Ageing and rehabilitation of water wells

Experiences from Germany

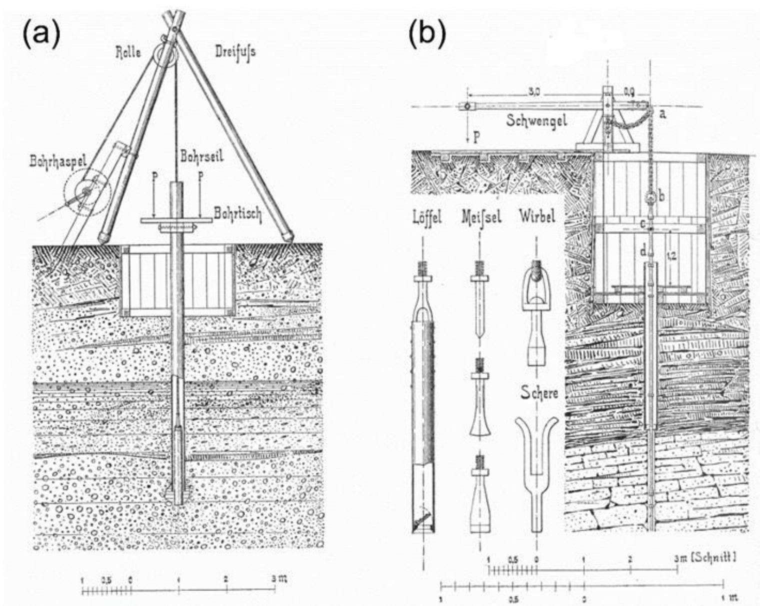
Georg Houben

Federal Institute for Geosciences
and Natural Resources (BGR)
Hannover/ Germany

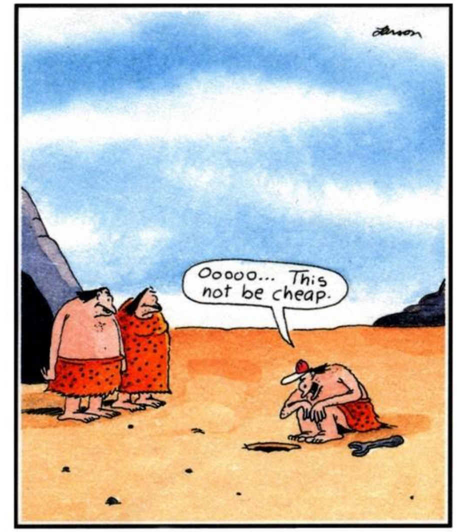
georg.houben@bgr.de

The history of wells in Germany

- oldest wells: more than 7000 years old (5,260 BC), up to 13 m deep, wooden
- prior to industrial revolution:
  - Erfurt: 45,000 people, 700 wells (64:1)
  - Hagen: 26,000 people, 1,380 wells (19:1)
  - Bielefeld: 30,000 people, 2,000 wells (15:1)
  - Oldenburg: 18,400 people, 2,000 wells (9:1)
- Berlin 1802: 48 master drillers



(Grahn 1902; Lueger & Weyrauch 1914; Houben 2019; Der Spiegel)



early well rehabilitation

The history of well cleaning

Example Duderstadt

- 18 public wells in 1728, one serving 30-40 members of “well neighborhood”
- in 1518 city introduced mandatory well cleaning, interval of two to three years
- cleanings taken as occasion for “well cleaning fest”
- 5 barrels beer served free of charge during festivity, caused *“…on the one hand much exuberance, fighting and desecration of the holy days, on the other hand also the ruin of citizens and neighbors, as some do not have the means to buy the one barrel of beer, which would be their turn…”*
- well fest abolished in 1724
- since 1849 regular maintenance by municipality

- well fests survived in Sachsenhausen (1490), Wunsiedel, Jever

(Veh: in Porath & Rapsch 1998).

Groundwater becomes dominant water source in the 19th century: problems

- deeper wells: higher probability of encountering iron-rich and corrosive water

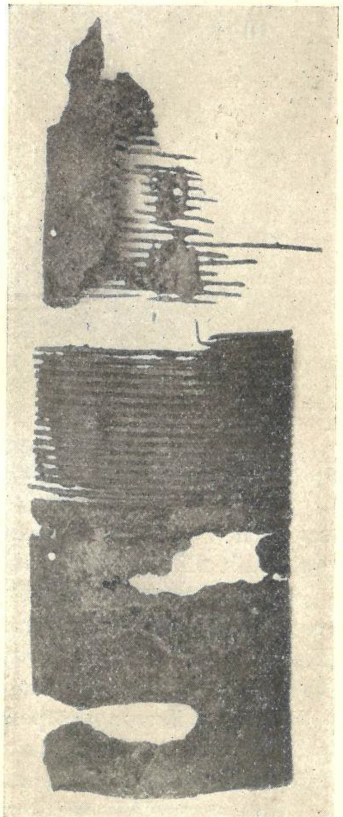
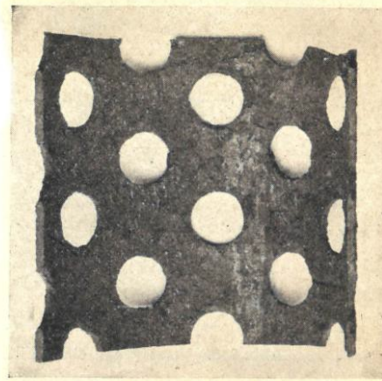
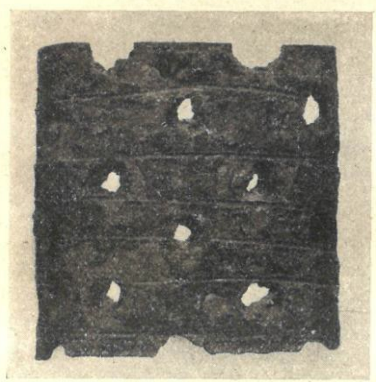


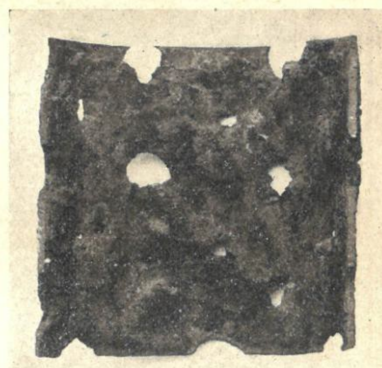
Abb. 307. Durch Grundwasser zerstörtes schmiedeeisernes Bohrrohr. (Nach 3 Jahren.)

Abb. 308. Angriff von Grundwasser auf die schmiedeeiserne Öse eines Rohrbrunnens aus Gußeisen.



1. Ursprüngliche Beschaffenheit.





Verstopfter Zustand:

2. äußerer Mantel.

3. innerer Mantel.

Abb. 309. Durch Eisenockeransatz undurchlässig gewordener Filterkorb.

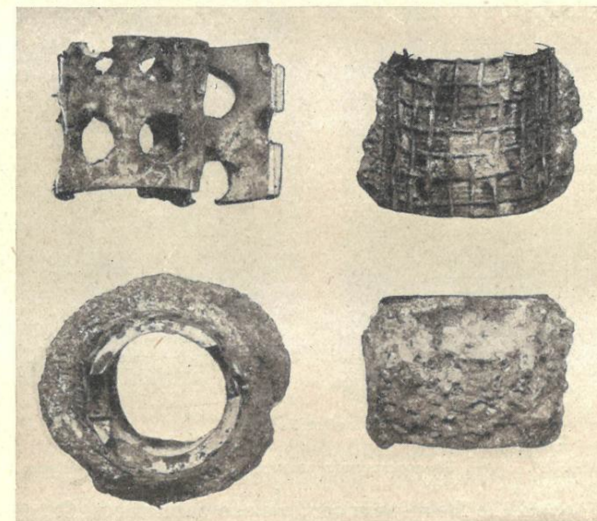
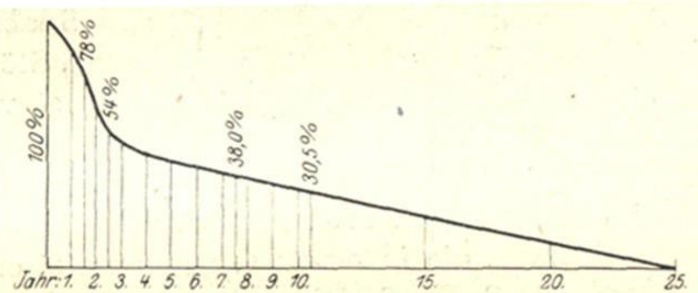


Abb. 311. Verstopfung eines Filterkorbes durch Bildung eines betonartigen Mantels, bestehend aus Eisen, Kalk und Sand. (Nach 2 Jahren.)



Early steps in well rehabilitation

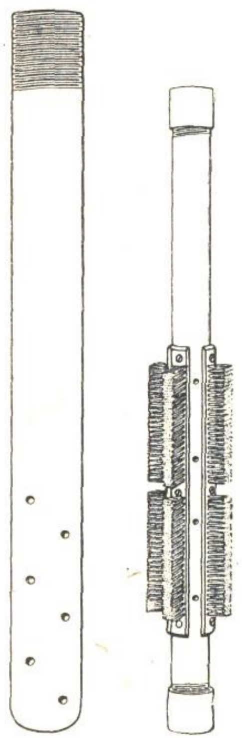


Abb. 318. Spritzrohr zum Brunnenreinigen.

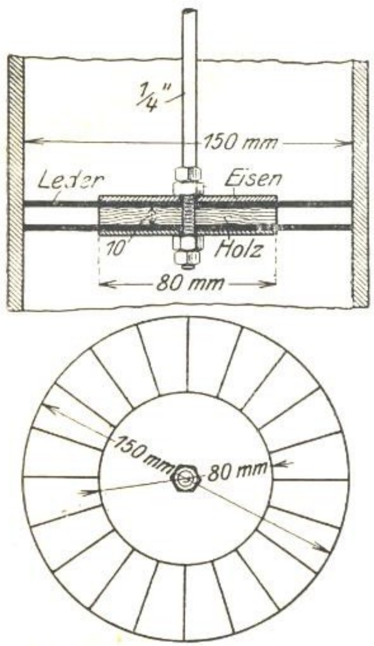


Abb. 317. Vorrichtung zum „Stöpseln" der Brunnen.

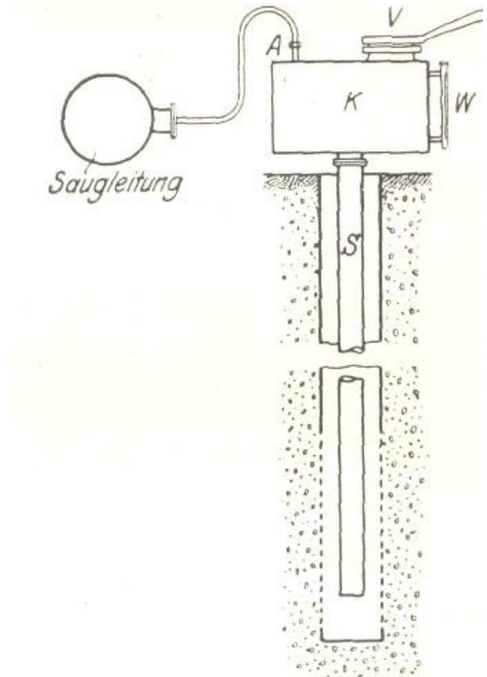
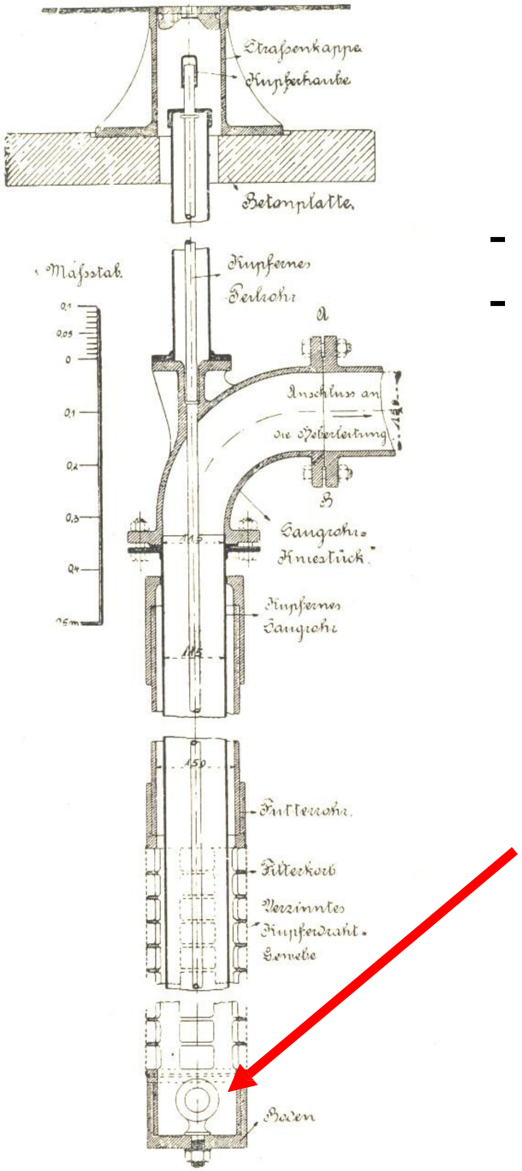


Abb. 316. Stoßvorrichtung zum Entsanden von Brunnen.

