different than the water level measured inside the zone testing tools, whether the zone is being actively pumped or is at rest.
- After airlifting and prior to installation of the submersible test pump, a static water level shall be taken from within the zone test tool.
- A high-capacity submersible pump, capable of producing a minimum of 757 L/min (200 gal./min) from 213.4 m (700 ft), shall be placed within the 177.8 mm (7 in.) ID drill pipe. The performance curve for the submersible pump used in zone testing shall be submitted to the hydrogeologist prior to the start of the work. The use of a 6-in. ID drill pipe and a nominal 6-in. test pump is not acceptable as head losses due to friction that will quickly erode the capability of the pump. A larger diameter "pump chamber" placed at an appropriate depth (as determined by the hydrogeologist) is acceptable in lieu of the 7-in. ID drill pipe, if it is not available. In other words, if the contractor does not have 7-in. ID drill pipe, a 6-in. ID drill pipe may be used in combination with a larger diameter (7-in. ID or larger)

pump chamber in order to accommodate a high-capacity submersible pump capable of 200 gal./min. A calibrated flowmeter with a totalizer and a gate valve, shall be installed in the discharge line for accurate measurement and control of the flow rate. In addition, a sampling port shall be installed (at an easily accessible location) on the discharge line to obtain the water quality samples.

- Once pumping has begun, the integrity of the seal shall again be determined to the satisfaction of the hydrogeologist. The isolated zone shall be pumped at its maximum capacity until the discharged water has a turbidity measurement of less than 10 standard turbidity units (NTUs) or is acceptably clean and clear as certified by the hydrogeologist.
- Once the discharge is determined by the hydrogeologist to be acceptably clean and clear, and measures less than 10 NTU in turbidity, the isolated zone then shall be pumped continuously (at its maximum rate) for a minimum of 6 h, without interruption. During this time, hourly measurements shall be made of the discharge rate and the pumping water level to determine aquifer yield. At 1-h intervals during pumping, the depth to water, instantaneous gal./min, flowmeter totalizer, and exact time (hours and minutes) of each reading shall be read and recorded.
- Water quality samples will be collected by [owner/client] or the hydrogeologist at the end of the 6 h of continuous pumping and shall be submitted for analysis. Water quality analyses for volatile organic chemicals (VOCs), in addition to general mineral and general physical properties, will be required. However, the cost of the analyses is not the responsibility of the contractor. All water quality samples shall be collected in sterile, nonpreserved containers.
- Water quality samples shall be obtained in appropriate sterilized laboratory containers. It is essential that the water samples collected have minimal turbidity, as many constituents have very low detection limits and even moderate turbidity in the sample will give erroneous lab results. For example, it is known that in samples collected with visual turbidity, very fine colloidal particles still pass a 0.45 μ opening, the smallest possible opening for paper filters.
- After removing the submersible pump from the zone testing tool, a second static water level measurement shall be taken and recorded.
- Once zone testing has been completed on the selected zone, the test screen shall be removed from the borehole and cleaned. The hydrogeologist shall inspect the zone testing tools before they are reinstalled to test the next selected zone.

No payment shall be made for any aquifer zone test from which an acceptable water quality sample has not been obtained as a result of the contractor's failure to provide an acceptable seal or an acceptably clean and clear sample.

B.3.5 Final Design of Casing, Screen, and Filter Pack

The final design, including depth and diameter of the borehole and filter pack recommendations shall be provided by the hydrogeologist following receipt of water quality results from the aquifer zone testing. However, the final design will not be provided to the contractor until the hydrogeologist has received results of laboratory analyses. The contractor shall allow a minimum of 5 to 7 days' time for the laboratory to run the necessary analyses. The contractor shall provide within the work price the cost for being shut down a minimum of 1 week (from the completion of zone testing to receipt of the well design). No standby time will be paid to the contractor during this time. The well design will be determined from the geophysical borehole logs, aquifer zone testing, and the lithologic log.

B.3.6 Reaming the Pilot Borehole

Upon receipt of the final well design letter, the contractor shall enlarge the 444.5 mm (17 ½ in.) diameter pilot borehole to its final diameter of 711.2 mm (28 in.) from 15.24 m (50 ft) (bottom of the conductor casing) to total depth. For bidding purposes, the expected completion depth of the borehole is ____ m bgs (____ ft bgs). During the reaming process, the contractor shall strictly adhere to the drilling fluid properties as described in Section B.2.3, Drilling Fluid—Reverse Circulation Drilling Method.

Once the completion depth has been reached with the final reaming pass, the drilling fluid shall be thinned and conditioned as per Section B.2.3, Drilling Fluid—Reverse Circulation Drilling Method, prior to running a caliper log. The caliper log will be run to determine borehole diameters and the condition and stability of the borehole prior to installing the casing and screen.

B.3.7 Blank Well Casing

All blank well casing shall be fabricated from copper-bearing steel using the spiral weld process. The steel used in the manufacture shall conform to the physical properties of the American Society for Testing Materials (ASTM) Specification A139, Grade B containing not less than 0.2% copper by ladle analysis. Roscoe Moss Company, or another approved U.S. manufacturer, shall fabricate the casing.

The blank well casing shall have an inside diameter (ID) of 457.2 mm (18 in.), with a 7.94 mm (5/16-in.) wall thickness with a collapse strength of not less than 207 psi (145.7 m [478 ft] of water). The final casing design will be specified by the hydrogeologist after completion of the pilot borehole drilling and testing, and prior to reaming.

For bidding purposes, it is assumed that a total of 231. m (760 ft) of 457.2 mm (18 in.) ID by 7.94 mm (5/16-in.) wall copper-bearing steel blank casing will be installed (see Fig. B-3).

B.3.8 Louvered Well Screen

The louvered well screen used shall be manufactured in accordance with the aforementioned casing requirements of ASTM Specification A139 Grade B. Roscoe Moss Company, or another approved U.S. manufacturer, shall fabricate the screen. The screen shall be a horizontal louvered shutter screen (ful-flo pattern) with 14 openings per circle, and 100 openings per 184 mm (168 openings per lineal foot). The inside diameter of the screen shall be 457.2 mm (18 in.) and shall have a 7.94 mm (5/16 in.) wall thickness. The collapse strength of the screen must not be less than 269 psi (621 ft of water). The final screen design will be specified by the hydrogeologist in a separate letter following completion of the pilot borehole drilling and testing, and receipt of the water quality analytical results.

For bidding purposes, the slot size of the screen is expected to be 2.388 mm (0.094 in.) with a variance of ±0.127 mm (0.005 in.). The final slot size is subject to the results of examination of the drill cuttings, mechanical grading analysis, and selection of the filter pack material. The final slot size will be specified by the hydrogeologist in a design letter following completion of the pilot borehole drilling and testing, receipt of water quality results, and prior to reaming.

For bidding purposes, it is assumed that a total of 225.55 m (740 ft) of 457.2 mm (18-in.) ID by 7.94 mm (5/16-in.) wall louvered screen will be installed (see Fig. B-3).

B.3.9 Casing and Screen Installation

Immediately following the caliper log and prior to the installation of the casing and screen, a tremie pipe shall be set in the reamed borehole to a depth of approximately ____ m (____ ft), or in any case, not more than 12.19 m (40 ft) above the bottom of the reamed borehole. Installation of the tremie pipe, casing, and screen shall be performed by such methods that will ensure no damage to the casing and screen during installation. The tremie pipe shall be either flush-threaded or shall have the shoulders of each collar removed so that the collars will not be capable of catching on the louvered well screen.

During installation, the casing shall be suspended above the bottom of the borehole a sufficient distance to ensure that the casing will not be supported by the bottom of the borehole prior to the start of the gravel packing procedure.

Both the casing and the screen shall be fitted with approved centering guides, or centralizers, which shall be installed at points as directed by the hydrogeologist, but under no circumstance shall they be spaced more than 36.58 m (120 ft) apart. The centralizers shall be placed such that they center and hold the casing and screen in the proper position until installation of the filter pack has been completed.

For field assembly by welding, the ends of casing and screen sections shall be furnished with collars in accordance with the following standards:

- Casing collars shall be of the same thickness and have the same physical and chemical properties as their corresponding casing or screen sections and shall be 127 mm (5 in.) minimum in width, rolled to fit the outside diameter of the casing and screen. The collars shall be welded to each casing or screen section. The inside edge of the collars shall be ground or sufficiently smoothed to remove sharp edges or burrs.
- Section ends shall be machined perpendicular to the axis of the casing or screen and shall not vary by more than 0.25 mm (0.010 in.) at any one point from a true plane at right angles to the axis of the casing.
- A minimum of three 7.94 mm (5/16-in.) diameter alignment holes shall be provided in each collar to ensure proper matching of the sections. These sight holes must be welded shut to provide a watertight seal.

B.3.10 Welding

Competent and experienced workers with adequate equipment, using the ARC welding process, shall do all field welding. All welding procedures and qualified welders shall be in accordance with the provisions of Section IX of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

After each new casing or screen section has been seated in the casing collar and has been determined to be vertical, the casing shall be welded. A root pass shall be made at the fillet between the welding collar and the upper casing or screen section. After removing slag, one or two filler passes shall be made on the fillet, depending on the thickness of the casing and collar. The alignment holes shall be filled once the fillet weld is complete.

B.3.11 Casing and Screen Centering Guides

Centering guides shall be installed at no greater than 36.58 m (120-ft) intervals throughout the entire length of casing and screen, starting from the bottom of the screened interval. The centering guides shall consist of four shaped steel straps measuring ¼-in. × 2½-in. × 914.4 mm (36 in.). These straps, or centralizers, shall be welded at 90° to the casing in the field.

B.3.12 Sounding Tube Connection

The contractor shall furnish 2-in., schedule 40 mild steel pipe materials and shall fabricate the connection to the 457.2 mm (18-in.) ID copper-bearing casing. The connection of the sounding tube to the 457.2 mm (18-in.) ID casing will occur at a depth of 195.07 m (640 ft) bgs, as shown in Fig. B-3. The transition from the 50.8 mm (2-in.) sounding tube to the 457.2 mm (18-in.) diameter casing shall be smooth and free from rough edges. The top of the sounding tube shall be fitted with a threaded cap at the completion of the work.

B.3.13 Gravel Feed Pipe

A gravel feed pipe shall be installed in the annular space. The gravel feed pipe shall be 37.49 m (123 ft) in length, and shall be constructed of 76.2 mm (3-in.) diameter, schedule 40 mild steel material as shown in Attachment 3. The gravel feed pipe shall be ASTM A53, Grade B, and all material used shall be new.

The gravel feed pipe shall be welded covered at the surface with a threaded cap, as approved by the hydrogeologist. The specific location and orientation of the gravel feed pipe and the sounding tube in the annulus shall be as directed by either [owner/client] or the hydrogeologist prior to running casing.

B.3.14 Casing and Screen Alignment

The well borehole shall be constructed and all casing set sufficiently round, plumb, and true as to enable the free installation and operation of a line-shaft turbine deep well pump with the bowls set at approximately 304.8 m (1,000 ft) bgs. To satisfy this requirement, an alignment survey shall be run throughout the screened interval of the well, such that a line from the center of the well casing at the ground surface does not deviate from the vertical plane by more than 6 in. (152.4 mm) per 100 ft (30.48 m) of well depth. Any bends shall be no closer to the inside wall of the casing than 6 in. (152.4 mm).

To demonstrate the compliance of this work, the contractor shall furnish all labor, tools, and equipment, and shall perform an alignment test with a cage to the satisfaction of the hydrogeologist throughout the entire screened interval. The alignment test shall be performed immediately on removal of the test pump from the well. The information collected during the alignment survey shall be submitted to the hydrogeologist within 24 h of conducting the test.

Tests for plumbness and alignment must be made after the completion of the construction of the well and before its acceptance. The contractor shall furnish to the hydrogeologist two plots of plumbness and alignment in vertical planes, oriented at 90° with respect to each other and with supporting field measurements. The contractor, however, may make additional tests at any time during the performance of the work.

The outer diameter of the cage shall not be more than 12.7 mm (1/2 in.) smaller than the inside diameter of the casing to be tested. Should the well vary from the vertical in more than 101.6 mm (4 in.) per 30.48 m (100 ft) of depth from ground surface to total depth, or fail to meet the requirements for alignment, the contractor at contractor's expense shall correct it. If the alignment cannot be corrected, the well will be abandoned properly, according to state and local standards, and shall be redrilled, constructed, developed, and tested at the contractor's expense.

B.3.15 Artificial Filter Pack

The annular space between the 711.2 mm (28-in.) diameter reamed borehole and the 457.2 mm (18-in.) ID casing and screen shall be filled with a suitable filter pack material (e.g., gravel), from the bottom of the reamed borehole at approximately ___ m (____ ft) to a depth of 36.58 m (120 ft) bgs, or as directed by the hydrogeologist. The gradation and placement of the filter pack shall be determined based on the results of the drill cuttings, geophysical logging, and mechanical grading analysis. The hydrogeologist shall specify the gradation of the material after the results of mechanical grading analyses have been performed on the aquifers to be screened.

B.3.15.1 Filter Pack Material The following filter pack gradation is for bidding purposes only. The final filter pack selection will be based on sieve analysis of samples collected during the drilling of the pilot borehole. All bids must accommodate changes to the filter pack selection specified following, as final design of the filter pack may vary from the described detailed gradation. The gradation may change once sieve analyses on selected formation intervals have been completed. The contractor's cost should allow for changes in the source of the filter pack. A change order will not be given for such a change to the design.

