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Evaluation of Well Rehabilitation

MASTER THESIS

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DIPLOMA THESIS ASSIGNMENT

Samirahmed Iqbalahmed Mirza

Land and Water Management

Thesis title

Evaluation of well rehabilitation

Objectives of thesis

The aim of the study is to evaluate pumping tests at the well located at Snedovice in the district of Usti nad Ladem. From this hydrodynamics tests evaluate basic parameters- storativity and transmissivity and additional resistances before and after well rehabilitation. Discuss results and differences before and after rehabilitation of the well RD2 – Snedovice (Radouň).

Methodology

For evaluation hydraulics parameters (transmissivity and storativity)from hydrodynamics tests based on unsteady radial flow Jacob semilogarithmic method will be used. For evaluation skin factor van Everdigen concept is used.

The proposed extent of the thesis

cca 40 pages inc. illustrations

Keywords

well; pumping tests; rehabilitation; skin effect;

Recommended information sources

Cooper, H. H., & Jacob, C. E. (1946). A generalized graphical method for evaluating formation constants and summarizing well–field history. Eos, Transactions American Geophysical Union, 27(4), 526-534

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Van Everdingen, A. F. (1953). The skin effect and its influence on the productive capacity of a well. Journal of petroleum technology, 5(06), 171-176

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Prague on 16. 04. 2016

Declaration:

Hereby I declare that I worked out the thesis entitled "Evaluation of Well Rehabilitation" on my own with use of the cited literature and according the instructions of my supervisor.

In Prague on 11.04.2016 Samirahmed Mirza

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Samirahmed Mirza

Abstract

Pumping test of the well located at Radouň in Czech Republic is evaluated to check the success of well rehabilitation process. The rehabilitation is a very useful process to increase life span of well and improve performance. Jacob’s method for pumping test is used as it is simplification of Thies’s method to find the parameters of an aquifer such as the storativity and the transmissivity. The drawdown vs time interval data is advocated to estimate the transmissivity and observation well data is recommended to estimate the storativity. The well is situated at Snedovice (Radouň) in the district of Usti nad Labem of Czech Republic which was built in 1975. The pumping test is conducted for long duration and two semi-log lines are obtained of drawdown vs time for pumping and observation well.

The study investigates the pressure drop in terms of additional drawdown in the well due to additional resistances that is estimated before and after rehabilitation process takes place. The additional resistances caused by skin effect for both the cases have been calculated by comparing actual well data with ideal well condition. The resulted difference between additional drawdown before and after rehabilitation is positive which indicates the success of rehabilitation process.

Key Words: Well, pumping test, rehabilitation, additional resistances, skin effect.

Abstrakt

Čerpací zkoušky na vrtu v Radouni v České republice byly provedeny z důvodu vyhodnocení úspěšnosti provedené regenerace. Regenerace je zásah na vrtu, který vede ke zvýšení vydatnosti studny a k prodloužení její životnosti. K vyhodnocení byla použita Jacobova semilogaritmická metoda vycházející z Theisova řešení základní rovnice popisující symetrické radiální proudění k vrtu za neustáleného režimu. Ze vztahu snížení vs. logaritmus času na čerpaném vrtu je určena transmisivita a z hodnot čerpací zkoušky na pozorovacím vrtu storativita. Vrt je situován nedaleko Snědovic (Radouň) v Ústeckém kraji. Vrt byl zhotoven v roce 1975. Čerpací zkouška byla provedena dostatečně dlouho, aby byly získány oba přímkové úseky pro vyhodnocení.

V diplomové práci je zkoumán dodatečný pokles hladiny -snížení- v odčerpávaném vrtu způsobený dodatečnými odpory před o po provedené regeneraci. Dodatečné odpory způsobující „skin efekt“ byly určeny pro oba případy před a po regeneraci srovnáním skutečného průběhu snížení v čase s průběhem při uvažování ideálního vrtu. Výsledný rozdíl v dodatečném snížení před a po regeneraci je pozitivní, což vypovídá o úspěšnosti provedeného regeneračního zásahu na vrtu.

Klíčová slova: vrt, čerpací zkouška, regenerace, dodatečné odpory, skinový efekt.

Table of Contents

List of Symbols

WP	Well productivity using exponential distribution function.
h	Hydraulic head or piezometric head, L
z	Elevation head, L
J	Hydraulic gradient, unitless
p	Fluid pressure, $ML^{-1}T^{-2}$
ρ	Density, ML^{-3}
μ	Dynamic viscosity, $ML^{-1}T^{-1}$
v	Velocity of groundwater, LT^{-1}
h_p	Pressure head, L
g	Gravitational acceleration $L\ T^{-2}$
Q	Flow rate or discharge rate, L^3T^{-1}
q	Specific discharge, LT^{-1}
K	Hydraulic conductivity, LT^{-1}
k	Permeability, L^2
T	Transmissivity, L^2T^{-1}
S	Storage Coefficient or Storativity,
S_s	Specific storage, L^{-1}
S_y	Specific yield, unitless
r	Distance from pumping well to observation well, L
s	Drawdown, L
b	Thickness of an aquifer, L
$W(u)$	Theis well function
u	Dimensionless Theis parameter of well function.

r_w	Radius of pumping well, L
A	Cross-sectional area in the direction of flow, L^2
W	Additional resistances, L
s_w	Drawdown, L
h_0	The equilibrium water level before pumping starts, L
h_1, h_2	Water level during pumping, L

*** SI (Standard International) Unities are used to described parrameters where M is mass (kg), L is Length (m) and T is time (sec).

1. Introduction

The large portion of global freshwater is present as groundwater containing 29.9 % of the global freshwater and 0.3% exists in surface fresh water (Shiklomanov, 1998). Surface freshwater is easily accessible and relatively less costly than groundwater extraction due to high energy and infrastructures are required to get access. Hence, surface water is largely used for industrial, agricultural and domestic purposes but surface fresh water is being more polluted comparatively. Groundwater is less polluted compared to surface freshwater and it is emerging as the main freshwater source due to its accessibility in dry seasons and at any point of surface where it is available underground. Groundwater is also the main source of drinking water for 1.5 to 3 billion people in the world (Doell et. al., 2009). Simultaneously, groundwater demand has increased for domestic, agricultural and industrial use even if groundwater is more expensive than surface water. Surface water has decreased drastically due to climate change, man-made and natural circumstances, and surface fresh water may not be available in some regions of South-Asia and Australia in coming future (Doell et. al., 2009). On the other hand, exploitation of groundwater causes depletion in groundwater table, groundwater pollution has also increased and cleaning of groundwater is very difficult process. Hence, there is necessity to develop complex groundwater system which can maintain this crucial and reliable water source.

In order to evaluate and manage groundwater, pumping test is carried out in different ways in different aquifers. In this test, transmissivity and storage properties of an aquifer are studied because these properties are mainly useful for water-supply chain. A Pumping evaluation is conducted using geologic model and it will be used for economic modelling. Thus, it provides information to establish engineering water extracting projects at appropriate location. Traditional well testing depends on some analytical and specific line-curve methods. A groundwater well is pumped in a controlled flow rate conditions and water table response is observed from observation wells. All wells have particular response that depends on properties of soil or rock and fluid characteristics. This model is solved with appropriate matched variables to interact with mathematical model, but there is limit to observe limited parameters. The interpretation techniques depend on straight-line or specific type of curve for a particular flow pattern and period such as radial flow, liner flow and steady-state flow. The solution shows that a drawdown is considered consisting of dependent and independent components of closing by well properties (Butler, 1988). Each aquifer has unique properties so the main concern of unique assumption of specific well arises. A traditional numerical method cannot provide relations between different variable but an analytical does provide this information. Both evaluation methods are useful to give overall characteristics of an aquifer and flow pattern.

2. Objective of the study

The aim of the study is to evaluate pumping test on a well located at Snevodice in the district of Usti nad Ladem. In this test, parameters such as storativity and transmissivity are evaluated before well gets cleaned and after gets cleaned. According to both evaluations before and after cleaning, the differences are discussed.

The main research question: "*Evaluate pumping test before and after cleaning of well.*"

The sub research questions:

1. Calculate the transmissivity of an aquifer.
2. Calculate the storativity of an aquifer.
3. Calculate the additional resistances before and after rehabilitation.
4. Calculate the effects of cleaning.

Estimate additional drawdown caused by skin effect.

3. Review of Literature

3.1 Well Productivity

The performance of well is simply indicated by rate of pumping or discharge flow rate per unit drawdown. Each aquifer is produced by several wells with unique drainage. The well performance or productivity is depending on lineament distribution in an aquifer. The geologic lineament can be defined as assumed origin of linear feature (Sander, 2007) and the assumption of lineament is a feature which shows vertical area of fracture concentration (Lattman, 1958) and permeability is depending on fracturing in an aquifer (Davis, 1988). However, the fractured aquifer's properties are hard to relate with well productivity quantitatively. The effect of high permeability on well productivity can be calculated by spatially distributed exponential function distance to the lineament. For the estimation of well productivity, the shape of lineament is transformed into circular computational domain. Figure 3.1 shows the transformation to unit radii circle.

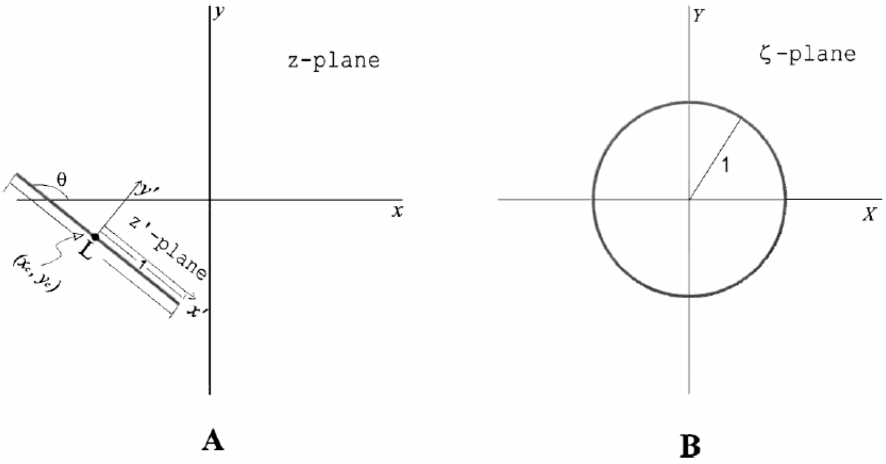


Figure 3.1 Transformation of liner lineament to circular domain (Park et al., 2000; p.607)**.**

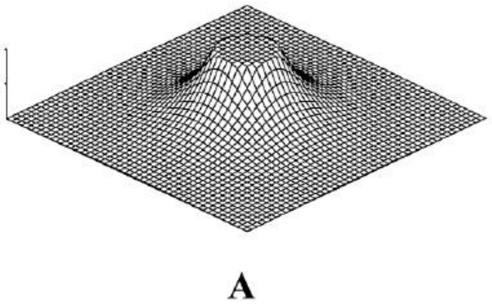


Figure 3.2 Distribution of well productivity using exponential distribution function (Park et al., 2000; p.608)**.**

The productivity around the unit circle is assumed to decrease exponentially as shown in figure 3.2. The well productivity distribution *(WP)* is indicated from the distance of *(r-1)* to the unit circle and well productivity *(WP_0)* as following (Park et al., 2000):

$$WP = WP_0 \cdot exp\frac{1-r}{\lambda} \qquad (3.1)$$

3.2 Groundwater Characteristics

Groundwater characteristics are observed before implementation of big well installation for water extraction such as location of well, quality of water, flow and availability and source of water.

3.2.1. Location

The surface reservoir and flow of water follow a particular flow path, but groundwater cannot be described in the same manner as surface flow pattern, because it is extended in large area and which is hard to define. There is no need of dams and other infrastructures which are built for surface water use for the extraction of groundwater. On the other hand, wells are dug in an aquifer to pump out water as required where it is available under the ground (Bear & Cheng, 2010). There is no necessity to build reservoir as in case of surface water system because an aquifer itself works as conduit and reservoir.

3.2.2. Groundwater Occurrence

There is a seasonal fluctuation in the flow of surface water but there is no such kind of seasonal fluctuation in the groundwater flow. The volume of water which is stored in an aquifer acts as buffer that will also be available in the draught condition. Groundwater flow is also an integral part of hydrologic cycle. Water from the surface enters in the ground through infiltration and percolation creating saturated zone that acts as a medium for groundwater flow (Todd, 1964).

3.2.3. Groundwater Distribution

Water penetrates underground mainly present in two zones: unsaturated and saturated zones, each separates according to air and water filled in the pore space in the soil. The pore space which is filled only with water is known as saturated zone and the pore space which is filled with air as well as water is called as unsaturated zone. The unsaturated zone is the largest reservoir of groundwater. The upper layer of ground serves as unsaturated zone consisting: root zone, intermediate zone and capillary fringe zone. Water enters in this zone or the unsaturated zone gets recharged and water moves to the deep saturated zone gradually (Nielsen & Biggar, 1986). This zone faces fluctuation in water storage due to plant uptake, precipitation and evapotranspiration (Figure 3.3).