- brushing
- water jetting
- surge plunger
- impulse
- pressurized air injection
- steam injection
- acidification

(Prinz 1919)

Early well reconstruction & sand prevention

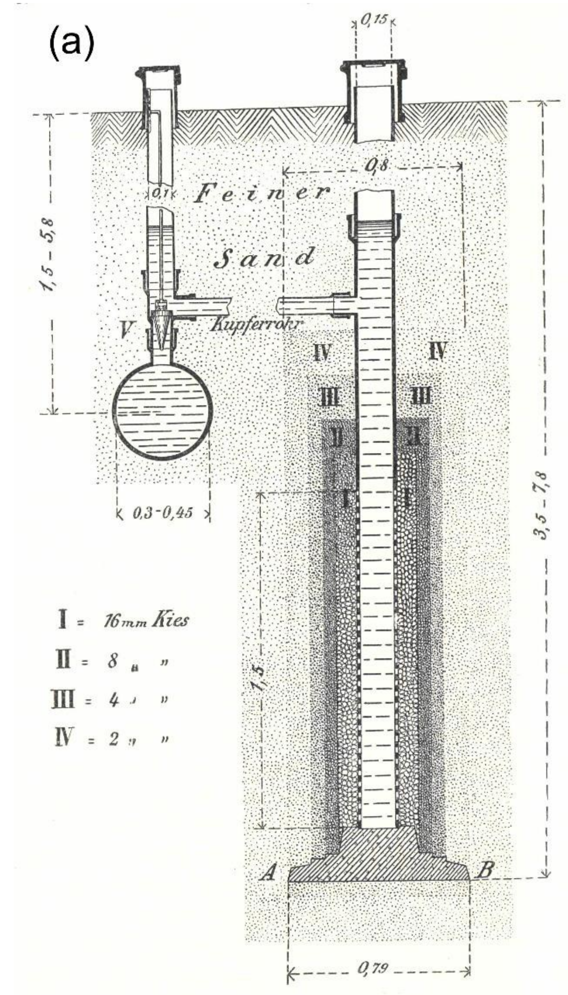


Bauart 1894

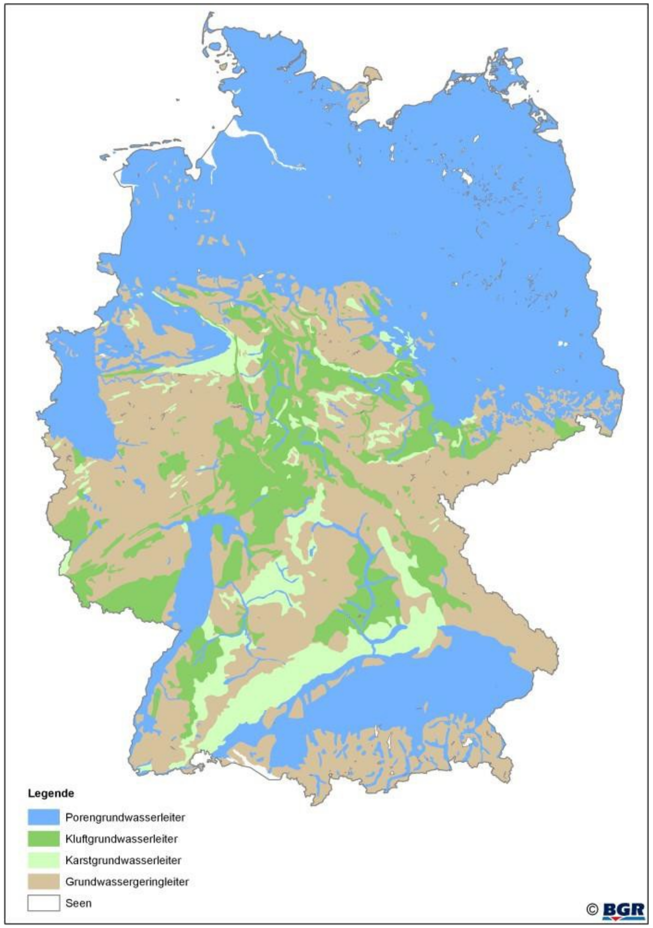
- pulling
- separately removable screen

Abb. 308. Angriff von Grundwasser auf die schmiedeeiserne Öse eines Rohrbrunnens aus Gußeisen.

(a)



(Ground)water supply in Germany

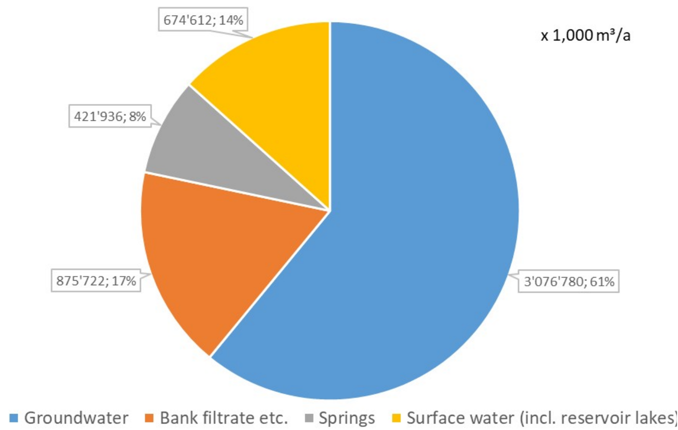


Pore aquifers N. Germany (glacial, fluvial)

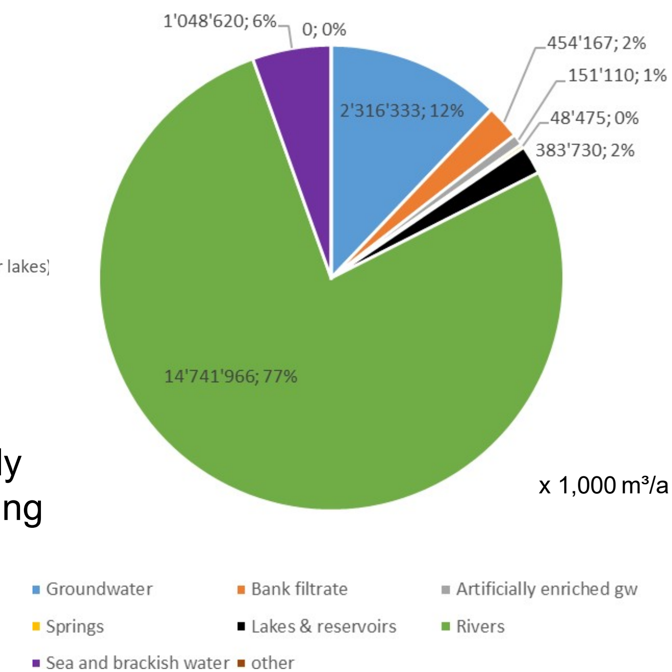
Fractured aquifers in mountainous areas

Karst aquifers (7% of water supply)

Public water supply:
- 5.05×10^9 m³/a
- 4,500 water supply companies, mostly public
- 16,000 abstraction sites (incl. 4,900 springs)
- more than 75 % from underground

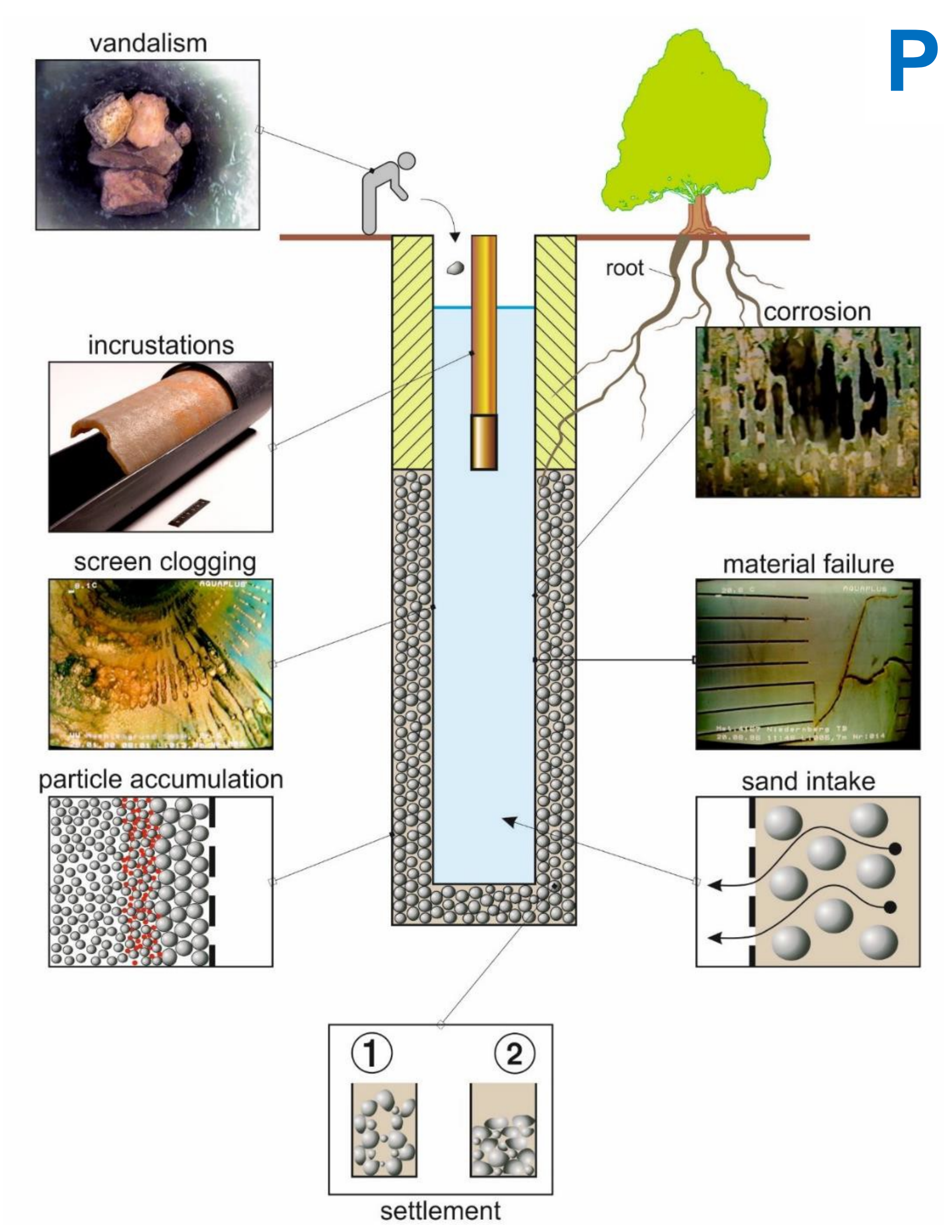


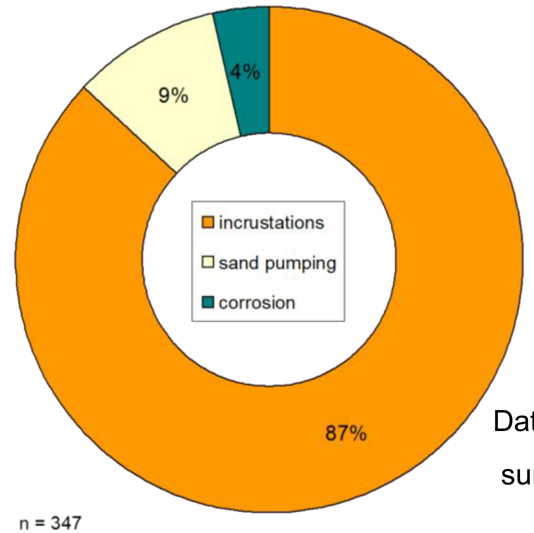
Industry water supply:
- 19.1×10^9 m³/a
- 10,000 companies with own supply
- predominantly river water for cooling



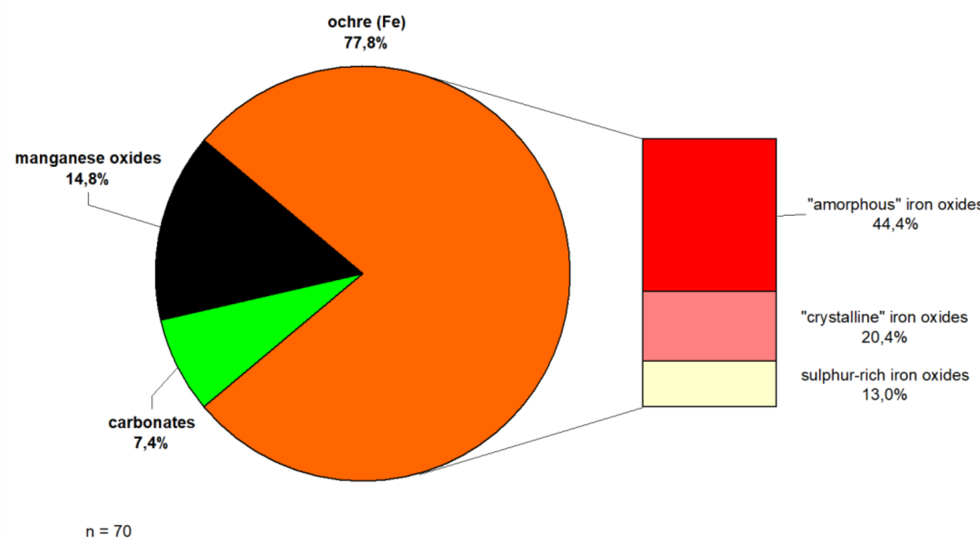
Agriculture
- 9,000 farmers with own supply
- 150 x 106 m³/a (77 % gw)

Problems of water wells

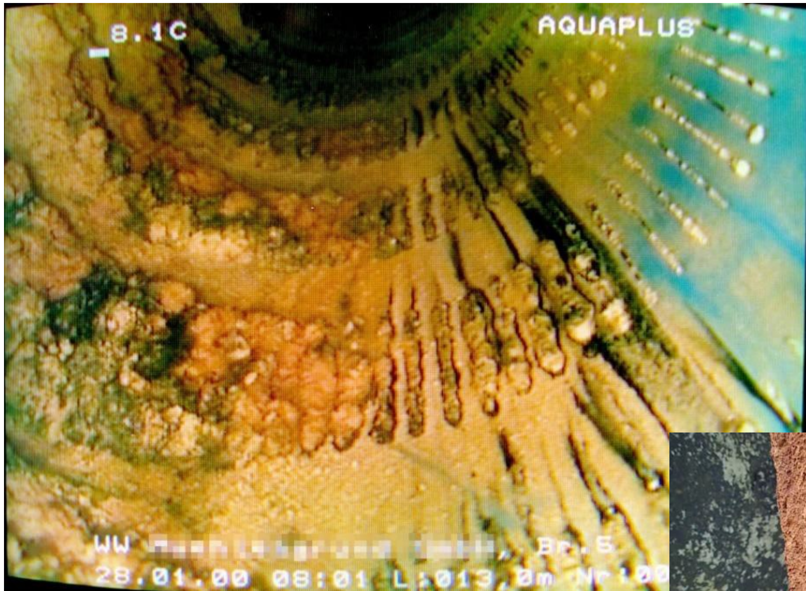


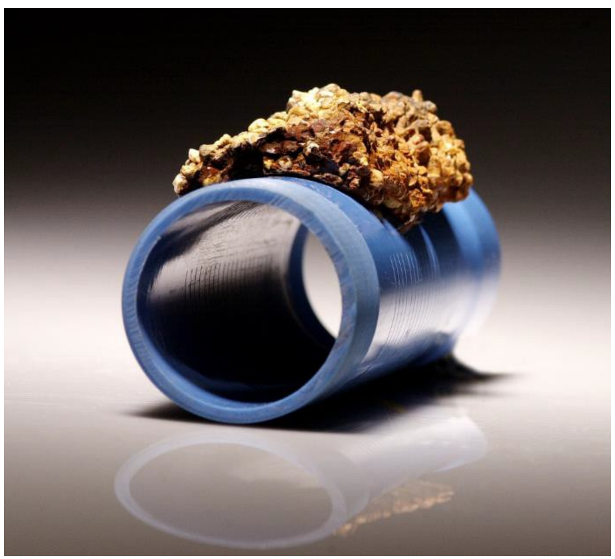


Data after a DVGW survey (Niehues 1999)