Table B-1. Proposed filter pack design—size range: ¼ in. × No. 16 custom blend

U.S. Standard Sieve No.	Sieve Opening [in.]	Sieve Opening [mm]	Cumulative Percent Passing
⅜″	0.375	9.53	100
¼″	0.250	6.35	90
4	0.187	4.75	70
8	0.094	2.38	17
10	0.079	2.00	10
12	0.066	1.68	7
16	0.047	1.19	2
20	0.033	0.84	0.1

The filter pack material shall be ¼ in. × No.16 Blend, or equivalent, with approximate gradation listed in Table B-1.

The filter pack material shall be composed of sound, durable, well-rounded particles of natural gravel, free from flat or elongated particles. Thin, flat, or elongated particles are particles with a length to width ratio of greater than 3:1. The filter pack material shall be washed so that it is free from organic matter, shale, carbonates, mica, silt, clay, or other deleterious materials. The uniformity coefficient of the filter pack material shall be between 2.0 and 3.0, unless otherwise specified by the hydrogeologist. The uniformity coefficient is defined as the ratio of the D_{60} size to the D_{10} size of the material (D_x, where x is the percent passing). Filter pack material shall conform to the AWWA A100 Standard, Section 6.3.4 that stipulates that not more than 5% of the gravel pack shall be soluble in hydrochloric acid.

The filter pack material shall be tested and approved by the hydrogeologist, and the contractor shall submit a certificate of quality and gradation. It shall be well graded and shall be within the limits (with minor variations) determined and approved by the hydrogeologist at completion of the drilling and testing. Under no circumstances shall crushed rock be installed in the well.

The filter pack material shall be delivered to the site either in bags or in bulk. If delivered in bulk, the filter pack material shall be protected from direct contact with the ground surface by a plastic sheet that is a minimum of 2 mm in thickness. Filter pack material that has been in direct contact with the ground surface shall not be used. All materials shall be protected from contamination until installed in the well.

All filter pack material shall be delivered to the well site not less than 48 h prior to casing and screen installation in order to allow for adequate time for inspection, testing and approval.

B.3.15.2 Placement of Filter Pack Material After the assembled casing and screen is centered in the borehole, circulation shall be established in the annulus through the tremie pipe. The contractor shall provide only flush-threaded tremie pipe for the purpose of installing the filter pack. Tremie pipe with collars will not be allowed. During placement of the filter pack material, the contractor shall exercise care when removing tremie pipe to ensure that it does not catch on well screen materials that have been installed downhole. Should damage occur to the well screen during construction, it shall be repaired by the contractor to the satisfaction of the hydrogeologist and at no cost to the owner.

During placement of the filter pack, liquid chlorine shall be added at a rate of 2.48 L of 12.5% hypochlorite solution per cu m (1/2 gal./cu yard) of the filter pack material to disinfect the filter pack and to assist in degrading any drilling additives that may have been used during the drilling process.

During placement of the filter pack, water shall be pumped with the gravel through the tremie pipe (which has been placed near the bottom of the screen); into the annular space in a manner that ensures continuity of the filter pack material without bridging, voids, or segregation. As the gravel and water mixture exits the end of the tremie and builds up around the screen, the end of the tremie will become plugged, causing circulation to stop. When this occurs, a maximum of two sections, or 18.9 m (62 ft), of tremie pipe may be removed at any one time, until the top of the filter pack material in the annulus reaches 36.58 m (120 ft) bgs (which is 3 ft above the bottom of the gravel feed pipe), or as otherwise instructed by the hydrogeologist.

The top of the filter pack material shall be tagged frequently to verify the level of the material in the annular space. At no time shall the contractor allow the filter pack material to fall more than 9.14 m (60 ft) below the bottom of the tremie. This method will ensure the proper placement of the filter pack material, while simultaneously washing sand, silt, and drilling mud from the filter pack material as it is placed in the annulus.

The contractor shall make adequate preparations to ensure that circulation is continuous from the time that thinning of the drilling fluid in the borehole begins (following completion of the reaming pass), until the time that the filter pack is completely in place.

The top of the filter pack shall be tagged and recorded prior to adding the fine sand layer. Adequate time shall be allowed for the filter pack material to settle into place before introducing the fine sand to the annulus.

All materials required for the artificial filter pack placement (gravel, gravel pump, gravel feed line, etc.) must be on site a minimum of 24 h prior to completion of the reaming of the borehole, for inspection and sampling by the hydrogeologist.

B.3.16 Placement of Fine-Sand Layer

Following placement of the filter pack material, a 1.52 m (5 ft) layer of fine sand shall be placed. The fine sand shall consist of 3 ft of uniformly graded, fine to medium “construction” sand. The fine-sand layer shall be placed on top of the filter pack material through a tremie pipe. The top of the fine-sand layer shall be tagged and recorded. The purpose of the fine sand is to prevent infiltration of the cement slurry into the upper portion of the filter pack.

A 30-mesh construction sand, or approved equal, shall be placed through the tremie in the same fashion as the filter pack material. The fine sand shall be placed from 36.58 to 35.05 m (120 to 115 ft) bgs. The top of the fine-sand layer shall be tagged 1 h after placement to verify its level.

B.3.17 Sealing of Upper Zones by Cement Grouting

At the direction of the hydrogeologist and based on results of aquifer zone testing, sealing of upper aquifer zones may be required. After placement of the filter pack to the depth specified, the annular space between the 45.72 cm (18-in.) ID well casing and the 71.12 cm (28-in.) diameter borehole hole shall be filled with a 10.3 sack sand-cement slurry from the top of the fine-sand layer (at 35.05 m [115 ft] bgs) to 4.57 m (15 ft) bgs. The sand-cement grout mixture shall consist (per cu m) of 331.17 kg (968 lb/cu yard) of Type II cement (ASTM C150-95 Standard Specification for Portland Cement) and 662.35 kg (1,936 lb/cu yard) of washed sand to create a volume of 1 cu m of material. Approximately 180 L of water per cu m (63 gal./cu yard) shall be added, with a maximum of 188.25 L/cu m (66 gal./cu yard) allowed, if necessary to make the mixture more fluid for pumping. Care must be taken to avoid segregation of the grout mix by the addition of excessive quantities of water. The weight of the mixture shall be approximately 2180.5 kg/cu m (136-lb/cu ft.)

A maximum of 2% by weight of bentonite and 2% by weight of calcium chloride may be added to condition the slurry for a fluid mix and to accelerate the setup time for the cement. The addition of bentonite will reduce shrinkage and cracking of the cement; however, if used, it shall be added to the water first and shall be allowed to hydrate a minimum of 10 min prior to the introduction of cement to the mixture.

In no case shall more than 2 h elapse from the time of addition of water to the mixture at the ready mix plant to time of pumping down the hole.

Personnel thoroughly trained in the operation and application of their equipment shall operate all cementing equipment and specialized tools. The placing of the cement shall be done in a manner such that the casing is sealed entirely against infiltration by water. Each grouting event shall be accomplished in one continuous operation by pumping the cement mixture through a tremie pipe to force the cement slurry into the annular space. The end of the tremie pipe shall remain submerged in the wet cement slurry at all times while pumping each lift. The cement shall be placed to the depth directed by the hydrogeologist. The contractor should be aware of and provide protection against any large hydrostatic forces that may be involved, and if necessary, stage the cementing operation (on the basis of the collapse strength of the casing), allowing sufficient time after each interval has been cemented for hydration and consolidation of the cement.

The 10.3-sack sand-cement slurry then shall be pumped into the annulus (through the tremie pipe) from the top of the fine sand layer to approximately 4.57 m (15 ft) bgs (see Fig. B-3).

The cement seal in the annulus shall remain undisturbed for a minimum of 24 h before further work is performed in the well. Should the top of the cement seal drop below 4.57 m (15 ft) bgs, it shall be topped off with additional cement.

After the cement seal has been placed, additional filter pack (or equivalent material that has been approved by the hydrogeologist) shall be placed in the annulus from approximately 4.57 m (15 ft) below ground surface to the ground surface. The purpose of the filter pack is for proposed wellhead design construction activities.

B.3.18 Air Vent

The contractor shall install approximately 1.22 m (4 ft) of nominal 76.20 mm (3-in.) schedule 40 mild steel pipe to be used as an air vent for the well casing as shown on the plans. The top of the vent shall be fitted with a threaded cap. The air vent pipe shall be ASTM A53, Grade B, all new material.

B.3.19 Well Cover

The top of the well casing shall be provided with a metal cap securely welded to the casing to cover and protect the well and to guard against entrance by foreign objects or materials until the permanent pump is installed.

B.3.20 Initial Airlift Development between Packers

The contractor shall provide a combination swab/airlift tool with a double rubber packer assembly spaced 3.05 m (10 ft) apart, designed to be run on drill pipe in the 457.2 mm (18 in.) screened portion of the well. The tool shall be designed such that it will allow simultaneous pumping (by airlift) and swabbing to occur.

Immediately following gravel packing, the contractor shall run the drill pipe open-ended to the bottom of the well. Fluids shall be circulated from the well (by the airlift process) a reasonable amount of time in order to remove all heavy fluids remaining in the bottom of the well. The circulation process also will serve to balance the fluids throughout the well prior to airlifting in stages throughout the screened interval.

Initial development and cleaning of the filter pack and aquifer shall be accomplished by airlift pumping and swabbing (using a double-packer swabbing tool) in stages opposite the entire screened interval until the filter pack is clean and consolidated. Vigorous swabbing is necessary to dislodge fine-grained sediments and drilling fluid mechanically from the filter pack and near-well zone of the aquifer. Following swabbing, the loosened materials shall be removed immediately by airlifting before proceeding to the next 3.05 m (10 ft) interval.

Airlift development shall begin at the top of the screened interval and shall proceed downward. Water shall be added to the top of the filter pack through the gravel feed pipe at all times during the development process, and any changes in the level of the filter pack shall be recorded.

The contractor shall furnish all labor, material, equipment, and services necessary to neutralize the residual chlorine in the discharge water prior to allowing water to be discharged from the site. The residual chlorine in the neutralized effluent water shall be 0.1 mg/L or lower before being discharged from the site. The use of aboveground tanks may be necessary to fulfill this requirement. The contractor shall use tanks with sufficient capacity to accommodate flow rates of at least 3,785 L/min (1,000 gal./min) for the temporary storage of effluent prior to discharge. The contractor shall provide the temporary discharge piping required to convey the neutralized effluent to the appropriate disposal area, approved by [owner/client]. The contractor shall be responsible for monitoring, treating, testing, and disposing of the effluent water.

An air compressor shall be capable of airlifting 1,135.5 L/min (300 gal./min) during initial development. The swabbing and airlifting operations shall be conducted simultaneously over no more than one length of drill pipe and until that section is adequately developed as directed by the hydrogeologist.

A continuous stream of clear water shall be added to the gravel feed pipe at all times during initial airlift development between packers.

B.3.21 Development by Wireline Swabbing and Bailing (If Necessary)

If drilling conditions dictate a full drilling mud program, or the use of loss of circulation materials, further development by wireline swabbing and bailing may be necessary.

Immediately after placement of the artificial filter pack, the contractor shall set up a rig with sufficient horse power to permit the uninterrupted hoisting of a wireline swabbing tool consisting of a single or double packer assembly fabricated on a heavy scow or bailer with a flapper valve. The flapper valve will allow the swab to fall rapidly through the column of water in the well. The swab rubbers shall have no more than 12.7 mm (½ in.) clearance within the well screen and shall be replaced if clearance exceeds this value. During development a steady stream of water shall be added to the top of the filter pack through the gravel feed pipe.

Wireline swabbing shall begin at the top of the screened interval and shall continue in short intervals (less than 16 m [50 ft]) to the bottom of the screened interval. The swab shall be repeatedly hoisted through each interval with the speed and length of hoisting increased until the swab, with full engine horsepower, is pulled through the entire screen. The well should be bailed frequently to remove and evaluate the materials drawn in through the filter pack and screened section during development.

As the filter pack drops in the annulus, it shall be "topped off" with the quantity of filter pack material added, and type of material shall be removed and recorded. The total amount of filter pack material placed in the annulus during the filter packing operation and by topping off shall not be less than the total volume of the annulus. Development by wireline swabbing shall continue as directed by the hydrogeologist until there is no appreciable movement of the filter pack or further accumulation of material in the bottom of the well.

A continuous stream of clear water shall be added to the gravel feed pipe at all times during development by wireline swabbing. If the gravel feed pipe does not receive water at an acceptable rate, the contractor shall clean it by removing all material and refill it with clean filter pack material.

B.3.22 Well Development by Pumping

The depths and rates provided in this section are for bidding purposes only, and are subject to modification following final design of the well. Within 7 days of completion of initial development by swabbing and airlifting, the contractor shall begin demobilizing the drilling rig and shall furnish, install, operate, and remove a deep-well turbine pump for final development of the well. The pump and prime mover shall have a minimum capacity of 15,140 L/min (4,000 gal./min) (at 1,800 rpm), against a total head of at least 188.98 m (620 ft) bgs, with a pump bowl setting of approximately 1,000 ft bgs.

The prime mover shall be a variable speed type. The contractor shall furnish and install discharge piping of sufficient size and length for the pumping unit to conduct water to a point acceptable to [owner/client].