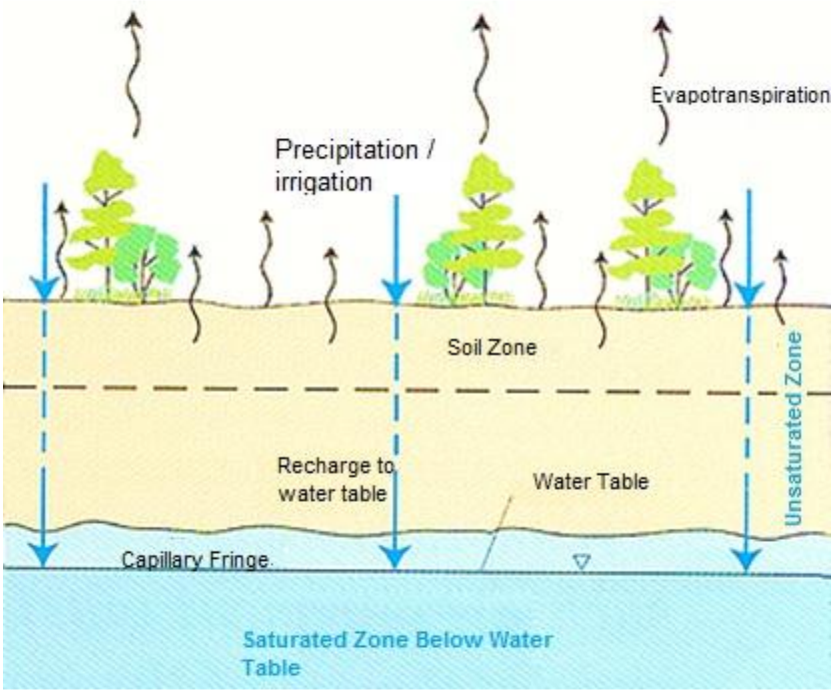


Figure 3.3 Saturated and Unsaturated Zones (Source: US geological survey).

The lowest zone is saturated zone where all the voids are filled with water molecules below the capillary zone. Water occurs in saturated zone under hydrostatic pressure.

3.2.4. Forces on Water

The forces acting on the water underground are mainly gravitational force, atmospheric pressure, the pressure of upper layer, adhesive and cohesive forces between molecules of water and soil. Water vapour moves from high to low pressure and condenses under subsurface, which is absorbed by the solid particles of soils. Water molecules retained by solid particles with adhesive forces and water molecules those are not attracted to solid surface are influenced by gravitational force. The capillary forces are due to air, water and solid particles interface that builds attraction or repulsion force between solid particles and it depends on the contact angle at the interface. Water between capillary fringes builds strong adhesive force (Shang et. al., 2009). Groundwater flows through interconnected pores due to the pressure difference and the pressure difference is expressed in terms of hydraulic head *(h)*. Thus, Bernoulli's equation is defined as follows:

$$h = z + \frac{p}{\rho g} + \frac{v^2}{2g} \qquad (3.2)$$

Where, h is the hydraulic head, z is the elevation above datum, p fluid pressure, ρ is the density of water, v is the velocity of water and g is the gravitational acceleration. Pressure head (h_p) is defined as follows from Equation 3.2:

$$h = \frac{p}{\rho g} \qquad (3.3)$$

The groundwater velocity is very low so, it is neglected. Thus, hydraulic head is defined as follows:

$$h = z + \frac{p}{pg} \qquad (3.4)$$

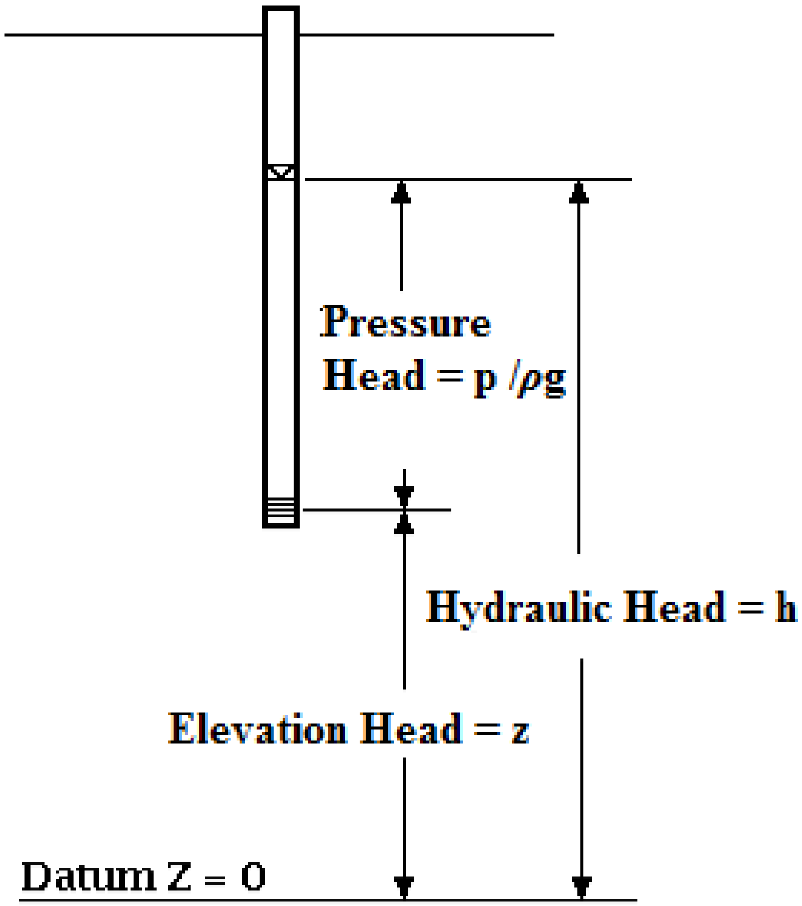


Figure 3.4 Hydraulic head, pressure head and elevation head

3.2.5. Water Table

Water table is the height of water in a well summing of pressure head and elevation above datum. It is the water level where water pressure in pores is equal to the atmospheric pressure (Holzer, 2010). Figure 3.4 shows water table above the screen of well which is equal to pressure head above the well screen.

3.2.6. Aquifers

An aquifer is geologically store water in subsurface and transmits water under the subsurface. An aquifer is classified according to its occurrence namely: confined aquifer, unconfined aquifer, semi confined aquifer, Leaky aquifer and preached aquifer (Olorunfemi & Fasuyi, 1993).

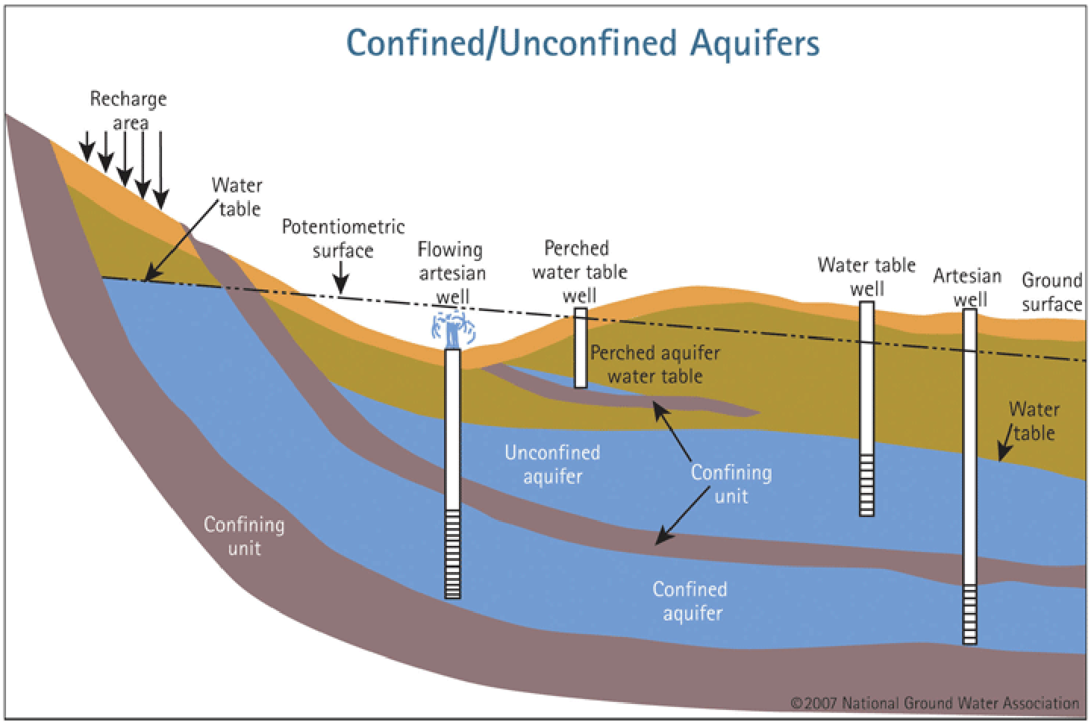


Figure 3.5 Types of Aquifer (Smith, 1982)

Unconfined aquifer is not compacted by impervious layers (confined layer) from the upper side. It is mostly held near to the ground level and water table does not change due to atmospheric pressure effect. An inverted cone of depression occurs while pumping out water from an unconfined aquifer and water is filled in the depression of cone after pumping stops. Pumping out water depends on gravity drainage principle (Smith, 1982). The confined aquifer occurs between aquitards or very low permeable layers. The confined aquifer is under pressure due to overlain layers than atmospheric pressure and water table rises above the aquifer in the well. The pumping from confined aquifer is not due to gravity discharge. A semi confined and a leaky aquifer occurs in strata type semi pervious layer while pumping out water from the well, water moves horizontal as well as vertical direction in a semi confined aquifer (Hemker, 2003).

3.3 Groundwater Movement

Groundwater moves from high to low pressure of hydraulic head. Hydraulic head is an elevation of water in piezometer above the datum of water aquifer which is the same water table in an unconfined aquifer and it is not similar in a confined aquifer (Liddle & Johnson, 1997). The movement of water depends on the aquifer composition and liquid properties.

3.3.1. Darcy's Law

Henry Darcy (1856) derived an empirical equation of flowing fluid through porous media. Darcy described that the flow rate of fluid in the porous media at a constant density and temperature is proportional to the hydraulic gradient of the two observing point in an aquifer (Whitaker, 1986 & Nimmo et al., 1987). The equation of Darcy's law is as follow:

$$Q = -KA\frac{dh}{dl} \tag{3.5}$$

Where, Q is the flow rate, *A* is the cross-sectional area through which fluid passes, K is the hydraulic conductivity, h is the piezometric head and l is the distance between two observing points. Darcy's law is generally valid for laminar flow and small Reynold's number of Newtonian fluid in a porous aquifer, the flow is one dimensional in a homogenous porous media (Neuman, 1977). The extension of Darcy's law in three dimensions (Bear & Cheng, 2010) can be written with parameters shown in Figure 3.5 as follow:

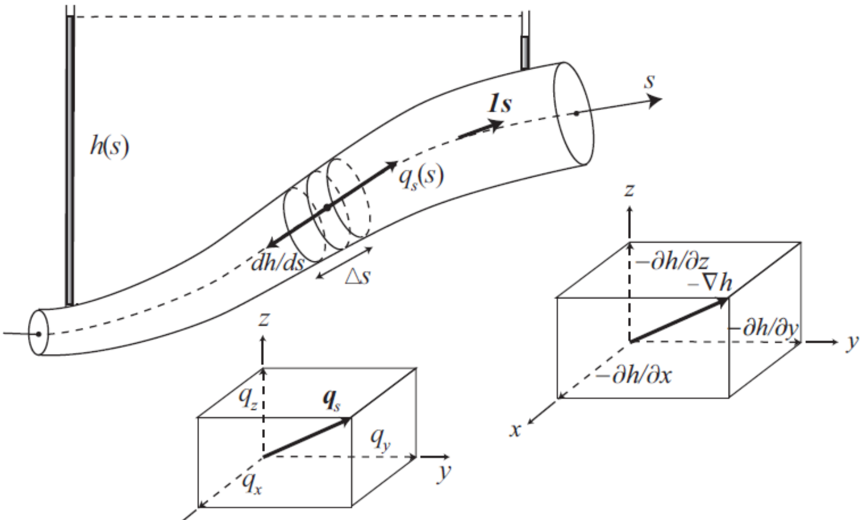


Figure 3.5 Three dimensional tube of flow. (Bear & Cheng, 2010; p. 114)

$$q = -K(x, y, z)\left(\frac{\partial h}{\partial x} + \frac{\partial h}{\partial y} + \frac{\partial h}{\partial z}\right) \tag{3.6}$$

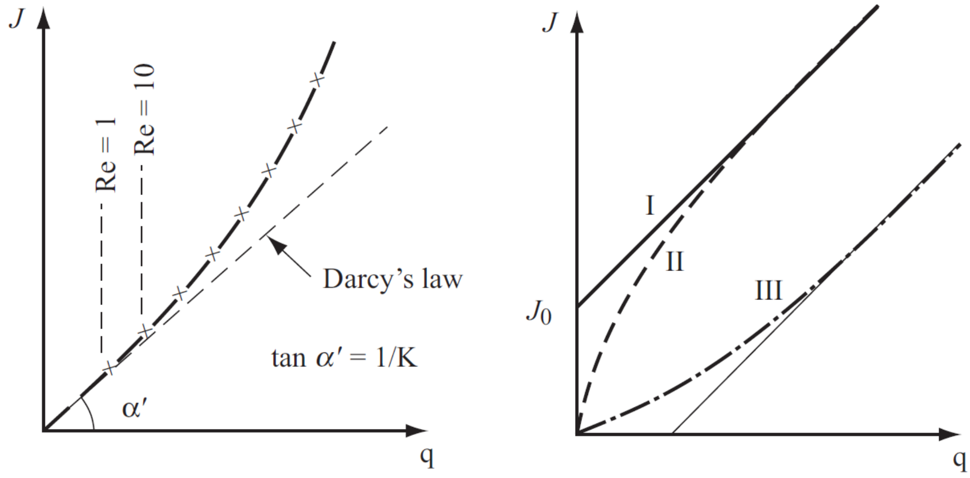
Where q is specific discharge and $\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y} \& \frac{\partial h}{\partial z}$ are three dimensional components of the hydraulic gradient vector.

When the permeability of an aquifer at a given point is not depending on the directions then, the porous media is called anisotropic medium. The equation 3.7 expresses Darcy’s law for anisotropic media.

$$q_x = K_x \cdot \frac{\partial h}{\partial x} \;\; , \;\; q_y = K_y \cdot \frac{\partial h}{\partial y} \;\; and \;\; q_z = K_z \cdot \frac{\partial h}{\partial z} \qquad (3.7)$$

3.3.2. Non Darcian Groundwater Motion

Darcy’s law shows liner relationship between specific discharge (q) and hydraulic gradient (J) but this situation exits at low Reynolds number (R_e<1). But the liner relation between specific storage (q) and hydraulic gradient (J) is not linear in some cases as shown in Figure 3.6.