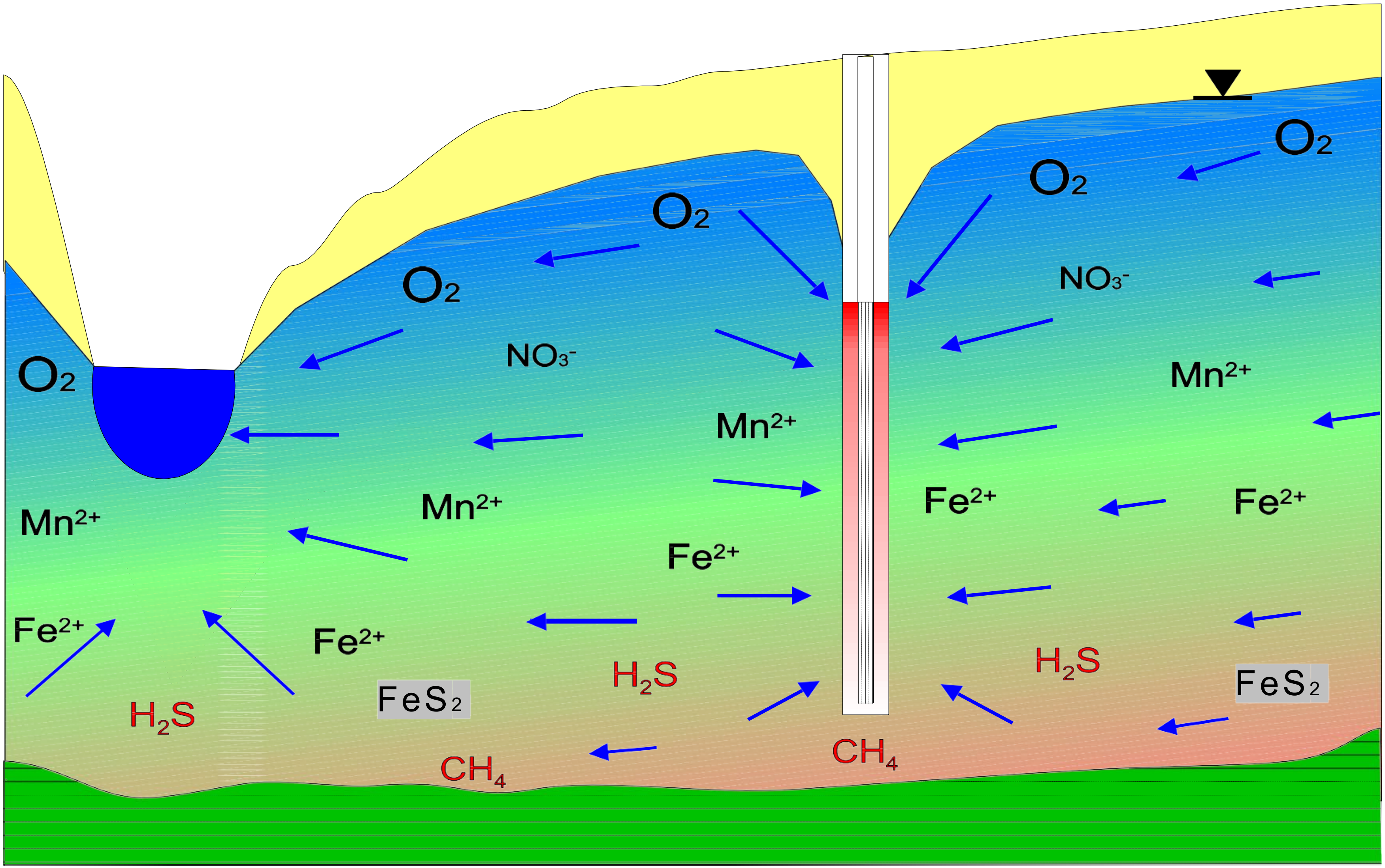
Iron oxide incrustations





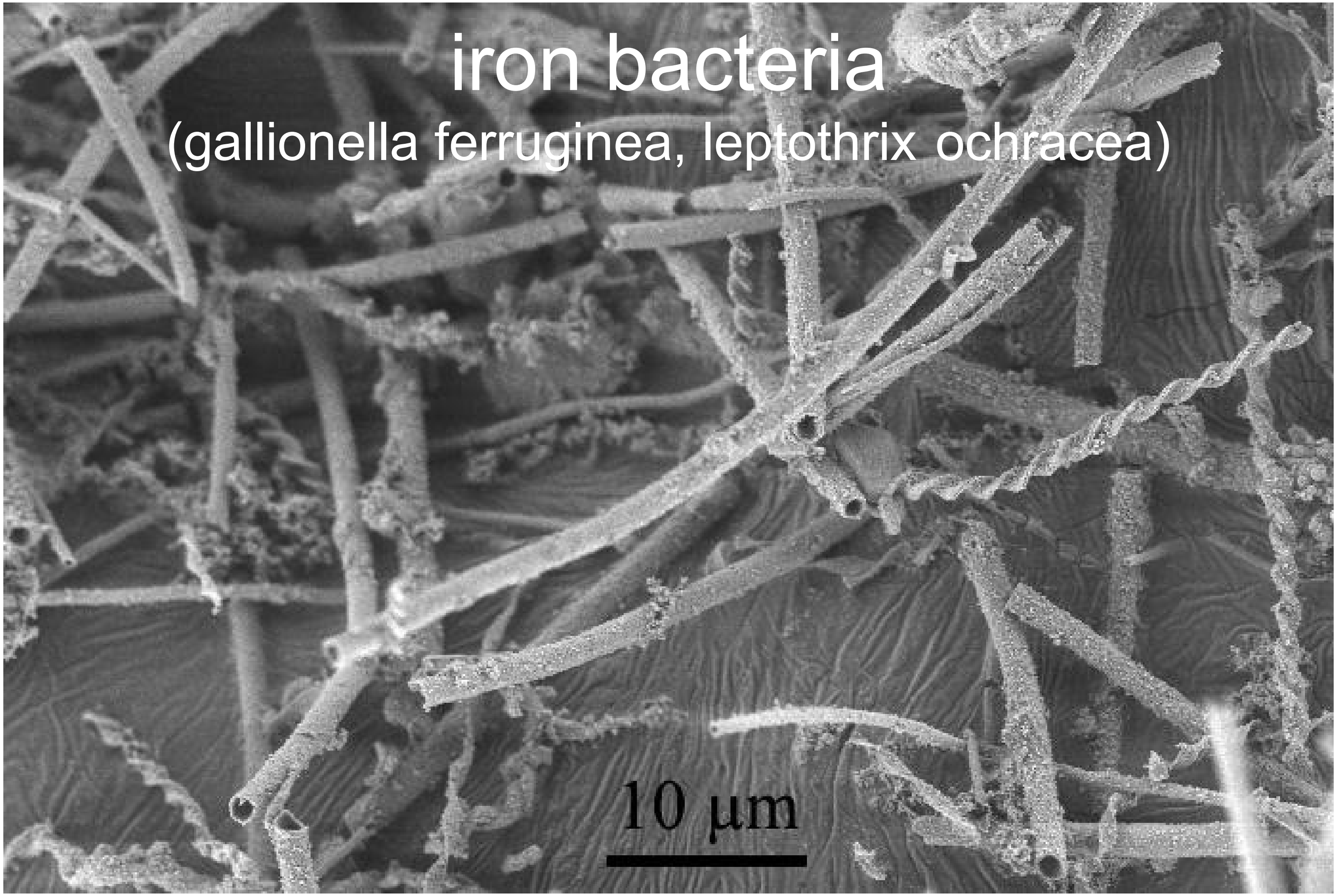
Photos: Aquaplus, Weitze, Houben, Sander

Wells and the redox zonation of aquifers



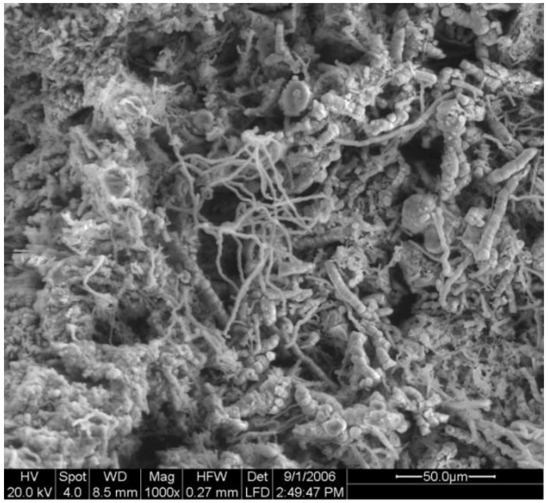
- ohne Maßstab -

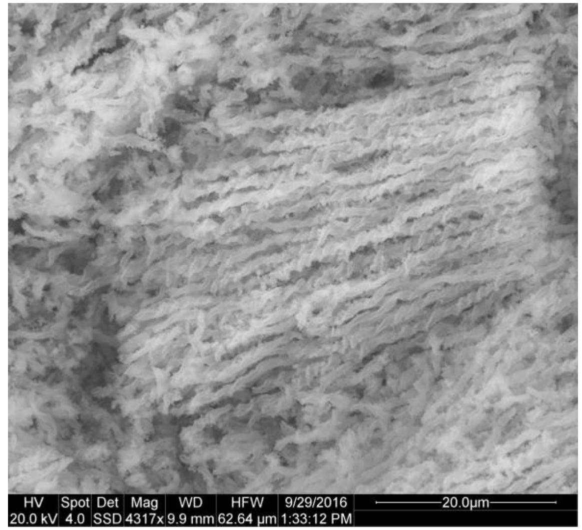
“Rusty little monsters“

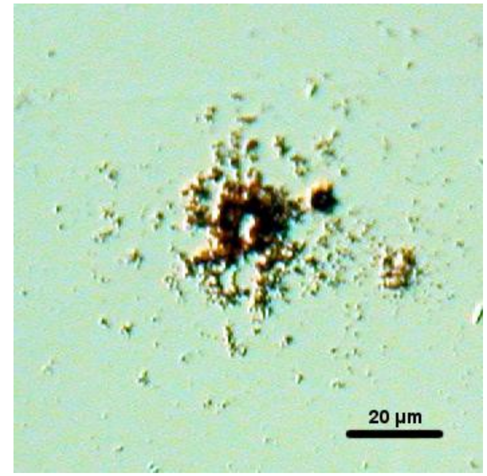


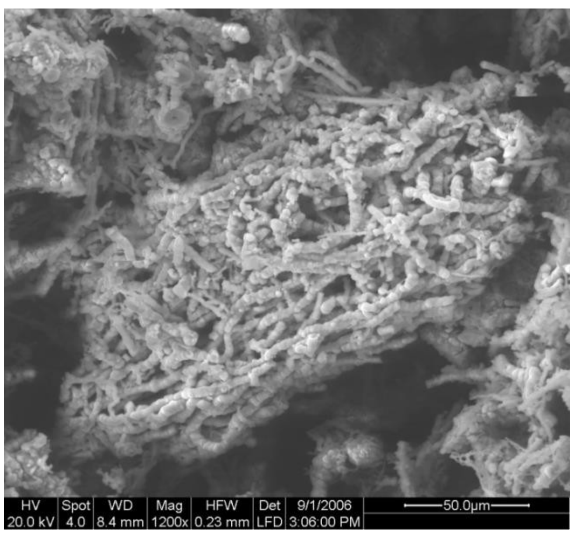
Banfield & Zhang (2001)

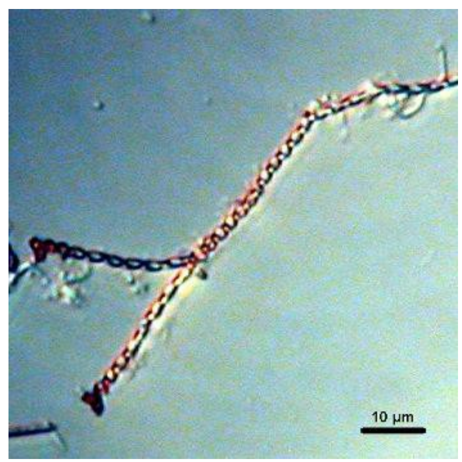
Iron bacteria **et al**.: the (bio)film business