The discharge piping shall include acceptable orifices, meters, valves, or approved devices that will measure accurately and control the discharge rate. The metering device shall have an instantaneous reading in gallons per minute, and shall have a totalizer that shall measure the pump discharge rate in gallons, acre-feet, or cubic feet. An airline, complete with a properly calibrated pressure gauge, with readings to 0.5 psi and suitable air supply, shall be provided to measure the depth of water in the well.

A Rossum centrifugal sand tester shall be installed in the discharge line to measure the sand concentration during final development and test pumping.

The initial pumping rate shall be restricted and, as the water clears, it shall be increased gradually until the maximum rate is reached. The hydrogeologist will determine the maximum pumping rate after consideration of the well's drawdown and discharge characteristics. At intervals, the pump shall be stopped, and the water in the pump column shall be allowed to surge back through the pump bowls and into the perforated area. While pumping and surging, a continuous stream of water shall be added through the gravel feed pipes.

The cycle of pumping and surging shall be repeated until the discharged water is clear and free of sand, silt, and mud and until there is no increase in the specific capacity during at least 24 h of continuous pumping and surging.

Specifically, the contractor shall continue pump development until, in the hydrogeologist's opinion, the following conditions have been met:

- The quantity of filter pack material placed in the annulus shall be at least as great as the calculated volume of the annulus.
- There is no further settlement of the filter pack in the gravel feed pipe.
- A test for sand concentration shall be made 20 min after the start of pumping while at the maximum drawdown and discharge rate as specified by the hydrogeologist. At this time, the sand concentration shall be less than 5 mg/L, and the average sand concentration shall not exceed 5 mg/L for any 2 h cycle. The sand concentration shall be measured by a centrifugal sand-separating device (i.e., using a Rossum sand tester).
- There shall be no increase in the specific capacity with further development.

B.4 TESTING FOR YIELD AND DRAWDOWN

The contractor shall furnish all necessary equipment and materials and perform complete pumping tests on the well following development. The pumping test equipment shall have a capacity of not less than that listed under Section B.3.22, Well Development by Pumping, and shall be capable of discharging water at the ground surface from the depth specified. Water shall be disposed of as approved by [owner/client].

During test pumping, the contractor shall provide an approved measuring device (propeller meter or orifice plate) that is suitable for the range of discharge rates expected for the test pumping as determined during development by pumping. The contractor also shall provide for true and accurate depth to water level measurements within the 2 in. diameter sounding tube during test pumping and recovery. Readings and recordings of the pump discharge rate and the depth to water shall be made by the contractor at intervals directed by the hydrogeologist but in no case less frequently than every 30 min.

Drawdown (change in pumping water level from "static" water level conditions) shall be measured by means of an electric wire-line sounder, or airline, pressure gauge and pressurized air bottle, or as approved by the hydrogeologist. If an airline is used, the bottom of the airline shall be verified using an electric wire-line sounder and the static (nonpumping) airline reading.

Recording the time of pump startup, pump shutdown, and all interim measurements shall be made with reasonable accuracy (±0.5 min). Any irregular events (e.g., pump failure and restart) occurring during the pumping test shall be noted and their time recorded. Should these events occur, the hydrogeologist must be notified and decisions made as to the validity of the pumping test. If the pumping test is interrupted due to malfunction of the contractor's equipment, the pumping test shall be performed again at the contractor's expense.

Prior to constant rate test pumping, depth to water measurements shall be taken on all pumping and nonpumping wells in the nearby area, as directed by the hydrogeologist. The time interval between depth to water measurements may vary between acceptable limits.

B.4.1 Step-Drawdown Test

The contractor shall conduct a step-drawdown test by pumping the well at a sufficient number of rates (at least three) to determine the specific capacity and well efficiency relationships. The range of discharge rates shall be within a maximum of 15,140 L/min (4,000 gal./min), or the maximum capacity of the well, as directed by the hydrogeologist.

Pumping shall continue at each rate for a sufficient length of time to bring about a stable (or predictable) water level trend, as determined by a semilogarithmic plot of the pumping level versus time. The total duration of the step-drawdown test shall not be more than 10 h.

Step-drawdown data shall include the pump discharge rate in gallons per minute, the static water level depth and the drawdown in feet. The data shall be sufficient such that the following results may be obtained:

- A specific capacity diagram showing formation loss and well loss curves for the range of discharge rates tested,
- A well efficiency diagram for the range of discharge rates tested, and
- A recommended production pumping rate with total dynamic head and depth of pump setting.

B.4.2 Constant-Rate Pumping Test

To predict long-term drawdown effects, the contractor shall perform a constant-rate pumping test for a period of at least 24 h at the design discharge rate (or other specified rate), or as directed by the hydrogeologist. The constant-rate test shall be conducted only after recovery from the step-drawdown test is complete (or exhibits a predictable trend when residual drawdown versus time is plotted on a semilogarithmic scale). During the constant-rate test, measurements of depth to water shall be made in the pumping well, as well as in any other available nearby wells at the time intervals recommended in the previous section. Measurement of water levels in nearby wells and piezometers shall be as directed by the hydrogeologist. Measurement intervals shall not exceed those provided in Table B-2.

The constant-rate test shall be sufficient to provide information regarding aquifer parameters (i.e., transmissivity and storativity) and shall include the pump discharge rate in gallons per minute and static water level and drawdown in feet. The contractor shall provide a spinner (flowmeter) survey at the end of the constant-rate interference test that is to be conducted without shutting down the pump. Immediately following completion of the spinner survey (see Section B.4.3, Flowmeter [Spinner] Survey) and shutting down the test pump, recovery measurements shall be conducted for a minimum of 4 h.

Table B-2. Minimum Measurement Intervals during Pumping Tests

Time After Beginning of Each New Discharge Step [min]	Recommended Measuring Interval [mins]
1–10	2
10–30	5
30–60	10
60–120	15
120–720	30
>720	60

In addition, water quality samples shall be collected as directed by the hydrogeologist and shall be submitted at the owner's expense to an approved laboratory for full Title 22 analysis, as per the California Code of Regulations, as well as any other tests that may be required by [owner/client].

After completion of the pumping tests and removal of the test pump equipment, the contractor shall bail all sediment, silt, sand, and debris from the bottom of the well.

B.4.3 Flowmeter (Spinner) Survey

At completion of the constant-rate pumping test and prior to recovery measurements, a flowmeter (or spinner) survey shall be run throughout the entire length of the screened interval. The spinner survey shall be conducted by a company retained by the contractor and approved by the hydrogeologist. The cost of the spinner survey shall be borne by the contractor. There will be no additional payment for either rig time or standby time while logging is being performed or while the contractor is waiting on a subcontractor.

A company that is mutually acceptable to [owner/client], the hydrogeologist, and the engineer shall run the spinner survey. The same pump used for the constant-rate pumping test shall be used during the spinner survey. Therefore, the contractor shall ensure that the spinner tool will be able to pass the pump bowls. No additional payment shall be made if it is necessary for the contractor to pull the test pump and replace it with a smaller diameter pump in order to conduct the spinner survey.

To accomplish the spinner survey, the contractor shall install a length of PVC or steel pipe within the well that has a minimum diameter of 63.5 mm (2 ½ in.). This length of pipe shall extend from the ground surface to just below the intake of the pump, and the spinner tool shall be passed through it during testing. The contractor shall ensure that this pipe is not plugged or collapsed prior to conducting the spinner survey.

Each spinner survey shall be conducted in the perforated section of the well. For the purpose of this specification, the perforated interval is defined as the lineal distance between the top of the uppermost perforations to the bottom of the lowermost perforations. The spinner survey shall be continuous and shall traverse the complete perforated interval irrespective of the fact that in some cases, the perforated interval may contain embedded sections of blank casing.

The spinner survey shall be conducted with the pump operating at a constant discharge rate, as determined in the field by the hydrogeologist. The spinner survey shall consist of at least three "down-run" passes. Both static and dynamic tests shall be made. Each static (stop count) test shall consist of 2-min readings made at 6.1 m (20 ft) intervals throughout each screened interval, or as otherwise directed. Each dynamic test shall be conducted at different line speeds (in ft/s), unless otherwise approved by the hydrogeologist. The record for each test shall indicate either meter speed or percentage of total meter speed with depth. The meter used for the survey shall be calibrated within the uppermost and lowermost sections of blank well casing.

The spinner survey shall become the property of [owner/client] at the time the survey is completed. The survey shall be run in the presence of the hydrogeologist. The contractor shall provide six copies of the survey to the hydrogeologist immediately upon completion, as well as one reproducible original, at no additional cost. In addition, the contractor shall provide interpretation or analysis of the spinner survey to the hydrogeologist within 7 days of conducting the survey. Spinner survey measurements also shall be provided in an electronic format and on suitable storage media.

The contractor shall be required to provide whatever assistance may be required to accomplish the spinner survey.

B.5 VIDEO SURVEY

Following the constant rate pumping test, the contractor shall conduct a *dual-cam video survey* through the entire length of installed casing and screen. The video survey shall be conducted using equipment that includes a downhole closed-circuit color television camera with side-scan capability. The video survey shall be conducted throughout the entire length of the casing and screen. The video equipment shall include a real-time monitor that records the camera depth readout superimposed on the video picture.

The video survey, preserved in digital format, shall serve as the final inspection of the finished well product, and shall be retained by the [owner/client] as a permanent record of the completed well. Should visibility be poor, or should simultaneous downhole and sidewall views not be acceptable, the contractor shall rerun the video survey at contractor's expense.

Two copies of the video survey shall be submitted to the hydrogeologist within 24 h of conducting the survey.

B.6 WELL DISINFECTION

The contractor shall provide for disinfection of the well as soon as construction of the well, development, and pumping tests have been performed. The contractor shall carry out adequate cleaning procedures, of the bottom sump immediately before disinfection when evidence indicates normal well construction and development procedures have not cleaned the well adequately. All oil, grease, soil, and other materials, which could harbor and protect bacteria from disinfectants, shall be removed from the well.

Where test pumping equipment is to be utilized, such equipment shall be thoroughly cleaned of foreign material prior to installation in the well. The contractor shall swab the development pump (columns and bowls) with a strong chlorine solution as it is lowered into the well for development pumping.

The contractor shall add a strong chlorine solution to the well following removal of the test pump to obtain required minimum concentration of 100 mg/L free chlorine concentration (see Table B-3).

Only chlorine or other compounds approved by the State Department of Health Services, Drinking Water Board, and the National Sanitation Foundation (NSF Standard 60), shall be used as disinfectants. The disinfectant shall be delivered to the site of the work in the original closed containers bearing the original label indicating the percentage of available chlorine. The disinfectant shall be purchased recently. Chlorine compounds in dry form shall not be stored for more than 1 year, and storage of liquid compounds shall not exceed 60 days.

During storage, disinfectants shall not be exposed to the atmosphere or to direct sunlight. The method used to introduce the chlorine into the well shall ensure that chlorine solution reaches all portions of the well in which contamination might have occurred during construction. The chlorine solution shall be of such volume and strength and shall be so applied that during the pumping procedure a concentration of at least 100 mg/L of chlorine shall be obtained initially at the pump discharge.

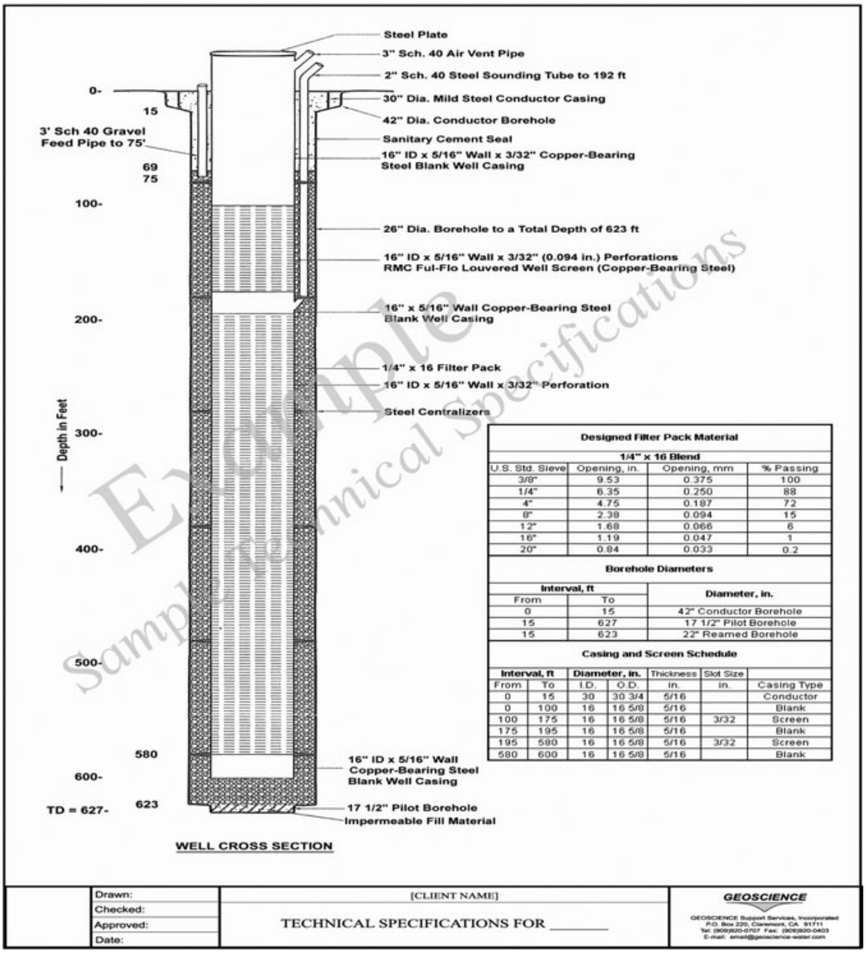
Table B-3. Chlorination Compounds and Concentrations Required to Obtain 100 mg/L per 100 ft of Casing or Screen

	SI Units	Customary Units
Inside Casing Diameter	45.72 cm	18 in.
Casing Volume	5004.3 L/30.48 m	1,322 gal./100 ft
Volume of Casing or Screen and 30% of Annular Space	7135.5/30.48 m	1,885 gal./100 ft
Required Amount of Sodium Hypochlorite (12.5% Available Chlorine)	6.06 L	1.6 gal.