A-Sand **B-Clay**

Figure 3.6 Relationship between hydraulic gradient (J) and specific discharge (q). (Bear & Cheng, 2010)

The Reynolds number is used to indicate the type of flow such as laminar, turbulent or transient flow of fluid. Most of the groundwater flow in a porous media has a Reynolds number less than 1 but, in some cases of high pumping rate and recharging, the Reynolds number is not less than 1. High R_e exists in a high porous media including lime stones (Firdaouss et al., 1997). Non darcian law for a leaky aquifer can be derived by analytical solution of the cone of depression and drawdown changes in the observation well (Sen , 2009).

3.3.3. Hydraulic Conductivity

The hydraulic conductivity *(K)* is defined as the ability of soil media to transmit water which is used as a boundary condition in the soil-water relation study (Klute & Dirksen, 1986). The hydraulic conductivity *(K)* depends on the shape and the size of soil particles (geometry and packing factor of pore space), the diameter of pores and the permeability of an intrinsic medium (Fair & Hatch, 1933). The hydraulic conductivity can be expressed as follow:

$$K = k \cdot \frac{\rho g}{\mu} \tag{3.8}$$

Where, ρ is the density of a fluid, μ is the dynamic viscosity of fluid, g is the gravitational acceleration and k is the permeability. The permeability is the function which depends on the shape and the size of a pore space of the porous media. The permeability can be expressed as below:

$$k = Cd^2 \tag{3.9}$$

Where C is the dimensionless constant and d is the characteristic diameter of a pore with the dimension of length. The hydraulic conductivity does not depend on fluid property but it depends on the configuration of a void space and the interconnectedness of voids.

3.3.4. Transmissivity of an Aquifer

The transmissivity is defined as the amount of water which is transmitted horizontally through unit width of the fully saturated aquifer at a unit hydraulic gradient. The transmissivity can be expressed as follows:

$$T = bK \tag{3.10}$$

Where, b is the thickness of an aquifer and K is the hydraulic conductivity. The transmissivity (T) depends on the heterogeneity of the porous media and interconnectedness of voids (Richard et. al., 2016).

3.3.5. Storage Coefficient or Storativity

The storativity *(S)* can be defined as the volume of water which is drained from an aquifer at a unit difference in the hydraulic head through unit the area by the gravity flow at water table. Water is drained due to hydrostatic pressure in the voids below the water table from an aquifer (Cheng, et al., 2005). The specific storage (Ss) is the volume of water in a formation, it is drained from the storage at a change in a unit hydraulic head (Helm, 1975). The specific storage for a confined aquifer with thickness b can be expressed as below:

$$S = bS_s \qquad (3.11)$$

The storativity is generally less (< 0.005) for a confined aquifer (Todd, 1980). The specific storage for an unconfined aquifer can be expressed as below:

$$S = S_y + hS_s \qquad (3.12)$$

Water is drained due to the gravitational force is known as the specific yield (S_y). The specific storage is high in clay and silt than sand, it considers compressibility of the fluid and the deformity of soil structure due to compaction of the soil structure.

3.3.6. General groundwater flow equation for ideal aquifer

Dupit (1863) has given assumption for an ideal confined aquifer with no recharge and leakage from an aquifer, which has an infinite length with a constant thickness. The transmissivity and the storativity are homogenous through-out the aquifer length. The pumping is done at a constant rate of discharge (Q) and the hydraulic head is constant in time and space. The discharge can be calculated by Darcy's law which is written as follows:

$$Q = -2\pi r T \frac{\partial h}{\partial r} \qquad (3.13)$$

Where T is the transmissivity, r is the radial distance of pumping well at a given point in an aquifer and h is the hydraulic head in an aquifer.

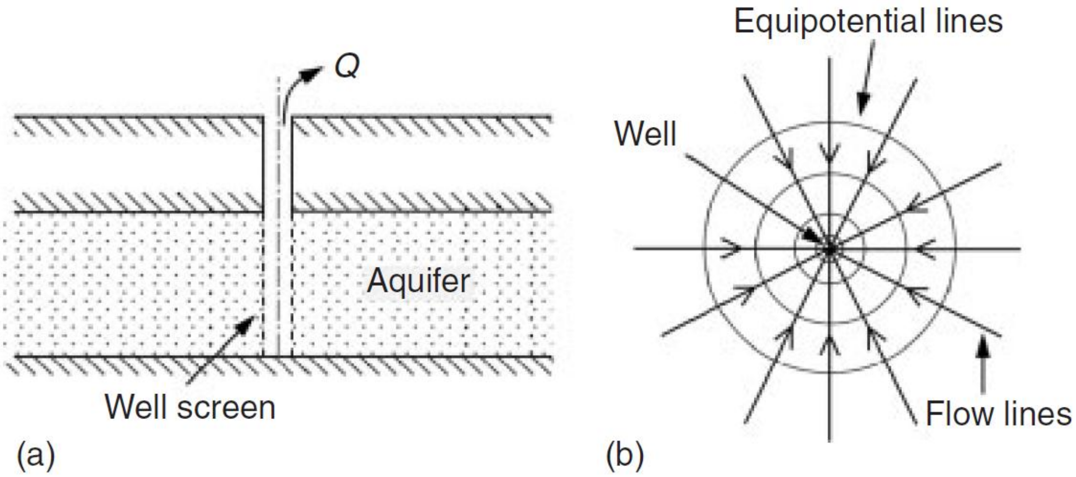


Figure: 3.7 (a) Ideal Confined Aquifer and (b) Radial water flow to the well penetrating completely (Renard P. , 2006; p:3)

The assumed aquifer is confined and the compressibility is very low. According to the mass conversation law in the well for particular time duration can be given as follow:

$$\frac{\partial Q}{\partial r} = -2\pi r S \frac{\partial h}{\partial t} \qquad (3.14)$$

Where S is the storativity of a confined aquifer. The general equation can be derived from the equation (3.13) and (3.14) as,

$$\frac{1}{r}\frac{\partial h}{\partial r} + \frac{\partial^2 h}{\partial r^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (3.15)$$

The equation (3.15) is a general equation with cylindrical coordinates for an ideal confined aquifer in which the hydraulic head is assumed to be constant before pumping starts.

3.3.7. Theis Solution for Ideal Well

Thiem (1906) derived a solution with two observation wells which are located at a distance of r_1 and r_2 from the pumping well and expressed in terms of drawdown s_1 and s_2 in both observation wells.

$$T = \frac{Q}{2\pi(s_2 - s_1)} \cdot ln\frac{r_1}{r_2} \qquad (3.16)$$

This equation 3.16 has been derived from steady state conditions but Theis and Jacob had also derived the equations for transient flow which is similar to Thiem equation. The assumptions as the same in the Dupit- Thiem solution are considered for the transient groundwater flow in a confined and a homogeneous aquifer in which well is fully penetrated through a confined aquifer with a negligible well diameter (Theis, 1935). Theis derived solution as follows:

$$s(r,t) = \frac{Q}{4\pi\, T}\int_{u}^{\infty}\frac{e^{-u}}{u}du \qquad (3.17)$$

$$u = \frac{r^2 S}{4tT} \qquad (3.18)$$

Where *s(r,t)* is the drawdown at a distance *r* from the pumping well. This integration can be written as well function as below (Fetter, 2001):

$$W(u) = \int_{u}^{\infty}\frac{e^{-u}}{u}du \qquad (3.19)$$

At the time zero, the drawdown *s* is also zero prior to pumping starts. The boundary conditions at time *t=0*, drawdown *s=0* and constant discharge from the well:

$$\lim_{r\to\infty} s = 0 \qquad (3.20)$$

$$\lim_{r\to 0} 2\pi T r\frac{\partial s}{\partial r} = -Q \qquad (3.21)$$

Theis derived solution from the equation 3.15 from the initial and given the boundary condition (Equation 3.20) and (Equation 3.21) which is expressed as follows (Renard P. , 2006):

$$s = \frac{Q}{4\pi\, T}\int_{0}^{\infty}\frac{r^2 S}{4tT} \qquad (3.22)$$

This Equation (3.22) express drawdown with time and space including an aquifer's storativity *S* and transmissivity *T*.

3.4 Pumping Test

The pumping test is used to determine the properties of groundwater aquifer such as hydraulic conductivity, transmissivity, storativity, etc. The pumping test analysis is referring tool to determine coefficients of an aquifer assuming a homogeneous and an isentropic aquifer composition, the pumping rate is constant and well radius is very small (Renard P. , 2006). The method of estimating aquifer parameters for a confined and an unconfined aquifer are described in next chapter.

Fokker et al. (2013) studied well permeability and compressibility in the heterogeneous aquifer with periodic pumping test in which expeltion and recharge are applied in a periodic way. The advantage of this method is that the operation is not interrupted in the test using Fourier analysis. An effective 2D geologic feature can be obtained with the log data. This intra-well periodic estimation express proper geologic feature of the reservoirs without interrupting production. Butler Jr & Liu (1991) described semi-analytical linear infinite model for the pumping test with integral transformation. This integral transformation revealed that at higher transmissivity; a matrix, a liner and a bilinear flow patterns are major indication in the pumping test and if the matrix properties are not high than radial flow, is the primary flow indication. Pechsteinet al. (2016) estimate non-uniform tramsnissivity distributed in a confined aquifer using single well pumping. This estimation indicates that homogeneous aquifer is not assumed for heterogenous aquifer rather than upscaling of a heterogenity domain is better for interpretation of the pumping test.

The quality of well is estimated while comparing real well with ideal well parameters but this comparision may lead to increase or decrease the perfomarnce of real well. This stimulation and damage is evaluated by skin factors. The resistance as the pressure drops due to the skin of real well (composotion and peroperties of soil arround real well). These additional resistances and wellbored storage affects pumping test at real well. The pressure drop is due to resistance formation, viscosity of liquid, skin zone and the additional resistance concentrated arround the real well (Van Everdingen, 1953 & Pech, 2004).

3.5 Additional Resistances

In general, it is assumed that well penetrates through-out the thickness of an aquifer but it does not happen in actual condition. Well is partially penetrating into an aquifer with a finite thickness of the skin. Well-bore has also some diameter which allows to store water in well-bore. This well-bore delay the movement of water to entre in the well from an aquifer. In addition to this effect the damaged or the material left during drilling of well, affects water movement which is called as skin effect (Moench, 1985). While drilling well-bore, mud accumulates around well screens which alter permeability around the well walls with compare to the surrounding aquifer. According to altered permeability, skin effect can be positive or negative (Chen & Chang, 2006). Hence, it is assumed that well-bore strage and skin are insignificantly thin for pumping, observation well and skin has no storativity to be convineint for methemetical solution (Pasandi et al., 2008). Another assumption is the homogenity of porous surrounding skin which is used in constant rate of pumping and it does not discontinue head at the opening of drilled well (Chen & Chang, 2002).

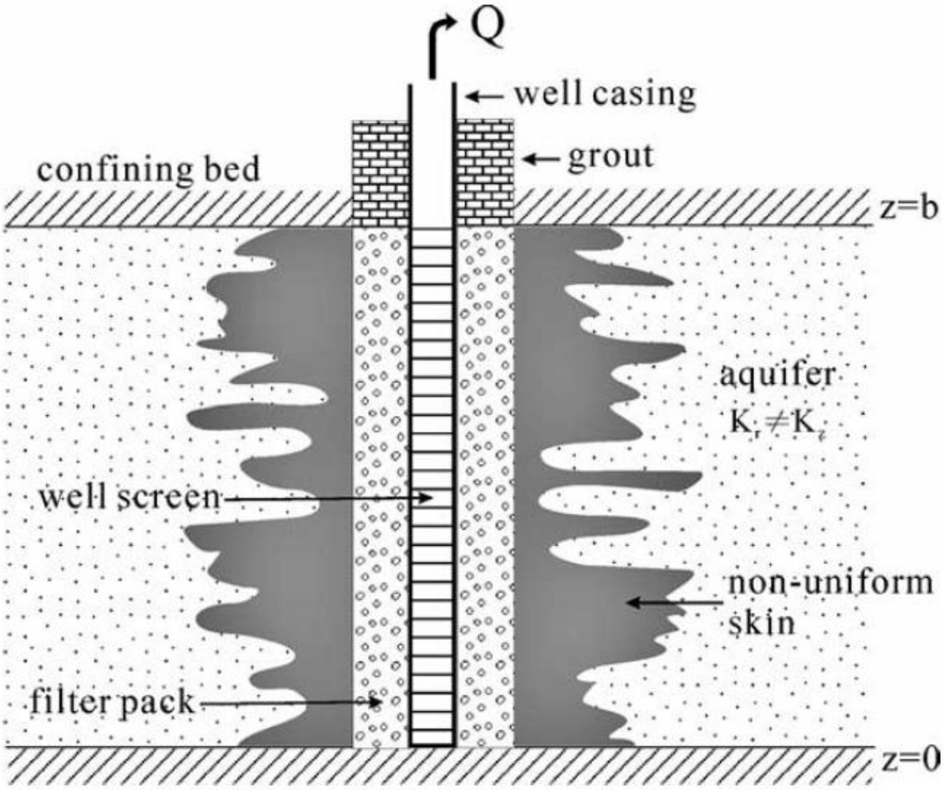


Figure 3.8 Schematic diagrame of skin arround well (Chen & Chang, 2006; p:192)**.**

Figure 3.8 shows the non-homogeneous skin around the well screens and packing and construction material to build well. The estimation of these all resistances is very hard and it may contain many errors. All these resistances togather can be evaluated by comparing actual test with an ideal well conditions which provides overall additional resistances.

4. Materials and Methods

This chapter starts with a research proposal, a description of study area, measurements and equipment, various methods for the pumping test and the additional resistances estimations.