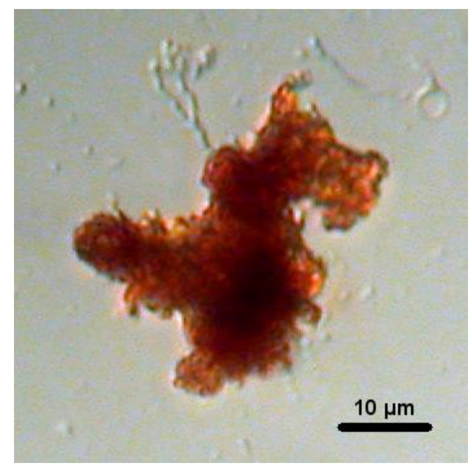






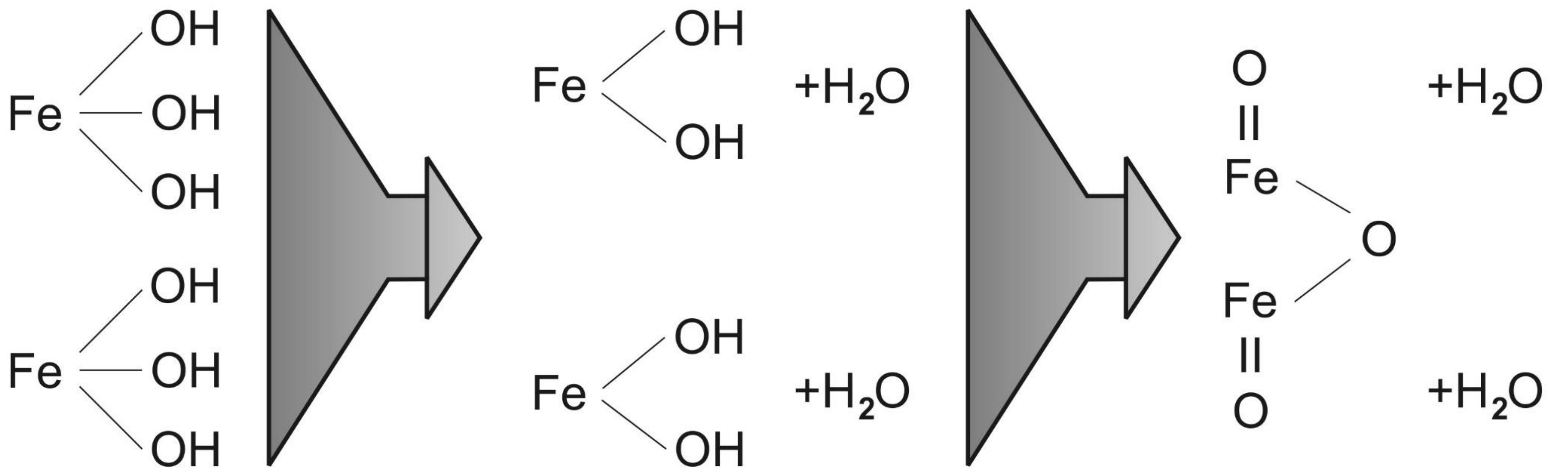






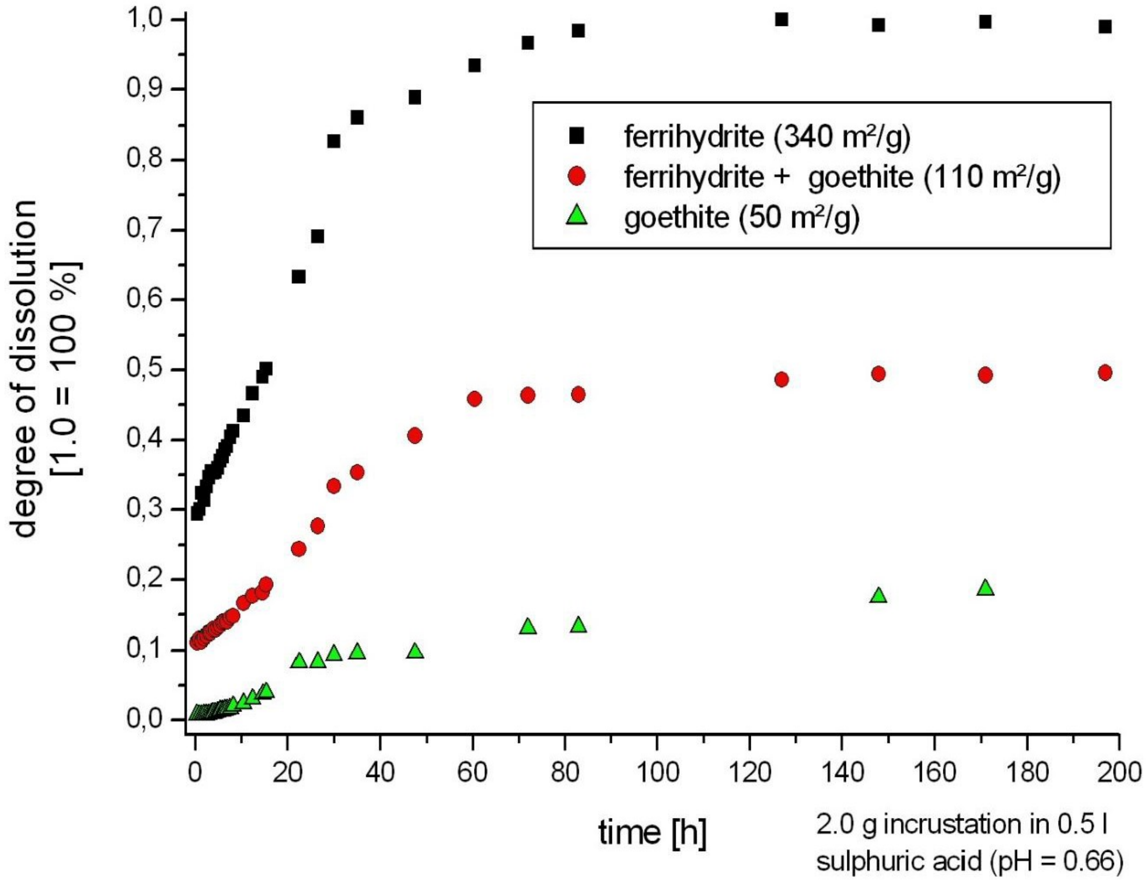
Photos: Oliver Thronicker, Georg Houben

Crystallisation and re-crystallisation of iron oxides



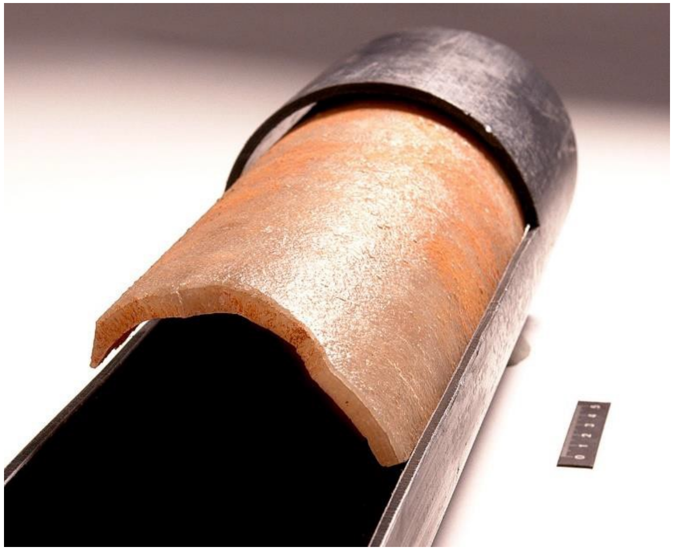
“$Fe(OH)_3$”	FeOOH	Fe_2O_3
ferrihydrite	goethite, lepidocrocite	hematite

Crystallisation and re-crystallisation of iron oxides



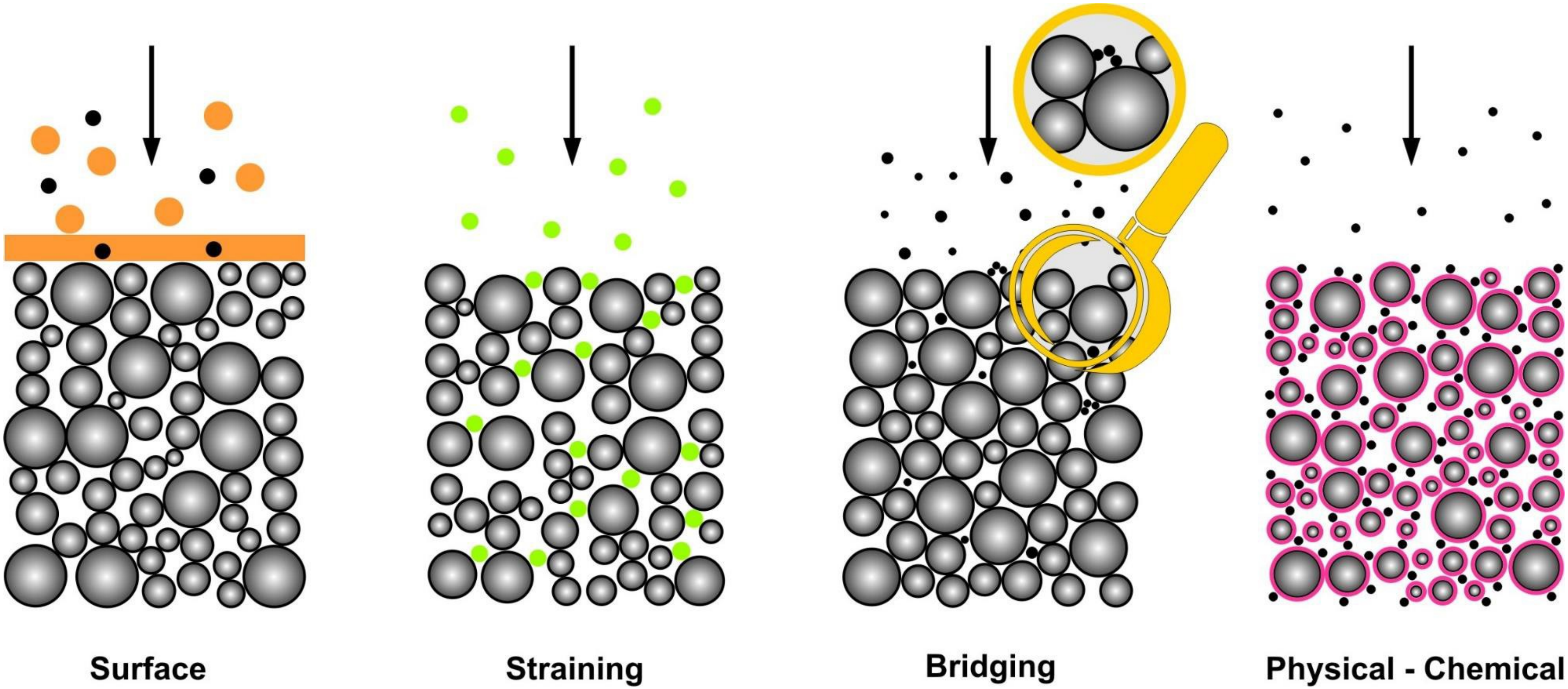
Re-crystallisations leads to hardening and decreased solubility!

Carbonate incrustations



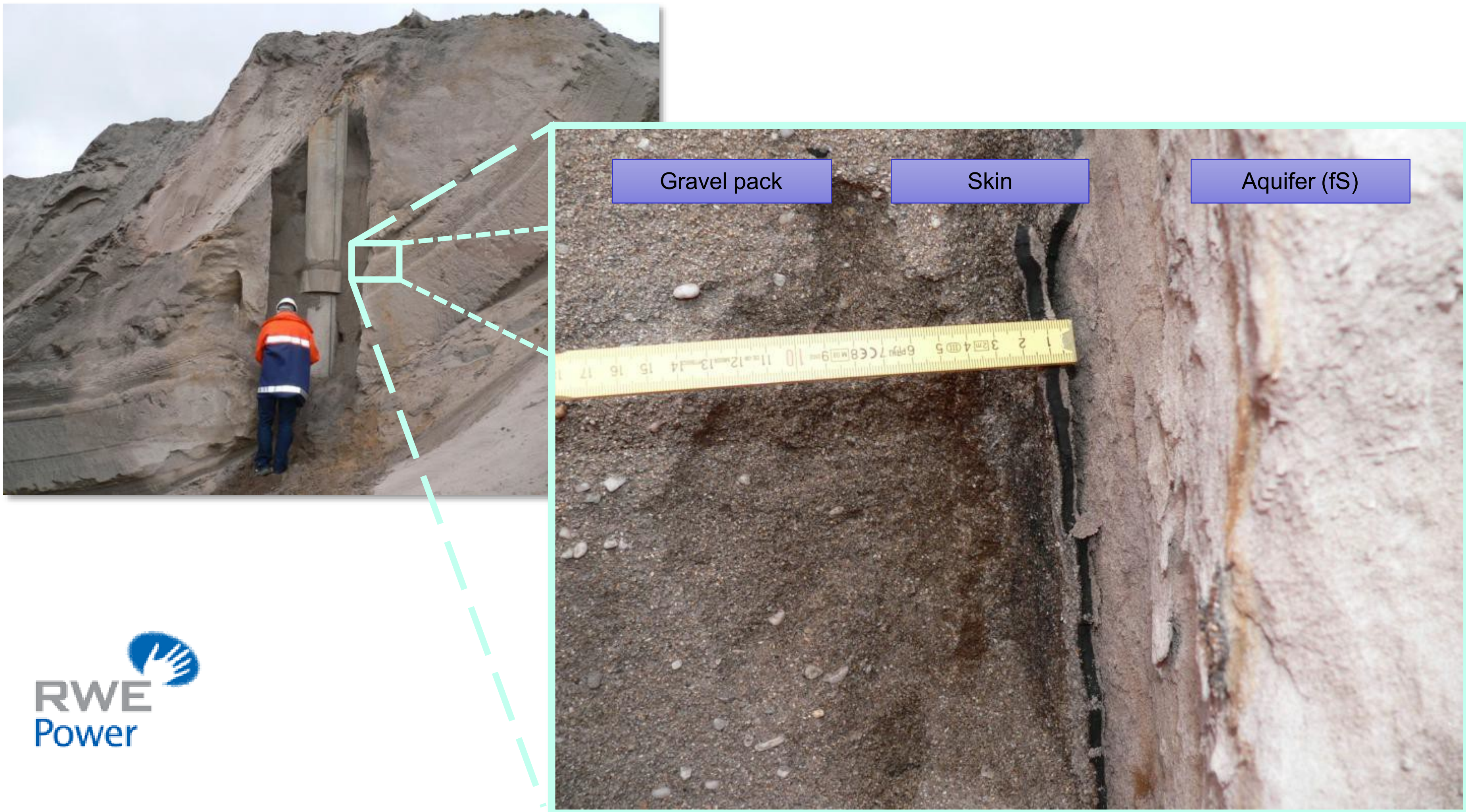
Photos: Weitze, Houben, pigadi

Particle clogging (mechanical)



Lignite open pit mines

sampling wells from the outside



RWE Power

Particle clogging: skin layer

RWE Power

Lignite open pit mine Garzweiler Photos: Weidner, Ho u

Groundwater

Analysis of Wellbore Skin Samples—Typology, Composition, and Hydraulic Properties

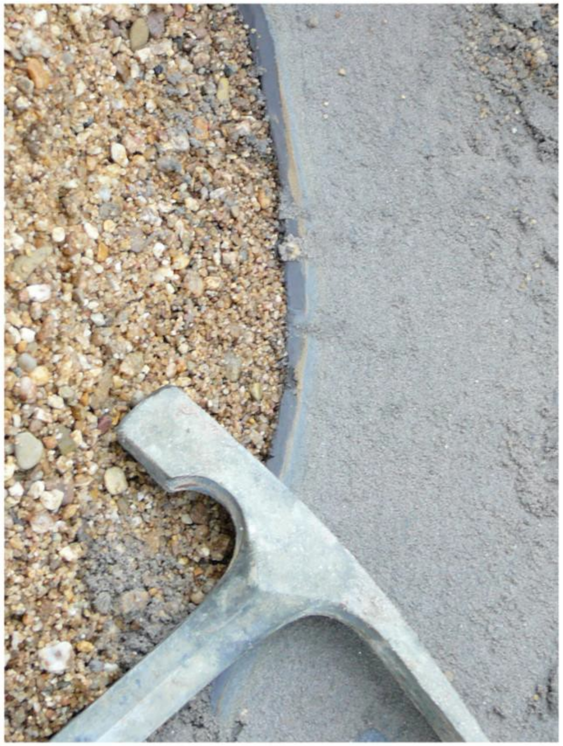
by Georg J. Houben[1], Matthias Halisch[2], Stephan Kaufhold[3], Christoph Weidner[3], Jürgen Sander[4], and Morris Reich[5]

Abstract

The presence of a wellbore skin layer, formed during the drilling process, is a major impediment for the energy-efficient use of water wells. Many models exist that predict its potential impacts on well hydraulics, but so far its relevant hydraulic parameters were

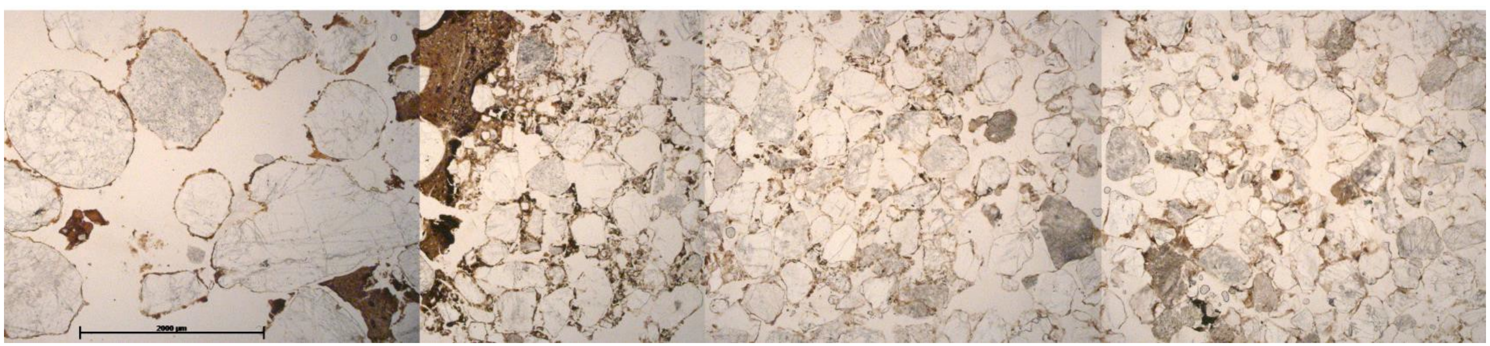
Particle clogging: skin layer

(a)



(b)