The quantity and type of chlorine compound used for disinfection of the well shall be submitted to the hydrogeologist within 24 h of disinfecting the well.

B.7 FIGURES

[Placeholder – This should be a general location map showing nearby wells]
Fig. B-1. General location of well [name]
[Placeholder – Detailed site plan of well (name)]
Fig. B-2. Detailed location of well [name]



Designed Filter Pack Material

1/4" x 16 Blend			
U.S. Std. Sieve	Opening, in.	Opening, mm	% Passing
3/8"	9.53	0.375	100
1/4"	6.35	0.250	88
4"	4.75	0.187	72
8"	2.38	0.094	15
12"	1.68	0.066	6
16"	1.19	0.047	1
20"	0.84	0.033	0.2

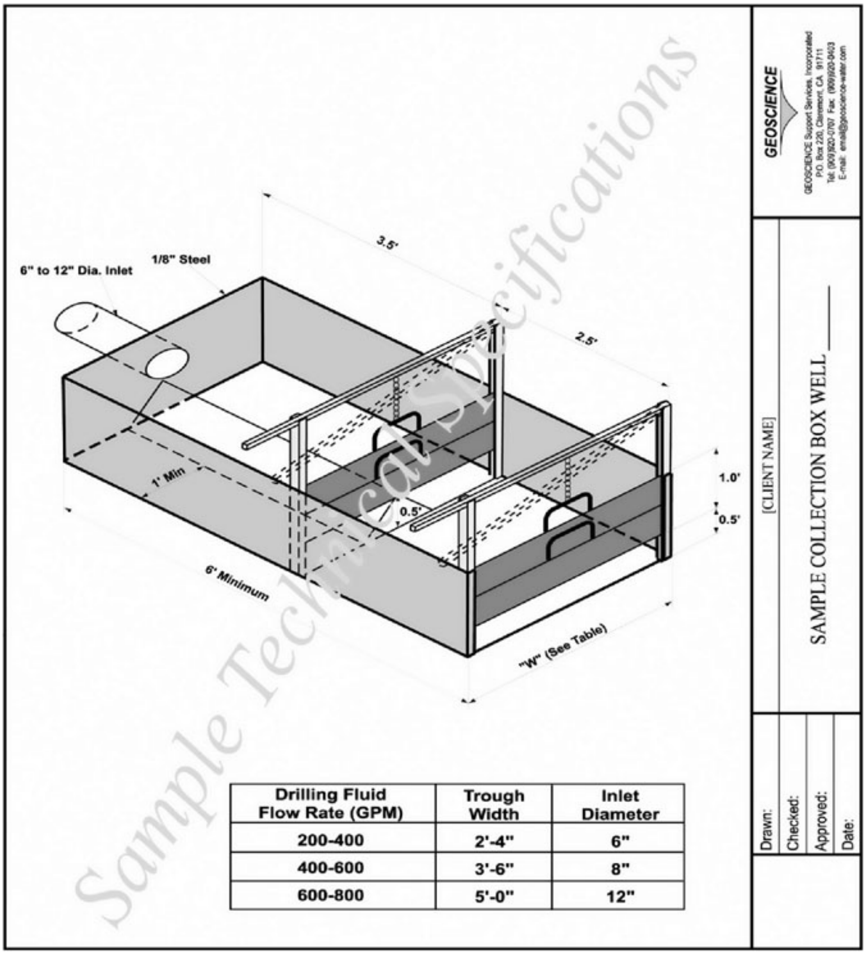
Borehole Diameters

Interval, ft		Diameter, in.
From	To	
0	15	42" Conductor Borehole
15	627	17 1/2" Pilot Borehole
15	623	22" Reamed Borehole

Casing and Screen Schedule

Interval, ft		Diameter, in.		Thickness	Slot Size	
From	To	I.D.	O.D.	in.	in.	Casing Type
0	15	30	30 3/4	5/16		Conductor
0	100	16	16 5/8	5/16		Blank
100	175	16	16 5/8	5/16	3/32	Screen
175	195	16	16 5/8	5/16		Blank
195	580	16	16 5/8	5/16	3/32	Screen
580	600	16	16 5/8	5/16		Blank

Fig. B-3. Conceptual well completion diagram—[well name]



Drilling Fluid Flow Rate (GPM)	Trough Width	Inlet Diameter
200-400	2'-4"	6"
400-600	3'-6"	8"
600-800	5'-0"	12"

Fig. B-4. Sample collection box detail—[well name]

B.8 ATTACHMENTS

ATTACHMENT B.8.1: Well Completion Report and Borehole Lithologic Log for Well in the Vicinity of [Well Name]

Note: One or more completed forms from nearby wells would follow. This blank form was obtained from the State of California's Division of Planning and Local Assistance website at http://www.dpla2.water.ca.gov/publications/groundwater/dwr188_prd.pdf.

ORIGINAL
File with DWR

Click here for a new number

STATE OF CALIFORNIA
WELL COMPLETION REPORT
Refer to Instruction Pamphlet

No. XXXXXXX

DWR USE ONLY — DO NOT FILL IN

STATE WELL NO./STATION NO.

LATITUDE LONGITUDE

APN/TRS/OTHER

Page ___ **of** ___
Owner's Well No. ____________
Date Work Began ____________, Ended ____________
Local Permit Agency ____________
Permit No. ____________ Permit Date ____________

GEOLOGIC LOG

ORIENTATION (✓) ___ VERTICAL ___ HORIZONTAL ___ ANGLE ___ (SPECIFY)

DRILLING METHOD ____________ FLUID ____________

DEPTH FROM SURFACE Ft. to Ft.	DESCRIPTION *Describe material, grain size, color, etc.*

TOTAL DEPTH OF BORING ________ (Feet)
TOTAL DEPTH OF COMPLETED WELL ________ (Feet)

WELL OWNER

Name ____________
Mailing Address ____________
CITY STATE ZIP

WELL LOCATION

Address ____________
City ____________
County ____________
APN Book ______ Page ______ Parcel ______
Township ______ Range ______ Section ______
Latitude ___ DEG. ___ MIN. ___ SEC. NORTH Longitude ___ DEG. ___ MIN. ___ SEC. WEST

LOCATION SKETCH

NORTH
WEST
EAST
SOUTH

Illustrate or Describe Distance of Well from Roads, Buildings, Fences, Rivers, etc. and attach a map. Use additional paper if necessary. ***PLEASE BE ACCURATE & COMPLETE.***

ACTIVITY (✓)

___ NEW WELL

MODIFICATION/REPAIR
___ Deepen
___ Other (Specify)

___ DESTROY *(Describe Procedures and Materials Under "GEOLOGIC LOG")*

PLANNED USES (✓)

WATER SUPPLY
___ Domestic ___ Public
___ Irrigation ___ Industrial

MONITORING ___
TEST WELL ___
CATHODIC PROTECTION ___
HEAT EXCHANGE ___
DIRECT PUSH ___
INJECTION ___
VAPOR EXTRACTION ___
SPARGING ___
REMEDIATION ___
OTHER (SPECIFY) ___

WATER LEVEL & YIELD OF COMPLETED WELL

DEPTH TO FIRST WATER ______ (Ft.) BELOW SURFACE
DEPTH OF STATIC WATER LEVEL ______ (Ft.) & DATE MEASURED ______
ESTIMATED YIELD * ______ (GPM) & TEST TYPE ______
TEST LENGTH ______ (Hrs.) TOTAL DRAWDOWN ______ (Ft.)
** May not be representative of a well's long-term yield.*

DEPTH FROM SURFACE Ft. to Ft.	BORE-HOLE DIA. (Inches)	CASING (S) TYPE (✓) BLANK	SCREEN	CON-DUCTOR	FILL PIPE	MATERIAL / GRADE	INTERNAL DIAMETER (Inches)	GAUGE OR WALL THICKNESS	SLOT SIZE IF ANY (Inches)

DEPTH FROM SURFACE Ft. to Ft.	ANNULAR MATERIAL TYPE CE-MENT (✓)	BEN-TONITE (✓)	FILL (✓)	FILTER PACK (TYPE/SIZE)

ATTACHMENTS (✓)

___ Geologic Log
___ Well Construction Diagram
___ Geophysical Log(s)
___ Soil/Water Chemical Analyses
___ Other ____________

ATTACH ADDITIONAL INFORMATION, IF IT EXISTS.

CERTIFICATION STATEMENT

I, the undersigned, certify that this report is complete and accurate to the best of my knowledge and belief.

NAME ____________
(PERSON, FIRM, OR CORPORATION) (TYPED OR PRINTED)

ADDRESS CITY STATE ZIP

Signed ____________ WELL DRILLER/AUTHORIZED REPRESENTATIVE ____ DATE SIGNED ____ C-57 LICENSE NUMBER

DWR 188 REV. 11-97

IF ADDITIONAL SPACE IS NEEDED, USE NEXT CONSECUTIVELY NUMBERED FORM

BOREHOLE LITHOLOGIC LOG

Job Number:

Well Number/Name:

Sample Depth (ft)	Color: Munsell Name and Class	Moisture Content			Particle % Dist.			Sorting			Grain Shape				Plasticity				Cementation				Mineral Composition						Alteration Visible	Grading Analysis	Rock Type (USCS Group)	Comments
		Dry	Moist	Saturated	Cobbles	Sand & Gravel	Silt & Clay	Well	Medium	Poor	Angular	Sub-Angular	Sub-Rounded	Rounded	High	Medium	Low	None	None	Week	Moderate	Strong	Quartz	Feldspar	Mica	Amphibole	Evaporites	Other				

ATTACHMENT B.8.2: National Pollutant Discharge Elimination System (NPDES) General Discharge Permit

Placeholder—The Permit should be inserted here

ATTACHMENT B.8.3: Sample Bid Schedule

BID SCHEDULE [Owner/Client Name] [Well Name]

Item No.	Description	Qty	Unit Price	Total Item Price
1.	Mobilization, demobilization, site cleanup and restoration	__ each	$ Lump Sum	$
2.	Provide noise control measures as specified	__ each	$ Lump Sum	$
3.	Testing and disposal of drill cuttings from pilot and conductor boreholes, if required	__ each	$ Lump Sum	$
4.	NPDES compliance for waste water discharge treatment	__ each	$ Lump Sum	$
5.	Drill 48-in. diameter conductor borehole, furnish and install 36-in. diameter by 5/16-in. wall conductor casing; cement into place.	____ ft	$ ____ /ft	$
6.	Drill maximum 17-½-in. diameter pilot borehole (est. TD = 1,540 ft).	____ ft	$ ____ /ft	$
7.	Provide geophysical borehole logs, as specified.	__ set(s)	$ Lump Sum	$
8.	Perform isolated aquifer zone testing on four zones.	__ zones	$ ____ /zone	$
9.	Abandonment of pilot hole in accordance with county standards, if required	____ ft	$ ____ /ft	$ N/A

Continued

ATTACHMENT B.8.3. Sample Bid Schedule (*Continued*)

BID SCHEDULE [Owner/Client Name] [Well Name]

Item No.	Description	Qty	Unit Price	Total Item Price
10.	Ream 17-½ in. pilot bore hole to 30 in. in diameter.	____ ft	$ ____ /ft	$
11.	Provide caliper survey of reamed borehole.	__ each	$ ____ /ea	$
12.	Furnish and install 20-in. ID diameter × 5/16 in. wall copper-bearing blank casing.	____ ft	$ ____ /ft	$
13	Furnish and install 20-in. ID diameter × 5/16 in. wall copper-bearing ful-flo louvered screen.	____ ft	$ ____ /ft	$
14	Furnish and install 2-in. sch 40 sounding tube, as specified.	____ ft	$ ____ /ft	$
15	Furnish and install 3-in. sch 40 gravel feed pipe, as specified.	____ ft	$ ____ /ft	$
16	Furnish and install filter pack material and fine sand layer, as specified.	____ ft	$ ____ /ft	$
17	Furnish and install annular cement seal, as specified.	____ ft	$ ____ /ft	$
18	Develop and clean well by airlifting and swabbing from between packers.	___ hrs	$ ____ /ft	$
19	Install and remove development/test pump to 1,000 ft bgs.	__ each	$ Lump Sum	$

ATTACHMENT B.8.3. Sample Bid Schedule (*Continued*)

BID SCHEDULE [Owner/Client Name] [Well Name]

Item No.	Description	Qty	Unit Price	Total Item Price
20	Deduction amount should the pump be set to 750 ft bgs and with a diffuser	__ each	$ ____ LS	$ N/A
21	Provide development by pumping and surging with deep well turbine pump.	___ hrs	$ ____ /hr	$
22	Provide pumping tests for yield and drawdown as specified.	___ hrs	$ ____ /hr	$
23	Provide spinner survey, as specified.	__ each	$ Lump Sum	$
24	Complete wellhead as designed and cleanup well site, including plumbness and alignment surveys and disinfection.	__ each	$ Lump Sum	$
25	Provide Dual-Cam video survey on VHS format.	__ each	$ Lump Sum	$
	TOTAL BID PRICE - ITEMS 1–25 (excluding Items 9 and 20):		$	

APPENDIX C
GLOSSARY

Acoustic/Sonic Logs—Logs the velocity of sound through the wallrock. They utilize an acoustic wave transmitter and receiver that are lowered into the borehole.