4.1 Research Plan

The pumping test is to be carried out for a pumping well in the research area. For this test, a large number of observations were collected in February, 2015 from a pumping well and an observation well.

Data collection from pumping well as well as observation were primarily significant task for actual results. In this data collection: date and time, head, draw-down and discharge were measured for pumping well. The sheet for data collection for the pumping well is shown in following Table 4.1.

Sr. No.	Date and Time	Time, t [m]	H_{logger} [m]	H_{logger} [m from O.B.]	s[m] - pumping well	$H_{manually}$[m from O.B.]	Q_{RD2}[l/s]
1							

Table 4.1 Formats for taking observation from pumping well.

The observed data is collected to evaluate the storativity and the transmissivity. To estimate this parameters following observations were conducted for observation well shown in Table 4.2

Sr. No.	Date and Time	Time, t [m]	H_{logger} [m]	H_{logger} [m od O.B.]	s[m] - pumping well	H_{Manual} [m od O.B.]
1						

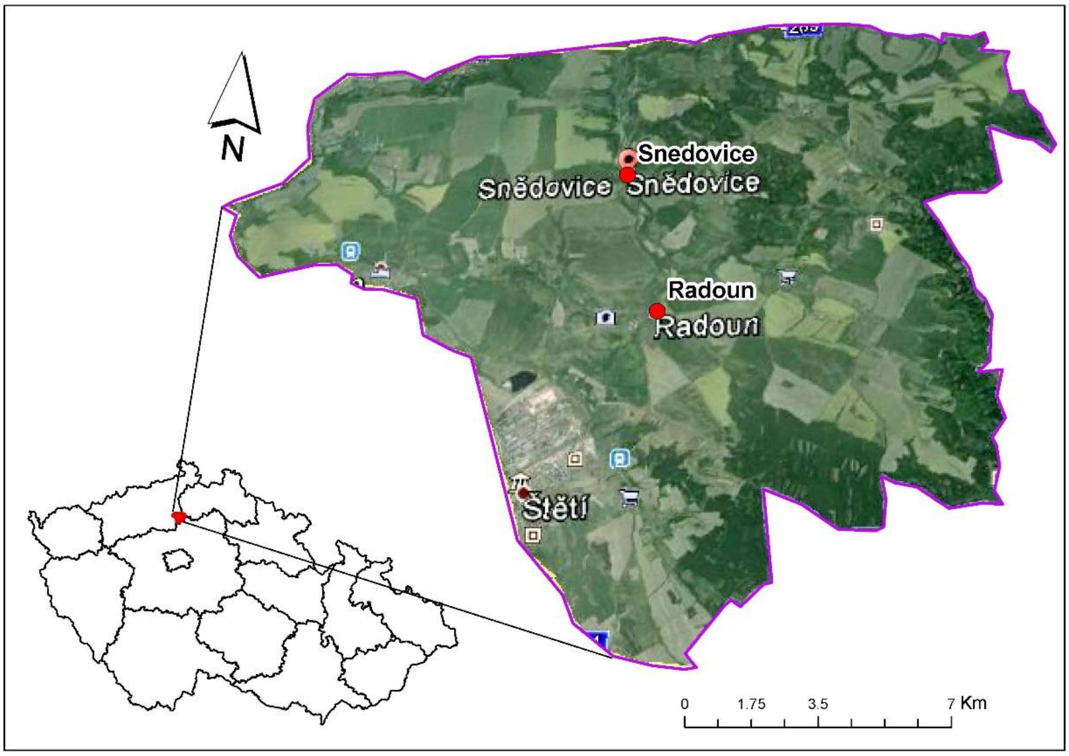
Table 4.2 Formats for taking observation from observation well.

4.2 Research Area

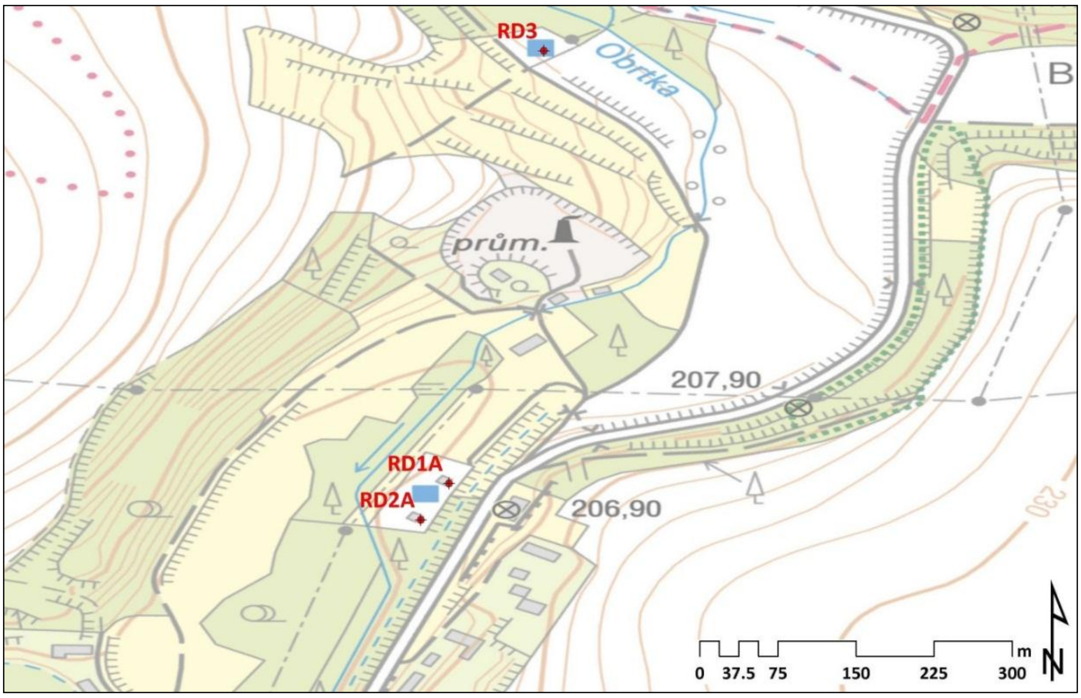
The study area is situated at the North of Czech Republic called Snedovice in the district of Usti nad Labem. The well is located in Radoun near Snedovice. The well was built in 1975. The construction details of well is shown in following Table 4.3.

Construction year	1975
Depth of well	50 m
Diameter of well	630 mm
Perforation of well screen	15 – 48.2 m
Casing of well in 1993	PVC
Water Level at time of measurement (27.02.2015)	4.08 m

Table 4.3 Construction details of pumping well.



(a) Location of study area.



(b) Pumping Site

Figure 4.1 (a) Location of study area in Czech Republic and (b) Location of bumping site RD2A in RADOUŇ region

Initially, the steel arm was inserted of 630 mm diameter, it is being corroded gradually but it is still functioning. The sludge and other foreign material is collected below the depth of 16.65 m from ground in a column. It is recommended that this well should be clean for proper functioning.

4.3 Measurements of parameters

Before collecting the data, there should not be any open zone near pumping well, pumping and observation wells must be inserted in the same groundwater reservoir. The recordings inside the well are done by downhole recorders. Initially, the pressure and the temperature are recorded using pressure gauge. Wireline link is used to measure surface pressure. The drawdown can be measured with direct push method using small diameter pressure transducer. Transducer is useful due to less expensive and less time consuming process. This direct push method does not use cable movement. Instead of this, polythene tube is used to insert transducer which measures air pressure above the water column in the existing tube (Butler et. al., 2002). Figure 4.2 shows the plot of pumping test in general using pressure transducer.

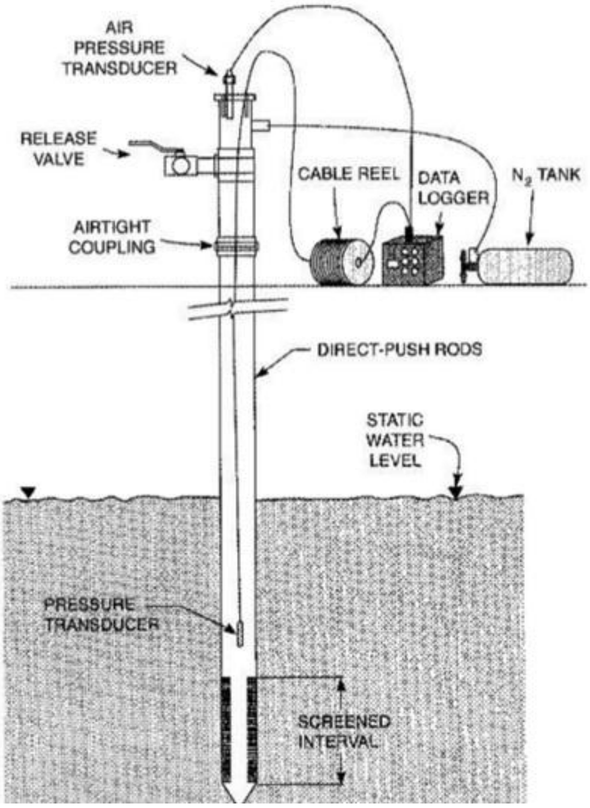


Figure 4.2 Schematic diagram to measure drawdown with pressure transducer (Butler et. al., 2002).

For water level measurement, a floating steel tape is also used with electronic sounder and pointer. Automatic recorder is generally used for measuring the water level in an observation well because the water level changes quickly at the initial period of test (Dalton et. at., 1991).

4.4 Methods to Evaluate Pumping Test

Groundwater is pumped out through well and the response of a pumping well is observed by an observation well which gives drawdown of hydraulic head. The soil around the pumping well creates resistance to flow, a head-loss forms depression and creates hydraulic gradient to occur flow. This depression is known as cone of depression. The drawdown of a hydraulic head is used to characterise the hydraulic characteristics of an aquifer including the storage co-efficient or the storativity (S), hydraulic conductivity (K) and the transmissivity (T). The storativity is the volume of water released at unit decline in a hydraulic head per unit area of a surface of the aquifer, the hydraulic conductivity is the rate of flow under unit hydraulic gradient and the transmissivity is the rate of flow at unit hydraulic gradient through unit width of cross-section of the aquifer. The pumping test depends on flow (steady state or unsteady state flow) of water and types of aquifers from which water is pumped.

4.4.1 Pumping Test for Steady-State Slow

The groundwater flow properties do not change over time but in general, it does not exit. The well is fully penetrating through a confined aquifer and water flow out radially with time. Water is pumped out from the storage in the aquifer which tends to occur only unsteady-state flow. In practice, the flow is considered steady-state due to negligible change in drawdown with time.

4.4.1.1 Confined Aquifers –Thiem Analysis

The confined aquifer is overlain by impermeable layers of rocks and clay. The groundwater exists in the confined aquifer are under high pressure than atmospheric pressure. The assumptions and conditions for the pumping test for a steady-state flow are as follows:

a) The aquifer is confined from both sides.

b) The aquifer has infinite aerial extent. Cone of depression does not increase with time.
c) The aquifer is homogeneous, isotropic and of uniform thickness.
d) The piezometric surface is horizontal prior to pumping.
e) Water flows radially towards well.
f) Darcy’s law is valid.
g) The groundwater level changes due to only pumping.
h) The density and the viscosity of groundwater do not change in space and time.
i) The aquifer is pumped at a constant discharge rate.
j) The well penetrates to the full thickness of an aquifer and thus, receives water by horizontal flow (see Figure 4.3)

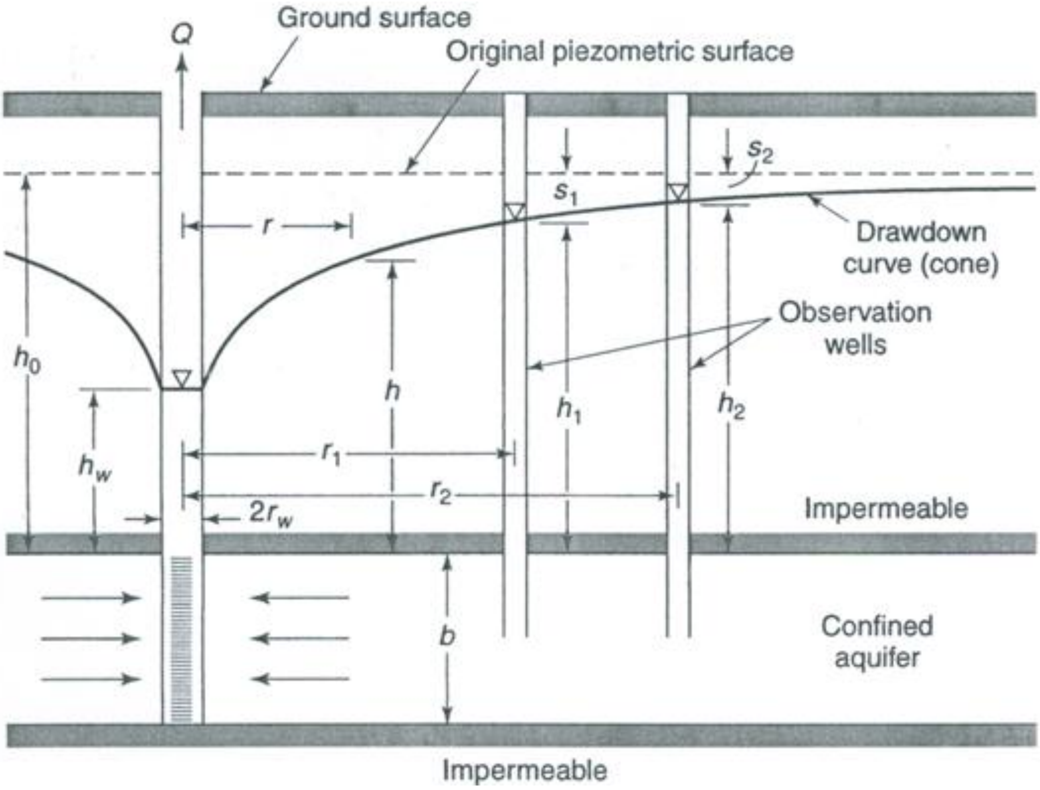


Figure 4.3 Cross-section of a pumped confined aquifer (Todd & Larry, 1980).