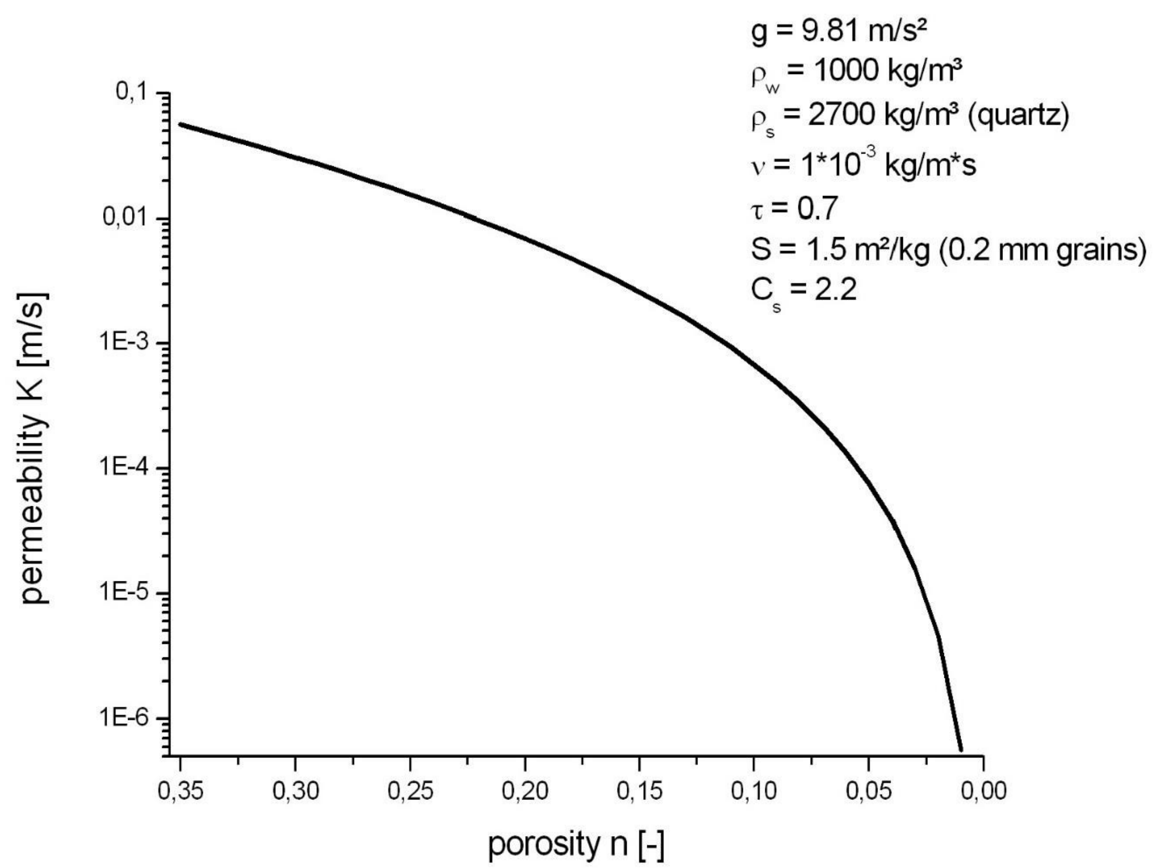
(c)



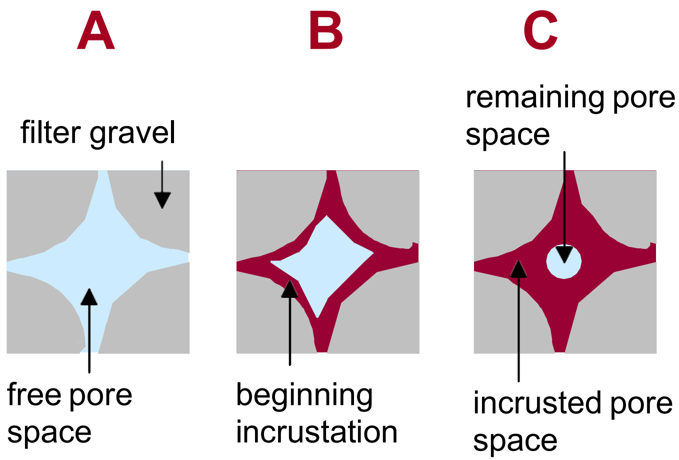
Clogging of wells

Clogging → reduction of pore spaces → reduction of permeability and well yield

Calculation using the **Kozeny-Carman** equation



Development of yield in clogging wells

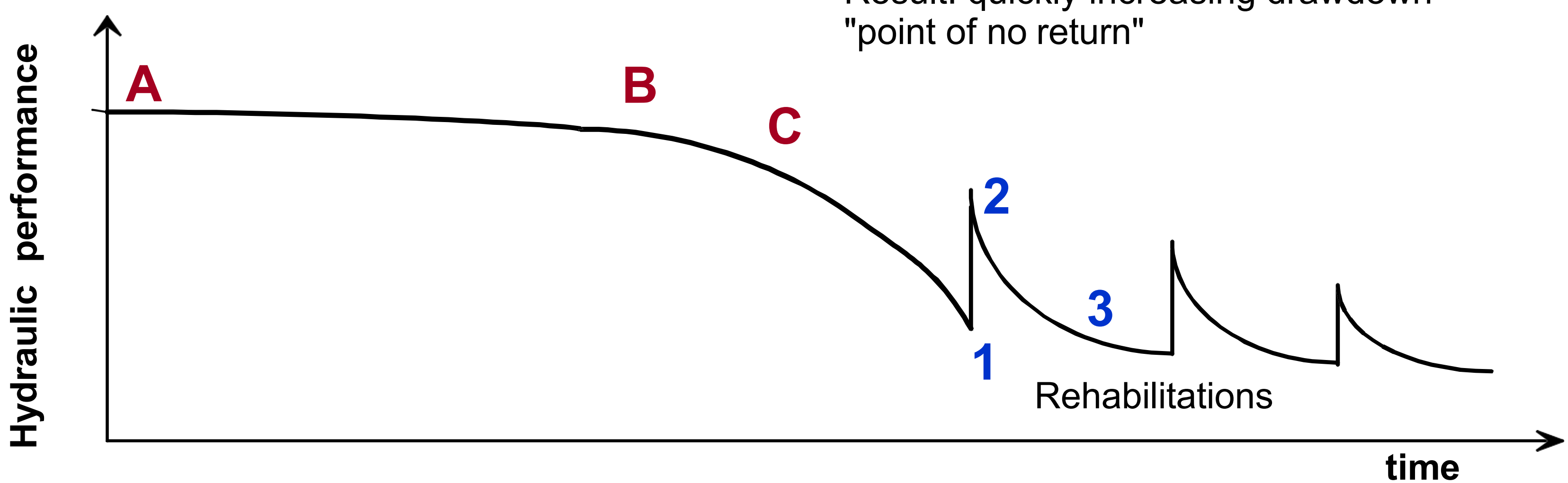


Explanation

A New well:
pore scace is open, unhindered flow

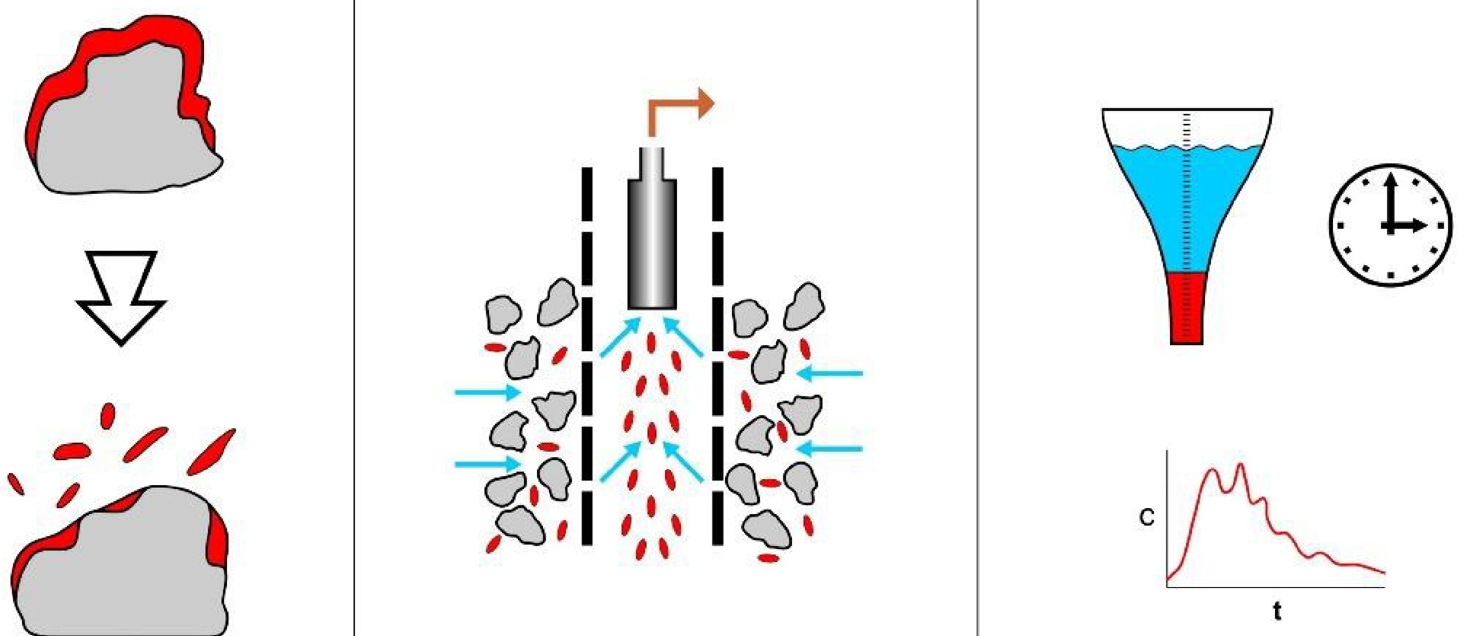
B Slow well ageing:
formation of incrustations at rim of flow channels and in dead-end pores
Result: slowly increasing drawdown

C Fast well ageing:
incrustations reach main part of flow channels
Result: quickly increasing drawdown
"point of no return"



Rehabilitation: steps

Step I separation	Step II removal	Step III monitoring



Rehabilitation processes

Mechanical processes:

(1) Thermal (heating/freezing)

(2) Erosion (by flowing water)

(3) Impulse (explosives, ultrasonic…)

Chemical processes:

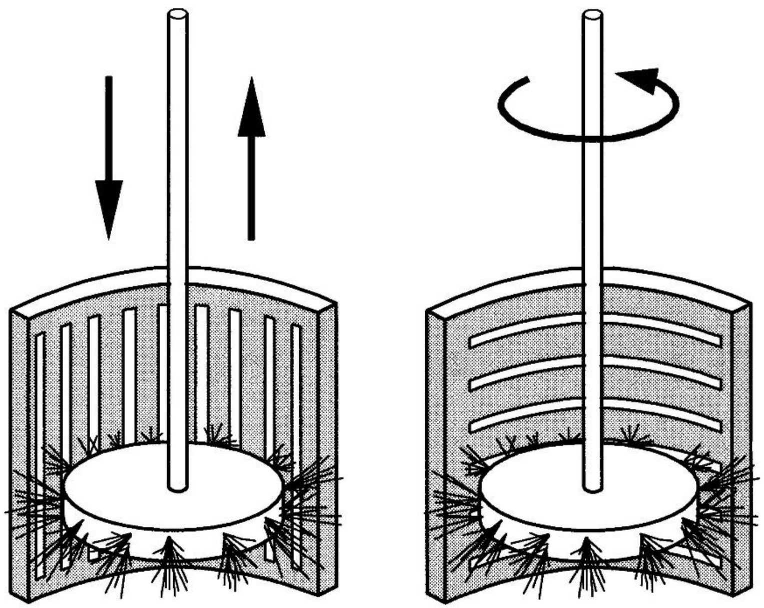
(1) proton-asssited dissolution (acids, organic/inorganic)

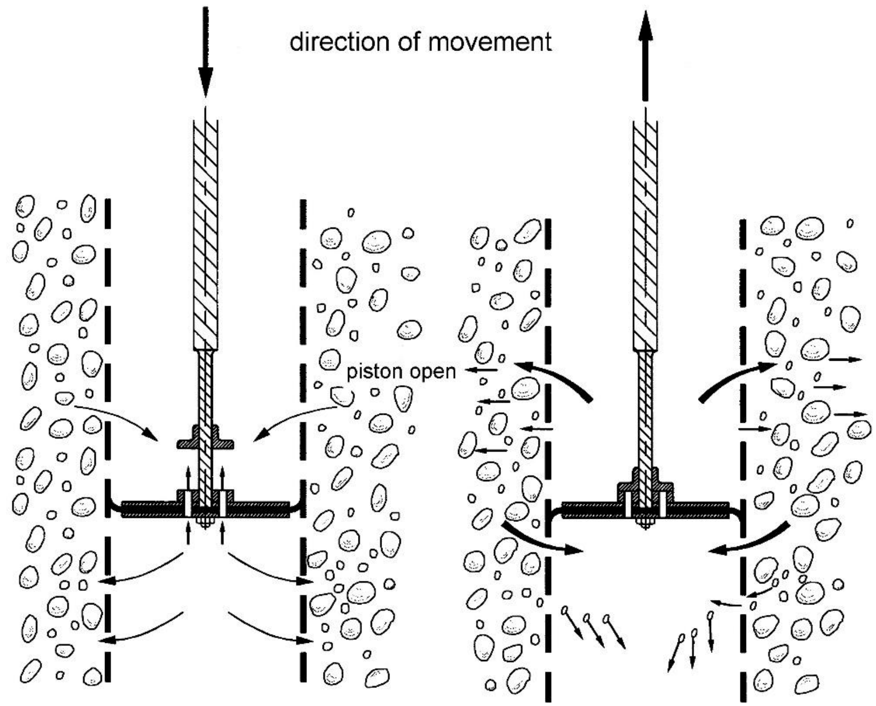
(2) reductants (pH neutral)

(3) desinfection: strong oxidants (e.g. hydrogen peroxide)

Mechanical rehabilitation: techniques (1)

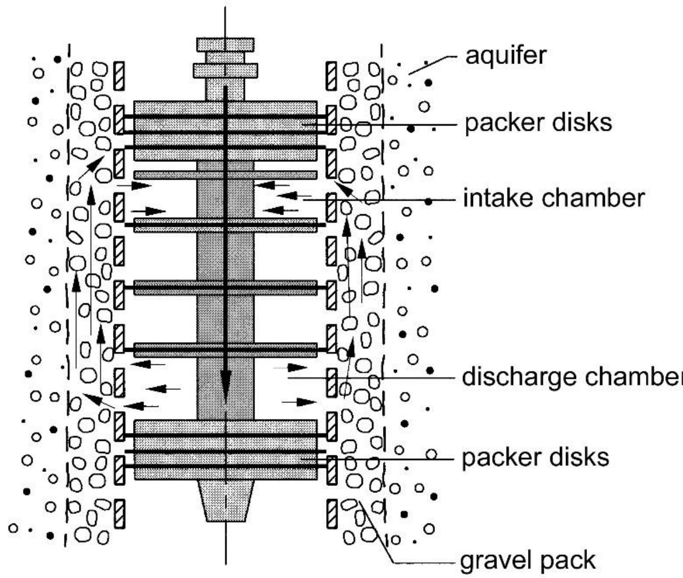
Brushes & plungers





Mechanical rehabilitation: techniques (2)