Adenosine Triphosphate Determination—Determines the amount of adenosine triphosphate that is in a specific water volume after the bacterial cell walls have been lysed

Advective Transport—Transport of contaminant by moving water

Aeolian—Deposits from windblown sediments

Airlifting—Air forced in the column of fluid causing it to become buoyant and following the path of least resistance to lift the cuttings with the drilling fluid to the surface

Alluvial—Relating to beds of sand, gravel, silt, and clay deposited by flowing water

Alluvial Aquifer—An aquifer consisting of beds of sand, gravel, silt, or clay deposits that have been deposited by flowing water and are capable of yielding significant quantities of water to wells and springs

Ancillary Devices—A device that is added, but not essential, such as flowmeters

Anisotropic—Having different properties in different directions at any given point

Annular Seals—See sanitary seals.

Annulus—The space between the well casing and the borehole walls

Anode—A positively charged electrode

Aquiclude—A formation that, although porous and capable of absorbing water, does not transmit it at rates sufficient to furnish an appreciable supply for a well or spring

Aquifer—A formation, group of formations, or part of a formation that is sufficiently saturated permeable material to yield significant quantities of water to wells and springs and acts as a storage reservoir and as a conduit for transmission of groundwater

Aquifer Diffusivity—The ratio of the transmissivity and the storage coefficient

Aquifer Hydraulics—The action of groundwater flowing through an aquifer and the associated energy relationships

Aquifer Matrix—The solid phase skeleton of an aquifer

Aquifer Test—A test involving pumping a well at a constant rate for a period of several hours or days and measuring the change in water level in the pumped well or observation wells located at different distances from the pumped well

Aquifer Transmissivity—The rate at which water of prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient; equal to the hydraulic conductivity times the aquifer thickness

Aquifer Safe Yield—The maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in the hydraulic head in the aquifer

Aquitards—A confining bed that retards but does not prevent the flow of water to or from an adjacent aquifer; a leaky confining bed. It does not yield water readily to well or springs but may serve as a storage unit for groundwater.

Artesian Aquifer—An aquifer bounded above and below by beds of distinctly lower permeability than that of the aquifer itself; an aquifer in which ground water occurs under pressure due to the presence of a low permeability confining beds.

Artesian Well—A well deriving its water from an artesian or confined water body; the water level in an artesian well stands above the top of the artesian water body it taps. If the water level in an artesian well stands above the land surface the well is a flowing artesian well.

Atmospheric Zone—The zone that occurs above the static water level

Backwashing—The action of putting an artificial hydraulic head on the well, reversing the flow of water through the screen, dislodging and breaking up sediment bridges and particles

Bailer—A long, cylindrical container fitted with a valve at its lower end, used to remove water, sand, mud, drilling cuttings, or oil from a well

Biocides—Agents used in the attempt to reduce bacterial populations

Biocorrosion—Microorganisms inducing or sustaining corrosion mechanisms

Biofilm—Population of various microorganisms, trapped in a layer of slime and excretion products, attached to a surface, which can cause plugging of water pipes and pumps

Biofouling—The gradual accumulation of waterborne organisms (as bacteria and protozoa) on the surfaces of engineering structures in water that contributes to corrosion of the structures and to a decrease in the efficiency of moving parts

Biological Blockage—Incrustation or blockage of water flow in a well system usually slimy and composed of predominately bacterial growth

Biological Incrustation—Well blockage caused to some extent by biological growth

Blowing—Similar to surging; however, the air is injected into the well for a longer period of time. This action thus pumps (or "blows") the water out of the well.

Borehole—The well bore itself, including the open hole or uncased portion of the well. Borehole may refer to the inside diameter of the well bore wall, the rock face that bounds the drilled hole.

Calibration—The act of adjusting the accuracy of a measurement instrument by comparing with a standard

Caliper Log—A record of the average diameter of a borehole

Camera Access Tubes—Larger diameter sounding tubes up to a 4-in. diameter that can accommodate television equipment allowing for video surveys of the well

Capillary Force—Force created by the adhesion of the water to the surface of the containing media

Capillary Fringe—The lower subdivision of the unsaturated zone immediately above the water table in which the interstices are filled with water under pressure less than that of the atmosphere; being continuous with the water below the water table but held above it by surface tension, its upper boundary with the intermediate belt of the unsaturated zone indistinct

Casing—A cylindrical device that is installed in a well to maintain the well opening and to provide a seal

Cathode—A negatively charged electrode

Cathodic Depolarization—Classical microbial induced corrosion mechanism that theorizes that sulfate-reducing bacteria (SRB) consume hydrogen through the action of their hydrogenase enzymes and thus "depolarize" the cathode, accelerating corrosion

Cavitation—The formation and rapid collapse of gas bubbles in a liquid caused by the pressure within the fluid dropping to the vapor pressure of the liquid at that temperature. This phenomena is caused by contracting of the flow area or by the rapid movement of something through the liquid, such as a propeller.

Centralizer—A mechanical device that prevents the casing from contacting the well bore wall

Centrifugal Pump—A pump through which liquid is discharged through a pipe by the energy from a wheel or blades spinning in a case

Chemical Incrustation—A form of incrustation usually brought about by a chemical activity or change and, in most cases, results in the mineral form of deposit or blockage

Coalluvial—Weathered, unconsolidated materials transported and deposited by gravity

Colloids—Finely divided solids that will not settle but that may be removed by coagulation or biochemical action

Complete Gravel Envelope—Gravel envelope that extends all the way to the surface

Compressibility—Ratio of percent change in volume to the change in pressure applied to a fluid or rock

Cone of Depression—A depression in the water table or potientiometric surface of a groundwater body that is in the shape of an inverted cone and develops around a well which is being pumped. It defines the area of influence of the pumping well.

Confined Aquifer—See artesian aquifer.

Confining Bed—A body of impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers

Constant-Rate Test—A test used to verify the design discharge rate estimated from the step-drawdown test and used to measure long-term drawdown effects on the pumped well and any nearby wells

Corrosion—The deterioration of a material, which results from a reaction with its environment

Cost–Benefit Analysis—A method of project evaluation that compares the potential benefits with the anticipated costs

Crevice Corrosion—Corrosion that occurs in a crevice or other area with limited oxygen supply due to differential aeration

Cross-over—A type of pipe with four branches in horizontal and vertical form used in intersecting pipes

Cross-over Tool—A device sometimes utilized for placing gravel packs in deep, small-diameter wells

Darcy—A standard measurement of intrinsic permeability that is a function of the porous media only. It has units of area and 1 darcy = $9.87 \times 10^{-7}\,mm^2$

Darcy's Law—An empirical law based on experimental evidence for the flow of fluids with the assumption that the flow is laminar and that inertia can be neglected. It states that the velocity of the flow through a formation is directly proportional to the hydraulic gradient.

Degassing—The process of removing dissolved gases from the water entering the well

Dewater—To lower the water table or piezometric surface adequately to permit safe and dry construction

Differential Aeration—The description of the condition that occurs when the supply of oxygen is not uniform across a surface, such as a crevice or joint, allowing the low-oxygen area to become anodic and more vulnerable to corrosion

Dispersion—The process by which some of the water molecules and solute molecules travel more rapidly than the average linear velocity and some travel more slowly; spreading of the solute in the direction of the groundwater flow (longitudinal dispersion) or direction perpendicular to groundwater flow (transverse dispersion)

Downgradient—The direction in which groundwater or surface water flows (also referred to as down-slope); opposite of upgradient

Drawdown—The vertical distance the free water elevation is lowered, or the reduction of the pressure head due to the removal of free water

Earth Fissure—A long narrow opening or cleft in the earth

Effective Hydraulic Diameter—The area in which water from an aquifer can move freely into a well

Electric Sounder—A method of measuring the water level in a well. Graduated wires are lowered into a well and the depth is measured when the wires contact water and complete the circuit.

Electrochemical Corrosion—Corrosion involving the flow of electrons between cathodic and anodic areas

Elevation Head—The part of hydraulic head that is attributable to the elevation of a measuring point (e.g., mid-point of a well screen) above a given datum (e.g., mean sea level)

Encrustation—The deposition of a mineral on the well screen or gravel pack, which acts to restrict water from moving into the well; synonomous with incrustation

Exopolymer—The slime bacteria produce that allows them to stick to surfaces, such as well screens and gravel packs

Filter Pack—Specially graded sand or gravel that is clean and well rounded placed in the annular space of a well between the borehole wall and the well screen to prevent formation material from entering the screen. See also gravel pack

Formation Stabilizer—Clean, coarse sand or sand-gravel mixture installed in annular space surrounding well screen to assist in well development. More limited in scope than gravel pack

Glaciofluvial—Sediment deposits due to glacier activity

***Gallionella* Deposits—**Deposits of iron-oxidizing stalked bacteria

Galvanic Corrosion—Corrosion that is a result of a metal electronically connected to a dissimilar metal in the presence of an electrolyte

Geohydrology—The hydrologic or flow characteristics of subsurface water; often used interchangeably with hydrogeology

Geophysical Borehole Logs—Products of surveys that collect and transmit specific information about the geologic formations penetrated by a well by raising and lowering a set of probes or sondes that contain watertight instruments in the well. The data collected can be used to determine general formation geology, fracture distribution, vertical borehole flow, and water-yielding capabilities.

Ghanat—A series of vertical shafts spaced approximately 100 m apart that roughly parallels the slope of an alluvial fan located near the base of a mountain range

Gravel Envelope—See gravel pack.

Gravel Feed Pipe—Pipe used in gravel envelope wells to replenish and monitor the levels of gravel filter pack.

Gravel Pack—Filter material (sand, gravel, etc.) placed in the annular space between the casing and the borehole to increase the effective diameter of the well and to prevent fine-grained material from entering the well during pumping

Groundwater—1) That part of the subsurface water that is in the saturated zone; or 2) loosely, all subsurface water as distinct from surface water

Guard Resistivity (Laterolog)—A resistivity log made with a tool that achieves focusing through the use of additional current electrodes above and below a central measure-current electrode

Head Losses—The decreases in total head caused by energy loss due to pipe roughness, change in cross section, direction, or other fixtures

Heterogeneous—A characteristic of the geologic matrix of interest in which hydraulic conductivity is dependent on position

Heterotrophic Plate Count—HPC is the number of colonies of bacteria formed on an agar plate after the plate has been streaked with a given amount of the water to be tested

Homogeneous—As it pertains to hydraulic conductivity, hydraulic conductivity is independent of position within a geologic formation; hydrologic properties are identical everywhere.

Homogeneous Aquifer—An aquifer with hydrological properties that are identical everywhere

Hydraulic Conductivity—For an isotropic porous medium and homogeneous fluid, the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Replaces the term *field coefficient of permeability*

Hydraulic Gradient—Slope of the water table or potientiometric surface, or the change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic Jetting—A method of well development where high-pressure clean water is sprayed through the well screens to dislodge debris

Hydraulics—A branch of science and engineering that deals with the static and dynamic behavior of fluids

Hydrogeologic Mapping—Identification of groundwater flow divides, recharge areas, and aquifer boundaries (as depicted by lithological or depositional changes in the aquifer and confining materials) to determine the extent of the wellhead capture zone

Hydrogeology—The science that deals with subsurface waters and related geologic aspects of surface waters; also used in the more restricted sense of groundwater geology only

Hydrostatic Head—The pressure at a given point in a liquid measured in terms of the vertical height of a column of the liquid needed to produce the same pressure

Impeller—The rotating element of a pump that consists of a disk with curved vanes. The impeller imparts movement and pressure to a fluid.

Incrustation—Deposition of mineral on the well screen or gravel pack, which act to restrict water from moving into the well

Induction Logging—Borehole logging method that measures the electrical conductivity of the formation

Interaquifer Seal—A sack sand-cement slurry installed to fill the annular space between the blank casing and the borehole following installation of the filter pack material

Internal Combustion Engine—Engine commonly used to run pumping units all over the world where fossil fuels are abundantly available and cheaper than the electric power supplies

Intrinsic Permeability—A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and independent of the nature of the liquid and of the force field causing movement.

Isotropic—A medium whose properties are the same in all directions

Isotropic Aquifer—An aquifer whose properties are independent of direction

Karst—An area of irregular limestone in which dissolution has produced fissures, sinkholes, underground streams, and caverns

Key Holing—Deformation of the borehole, which can occur if the borehole deviates from vertical at depth and a thick buildup of wall cake occurs

Lacustrine Deposit—Lake sediment; usually fine laminated silts and clays

Laminar Flow—Fluid flow in which the energy loss is proportional to the first power of the velocity

Langelier Saturation Index (LSI)—A measure of the degree of saturation of calcium carbonate in water based on pH, alkalinity, and hardness; a positive LSI indicates that calcium carbonate may precipitate from solution to form scale.