The pumping well is fully penetrated through a confined aquifer. It has steady state condition where rate of water pumping (Q) is equal to the water enters to the well. The continuity equation for a steady state flow and Darcy’s law for the above condition:

Continuity Equation $Q = v_r \cdot A$ *(4.1)*

$$A = 2\pi rb$$

$$\text{Darcy's Law} \quad v_r = -K\left(\frac{\partial h}{\partial r}\right) \tag{4.2}$$

From The equation 4.1 and 4.2

$$Q = -2\pi rbK\left(\frac{\partial h}{\partial r}\right)$$

Where, Q is the pumping rate or well discharge, r is the radial distance from pump to circular section, b is the thickness of a confined aquifer, A is the cross-section area in the direction of flow in an aquifer, K is the hydraulic conductivity and $\partial h/\partial r$ is the hydraulic gradient.

Rearranging the equations while considering two observation wells with hydraulic head of h_1 and h_2 at a distance of r_1 and r_2 from pumping well (Figure 4.3).

$$\frac{Q}{2\pi Kb}\int_{r_1}^{r_2}\frac{1}{r}dr = \int_{h_1}^{h_2} dh$$

$$h_2 - h_1 = \frac{Q}{2\pi Kb} ln\frac{r_2}{r_1} \tag{4.3}$$

$$s_1 - s_2 = \frac{Q}{2\pi Kb} ln\frac{r_2}{r_1} \tag{4.4}$$

$$T = Kb = \frac{Q}{2\pi(s_1 - s_2)} ln\frac{r_2}{r_1} \tag{4.5}$$

Where, s_1 and s_2 are drawdowns and T is the transmissivity.

Thiem equation at equilibrium shows that the drawdown varies with logarithm of the distance from the pumping well to the observation well.

4.4.1.2 Unconfined Aquifers

An aquifer of water is bounded with impermeable or an aquiclude at the bottom is known as the unconfined aquifer. The conditions and the assumptions for an unconfined aquifer are as follows:

a) The aquifer is an unconfined.

b) The aquifer has the infinite aerial extent,

c) The aquifer is a homogeneous, an isotropic and consists of uniform thickness,

d) The water table is horizontal prior to pumping,

e) An aquifer is pumped at the constant discharge rate,

f) The well penetrates the full thickness of the aquifer and thus receives water from the entire saturated thickness of the aquifer (see Figure 4.4)

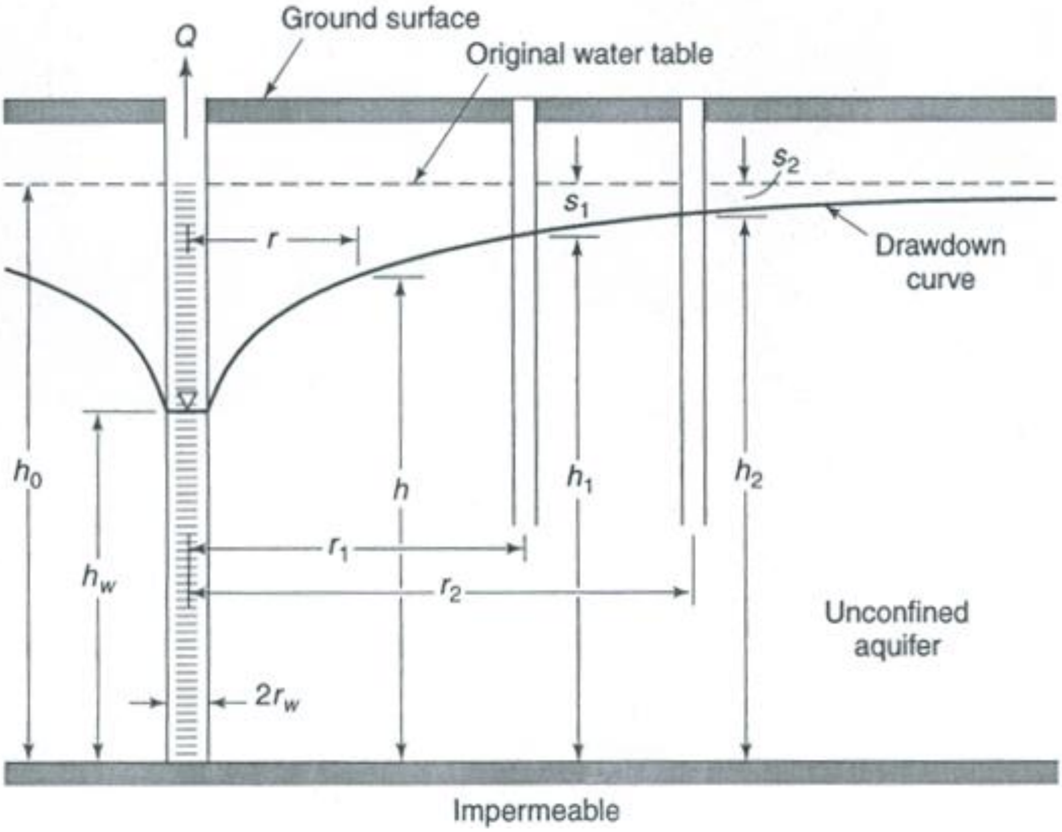


Figure 4.4 Cross-section of a pumped unconfined aquifer (steady-state flow)
(Todd & Larry, 1980).

The continuity equation for steady state flow and Darcy's law for the above condition:

Continuity Equation $Q = v_r \cdot A$ Darcy's Law $v = -K\frac{\partial h}{\partial r}$

From the equation 4.1 and 4.2 … $Q = -2\pi rhK\frac{\partial h}{\partial r}$

Rearranging the equations

$$\frac{Q}{2\pi Kb}\int_{r_1}^{r_2}\frac{1}{r}dr = \int_{h_1}^{h_2} dh$$

$$h_2{}^2 - h_1{}^2 = \frac{Q}{2\pi Kb} ln\frac{r_2}{r_1} \quad (4.6)$$

Where, r_1 and r_2 are the distance from pumping well to observation well, h_1 and h_2 are the hydraulic heads of observation wells, A is the cross-section area in the direction of flow in aquifer, Q is the discharge and K is the hydraulic conductivity.

4.4.2 Pumping Test for Unsteady-State Slow

Pumping water at the constant rate from a well penetrating in to an aquifer and water is pumped out from the aquifer storage due to reduction in the piezometric head. Removing water from well causing drawdown in the piezometric head is continuous process resulting in enlargement of influential radius. Thus, the steady-state flow cannot be occurred in above conditions. For an unsteady state flow which is defined in a confined and an unconfined aquifer. Theis method and Jacob’s method are used to observe an unsteady-state flow in a confined aquifer which are described further.

4.4.2.1 Confined Aquifer- Theis Method (Unsteady-State flow)

Water is pumped out at the constant rate through a well penetrating in an extensive confined aquifer, the radius of influence expands with time due to discharge. The general equation of an unsteady-state flow for a confined aquifer (Mutreja, 1986, p:396):

$$\nabla^2 h = \frac{S}{T}\frac{\partial h}{\partial t} \quad (4.7)$$

Where S is the storativity, T is the transmissivity and h is hydraulic head.

The differential equation can be re-write as

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S}{Kb}\frac{\partial h}{\partial t} \quad (4.8)$$

Polar coordinates for plane is reduced to

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (4.9)$$

Where T is transmissivity, t is the time since pumping starts, b is the thickness of confined aquifer, K is hydraulic conductivity and S is the storage coefficient. Theis presented solution of the equation 4.9 as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial h}{\partial r}\right) = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (4.10)$$

This equation can also be expressed in terms of the drawdown (s) as below:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial s}{\partial r}\right) = \frac{S}{T}\frac{\partial s}{\partial t}$$

Theis (1935) solved the non-equilibrium flow equations in radial coordinates based on the analogy between groundwater flow and heat condition. The initial drawdown (s) in observation well at time (t) after pumping starts at a radial distance from pumping well (r) is obtained as follows (Xiong et. al., 2013, p: 352).

$$s(r,t) = \frac{Q}{4\pi T}\int_u^{\infty}\frac{e^{-u}}{u}\,du \qquad (4.11)$$

The equation 4.11 is known as well function and can be re-written as:

$$W\ (u)\ = \int_u^{\infty}\frac{e^{-u}}{u}\,du \qquad (4.12)$$

$$u = \frac{r^2 S}{4Tt} \qquad (4.13)$$

where S is the ativity which is dimensionless and $W(u)$ is the Theis well function and u is the dimensionless parameter of well function. Taking logarithms and rearranging these equations gives

$$\log s = \log[W(u)] + \log\left(\frac{Q}{4\pi T}\right) \qquad (4.14)$$

And,

$$\log t = \log\left(\frac{1}{u}\right) + \log\left(\frac{r^2 s}{4T}\right) \qquad (4.15)$$

There are some assumptions and conditions to apply Theis method, describes as follows:

a) The potentiometric surface is approximately horizontal before pumping begins (No slope).

b) Darcy's equation is valid

c) Storativity (S) and Transmissivity (T) are constant in time and space.

d) The aquifer is a confined.

e) The aquifer is a homogeneous and an isotropic of uniform thickness over the area influenced by pumping.

f) The well is pumped at a constant rate,

g) The well is fully penetrating in a confined aquifer.

h) Water removed from storage is discharged instantaneously with decline in head.

i) The well diameter is small so that well storage is negligible.

The Data Required for the Theis Solution are

a) The drawdown vs. time data at an observation well.

b) Distance from the pumping well to an observation well.

c) The pumping rate of the well.

The procedure for finding parameters by Theis Method

a) On log-log paper, plot a graph of values of s_w against t measured during the pumping test.

b) Theoretical curve $W(u)$ versus $1/u$ is plotted on a log-log paper. This can be done using tabulated values of the well function). ready printed type curves are also available (see Figure 4.5).

c) The field measurements are similarly plotted on a log-log plot with (t) along the x-axis and (s_w) along the y-axis (see Figure 4.7).

d) Keeping the axes correctly aligned, superimposed the type curve on the plot of the data (i.e. The data analysis is done by matching the observed data to the type curve).

e) Select any convenient point on the graph paper (a match point) and read off the coordinates of the point on both sets of axes. This gives coordinates $(1/u, W(u))$ and (t, s_w) (see Figures 4.8).

f) Use the previous equations to determine T and S.

The points on the data plot corresponding to early times are the least reliable.

N.B. The match point doesn't have to be on the type curve. In fact, calculations are greatly simplified if the point is chosen where $W(u) = 1$ and $1/u = 10$.

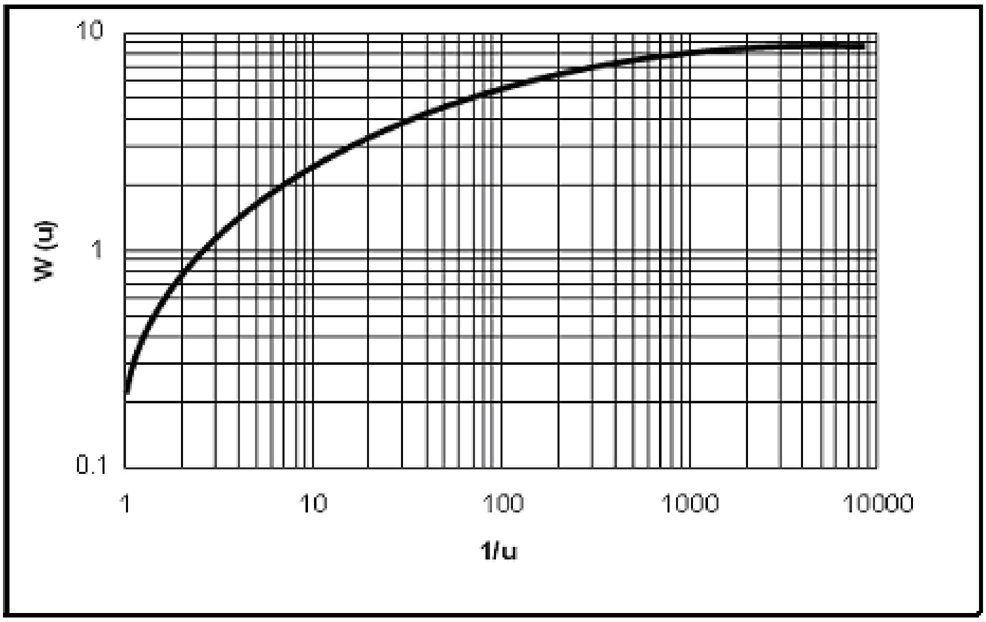


Figure 4.6 The non-equilibrium reverse type curve (Theis curve) for a fully confined aquifer

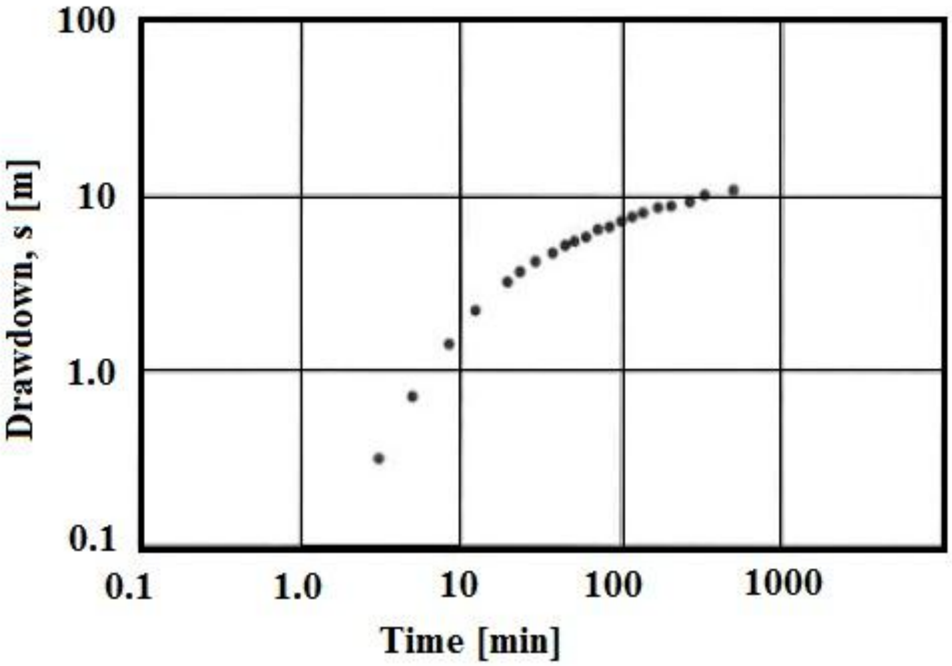


Figure 4.7 Field data plot on logarithmic paper for Theis curve-marching technique