Jetting and pumping systems

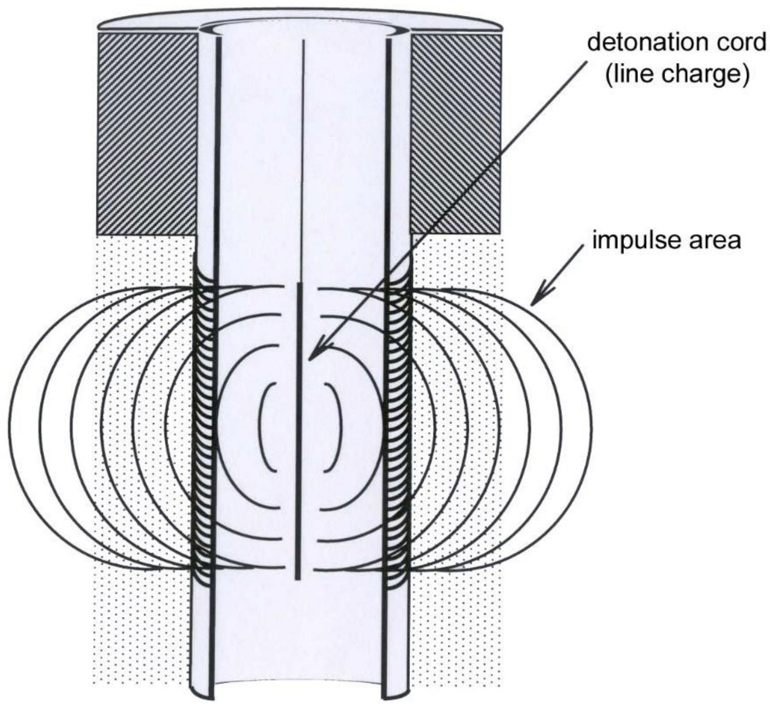


Source: Aquaplus, Detay 1997, BPS

Mechanical rehabilitation: techniques (3)

Impulse-based

- explosives
- ultrasonic
- cavitation



Source: pigadi, Sonic Ultraschall

Mechanical rehabilitation: energy losses

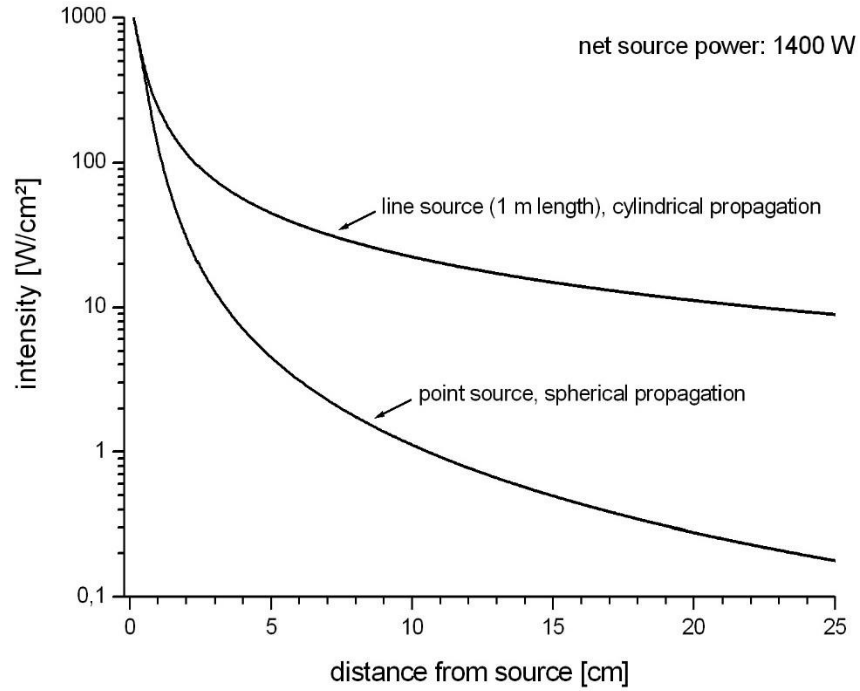
Energy losses due to:

- spatial dissipation of energy
- reflection, refraction

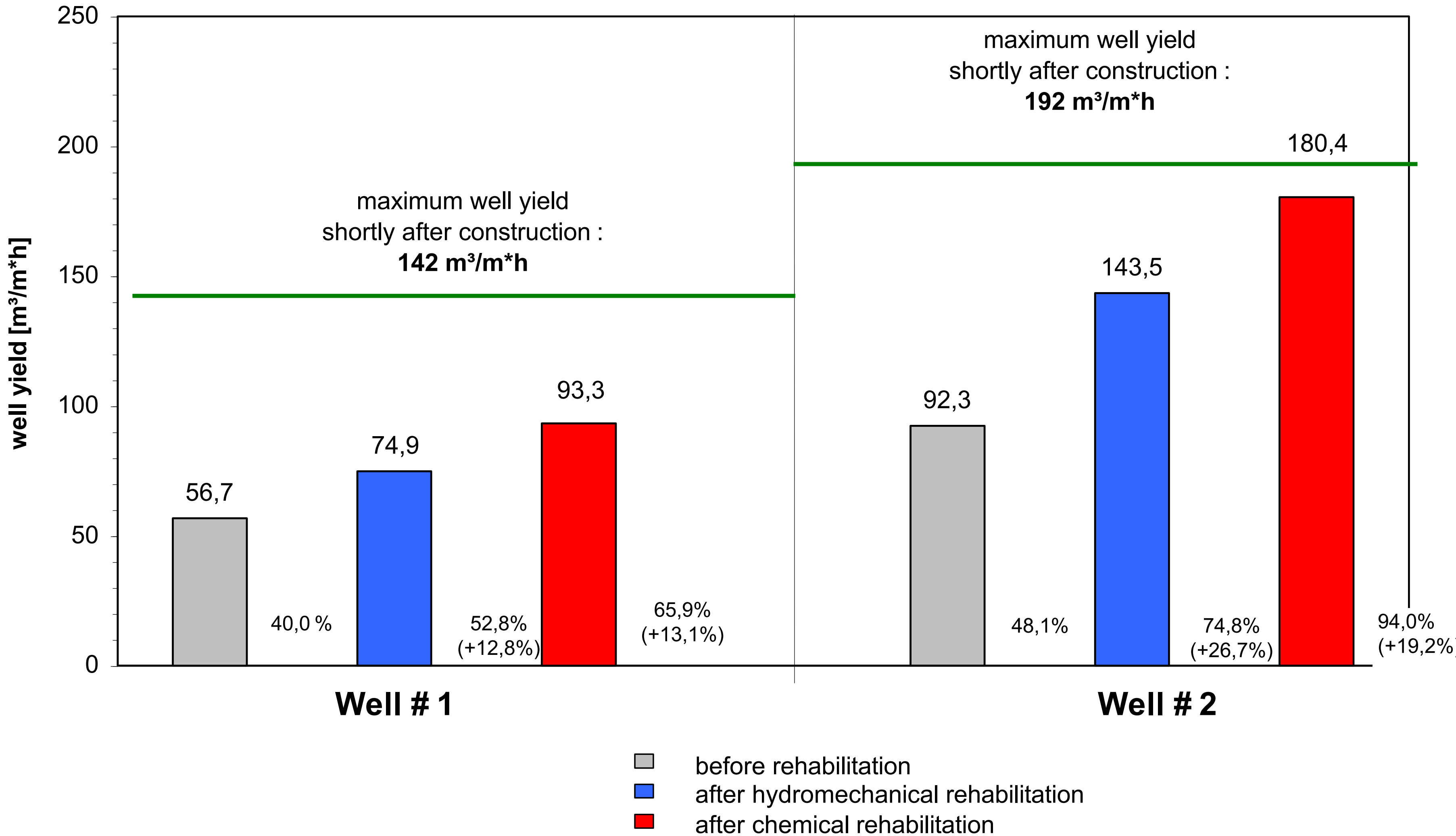
→ fast loss of energy away from source, efficiency behind screen often quite low

Solution: rehabilitate from outside

Example: ultrasonic

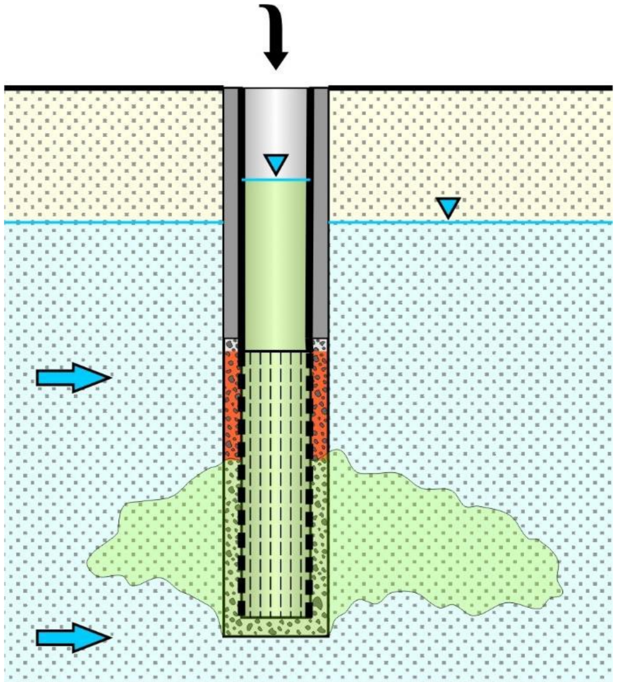


Chemical rehabilitations: really necessary?



Houben et al. (2000)

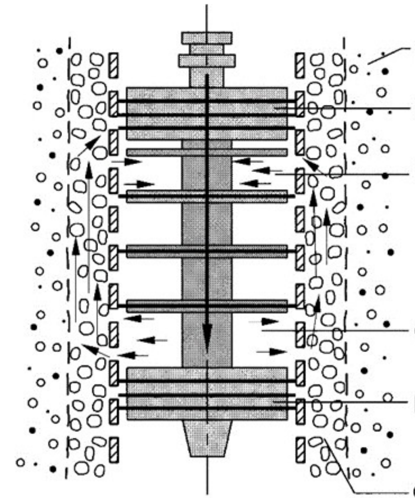
Chemical rehabilitations: what (not) to do ?



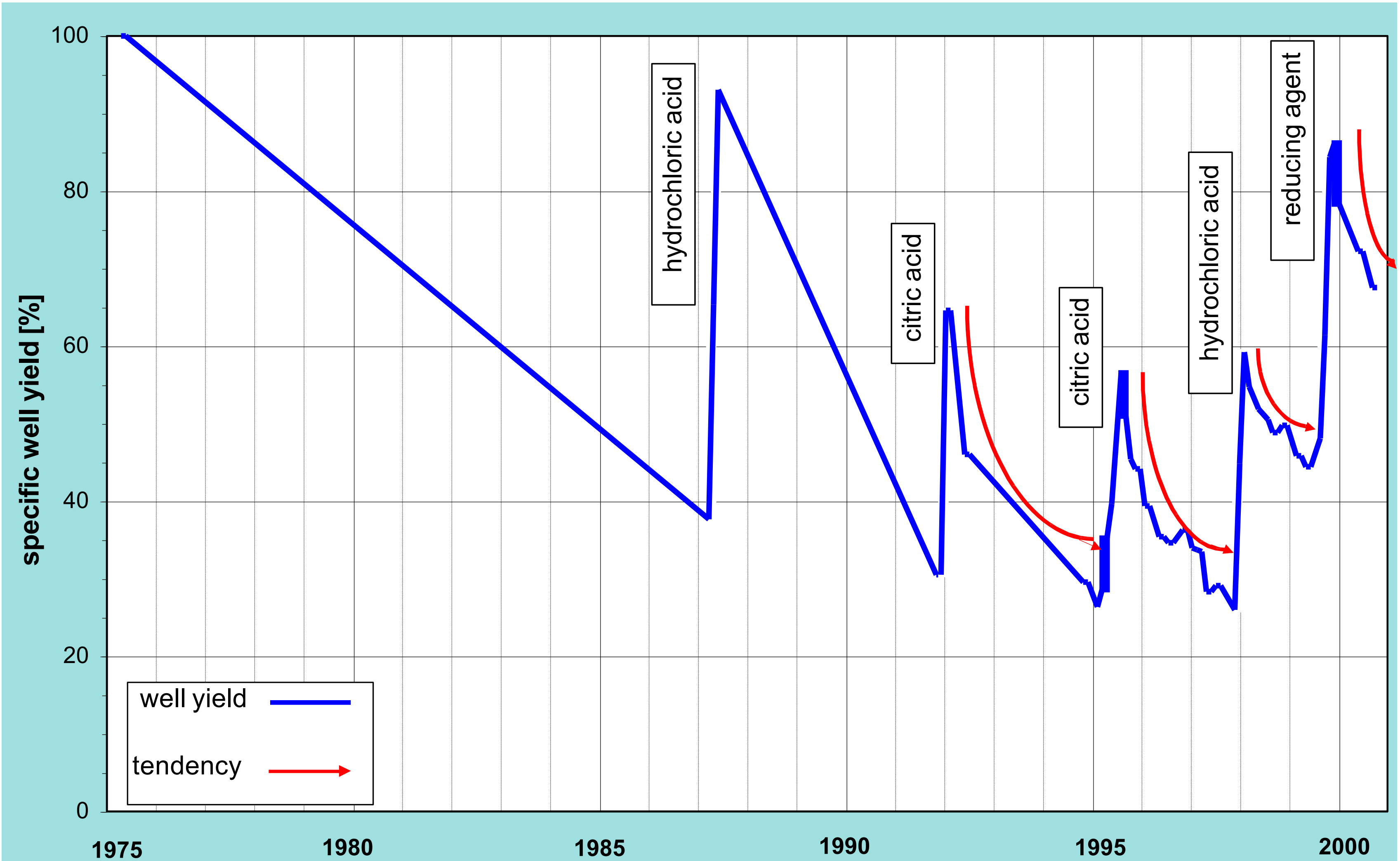
Dump & wait? Verboten!
- ineffective
- extensive clean-up