Leakage—(1) the flow of water from one hydrogeologic unit to another. The leakage may be natural, as through a semi-impervious confining layer, or human made, as through an uncased well; (2) the natural loss of water from artificial structures as a result of hydrostatic pressure

Leakance—A measure of the ability of the aquitard (i.e., leaky layer) to transmit water in semiconfined or leaky aquifers and is defined as the ratio of the hydraulic conductivity of the leaky layer to the thickness of the leaky layer

Lithologic Description—The activity of characterizing the qualitative properties of rock, such as the evaluation of hydrocarbon shows, sedimentary facies types or fossil abundance

Lithology—The branch of science and geology that studies rocks

Lyse—To cause cells to be destroyed by disruption of the bounding membrane

Manometer—An instrument that is used for measuring the pressure in liquids and gases

Mass Transfer—The transfer of mass into or out of a system, generally involving a change in state

Mechanical Grading Analyses—Separation of the various grade sizes of a sample. The most common methods are screening and hydrometer analysis.

Mechanical Surging—Water flow forced into and out of a screen by operating a plunger (surge block, or swab) up and down in the casing, similar to a piston in a cylinder

Microbial Biocorrosion—See biocorrosion.

Microflora—Plants that can only be seen under a microscope

Mineral Blockage—Incrustation or blockage of water flow in a well system precipitation of the calcium salts, dehydrated ferric iron, manganese oxides, etc.

Mixed Boundary—A linear combination of head and flux at a boundary; an example of a mixed boundary is leakage between a river and an underlying aquifer.

Moisture Content—Liquid volume within a porous media per unit volume of media

Mud Balance—A device to measure density (weight) of mud, cement, or other liquid or slurry.

Mud Rings—A buildup of highly viscous and plastic drilling fluid that can cause an increase in pressure and loss of circulation below the rings

Mud Scow—Heavy bailer with a cutting edge at its lower end

Multiple Zone Completion—Two or more separate zones, mechanically segregated one from the other and produced simultaneously from the same well

Natural Gamma Logs—A plot of the measurement of the natural emission of gamma rays by a formation. Gamma ray logs are particularly helpful, because shales and sandstones typically have different gamma ray signatures that can be correlated readily between wells.

Naturally Developed Well—A well with no artificial filter pack installed between well and borehole

Nonferrous Material—Material that does not contain iron

Normal Resistivity Log—A record of the resistivity (resistance to current) of a formation

Open Borehole Well—A well with no casing or screen

Orifice Meter—An instrument that records the flow rate of a fluid through a pipe. The flow rate is calculated from the pressure differential created by the fluid passing through an orifice of a particular size and other parameters, such as static pressure, temperature, density of the fluid and size of the pipe

Overpumping—Process of pumping water into the well at a higher rate than will be pumped when the well is put into production (easiest method of removing particulate matter from a well)

Oxidation—(1) A reaction in which there is an increase in valence resulting from a loss of electrons; (2) A corrosion reaction in which the corroded metal forms an oxide; usually applied to reaction with a gas containing elemental oxygen, such as air

Oxidation Reduction Potential (ORP)—The potential required to transfer electrons from an oxidant to a reductant that indicates the relative strength potential of an oxidation-reduction reaction

Oxide—Any element (but especially a metal) that forms a binary compound with oxygen

Packer—A piece of downhole equipment that consists of a sealing device, a holding or setting device, and an inside passage for fluids

Partial Gravel Envelope—A gravel envelope that does not extend to the surface of the borehole

Passivating Film—Coating of an object with an oxide layer in order to protect it against contamination and increase the electrical stability

Passivation—(1) A reduction of the anodic reaction rate of an electrode involved in corrosion; (2) The process in metal corrosion by which metals become passive; (3) The changing of a chemically active surface of a metal to a much less reactive state

Passivity—A condition in which a piece of metal, because of an impervious covering of oxide or other compound, has a potential much more positive than that at the metal in the active state

Pathline—The path a water molecule or solute would follow in a given groundwater velocity field

Phreatic Aquifer—An aquifer in which the water table forms the upper boundary

Phreatic Water—A term that originally was applied to water occurring in the upper part of the saturated zone under water-table conditions (synonym of unconfined groundwater

Physical Blockage—Incrustation or blockage of water flow in a well system

Physical Incrustation—Incrustation caused by sand, clays, and particulate matter from the formation as opposed to the minerals precipitated in the well systems

Piezometric Head—See potentiometric head.

Piezometric Surface—See potentiometric surface.

Polarization—A change in the potential of an electrode during electrolysis, such that the potential of an anode becomes more noble, and that of a cathode more active, than their respective reversible potentials; often accomplished by formation of a film on the electrode surface

Porosity—A measure of the volume of voids or fractures present in a unit volume of aquifer material, and may be expressed as a percent. It may range from less than 1% for dense, consolidated rocks to more than 30% for unconsolidated porous media.

Porous Media—Solid substances that contain pores, such as aquifers consisting of aggregates of individual particles, such as sand or gravel

Potential Energy—The energy of a particle or system of particles derived from position or condition, rather than motion

Potentiometric Head—The elevation to which water rises in a well

Potentiometric Surface—An imaginary surface representing the elevation and pressure head of groundwater and defined by the level to which water rises in a well or piezometer

Precipitation—(1) Any form of water, such as rain, snow, sleet, or hail, that falls to the earth's surface; (2) The process of separating a substance from a solution as a solid

Pressure Head—The hydrostatic pressure expressed as the height of a specific liquid (above a measurement point) in terms of the specific weight of that liquid

Propeller Meter—Device that measures the average discharge flow of a pipe by counting the number of revolutions of a propeller placed in the pipe

Pump—A mechanical device to lift the water to the ground surface and deliver it to the point of service

Pumping Water Level—Water level in a well when the well is being pumped

Pumping Lift—The distance water must be lifted in a well from the pumping level to ground surface

Pumping-plant Test—The test to determine or confirm the characteristics of installed pumps, including capacity, head, efficiency, and power consumption

Radial Flow—The flow of water in an aquifer toward a vertical well

Radial Well Collectors—Horizontal screens that extend laterally from a well's vertical shaft, which are used to collect and filter groundwater

Radius of Influence—The radial distance from the center of a well bore to the point where there is no lowering of the water table or potentiometric surface (the edge of its cone of depression)

Rawhiding—A process in which a column of water is raised a noticeable distance above the pumping water level and allowed to fall back into the well creating a surging action of the water in the well in order to develop or redevelop the well

Reaming Pass—A technique that is used to enlarging the borehole to its final diameter

Recharge—Replenishment of groundwater by downward infiltration of water from rainfall, streams, and other sources. Natural Recharge is recharge that occurs without assistance or enhancement by humans. Artificial Recharge is recharge that occurs when people deliberately modify the natural recharge pattern to increase recharge.

Recovery Test—A time measurement of the rate recovery of the water level from its drawdown as a result of a pumped test after the pumping has stopped

Reduction Reaction—Chemical reaction that involves a decrease in valence or the consumption of electrons and occurs in a cathodic region

Representative Element Volume (REV)—The volume of a sample at which the measured average properties of the sample can be considered representative of the whole

Residual Drawdowns—Measurements of drawdown below the original static water level (prior to pumping) during the recovery period

Reverse Circulation—The course of drilling fluid downward through the annulus and upward through the drill stem, in contrast to normal circulation in which the course is downward through the drill stem and upward through the annulus

Ryznar Stability Index (RSI)—A scale used to evaluate the corrosion or scaling potential of water

Safe Yield—The amount of water that can be withdrawn from the aquifer over the indefinite future without causing permanent harm to the aquifer

Sand Content—The percentage of solids (by volume) in drilling fluid that is not able to pass a 200-mesh screen

Sand Drive—The process by which the gravel pack around the well screen becomes compacted with sand due to surging process that occurs when the pumped well's pump is turned on and off

Sand Filter—See gravel pack.

Sand Pumping—Sand enters the well and is discharged into the water-supply system.

Sand Sealing—See sand drive.

Sanitary Seals—Seals to prevent infiltration of contaminates into the well

Saturated—A condition in which the interstices of a material are filled with a liquid, usually water. It applies whether the liquid is under greater than or less than atmospheric pressure, as long as all connected interstices are full

Saturation Index—See Langelier Saturation Index.

Sequestration—The formation of stable calcium, magnesium, iron complex by treating water or mud with certain complex phosphates

Shafting Arrangement—The layout of the pipes in the well operation

Sidewall Sticking—The condition where the drill pipe touches the bore-hole wall in the area were the thickened wall cake occurs and the force pressure differential effectively pushes the drill pipe into the wall cake

Single-Point Resistance Log—Record of the electrical resistance of a formation between the probe in a water-filled well below the bottom of the casing and an electrical ground at land surface

Sink Hole—A depression in the Earth's surface caused by collapse of overlying soils or rock into preexisting cave systems formed by dissolving of underlying limestone, salt, or gypsum. Drainage is provided through underground channels that may be enlarged by the collapse of a cavern roof.

Soil Skeleton—Individual soil grains loosely bonded together that can transmit loads via contact between particles

Sounding Tube—Pipe or tube used to check water levels and well fill in the cased well

Specific Capacity—The rate of discharge of water from the well divided by the drawdown of water level within the well

Specific Discharge—The volume of water flowing through a unit cross-sectional area of an aquifer

Specific Storage—The volume of water that a unit volume of aquifer releases from storage because of expansion of the water and compression of the void spaces and grains under a unit decline in average head with the unit volume

Specific Yield—The volume of water released by gravity drainage from a unit volume of aquifer material

Specified Flux—A model boundary condition in which the groundwater flux is specified; also called fixed or prescribed flux, or *Neumann boundary condition*

Specified Head—A model boundary at which the hydraulic head is specified; also called fixed or prescribed head, or *Dirichlet boundary condition*

Spinner Flowmeter—Device for measuring the velocity of fluid flow in a well based on the speed of rotation of an impeller, or spinner

Splash Zone—The internal surface of the casing between the static and pumping water levels

Spontaneous Potential Log—A well log of the difference between the potential of a movable electrode in the borehole and a fixed reference electrode at the surface

Static Water Level—Water level in a well where there are no groundwater pumping or other variable stresses existing that would cause dynamic changes in the groundwater system. It is the sum of the elevation head and the pressure head, the velocity head being negligible under conditions to which Darcy's law can be applied.

Steady Flow—When the hydraulic head at any point in the groundwater flow does not change with time and for a long period of pumping from or injecting into a well, the groundwater flow toward the well approaches a steady state.

Step-drawdown Test—Test that measures the drawdown in a well while the discharge rate is increased in steps

Storage Coefficient—The volume of water an aquifer releases from or takes into storage per unit surface area per unit change in hydraulic head. It is dimensionless but may be expressed as a percentage when multiplied by 100; also called *Storativity*

Storativity—See storage coefficient.

Strainer—A device, such as a filter or sieve, used to separate liquids from solids

Stratified—Having its substance arranged in strata, or layers

Stratum—A layer of sedimentary rock having about the same composition throughout

Stray Current Corrosion—Corrosion caused by currents from electrical equipment using an unintended metallic structure, such as a underground pipeline as a low-resistance pathway

Submerged Casing Zone—The well casing and well screens that are in continuous contact with groundwater

Submersible Pump—A pump that allows the motor to be submerged in a well below the water surface. This type of pump is required if water must be lifted more than 25 feet; also called a *deep-well pump*

Suction Pipe—The induction pipe of a pump

Surface Casing—A large-diameter, relatively low-pressure pipe string set in shallow yet competent formations

Surge Block—A plunger-like device used to force water in and out of the well screen

Surging—A method used in developing or redeveloping a water well where a plunger is moved up and down inside the casing, forcing water into and out of the well screen

Swab—A mechanical surging device that is pulled upward through the water column in a well

Swabbing—Reducing pressure in a well to clean or stimulate it by use of a swab

Telescoping Well Screens—Well screens with progressively smaller diameters as depth increases

Time-of-Travel (T-O-T)—The time required for a contaminant to travel from a distant point to the well

Toe Drain—A drainage conduit from a dam's structure used to carry seepage water away from the dam

Total Dynamic Head—The head loss due to frictional effects throughout the water-well system plus the static lift, usually expressed as a function of flowrate

Total Hydraulic Head—The sum of the elevation head, pressure head, and velocity head of a liquid. For groundwater flow, the velocity head component is generally negligible.

Transitional Flow—Flow between laminar and turbulent flow

Transmissivity—The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient; equal to the hydraulic conductivity times the aquifer thickness

Tremie Pipe—A pipe used to carry materials (usually grout) to a specific depth in a drilled hole; tremie pipes are slowly withdrawn as the material is placed in the well.

Turbidity—The amount of solid particles that are suspended in water and that cause light rays shining through the water to scatter

Turbulent Flow—(1). Water flow in which the flow lines are confused and heterogeneously mixed. It is typical of flow in surface water bodies. (2). Water flow in which the fluid particles move along very irregular paths.

Unconfined Aquifer—Aquifer that has an upper surface where the water pressure at that surface is equivalent to the atmospheric pressure. See also phreatic aquifer.

Unconsolidated Aquifer—Aquifer in sediment that is loosely arranged or unstratified or whose particles are not cemented together

Uniformity—Always the same, unvarying, being the same as or consonant with another or others

Unsaturated Zone—The zone between the land surface and the water table; it includes the capillary fringe and contains water under pressure less than atmospheric.

Upgradient—The direction of increasing potentiometric (piezometric) head

Vadose Zone—See unsaturated zone.