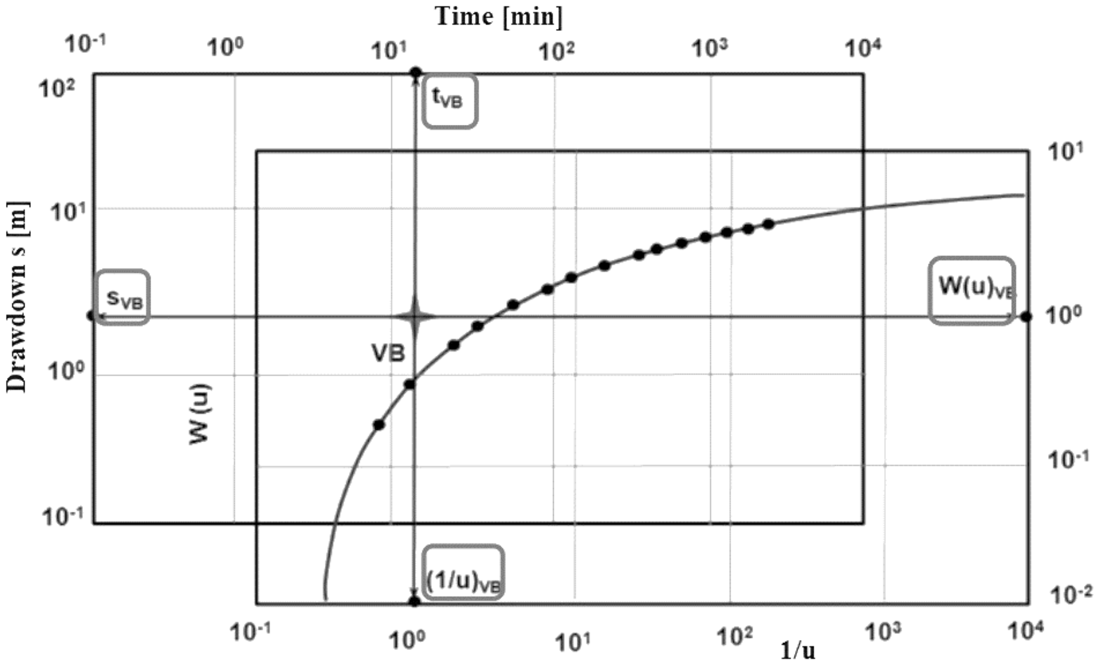


Figure 4.8 Match of field data plot to Theis Type curve.

The transmissivity (T) and the storativity (S) can be estimated from the below equations using Figure 4.8.

$$T = \frac{Q}{4\pi s_{VB}} W(u)_{VB} \qquad \text{and} \qquad S = \frac{4\,T\,u_{VB}\,t_{VB}}{r^2}$$

The overlapping of two curves will give less weightage to the data of early part in the development on the curve. At the starting, the is time lag between pumping starts and discharge of stored water. Thus discharge from the pumping well might be influenced and it would be settled by adjusting head. However, pumping continue and this influential factors are minimised with time.

4.4.2.2 Confined Aquifer- Jacob Method (Unsteady-State flow).

The Theis method is criticised due to subjective procedure for evaluation of aquifer characteristics. The Jacob method is consistent and calculate T and S for pumping well by one observation well (Cooper & Jacob, 1946). The analysis presented here is of a pumping test in which drawdown at a piezometer distance, r from the abstraction well is monitored over time. This is also based upon the Theis analysis.

W(u) (equation 4.12) can be expressed by Taylor's series expansion:

$$W\,(u) = -0.577 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} + \cdots \qquad (4.16)$$

$$s = \frac{Q}{4\pi T}\,W(u) = \frac{Q}{4\pi T}\,(-\,0.577 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \ldots) \qquad (4.17)$$

From $u = \frac{r^2 S}{4Tt}$, it will be seen that u decreases ($u \leq 0.01$) as the time of pumping increases and as the distance of the piezometer from the well decreases. So, for piezometers close to the pumping well after sufficiently long pumping times, the terms beyond $\ln u$ become negligible. Hence for small values of u, the drawdown from equation 4.17 can be approximated by:

$$W(u) \approx \ln \frac{0.562}{u}$$

$$h_0 - h_1 = s = \frac{Q}{4\pi T}\,\ln \frac{0.562}{u}$$

$$= \frac{Q}{4\pi T} ln\left(\frac{2.25T}{Sr^2} t\right) \qquad (4.18)$$

The equation 4.18 has transmissivity (T) at multiple location so that transmissivity (T) can be derived though manipulation of equation 4.18. Thus, drawdown s vs t on log graph gives straight line (Figure 4.9).

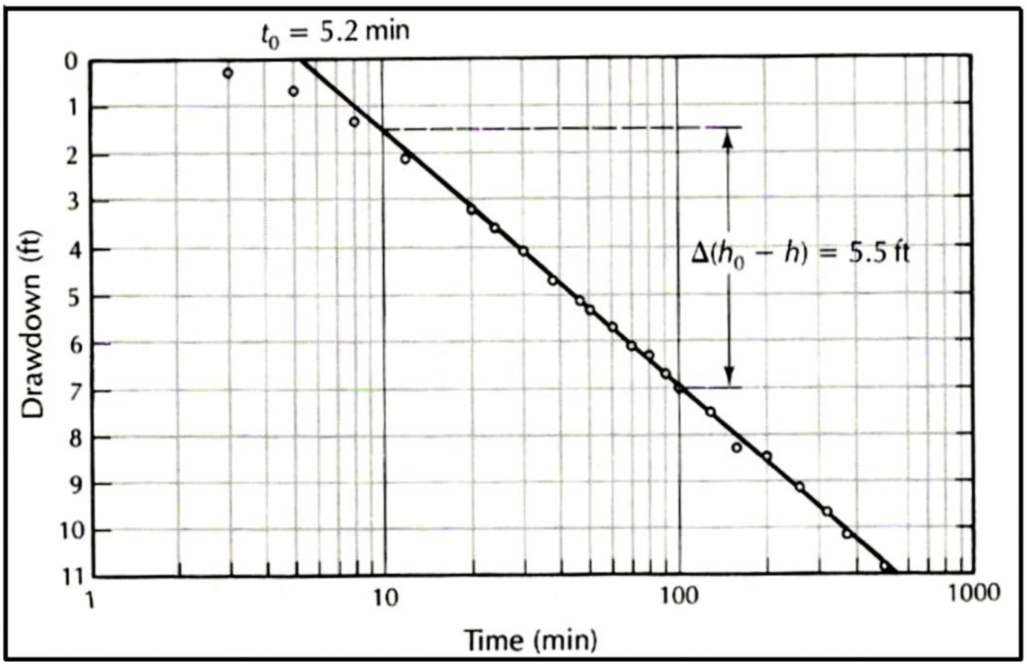


Figure 4.9 Jacob method of solution of pumping-test data for a fully confined aquifer. Drawdown is plotted as a function of time on semi-logarithmic paper.

The slope of this semi-log graph (Figure 4.9) will give head difference over logarithmic time. The equation 4.19 is line equation and the slope of build-up semi log graph is expressed in the square brackets:

$$s = \frac{2.3\,Q}{4\pi T}\left[log\, t + log\left(\frac{2.25\,T}{Sr^2}\right)\right] \qquad (4.19)$$

s=$m.\,t$ +b, Where $m = \frac{2.3\,Q}{4\pi T}$

Now, at different drawdown (s) can be expresses as below for time t_1 and distance r_1:

$$s_1 = \frac{Q}{4\pi T} ln \frac{2.25T}{r_1^2 S} t_1$$

$$= \frac{Q}{4\pi T} ln t_1 + \frac{Q}{4\pi T} ln \frac{2.25T}{r_1^2 S} \qquad (4.20\ a)$$

For the distance r_2 form pumping well at time t_2 can be expressed as below:

$$s_2 = \frac{Q}{4\pi T} ln \frac{2.25T}{r_2^2 S} t_2$$

$$= \frac{Q}{4\pi T} ln t_2 + \frac{Q}{4\pi T} ln \frac{2.25T}{r_2^2 S} \qquad (4.20\ b)$$

It is a straight line equation and therefore (Equation 4.20 a and 4.20 b),

$$\Delta s = s_1 - s_2 = \frac{Q}{4\pi T} ln \frac{t_1}{t_2}$$

$$\Delta s = s_1 - s_2 = \frac{2.3Q}{4\pi T} log \frac{t_1}{t_2} \qquad (4.21)$$

Note: Jacob method is valid for $u \leq 0.05$ or 0.01, t is large, r is small.

It follows that a plot of s against $log\ t$ should be a **straight line** (see Figure 4.9). Extending this line to where it crosses that t **axis** (i.e. where **s is zero** and $t = t_o$) gives

$$S = \frac{2.25T}{r^2} t_0 \qquad (4.22)$$

The gradient of the straight line (i.e. the increase per log cycle, Δs) is equal to

$$\Delta s = \frac{2.3\ Q}{4\pi T} = \frac{0.183\ Q}{T} \Rightarrow T = \frac{0.183\ Q}{\Delta s} \qquad (4.23)$$

At first T is calculated (Equation 4.23) then s can be calculated from the equation 4.22 by using T and t_0.

4.4.3 Additional Resistances

The additional resistances can be evaluated to compare resulted values of the pumping well in actual condition with ideal condition. The total drawdown can be evaluated from the below equation:

$$s_W = \frac{Q}{4\,\pi\,T}\,(\ln\frac{2.25\,T\,t}{r_W^2\,S} + 2W) \tag{4.24}$$

Where, s_w is the drawdown in m, T is the transmissivity, S is the storativity, r_w is the radius of pumping well in m and W is the additional resistances. The additional drawdown caused by the skin factor is expressed as below:

$$s_{skin} = \frac{Q}{2\,\pi\,T}\,W \tag{4.25}$$

The additional drawdown differences between before and after cleaning of well can be evaluated as below:

$$s_{skin\ldots before} - s_{skin\ldots after} \tag{4.26}$$

5. Results

In both cases of pumping test before cleaning and after cleaning of well, Drawdown was recorded at constant discharge rate (Q) with time (t).

5.1 Pumping test Before Well Cleaning

For the pumping test before cleaning of well, the drawdown recording was conducted for approximately 2 hours and 30 minutes in pumping well. This data was recorded in February (2015). The recordings are shown in the Table 5.1 for an example.

Date and time	**Time t, [min]**	**Logt [min]**	**H_{logger} [m]**	**H_{logger} [m from O.B.]**	**Drawdown s, [m]**	**H_{Manual} [m from O.B.]**	**Q_{RD2} [l/s]**
21-2-2015 12:03:17	0.00		11.38	0.63	**0.00**	0.625	0
21-2-2015 12:03:18	0.02	**-1.78**	10.75	1.26	**0.63**		14.8
21-2-2015 12:03:19	0.03	**-1.48**	11.40	0.60	**-0.03**		14.8
21-2-2015 12:03:20	0.05	**-1.30**	11.40	0.61	**-0.02**		14.8
21-2-2015 12:03:21	0.07	**-1.18**	11.36	0.64	**0.02**		14.8
21-2-2015 12:03:22	0.08	**-1.08**	11.35	0.65	**0.03**		14.8
21-2-2015 12:03:23	0.10	**-1.00**	11.33	0.67	**0.05**		14.8
21-2-2015 12:03:24	0.12	**-0.93**	11.29	0.71	**0.09**		14.8
21-2-2015 12:03:25	0.13	**-0.88**	11.25	0.75	**0.12**		14.8
21-2-2015 12:03:26	0.15	**-0.82**	11.21	0.79	**0.17**		14.8
21-2-2015 12:03:27	0.17	**-0.78**	11.17	0.84	**0.21**		14.8

21-2-2015 12:03:28	0.18	**-0.74**	11.12	0.88	**0.25**		14.8
21-2-2015 12:03:29	0.20	**-0.70**	11.08	0.92	**0.29**		14.8
21-2-2015 12:03:30	0.22	**-0.66**	11.04	0.96	**0.33**		14.8
21-2-2015 12:03:31	0.23	**-0.63**	11.01	0.99	**0.37**		14.8

Table 5.1 Drawdown measurement in pumping well before cleaning of well.

The measurement of whole test duration for a pumping well before well cleaning is shown in Figure 5.1. The graph of the drawdown vs time was plotted on semi-log graph.