Germany: 25-30% of rehabilitations involve chemicals

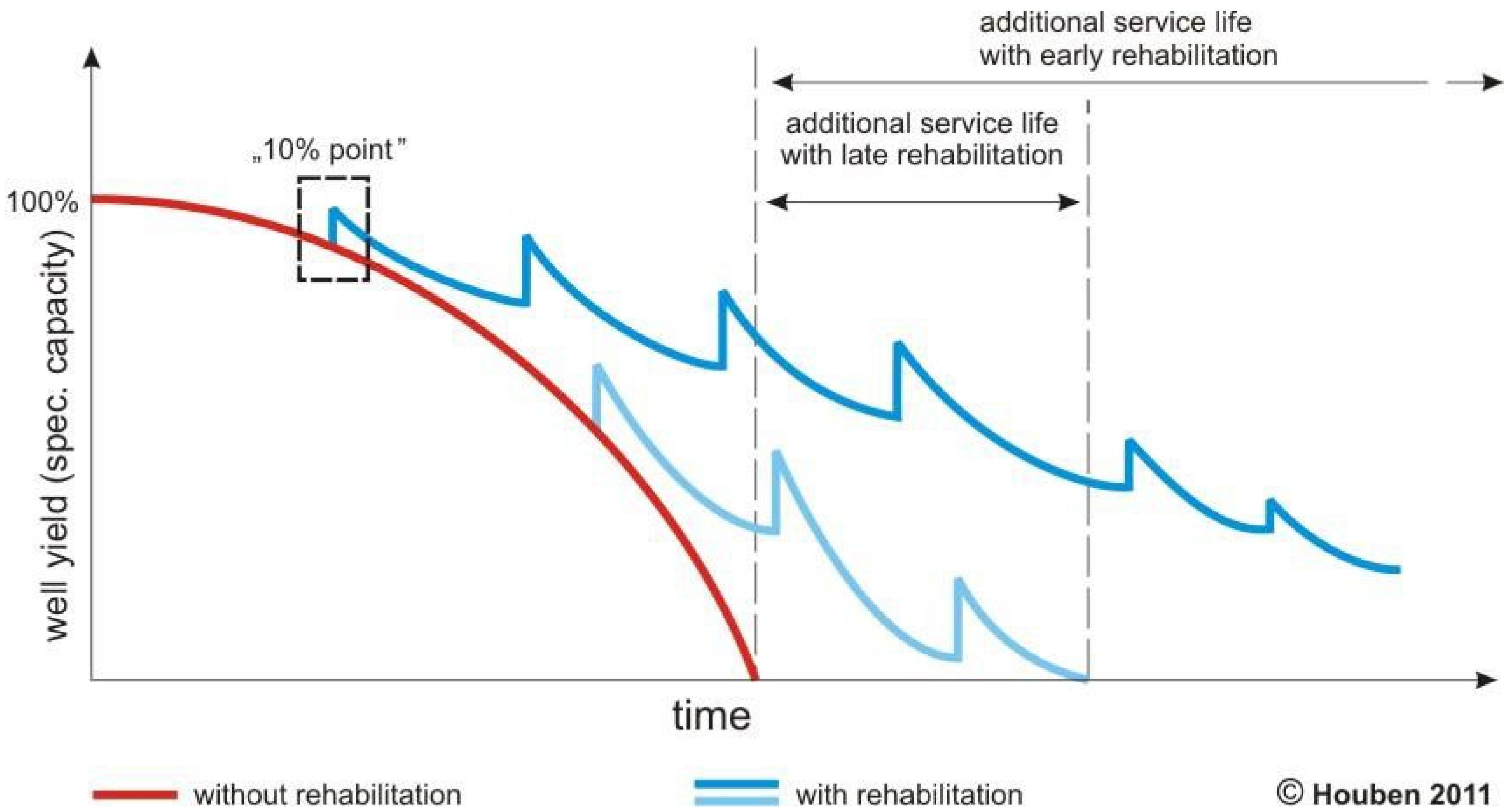
Best practice:
- chamber systems (recirculation)
- occupational safety!
- chemicals:
  - hydrochloric acid (pH 1)
  - sulphuric acid
  - additive to acid: hydrogen peroxide
  - neutralisation and disposal of acids!
  - alternative: sodium dithionite (pH neutral)



Short-lived successes?!

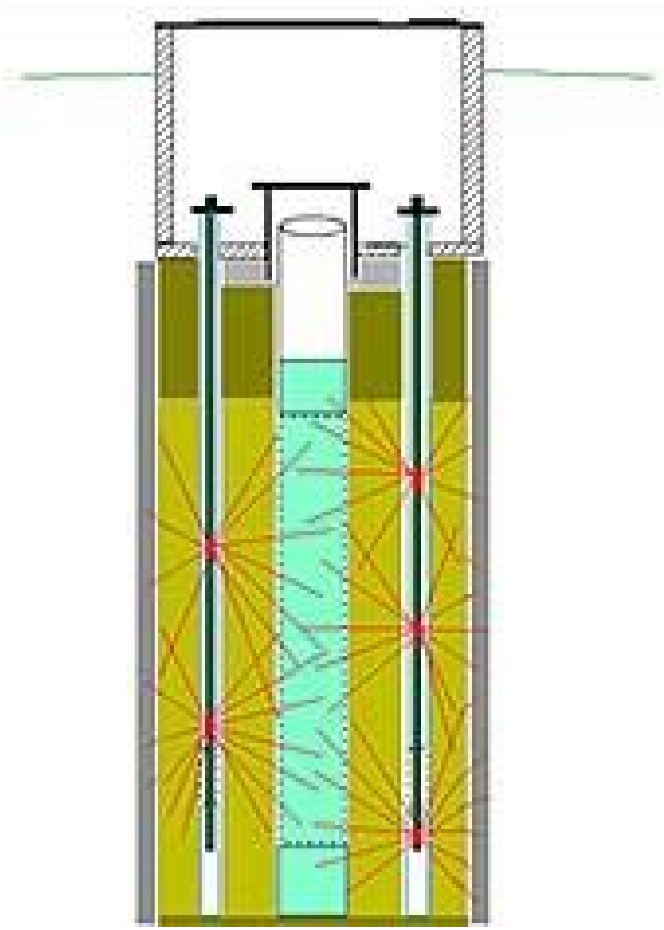


Rehabilitation = buying time



Prevention: killing rusty little monsters

(1) Soviet style (East Germany)



Cobalt-60 sources in stainless steel cover
(gamma radiation = kills bacteria)
Two probes in Gravel pack: 180° spacing
760 wells equipped, illegal after 1990
not all recovered

(2) West-Berlin style

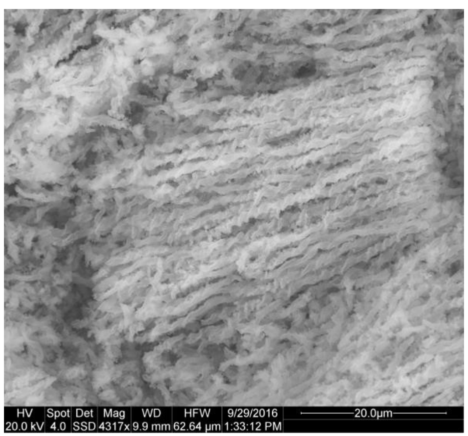
Hydrogen peroxide (1% solution)
24 h waiting period
→ remove by pumping (> 1 h)

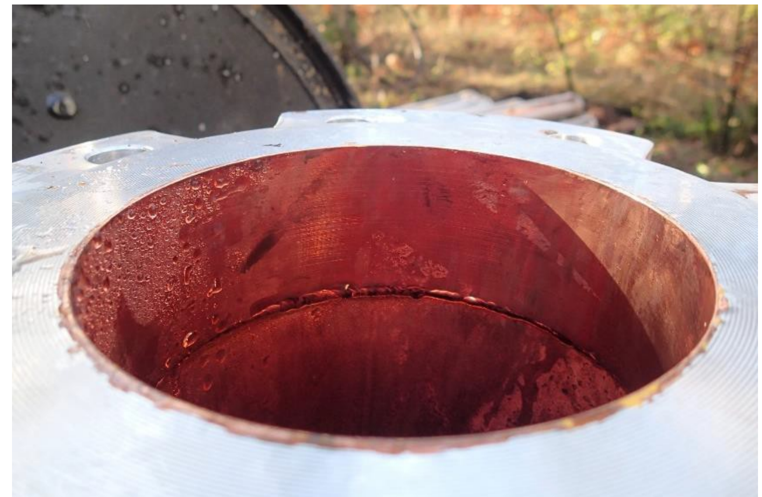
Problem: needs to be repeated regularly
(every 1-2 months, worst case: every second week)

Prevention: killing rusty little monsters

(3) reactive coatings

Problem Solution? silver coating copper coating





Prevention: killing rusty little monsters

(3) reactive coatings: after ≈ 300 days

Silver coating

slightly effective

copper coating

highly effective

Prevention: killing rusty little monsters

(3) reactive coatings: after ≈ 570 days

Silver coating

not effective

copper coating

hardly effective

Prevention: killing rusty little monsters
(3) reactive coatings: aftermath

silver coating

copper coating

Problem: effect wears off after a few months
due to erosion and chemical consumption

Prevention: killing rusty little monsters
(3) copper coating: small-scale

Experimental set-up

after four months

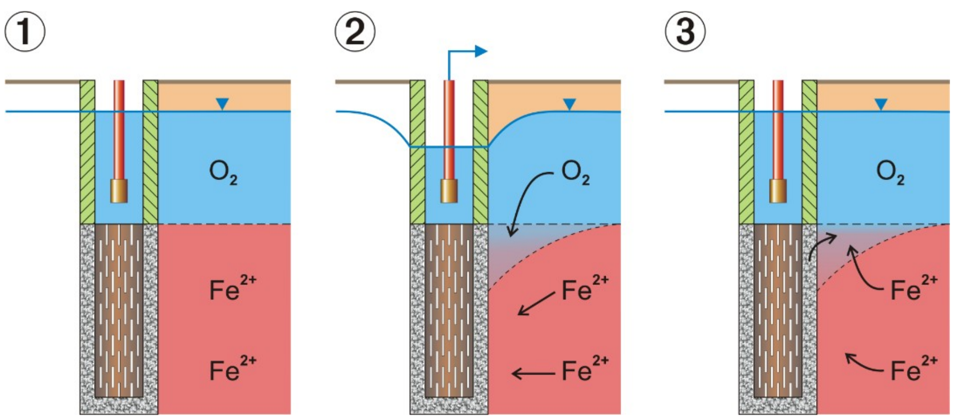
native polished, native oxidised, PVC blank, PVC spray-coated, PVC galvanized

Only polished copper showed (limited) potential

Prevention: operation

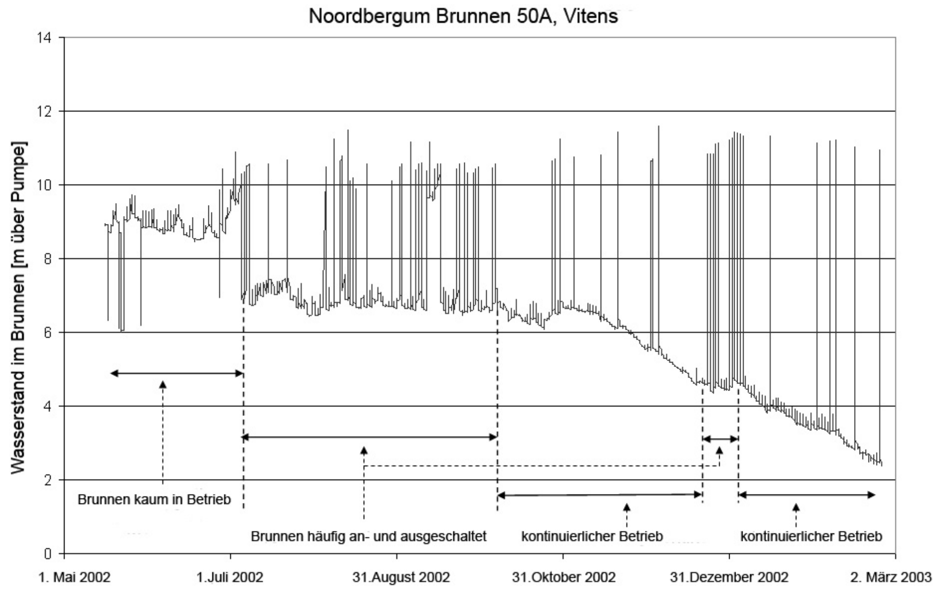
Problem: iron bacteria

Solution: prevent oxygen supply
→ avoid switching on/off
(continuous pumping)



Problem: particle clogging

Solution: prevent particle accumulation
→ switch on/off often
(discontinous pumping)



Prevention: good design & construction

- minimize entrance velocities
- avoid non-linear and turbulent flow
- avoid mixing of incompatible hydrochem. zones
- avoid formation of skin layer
- plug the well annulus

So, all you need to optimize is…
the mother of all equations

$$s_{tot} = \left\{ \left(\frac{1}{2 \cdot \pi \cdot B} \right) \left[\left(\frac{1}{K_{aq}} \cdot \ln \left(\frac{r_0}{r_b} \right) \right) + \left(\frac{1}{K_{sk}} \cdot \ln \left(\frac{r_{sk-o}}{r_{sk-i}} \right) \right) + \frac{1}{K_{gp}} \cdot \ln \left(\frac{r_b}{r_s} \right) \right] \right\} \cdot Q$$

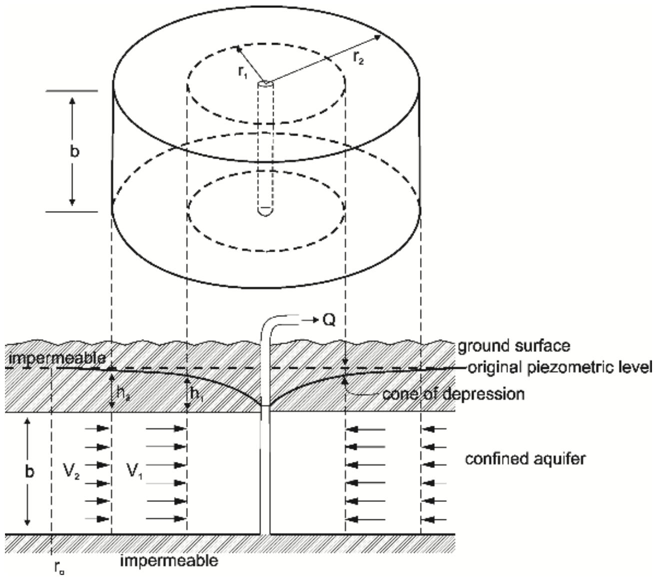
$$+ \left\{ \left(\frac{1}{2 \cdot \pi \cdot B} \right)^2 \cdot \left[\left(\beta^* \cdot \left(\frac{1}{K_{gp}} \right)^2 \cdot \left(\frac{1}{r_s} - \frac{1}{r_b} \right) \right) + \left(\frac{1}{2 \cdot g} \cdot \left(\frac{1}{r_s \cdot C_v \cdot C_c \cdot A_p} \right)^2 \right) + \left(f_{Ds} \cdot \frac{16 \cdot L_s \cdot B^2}{g \cdot {d_s}^5} \right) + \sum_{i=1}^{i=n_{cd}} \left(f_{Dc} \cdot \frac{32 \cdot L_c \cdot B^2}{g \cdot {d_c}^5} \right) \right] \right\} \cdot Q^2$$