Velocity Head—Energy contained by fluid because of its velocity

Volumetric Efficiency—In describing an engine or gas compressor, the ratio of volume of working substance actually admitted, measured at a specified temperature and pressure to the full piston displacement volume; for a liquid-fuel engine, such as a diesel engine, volumetric efficiency is the ratio of the volume of air drawn into a cylinder to the piston displacement.

Wall Cake—A layer of conditioned drilling fluid that forms a thin (less than 2/32 in.) but tough low permeability protective coating that is deposited on the borehole walls

Water Table—(1) The upper surface of a saturated zone except where that surface is formed by an impermeable body; (2) locus of points in soil water at which the pressure is equal to atmospheric pressure; or (3) the surface where groundwater is encountered in a well in an unconfined aquifer, the water table is a particular potentiometric surface

Water Well—A well that extracts water from the saturated zone or that yields useful supplies of water; or a well that yields groundwater information or that replenishes groundwater

Well—An artificial excavation (pit, bore, hole, tunnel) generally cylindrical in form and often walled in, sunk (drilled, dug, driven, bored, or jetted) into the ground to such a depth as to penetrate water-yielding rock or soil and to allow the water to flow

Well Alignment—Measurement of how straight or crooked the well is

Well Capacity—The maximum rate at which a well will yield water under a stipulated set of conditions, such as a given drawdown, pump, and motor or engine size

Well Efficiency—A measurement of the effectiveness of a well in removing water from an aquifer, the ratio of the theoretical water level drawdown for a 100% efficient well to the actual water level drawdown for a given discharge

Well Encrustation—See encrustation.

Well Field—Two or more wells drilled into an aquifer

Well Hydraulics—The subdiscipline of groundwater hydrology that studies the response of an aquifer to a pumping well

Well Hydrodynamics—The study of flow of groundwater near, into, and in the well used to emphasize the dynamics of the system. It deals with flow into the well through the screen and within the well through the pumping system.

Well Losses—Loss of hydraulic head associated with movement of groundwater into and through the pumping well

Well Production—The volume of produced fluid per unit of time

Well Rehabilitation—Restoring a well to its most efficient condition by various treatments or reconstruction methods

Well Screen—A wire-wound tube or factory perforated casing installed in a well that maximizes the entry of water from the producing zone and minimizes the entrance of sand and other aquifer materials

Well Yield—The volume of water per unit time pumped from the well

Wellhead Area—Groundwater area around a well, which contributes water to the well

Wellhead Protection—The protection of groundwater from contamination in a specified area (wellhead protection area) surrounding public water-supply wells

Wetted Perimeter—Length of the wetted contact between a conveyed liquid and the conduit conveying it, measured in a plane at right angles to the direction of flow

Wetted Tape—A method of measuring water level in a well; this method utilizes a calibrated steel tape with a weight attached to the end of the tape.

Wire-to-Water Efficiency—Ratio of mechanical output of a pump to the electrical input at the meter

Zone of Contribution (ZOC)—The area surrounding a pumping well that encompasses all areas or features that supply groundwater recharge to the well

Zone of Influence (ZOI)—The area surrounding a pumping well within which the water table or potentiometric surfaces have been changed due to groundwater withdrawal

APPENDIX D
NOTATION

Symbol	Quantity	SI Units	Customary Units	Dimension
A	area, gross area	m^2	ft^2	L^2
A	series of uniform payments in dollars		($)	
AC_c	annualized capital cost of the well in dollars		($)	
A_{ws}	cross-sectional area of well screen	m^2	ft^2	L^2
A_d	cross-sectional area of delivery pipe	m^2	ft^2	L^2
A_s	cross-sectional area of suction pipe	m^2	ft^2	L^2
A_s	open area of well screen	m^2	ft^2	L^2
A_{wc}	cross-sectional area of well casing	m^2	ft^2	L^2
A_{os}	open area of well screen	m^2	ft^2	L^2
A_x	area of flow in the x-direction	m^2	ft^2	L^2
AC	annual costs		($)	
AC_c	annualized capital cost of the well		($)	
ANB	annual net benefits		($)	
ANB_n	old annual net benefits		($)	
B	coefficient of formation losses			
B′	benefit		($)	

Continued

Symbol	Quantity	SI Units	Customary Units	Dimension
b	coefficient in head loss equation			
b	thickness of an aquitard	m	ft	L
b	saturated thickness of a confined aquifer	m	ft	L
b	well screen length	m	ft	L
b_i	thickness of the *i*th layer of porous medium	m	ft	L
b_0	saturated thickness of an unconfined aquifer	m	ft	L
$(bp)_{ww-\mathrm{I}}$	brake power or input power at the level of total drawdown	kW	$\mathrm{lb_f}$ ft/s	FL/T
$(bp)_{ww-\mathrm{II}}$	brake power or input power at the level of electric motor	kW	$\mathrm{lb_f}$ ft/s	FL/T
$(bp)_{ww-\mathrm{III}}$	brake power or input power at the level of internal combustion engine	kW	$\mathrm{lb_f}$ ft/s	FL/T
$(bhp)_{ww-\mathrm{I}}$	brake horsepower or input horsepower at the level of total drawdown	kW	$\mathrm{lb_f}$ ft/s	FL/T
$(bhp)_{ww-\mathrm{II}}$	brake horsepower or input horsepower at the level of electric motor	kW	$\mathrm{lb_f}$ ft/s	FL/T
$(bhp)_{ww-\mathrm{III}}$	brake horsepower or input power at the level of internal combustion engine	kW	$\mathrm{lb_f}$ ft/s	FL/T
C	calorific value of fuel	kJ/kg	$\mathrm{lb_f}$ ft/ slug s	L^2/T^3
C	total cost of electric power		($)	
C_n	cost of rehabilitating the well		($)	
C_c	contraction coefficient for flow through screen slot			
C_d	dimensionless orifice coefficient of discharge			

Symbol	Quantity	SI Units	Customary Units	Dimension
C_g	clogging factor for screen slots			
C_u	uniformity coefficient for for aquifer or gravel pack material			
C_v	velocity coefficient for flow through screen slot			
C	coefficient in head loss equation			
C	concentration of a dissolved constituent	mg/L	mg/L	M/L^3
C_s	concentration of a source or sink	mg/L	mg/L	M/L^3
D	well diameter	m	ft	L
D_d	diameter of delivery pipe	m	ft	L
D_H	hydraulic diameter	m	ft	L
D_{ij}	hydrodynamic dispersion coefficient	m^2/s	ft^2/s	L^2/T
D_s	diameter of suction pipe	m	ft	L
d	saturated depth of phreatic or confined aquifer	m	ft	L
E	voltage	V	V	V
E	efficiency of a water well system			
E_{SC}	well efficiency based on specific capacity			
$E_{ww-\mathrm{I}}$	well efficiency at the level of total drawdown			
E_{w-w}	wire-to-water efficiency at the level of electric motor			
$E_{0-\mathrm{III}}$	overall efficiency at the level of internal combustion engine			
F	future worth of the well cost in dollars		($)	
f	friction factor			
g	gravitational acceleration	m/s^2	ft/s^2	L/T^2

Continued

Symbol	Quantity	SI Units	Customary Units	Dimension
H	static water level depth in a well, or, saturated depth of aquifer	m	ft	L
H_s	static head in a well	m	ft	L
H_1	total dynamic lift (static head + total drawdown)	m	ft	L
H_2	head loss from the entrance of strainer to the delivery end of the elbow end of discharge head	m	ft	L
H_{mn}	external head loss in the service main	m	ft	L
h	total dynamic head	m	ft	L
h	dynamic water level in the well, measured downward from the free surface to the impermeable barrier	m	ft	L
h	depth of water body in a well, measured downward to the impermeable barrier	m	ft	L
h	water depth against the casing	m	ft	L
h	hydraulic head or piezometric head	m	ft	L
Δh	change in the hydraulic head	m	ft	L
h_{aq}	aquifer head loss	m	ft	L
h_d	total head loss in the vertical portion of delivery pipe	m	ft	L
h_{dis}	head loss in the elbow of discharge head	m	ft	L
h_{dp}	head loss in the vertical portion of delivery pipe	m	ft	L
h_{ent}	entrance head loss at the strainer	m	ft	L

Symbol	Quantity	SI Units	Customary Units	Dimension
h_f	head loss in a well equal to total drawdown	m	ft	L
h_{gp}	gravel-pack head loss	m	ft	L
$\sum h_i$	sum of several minor head losses	m	ft	L
h_{me}	rise or fall in elevation head of the service main	m	ft	L
h_{mn}	head loss due to pipe friction in the service main	m	ft	L
h_o	pressure head in well above the datum	m	ft	L
h_s	total head loss through the suction line	m	ft	L
h_{sh}	power loss due to shafting arrangement	m	ft	L
h_{su}	head loss for suction pipe	m	ft	L
h_{str}	head loss for strainer	m	ft	L
h_{val}	head loss for a check valve	m	ft	L
h_w	pressure head in the well above the datum	m	ft	L
h_{wb}	head loss in the well bore			
h_{wc}	well-casing head loss	m	ft	L
h_{ws}	well-screen head loss	m	ft	L
I	electric current	A	A	A
i	interest rate			
i	hydraulic gradient			
i	discount rate for economic loan			
K	hydraulic conductivity	m/s	ft/s	L/T
K	hydraulic conductivity	m/s	gpd/ft^2	L/T
K_1	value of water		($)	
K_2	cost of electricity		($/kW)	
K_3	a lumped conversion constant			
K_{ave}	average weighted hydraulic conductivity	m/s	ft/s	L/T

Continued

Symbol	Quantity	SI Units	Customary Units	Dimension
K_i	hydraulic conductivity of *i*th layer of porous medium	m/s	ft/s	L/T
K_L	hydraulic conductivity in the *L*-direction	m/s	ft/s	L/T
K_r	hydraulic conductivity in the radial direction	m/s	ft/s	L/T
K_x	hydraulic conductivity in the *x*-direction	m/s	ft/s	L/T
K_y	hydraulic conductivity in the *y*-direction	m/s	ft/s	L/T
K_z	hydraulic conductivity in the *z*-direction	m/s	ft/s	L/T
k	intrinsic permeability, permeability	m^2	ft^2	L^2
k_{ent}	entrance loss coefficient for the strainer			
k_{str}	loss coefficient of the strainer			
k_1	permeability of gravel pack	m^2	ft^2	L^2
k_2	permeability of aquifer	m^2	ft^2	L^2
L	length of a porous medium sample	m	ft	L
L	distance in the direction of or along the *L*-axis	m	ft	L
L	well screen length	m	ft	L
L_d	length of vertical portion of delivery pipe	m	ft	L
L_s	length of suction pipe	m	ft	L
L_{gp}	length of gravel pack envelope	m	ft	L
L_{wb}	length of wellbore	m	ft	L
L_{wc}	length of well casing	m	ft	L
L_{ws}	length of well screen	m	ft	L
NAW	net annual worth in dollars		($)	
NPW	net present worth in dollars		($)	
n	total porosity			

Symbol	Quantity	SI Units	Customary Units	Dimension
n	number of periods in years	t	t	T
n	number of years (economic life of well)	t	t	T
P	present worth of the well cost, present worth, severity of turbulence		($)	
PWB	present worth of benefits in dollars		($)	
PWC	present worth of costs in dollars		($)	
P_w	water pressure	kPa	lb_f/ft^2	M/LT^2
ΔP_w	change in water pressure	kPa	lb_f/ft^2	M/LT^2
P_w/γ	pressure head	m	ft	L
p_{ws}	percentage open-area of a well screen			
p	hydrostatic pressure	kPa	lb_f/ft^2	M/LT^2
p_1	hydrostatic pressure	kPa	lb_f/ft^2	M/LT
p_2	hydrostatic pressure	kPa	lb_f/ft^2	M/LT
pf	power factor			
Q	discharge,	m^3/s	ft^3/s	L^3/T
	well discharge, or,	m^3/s	gpm	L^3/T
	instantaneous discharge rate, or,	m^3/s	mgd	L^3/T
	flow through inhomogeneous media, or,	m^3/s	ft^3/s	L^3/T
	safe discharge to prevent sand drive, or,	s-m	s-ft	L^3/T
	% maximum discharge, or,	ha-m/yr	ac-ft/yr	L^3/T
	% maximum yield	L/min	gpm	L^3/T
Q_0	flow through homogeneous media	L/min	gpm	L^3/T
q	Darcy velocity, or, velocity, or, average velocity, or, apparent velocity, or, bulk velocity in groundwater, or specific discharge	m/s	ft/s	L/T

Continued

Symbol	Quantity	SI Units	Customary Units	Dimension
q_s	volumetric flux of water per unit volume of aquifer representing both sources and sinks	1/s	1/s	1/T
q_x	component of Darcy velocity in the *x*-direction	m/s	ft/s	L/T
q_y	component of Darcy velocity in the *y*-direction	m/s	ft/s	L/T
q_z	component of Darcy velocity in the *z*-direction	m/s	ft/s	L/T
R_e	Reynolds number			
$\sum_{k=1}^{k=N} R_k$	first order reaction term for N number of reactions	mg/L	oz/ft^3	M/L^3
R_{wc}	Reynolds number for well casing			
ROR	rate of return,		($)	
r	radial coordinate, or,	m	ft	L
	radial distance from center of well	m	ft	L
r	well screen radius	m	ft	L
r	calculated fixed radius of the contributing area, or, zone of a wellhead protection program	m	ft	L
r_0	radius at the outermost rim of cone of depression	m	ft	L
r_e	effective well radius measured from center of well	m	ft	L
r_{gp}	radius of gravel pack envelope measured from center of well	m	ft	L
r_{pe}	radius of the damage zone measured from center of well	m	ft	L