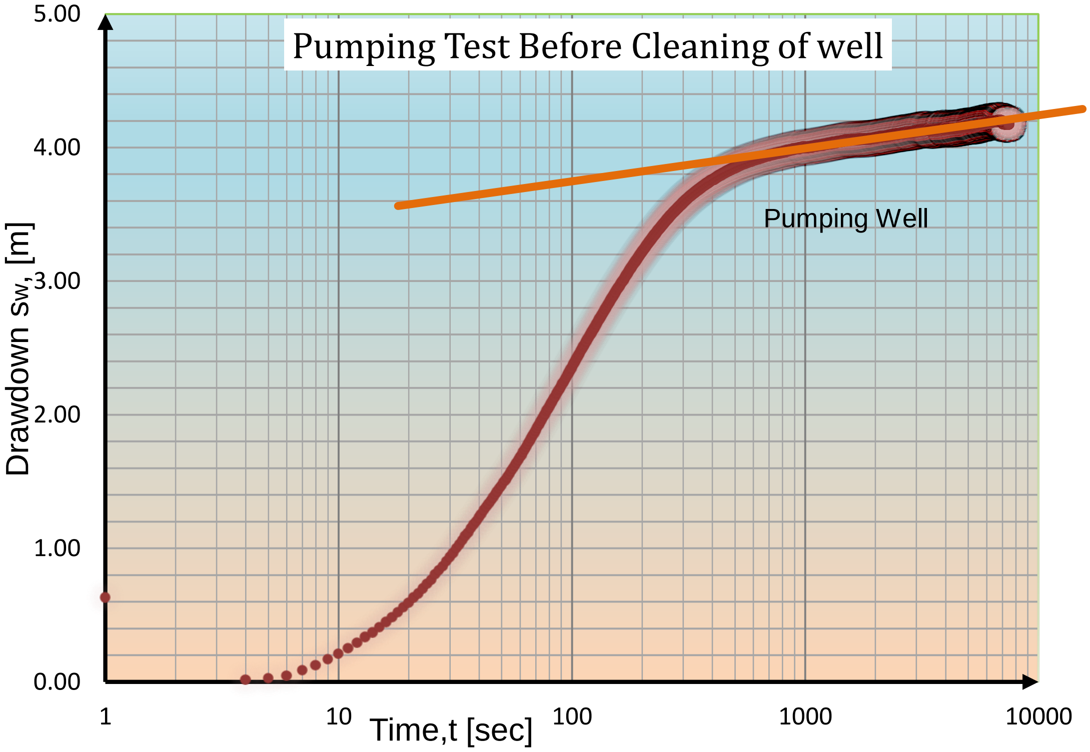


Figure 5.1 Drawdown (s_W) vs Time (t) in pumping well before cleaning of well.

The straight line is plotted in the graph to obtain straight line equation (Figure 5.1). the equation of this straight line is shown below:

$$s_w = 0.0948 ln(t) + 3.3524 \tag{5.1}$$

The same drawdown test was conducted in observation well located 40 m from the pumping well. The readings were carried out in following format shown in Table: 5.2.

The duration of this observation was approximately 2 hours and recordings were recorded in each 20 sec time intervals. The discharge rate was same as the pumping well. The data of drawdown and time was also plotted on semi-log graph. The drawdown vs time is shown in Figure 5.2 and the straight line is plotted that is very close to the observation values in the graph. The straight line equation for an observation well is obtained as below (Equation 5.2).

$$s_w = 0.1381ln(t) - 0.4733 \qquad (5.2)$$

Date and Time	**Time t, [min]**	**Log t [min]**	**H_{logger} [m]**	**H_{logger} [m from O.B.]**	**Drawdow, s [m]**	**H_{Manual} [m from O.B.]**
21-2-2015 12:03:20	0.00		9.14	0.77	**0.00**	0.77
21-2-2015 12:03:40	0.33	**-0.48**	9.12	0.79	**0.02**	
21-2-2015 12:04:00	0.67	**-0.18**	9.08	0.83	**0.06**	
21-2-2015 12:04:20	1.00	**0.00**	9.05	0.86	**0.09**	
21-2-2015 12:04:40	1.33	**0.12**	9.01	0.90	**0.13**	
21-2-2015 12:05:00	1.67	**0.22**	8.98	0.93	**0.16**	
21-2-2015 12:05:20	2.00	**0.30**	8.96	0.95	**0.18**	
21-2-2015 12:05:40	2.33	**0.37**	8.94	0.97	**0.20**	
21-2-2015 12:06:00	2.67	**0.43**	8.92	0.99	**0.22**	
21-2-2015 12:06:20	3.00	**0.48**	8.90	1.01	**0.24**	
21-2-2015 12:06:40	3.33	**0.52**	8.89	1.02	**0.25**	
21-2-2015 12:07:00	3.67	**0.56**	8.87	1.04	**0.27**	
21-2-2015 12:07:20	4.00	**0.60**	8.86	1.05	**0.28**	
21-2-2015 12:07:40	4.33	**0.64**	8.85	1.06	**0.29**	
21-2-2015 12:08:00	4.67	**0.67**	8.84	1.07	**0.30**	

21-2-2015 12:08:20	5.00	**0.70**	8.82	1.09	**0.32**	
21-2-2015 12:08:40	5.33	**0.73**	8.82	1.09	**0.32**	
21-2-2015 12:09:00	5.67	**0.75**	8.81	1.10	**0.33**	
21-2-2015 12:09:20	6.00	**0.78**	8.80	1.11	**0.34**	
21-2-2015 12:09:40	6.33	**0.80**	8.79	1.12	**0.35**	

Table 5.2 Drawdown measurement in observation well.

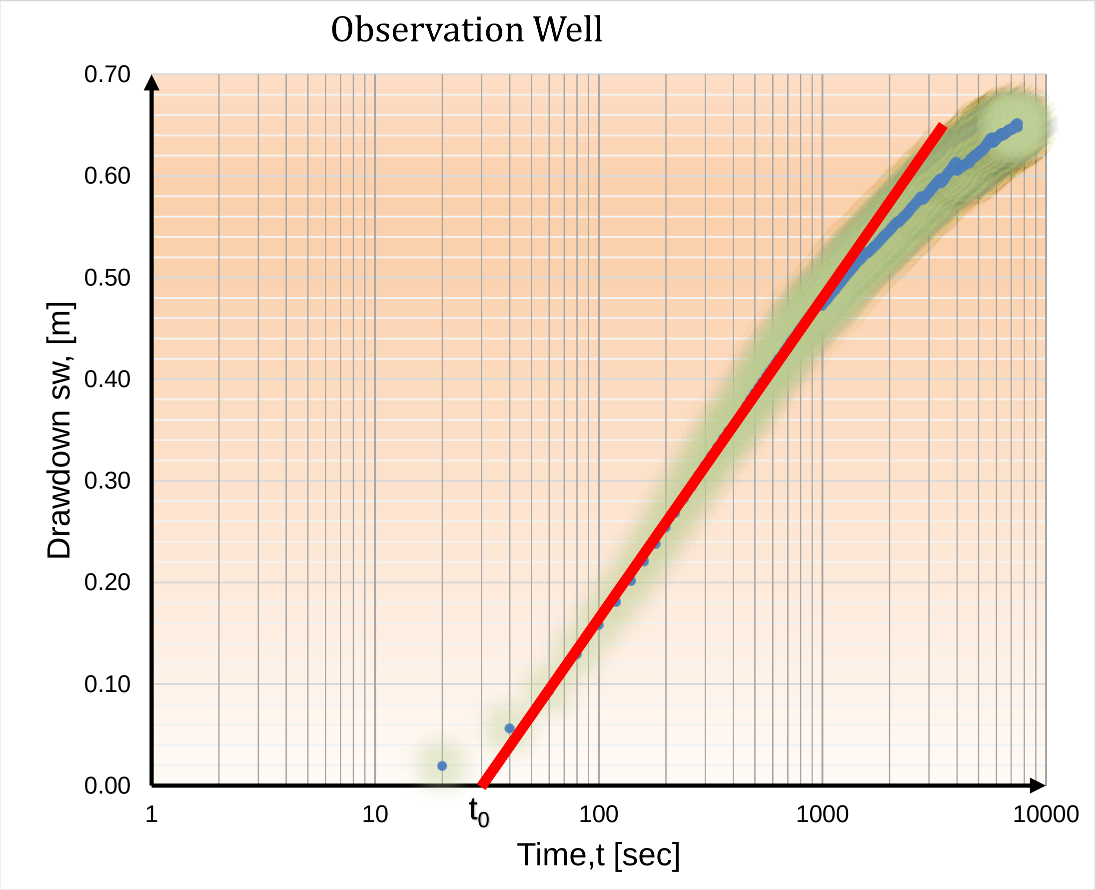


Figure 5.2 Drawdown (s_W) vs Time (t) in observation well.

From the equation 5.1 the drawdown (s_w) was calculated for the time (t) at 1000sec and 10000sec and the results are 4.00726m and 4.22554m respectively. The discharge rate was 0.0148 m^3/s. This results were used to estimated transmissivity (T) from rearranging the following equation of the drawdown (Equation 4.21):

$$\Delta s = s_1 - s_2 = \frac{2.3Q}{4\pi T} \log\frac{t_1}{t_2}$$

$$T = \frac{2.3\,Q}{4\,\pi(s_1 - s_2)}\,log\frac{t_1}{t_2}$$

The resulted transmissivity is 0.0124 m^2/s. Now, the data from observation well is used to calculate the storage coefficient or the storativity (S) and the equation for the storativity (S) is rearranged and expressed below (Equation 4.22):

$$S = \frac{2.25\,T}{r^2}\,t_0$$

The time is calculated when the drawdown (s_w) is zero with equation of straight line from observation well (Equation 5.2) and the result of time t_0 is 30.79sec. The distance of observation well to the pumping well is 40.15m (diameter of pumping well is 0.3m. The resulted storativity (S) is 0.000534.

5.2 Pumping test After Well Cleaning

The procedure for taking observations from the pumping well is the same as described as followed in the test before well cleaning. The observations were recorded in May (2015) after cleaning for the duration of approximately 2 hours with constant discharge rate of 14.2 litter per sec. The format of observation table for evaluation pumping test after cleaning of well (Table 5.3) as for example. The drawdown was recorded with a constant discharge in each second time intervals.

Date and time	**Time t, [min]**	**Logt [min]**	**H_{logger} [m]**	**H_{logger} [m from O.B.]**	**Drawdown, s [m]**	**H_{Manual} [m from O.B.]**	**Q_{RD2} [l/s]**
6-5-2015 14:19:50	0.00		9.09	0.63	**0.00**	1.26	0
6-5-2015 14:19:51	0.02	**-1.78**	9.21	1.14	**0.51**		14.2
6-5-2015 14:19:52	0.03	**-1.48**	9.07	1.28	**0.65**		14.2

6-5-2015 14:19:53	0.05	**-1.30**	9.09	1.26	**0.63**		14.2
6-5-2015 14:19:54	0.07	**-1.18**	9.07	1.28	**0.65**		14.2
6-5-2015 14:19:55	0.08	**-1.08**	9.05	1.30	**0.67**		14.2
6-5-2015 14:19:56	0.10	**-1.00**	9.02	1.33	**0.70**		14.2
6-5-2015 14:19:57	0.12	**-0.93**	8.98	1.37	**0.74**		14.2
6-5-2015 14:19:58	0.13	**-0.88**	8.94	1.41	**0.78**		14.2
6-5-2015 14:19:59	0.15	**-0.82**	8.90	1.45	**0.82**		14.2
6-5-2015 14:20:00	0.17	**-0.78**	8.86	1.50	**0.87**		14.2
6-5-2015 14:20:01	0.18	**-0.74**	8.82	1.53	**0.90**		14.2
6-5-2015 14:20:02	0.20	**-0.70**	8.78	1.57	**0.94**		14.2
6-5-2015 14:20:03	0.22	**-0.66**	8.75	1.61	**0.98**		14.2
6-5-2015 14:20:04	0.23	**-0.63**	8.71	1.64	**1.01**		14.2

Table 5.3 Drawdown measurement in pumping well before cleaning of well.

The data recorded as Table 5.3 was plotted on semi-log graph. The drawdown (s_w) vs time (t) is shown in Figure 5.3.

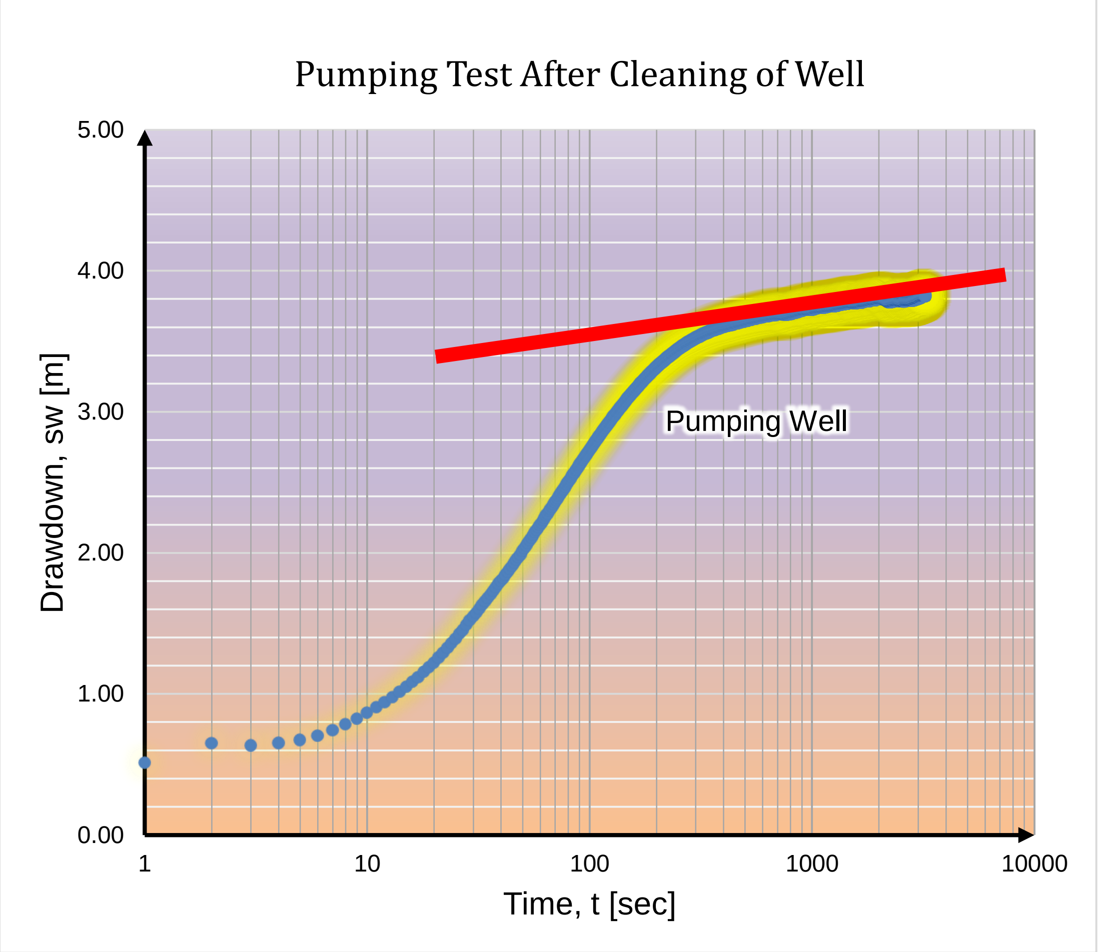


Figure 5.3 Drawdown (s_W) vs time (t) in pumping well after cleaning of well.