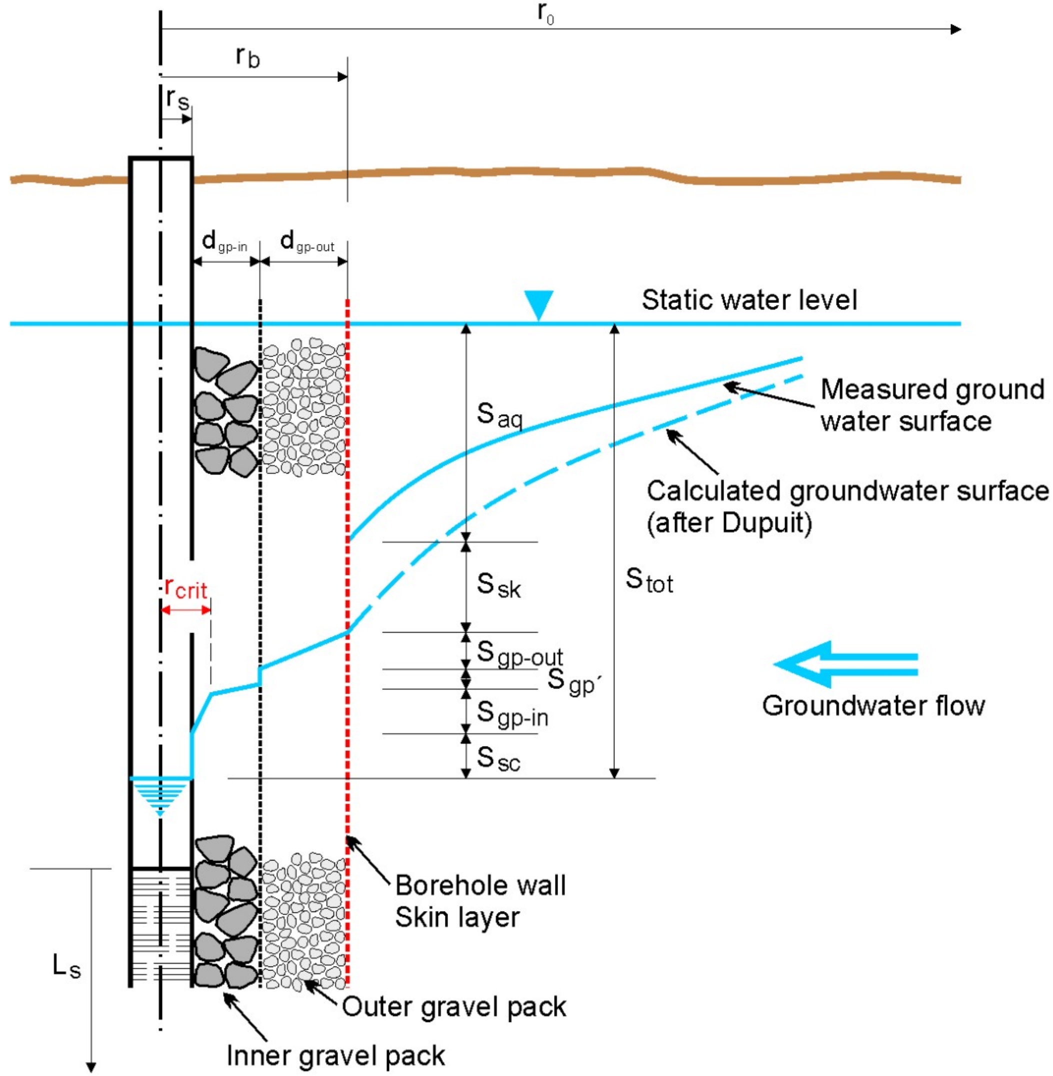
$$+ \quad \frac{Q}{2\pi \cdot T} \cdot \frac{(1 - p_p)}{p_p} \cdot ln \left[\frac{(1 - p_p) \cdot L_s}{r_w} \right]$$

Wells: components

Flowing goundwater passes through:

- Aquifer
- Borehole wall (skin layer)
- Gravel pack (single or dual)
- Screen (slots)
- Well interior (screen and casing)
- Pump
- Riser pipe





Houben & Treskatis (2007)

Total drawdown – the mother of all equations

$$s_{tot} = s_{aq} + s_{sk} + (s_{gp} + s_{cv}) + s_s + s_{up} =$$

$$= \frac{Q}{2 \cdot \pi \cdot K_{aq} \cdot B} \cdot ln \frac{r_0}{r_b}$$

~~Aquifer~~ – linear laminar (Darcy-Thiem)

$$+ \frac{Q}{2 \cdot \pi \cdot K_{sk} \cdot B} \cdot ln \frac{r_{sk-o}}{r_{sk-i}}$$

Skin layer – linear laminar (Darcy-Thiem)

Convergence (Boulton)

$$+ \frac{Q}{2 \cdot \pi \cdot K_{gp} \cdot B} \cdot ln \frac{r_b}{r_s} + \beta' \cdot \left(\frac{Q}{2\pi \cdot K_{gp} \cdot B} \right)^2 \cdot \left(\frac{1}{r_s} - \frac{1}{r_b} \right) + \frac{Q}{n_c \cdot K_{gp} \cdot B} log \frac{2}{1 - \cos\delta \cdot \pi}$$

Gravel pack

non-linear laminar (Forchheimer-Engelund)

$$+ \frac{1}{2g} \cdot \left(\frac{Q}{2\pi \cdot r_s \cdot B \cdot C_v \cdot C_c \cdot A_p} \right)^2$$

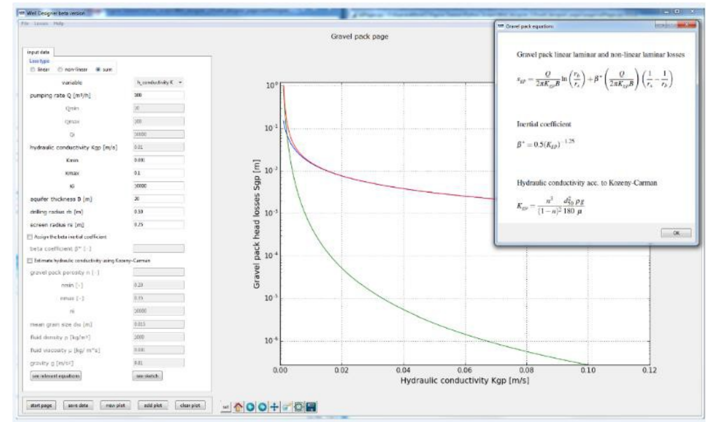
Screen – turbulent (orifice eq.)

$$+ f_D \cdot \frac{L_p}{d_p} \cdot \frac{\left(Q / \left(\frac{\pi \cdot d_p}{4} \right) \right)^2}{2g}$$

Well interior (upflow) – turbulent (Darcy-Weisbach)

But I was always bad at math…

- Excel tool, computes drawdown for all well components
- Allows comparison of options → optimization
- “virtual“ step-drawdown tests
- Python application



Welcome to Well Designer!

INPUT DATA

Parameter	Symbol	Unit	1st Well	3rd Well	4th Well
Pumping rate	Q	[m³/h]	75	125	200
Drilling diameter (at screen depth	d_b	[m]	0,45	0,335	0,45
Screen diameter	d_s	[m]	0,25	0,175	0,25
Casing diameter	d_{cs}	[m]	0,25	0,175	0,8
Aquifer thickness (screen length)	B (=L_s)	[m]	20	10	20
Radius of influence	r_0	[m]	1000	1000	1000
Aquifer hydraulic conductivity	K_{aq}	[m/s]	1,00E-03	1,00E-03	1,00E-03
Aquifer mean grain size	d_{50aq}	[mm]	1	1	1
Aquifer porosity	n_{aq}	[]	0,25	0,25	0,25
Gravel pack hydraulic conductivity	K_{gp}	[m/s]	5,00E-03	5,00E-03	5,00E-03
Gravel pack mean grain size	d_{50gp}	[mm]	5	5	5
Gravel pack porosity	n_{gp}	[]	0,3	0,3	0,3
Skin layer hydraulic conductivity	K_{sk}	[m/s]	1,00E-06	1,00E-06	1,00E-06
Skin layer thickness	d_{sk}	[mm]	1	1	1
Number of screen slots (total)	n_s	[]	100	100	100
Number of screen slots per circum	N	[]	100	10	10
Aperture of slot (slot opening wid	w_{sl}	[m]	0,002	0,002	0,002
Distance between slot centers	w_s	[m]	0,008	0,008	0,008

RESULTS

Parameter	Symbol	Unit	1st Well Value	1st Well Quality Control	3rd Well Value	3rd Well Quality Control	4th Well Value	4th Well Quality Control
Entrance velocity at borehole wall	$v_{f\text{-}aq}$	[m/s]	0,0007		0,0033		0,0020	
Entrance velocity at screen	$v_{f\text{-}sc}$	[m/s]	0,0013		0,0063		0,0035	
Entrance velocity at borehole wall	$v_{a\text{-}aq}$	[m/s]	0,0025	OK	0,0110	OK	0,0066	OK
Entrance velocity at screen	$v_{a\text{-}sc}$	[m/s]	0,0265	OK	0,1263	too high	0,0707	too high
Hydraulic conductivity screen	K_{sc}	[m/s]	0,654	OK	0,654	OK	0,654	OK
Reynolds number at borehole wall	Re_b	[]	0,7	OK	3,3	OK	2,0	OK
Reynolds number at screen	Re_{sc}	[]	6,6	OK	31,6	too high	17,7	slightly elevated
Reynolds number inside screen	Re_{sc}	[]	106.123	turbulent	252.675	turbulent	282.996	turbulent
Reynolds number inside casing	Re_{cs}	[]	106.123	turbulent	252.675	turbulent	88.436	turbulent
Upflow velocity inside screen (Q/A	$v_{up\text{-}sc}$	[m/s]	0,42	OK	1,44	OK	1,13	OK
Upflow velocity inside casing (Q/A)	$v_{up\text{-}cs}$	[m/s]	0,42	OK	1,44	OK	0,11	OK
Specific inflow	Q/L_s	[m³/s*m]	0,0010		0,0035		0,0028	
Petersen criterion	Pe	[]	28,0	OK	20,0	OK	28,0	OK
Skin factor	F_s	[]	4,4		6,0		4,4	
Critical radius	r_{crit}	[m]	0,02	OK	0,06	OK	0,05	OK
Gravel pack thickness	d_{gp}	[m]	0,100	OK	0,080	OK	0,100	OK
Gravel pack granulometry	d_{50gp}/d_{50aq}	[]	5,00	OK	5,00	OK	5,00	OK
Pump space (minimum)	$d_{pp} + d_{cool}$	[]	0,175	OK	0,300	pump won´t fit	0,300	OK

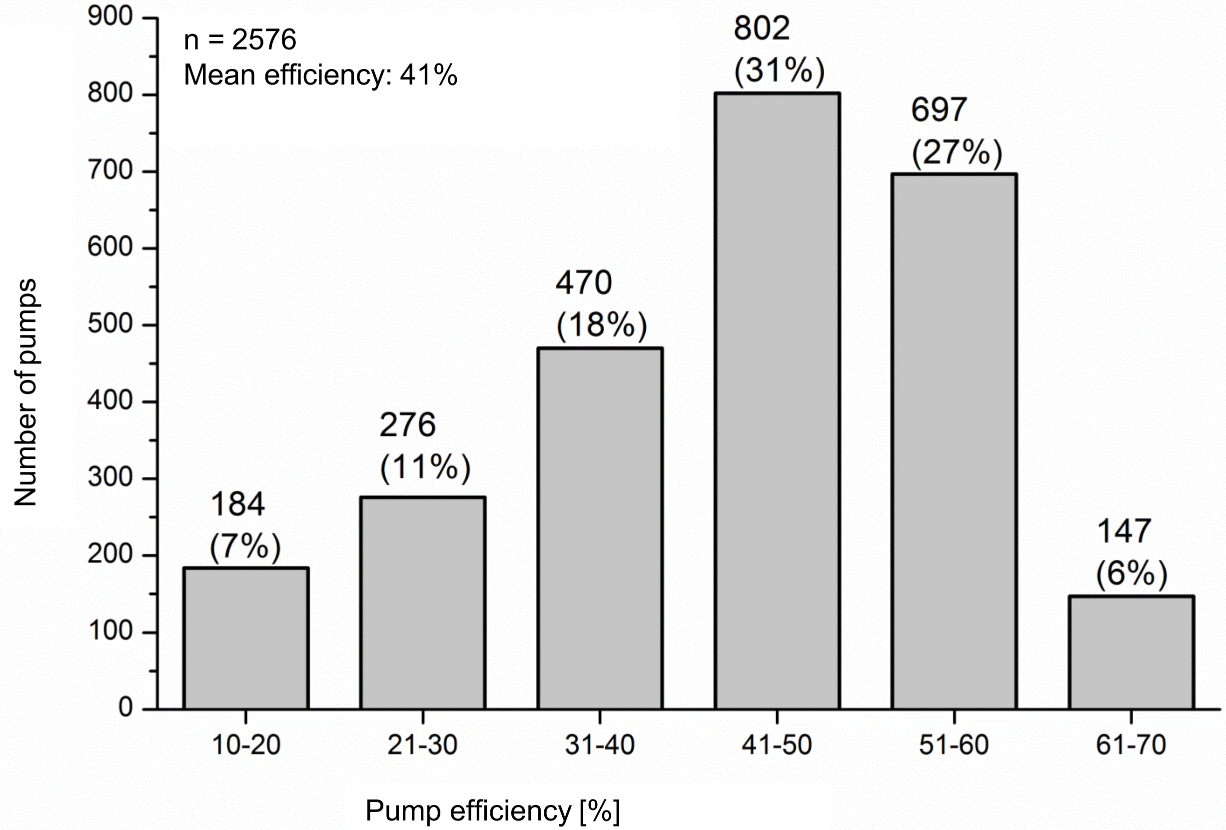
Pump (in)efficiency

Study by German pump industry. Causes for low efficiency:

1. wrong dimensioning/selection
2. ageing (incrustations…)

Great Britain (Environm. Agency):
η_p = 15 to 60 %
(residential pumps η_p = 40 %)

$$P_{gros} = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_p}$$



1 m drawdown ≡ 4.54*10^{-3} kWh/m³
at η_p = 0.6

Key lessons

Accept the inevitable: all wells age

Know your enemy: identify cause of ageing

Watch your enemy: continuously monitor well yield

Kill it before it grows: do not let incrustations harden or particles accumulate

Chose your weapon: select method according to well & ageing type

Rehabilitations do not stop ageing, they only buy more time

Don´t flog dead horses: think of reconstruction when rehabilitation fails

Best prevention measure: properly designed and constructed well

Want to know more?

Hydrogeol J (2015) 23:1633–1657
DOI 10.1007/s10040-015-1312-8

PAPER

Review: Hydraulics of water wells—flow laws and influence of geometry

Georg J. Houben[1]

Hydrogeol J (2015) 23:1659–1675
DOI 10.1007/s10040-015-1313-7

PAPER

Review: Hydraulics of water wells—head losses of individual components

Georg J. Houben[1]

Hydrogeol J (2016) 24:2093–2101
DOI 10.1007/s10040-016-1457-0

PAPER

How appropriate is the Thiem equation for describing groundwater flow to actual wells?

Franziska Tügel[1] · Georg J. Houben[2] · Thomas Graf[1]

Groundwater

Analysis of Wellbore Skin Samples—Typology, Composition, and Hydraulic Properties

by Georg J. Houben[1], Matthias Halisch[2], Stephan Kaufhold[3], Christoph Weidner[3], Jürgen Sander[4], and Morris Reich[5]

Thank you for your attention.

Questions are welcome !