Symbol	Quantity	SI Units	Customary Units	Dimension
r_w	radius of water well, or, radius of borehole	m	ft	L
S	storativity, or, storage coefficient			
SC	% maximum specific capacity			
SC_{act}	actual specific capacity from pumping test data	m^2/s	ft^2/s	L^2/T
SC_{max}	specific capacity calculated from original step-drawdown test	m^2/s	ft^2/s	L^2/T
SC_{theo}	theoretical specific capacity	m^2/s	ft^2/s	L^2/T
SC_T	theoretical specific capacity	m^2/s	ft^2/s	L^2/T
S_s	specific storativity	1/m	1/ft	1/L
S_y	specific yield			
s	% maximum drawdown,			
s_{theo}	theoretical drawdown	m	ft	L
s_w	total drawdown in a water well	m	ft	L
s_{wd}	total drawdown in a well based on step-drawdown test data	m	ft	L
s_1	partial drawdown in a well representing formation losses	m	ft	L
s_{1d}	partial drawdown in a well	m	ft	L
s_2	partial drawdown in a well	m	ft	L
s_{2d}	partial drawdown in a well	m	ft	L
T	transmissivity	m^2/s	ft^2/s	L^2/T
T	transmissivity	Lpd/m	gpd/ft	L^2/T
T_1	time the well is pumped	*s*	*s*	T
TAC	total annulized costs			
$TANB$	total annulized net benefits operated		($)	
t	time-of-travel	s	s	T

Continued

Symbol	Quantity	SI Units	Customary Units	Dimension
V	screen entrance velocity	m/s	ft/s	L/T
V_{af}	velocity in aquifer formation	m/s	ft/s	L/T
V_B	bulk volume of porous medium	m^3	ft^3	L^3
V_d	velocity in the delivery pipe	m/s	ft/s	L/T
V_{edg}	velocity at edge of cone of depression	m/s	ft/s	L/T
V_{ex}	exit velocity	m/s	ft/s	L/T
V_{gp}	velocity in the gravel pack	m/s	ft/s	L/T
V_L	Darcy velocity in the *L*-direction	m/s	ft/s	L/T
V_p	pore volume	m^3	ft^3	L^3
V_T	total volume of porous medium	m^3	ft^3	L^3
V_{wc}	velocity in well casing	m/s	ft/s	L/T
V_{ws}	velocity in screen slots	m/s	ft/s	L/T
V_r	velocity, or, average velocity, or, bulk velocity, or, Darcy velocity in porous medium in the r-direction	m/s	ft/s	L/T
V_w	volume of water removed	m^3	ft^3	L^3
V_x	velocity in the *x*-direction	m/s	ft/s	L/T
v	pore velocity, actual velocity	m/s	ft/s	L/T
v_x	pore velocity, or, actual velocity in the *x*-direction	m/s	ft/s	L/T
v_y	pore velocity, or, actual velocity in the *y*-direction	m/s	ft/s	L/T
v_z	pore velocity, or, actual velocity in the *z*-direction	m/s	ft/s	L/T
$(wp)_{ww-\mathrm{I}}$	waterpower or output power of water-well system I	kW	hp	FL/T

Symbol	Quantity	SI Units	Customary Units	Dimension
$(wp)_{ww-\text{II}}$	waterpower or output power of water-well system II	kW	hp	FL/T
$(wp)_{ww-\text{III}}$	waterpower or output power of water-well system III	kW	hp	FL/T
$(whp)_{ww-\text{I}}$	water horsepower, or, output horsepower of water well system I	kW	hp	FL/T
$(whp)_{ww-\text{II}}$	water horsepower, or, output horsepower of wate well system II	kW	hp	FL/T
$(whp)_{ww-\text{III}}$	water horsepower, or, output power of water well system III	kW	hp	FL/T
x	rectangular coordinate in the x-direction	m	ft	L
Δx	change in the distance, x	m	ft	L
y	rectangular coordinate in the y-direction	m	ft	L
z	rectangular coordinate in the z-direction	m	ft	L
z	elevation of point z above an arbitrary datum	m	ft	L
z_1	elevation of point z_1 above an arbitrary datum			
z_2	elevation of point z_2 above an arbitrary datum	m	ft	L
α	empirical constant	(s^2/m^6)	(s^2/ft^6)	(T^2/L^6)
β	empirical constant	(s^2/m^5)	(s^2/ft^5)	(T^2/L^5)
Δh	piezometric head difference between two locations	m	ft	L
Δp	pressure difference between two locations	kPa	lb_f/ft^2	M/LT^2
ΔP_w	change in water pore pressure	Pa	lb_f/ft^2	M/LT^2
ΔV_w	change in volume of water, drained from the medium	m^3	ft^3	L^3

Continued

Symbol	Quantity	SI Units	Customary Units	Dimension
β	compressibility of water	m^2/N	ft^2/lb_f	LT^2/M
ϕ	velocity potential			
γ	specific weight of water	N/m^3	lb_f/ft^3	$M/(L^2T^2)$
γ_w	specific weight of water	N/m^3	lb_f/ft^3	$M/(L^2T^2)$
μ	viscosity, or, dynamic viscosity	Pa s	$lb_f s/ft^2$	M/L T
θ	effective porosity			
ρ	density	kg/m^3	$slug/ft^3$	M/L^3
ρ_w	density of water	kg/m^3	$slug/ft^3$	M/L^3
σ	compressibility of aquifer skeleton	m^2/N	ft^2/lb_f	LT^2/M
υ	kinematic viscosity	m^2/s	ft^2/s	L^2/T

APPENDIX E
SI UNIT PREFIXES

Multiplication Factor	Prefix	Symbol
1 000 000 000 000 000 000 000 000 = 10^{24}	yotta	Y
1 000 000 000 000 000 000 000 = 10^{21}	zetta	Z
1 000 000 000 000 000 000 = 10^{18}	exa	E
1 000 000 000 000 000 = 10^{15}	peta	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10	deka*	da
1		
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a
0.000 000 000 000 000 000 001 = 10^{-21}	zepto	z
0.000 000 000 000 000 000 000 001 = 10^{-24}	yocto	y

*These prefixes are to be avoided where possible.
Source: ASTM E 380-85, *Practice for Use of the International System of Units (SI).*

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APPENDIX F

CONVERSION TABLE AND USEFUL CONSTANTS

	Customary Units	SI Units
Length	1 ft = 0.304 8 m	1 m = 1.093 6 yd
	1 mi = 1.609 4 km	1 m = 3.280 8 ft
	1 mi = 5 280 ft	1 m = 39.370 in
		1 km = 0.621 37 mi
Area	1 in^2 = 6.452 cm^2	1 cm^2 = 0.155 0 in^2
	1 ft^2 = 0.092 9 m^2	1 m^2 = 10.764 ft^2
	1 ft^2 = 929.0 cm^2	
	1 ac = 43 560 ft^2	1 ha = 10 000 m^2
	1 ac = 4 047 m^2	1 ha = 2.471 ac
	1 ac = 0.404 7 ha	
	1 mi^2 = 2.590 km^2	
	1 mi^2 = 640 ac	
Volume	1 ft^3 = 0.028 3 m^3	1 m^3 = 35.315 ft^3
	1 ft^3 = 28.320 L	
	1 ft^3 = 7.481 U.S. gal.	1 m^3 = 264.2 U.S. gal.
	1 U.S. gal. = 0.003 785 m	1 m^3 = 1 000 L
	1 U.S. gal. = 3.785 L	
	1 ac-ft = 43 560 ft^3	
	1 ac-ft = 3.259 × 10^5 U.S. gal.	
	1 ac-ft = 1 234 m^3	

Discharge	$1\ ft^3/s = 450\ gpm$	$1\ m^3/s = 8.64 \times 10^3\ m^3/d$
	$1\ ft^3/s = 27\ 000\ gph$	$1\ m^3/s = 10^3\ L/s$
	$1\ ft^3/s = 648\ 000\ gpd$	$1\ m^3/s = 35.315\ ft^3/s$
	$1\ ft^3/s = 1\ cfs = 2.365\ 2 \times 10^8\ gpy$	$1\ m^3/s = 264.2\ gps$
	$1\ ft^3/s = 0.028\ 320\ m^3/s$	$1\ m^3/s = 1.585\ 149 \times 10^4\ gpm$
	$1\ ft^3/s = 28.320\ L/s$	$1\ m^3/s = 95.108\ 943 \times 10^4\ gph$
		$1\ m^3/d = 4.087\ 384 \times 10^{-4}\ cfs$
		$1\ m^3/d = 24.524\ 305 \times 10^{-3}\ cfm$
		$1\ m^3/d = 14.714\ 583 \times 10^{-1}\ cfh$
		$1\ m^3/d = 35.315\ cfd$
		$1\ m^3/d = 18.393\ 229 \times 10^{-2}\ gpm$
		$1\ m^3/d = 66.215\ 623 \times 10\ gph$
		$1\ m^3/d = 1.589\ 175 \times 10^4\ gpd$
		$1\ m^3/s = 2.282\ 615 \times 10^7\ gpd$
		$1\ m^3/s = 22.826\ 15 \times 10^7\ mgd$
Mass	$1\ slug = 14.594\ kg$	$1\ kg = 0.068\ 5\ slug$
	$1\ lb_m = 0.454\ kg$	$1\ kg = 2.204\ 6\ lb_m$
	$1\ lb_m = 453.6\ g$	
Density	$1\ slug/ft^3 = 515.4\ kg/m^3$	$1\ kg/m^3 = 0.001\ 94\ slug/ft^3$
Density of water at 4 °C and air pressure of 760 mm Hg	$\rho_{H_2O} = 1.94\ slug/ft^3$	$\rho_{H_2O} = 1\ 000\ kg/m^3$
Density of air at 4 °C and air pressure of 760 mm Hg	$\rho_{air} = 0.002\ 47\ slug/ft^3$	$\rho_{air} = 1.275\ kg/m^3$
Velocity	$1\ ft/s = 0.305\ m/s$	$1\ m/s = 3.281\ ft/s$
Force	$1\ lb_f = 4.448\ N$	$1\ N = 0.225\ lb_f$
Specific weight of water at 4 °C and air pressure of 760 mm Hg	$1\ lb_f/ft^3 = 157.09\ N/m^3$	$1\ kN/m^3 = 6.365\ lb_f/ft^3$

Continued

	Customary Units	SI Units
Pressure	1 lb_f/in^2 = 6.895 kPa	1 kPa = 0.145 lb_f/in^2
	1 lb_f/in^2 = 2.31 ft of water at 60 °F	1 kPa = 20.89 lb_f/in^2
		1 kPa = 9.869 2 × 10^{-3} atmosphere
		1 kPa = 1.000 × 10^{-2} bar
		1 kPa = 10.000 millibar
		1 kPa = 1.000 × 10^4 dyne/cm^2
		1 kPa = 33.51 ft H_2O (4 °C)
Torque	1 ft lb_f = 1.356 N m	1 N m = 0.738 ft lb_f
	1 in lb_f = 0.113 N m	1 N m = 8.858 in lb_f
Energy	1 Btu = 1.055 kJ	1 k J = 0.948 Btu
	1 ft lb_f = 1.356 J	1 k J = 737.6 ft lb_f
	1 Btu = 778.16 ft lb_f	
Hydraulic conductivity		1 m/day = 24.54 gpd/ft^2
		1 m/day = 1.198 darcy (for water at 20 °C)
		1 cm/s = 2.126 ×10^4 gpd/ft^2
Power	1 hp = 0.746 kW	1 kW = 1.341 hp
	1 hp = 550 ft lb_f/s	1 kW = 737.6 ft lb_f/s
	1 Btu/hr = 0.2931 W	1 W = 3.4123 Btu/hr
	1 Btu/s = 1055.1 W	

Viscosity	1 lb_f s/ft2 = 47.88 Pa s	1 Pa s = 0.020 9 lb_f s/ft^2
Kinematic viscosity	1 ft^2/s = 0.092 9 m^2/s	1 m^2/s = 10.76 ft^2/s
Temperature		°C = (5/9)(°F − 32)
		K = °C + 273.15
	°R = °F + 459.67	
Specific heat capacity	1 Btu/(slug °R) = 0.13 [kJ/(kg K)]	1 [kJ/(kg K)] = 7.68 Btu/(slug °R)
		1 [kJ/(kg K)] = 5 980 [(ft lb_f)/(slug °R)
Gravitational acceleration	g = 32.174 ft/s^2	G = 9.81 m/s^2
Water at 4 °C and 760 mm Hg	γ_{H_2O} = 62.43 lb_f/ft^3	γ_{H_2O} = 9 810 N/m^3
	ρ_{H_2O} = 1.94 slug/ft^3	ρ_{H_2O} = 1 000 kg/m^3
	γ_{air} = 0.079 6 lb_f/ft^3	γ_{air} = 12.5 N/m^3
	ρ_{air} = 0.002 47 slug/ft^3	ρ_{air} = 1.275 kg/m^3

Note: cfs = cubic feet per second; cfm = cubic feet per minute; cfh = cubic feet per hour; cfd = cubic feet per day; gpm = gallons per minute; gph = gallons per hour; gpd = gallons per day; gpy = gallons per year; mgd = millions of gallons per day

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INDEX

Page numbers followed by *e*, *f*, and *t* indicate equations, figures, and tables, respectively.