The equation for the straight line is obtained from the upper portion of graph (Figure 5.3) and it is expressed below:

$$s_w \;=\; 0.0909 ln(t) \;+\; 3.091 \qquad (5.3)$$

The drawdown for the time t_1 = 1000 sec and t_2 = 10000 sec were calculated from the above equation 5.3 as 3.72 m and 3.93 m respectively. The discharge rate was 0.0142 m^3/s. This results were used to estimate the transmissivity (T) from rearranging the following equation of drawdown (Equation 4.21):

$$\Delta s = s_1 - s_2 = \frac{2.3Q}{4\pi T}\, log\frac{t_1}{t_2}$$

$$T = \frac{2.3\, Q}{4\, \pi (s_1 - s_2)}\, log\frac{t_1}{t_2}$$

The resulted transmissivity is 0.01244 m^2/s. Now, storage coefficient or storativity (S) can be obtained from the same observation as explained in 5.1. The equation for storativity (S) is rearranged and expressed below (Equation 4.22):

$$S = \frac{2.25T}{r^2}\, t_0$$

The tansmissivity (T), time (t_0) and distance from observation well to pumping well (r) were the same as in 5.1. The resulted storativity (S) is 0.000534.

5.3 Additional Resistances Before Cleaning of Well

Using the Equation 4.24 without additional resistances can be expressed as equation 5.4. Again the drawdown (s_w) vs time (t) evaluated for an ideal condition using Equation 5.4 and the values of the transmissivity (T) and the storativity (S) before well cleaning. These results are plotted in graph of pumping well before cleaning and drawdown vs time graph is shown in Figure 5.4.

$$s_w = \frac{Q}{4\,\pi\,T}\,(\ln\frac{2.25\,T\,t}{r_w^2\,S}) \qquad (5.4)$$

Where, s_w is the drawdown in m, T is the transmissivity, time t, S is the storativity and r_w is the radius of pumping well in m.

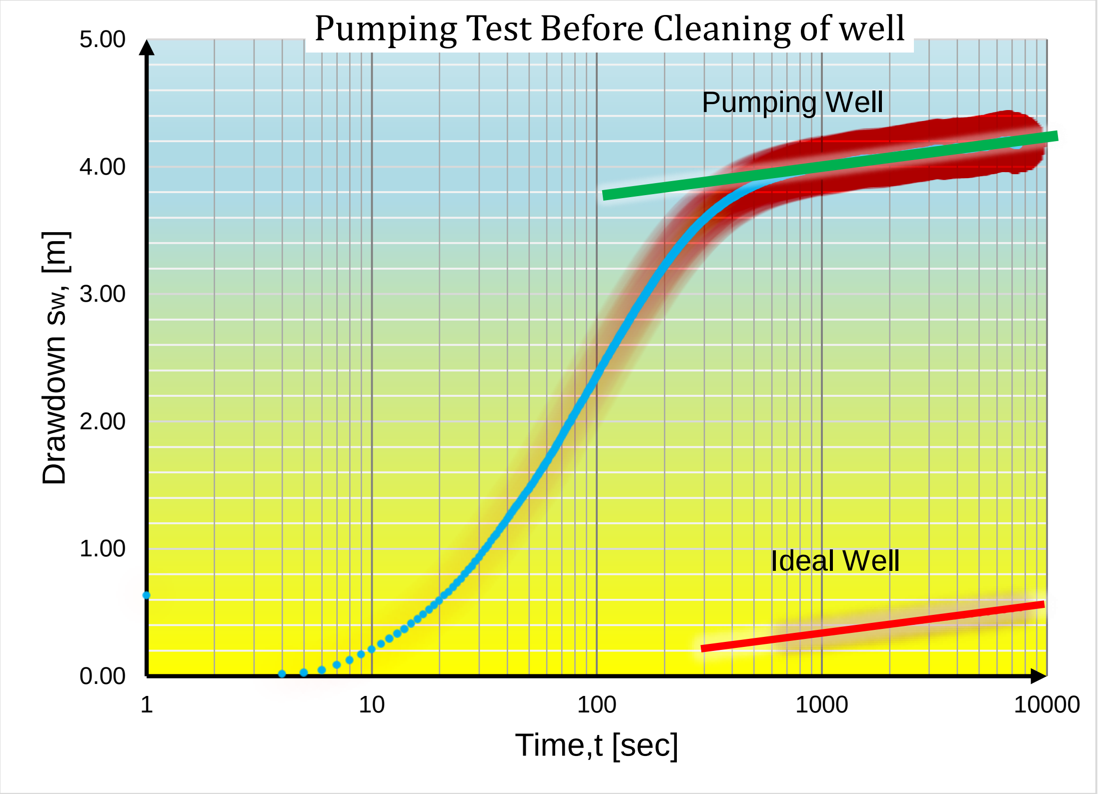


Figure 5.4 Drawdown vs time actual and ideal condition in pumping well before cleaning.

The straight line equation for ideal condition shown in Figure 5.4 is obtained as below:

$$s_w = 0.0948 \ln(t) - 0.3249 \tag{5.5}$$

The additional resistance before cleaning of well can be calculated by re arranging below equation for drawdown (Equation 4.24):

$$s_w = \frac{Q}{4\,\pi\,T}\left(\ln \frac{2.25\,T\,t}{r_w^2\,S} + 2W\right)$$

The resulted additional resistance (W) is 12.07 m. Now additional drawdown caused by skin effect can be evaluated from the Equation 4.25.

$$s_{skin} = \frac{Q}{2\,\pi\,T}\,W$$

The additional drawdown (s_{skin}) caused by the skin effect in pumping well before cleaning of well is 2.287 m.

5.4 Additional Resistances After Cleaning of Well

Using the same procedure as followed in finding additional resistance before cleaning of well is continued and the drawdown vs time for ideal condition is plotted as shown in Figure 5.6.

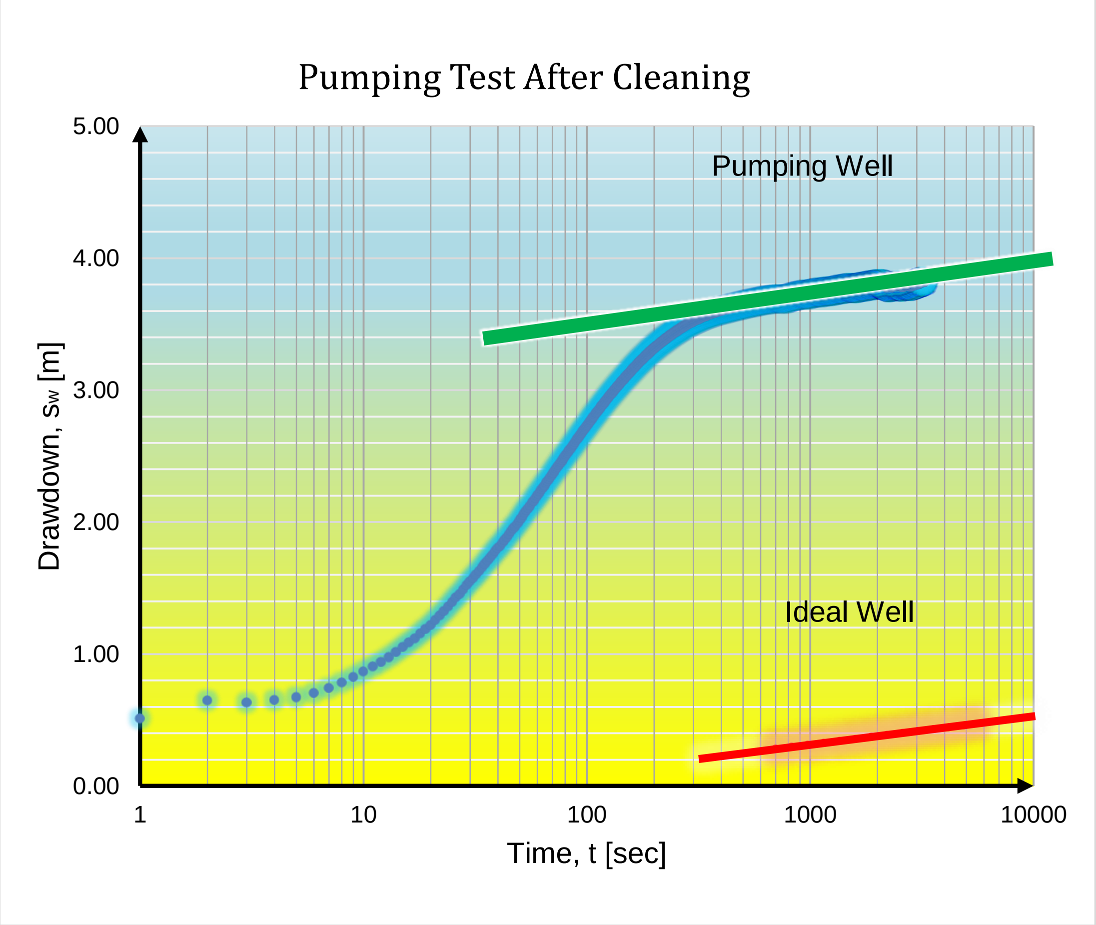


Figure 5.5 Drawdown vs time actual and ideal condition in pumping well after cleaning.

The straight line equation for ideal condition is obtain as below:

$$s_w = 0.0909 ln(t) - 0.3115 \qquad (5.6)$$

The additional resistances *(W)* is calculated for pumping well after cleaning using 5.3 procedure and the additional resistances resulted is 11.385 m. The additional drawdown (s_{skin}) caused by skin effect is calculated as 2.0699 m.

5.5 Additional Drawdown Difference Before and After Cleaning of Well

The results of the drawdown before and after cleaning of well is used to find the difference between both cases. The Additional drawdown before cleaning ($s_{skin\ bef.}$) is 2.28m and the additional drawdown after cleaning ($s_{skin\ aft.}$) is 2.07m. The additional drawdown difference between both cases of before and after cleaning is 0.218m.

6. Discussion

Pumping test is conducted for a well located at Radouň in Czech Republic. The test is carried out before and after cleaning or rehabilitation process of well. Rehabilitation process is done by removing foreign materials and applying various treatment to clean the well. The well is used for an experiment was built in 1975 and due to long duration of time, clogging occurred by clay, iron and manganese was used in construction of well as well as by sludge from surrounding walls and miscellaneous particles had fallen in the bore hole. The photograph of well cleaning or rehabilitation is shown in Figure 6.1. The rehabilitation is done to prolong well life by pumping maintenance, increase life of pipe fittings and joints. The cleaning is done by brushing the walls of well and applying pressurised water flow in well to remove foreign materials and screen cleaning.

Figure 6.1 Rehabilitation of cleaning of well at Radouň, Czech Republic

The storativity and the transmissivity are estimated before and after cleaning process has taken place. The resulted value of the storativity is 0.0005342 and 0.0005345 respectively before and after cleaning of well and the transmissivity is 0.0124298 m^2/s and 0.0124375 m^2/s respectively. The results of these estimations should be equal to each other. The transmissivity and the storativity must not be changed before and after cleaning of well due to the location of well in same aquifer. The results showed a little difference in values of both cases due to the drawdown. The data collection was done with different discharge rate in both cases and in different time segments in pumping well which causes difference between both values in before and after cleaning.

To estimate the effectiveness of rehabilitation process, the additional resistances present before and after rehabilitation process is evaluated. The additional resistances are calculated by comparing observed pumping well data with ideal well condition and the resulted additional resistances are 12.07m and 11.39m respectively before and after cleaning. The value of additional resistance after cleaning has decreased which shows the effect of rehabilitation is positive. The additional drawdowns due to skin effect before and after cleaning are 2.287m and 2.0699m respectively and the difference between these drawdowns is 0.22m. These additional resistances delay the response of drainage and pumping by lowering the drawdown.

7. Conclusion

Quantitative measurement of the storativity and the transmissivity were evaluated before and after rehabilitation process of well. The pumping test is conducted using Jacob’s method as It is simplification of Theis method. The values of storativity and transmissivity are almost similar in both the cases and the little difference is caused by the procedure of testing by different pumping rate and time intervals. Additionally, the adopted time intervals just after pumping starts and the radial distance of an observation well from pumping well may cause difference in the value impractical. The observation well placed close to the pumping well should provide clear readings of drawdown vs time and it should provide correct information of cone of depression.

The pumping test is evaluated to check and monitor the positive effect of rehabilitation process and well performance. The rehabilitation process is to remove sediments and cleaning the perforation surrounding area of bore walls. Hence, additional resistance and additional drawdown caused by skin effect are measured. The procedure used to analysis can accurately measure the parameters of well testing. The results show that drawdown is correlated with skin effect. The result of the difference of additional drawdown caused resistances before and after pumping is significant which shows that the rehabilitation process was successful. The life of well and pump can be increased by rehabilitation process.

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