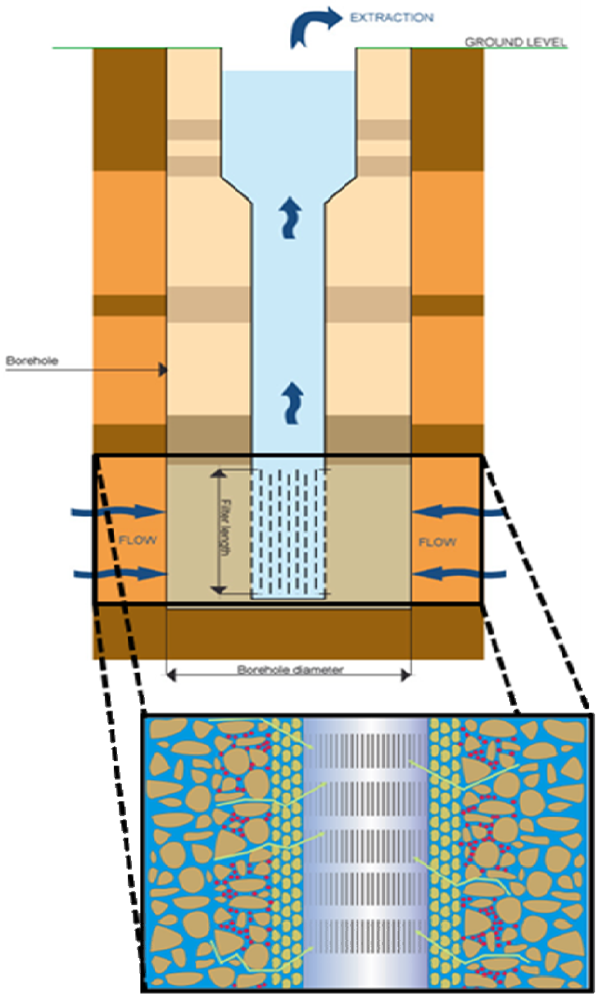

Analysis and improvement of well capacities in fine grained sand aquifers

Master Thesis
Hydrogeology, Environmental Hydrogeology Track

by Mark Janssen Lok

Supervised by Drs. B.C. Drijver from IF Technology
and Prof. Dr. R. Schotting from Utrecht University

Universiteit Utrecht

Abstract

Minimizing well clogging by particles is considered one of the most important aspects of well design. Well design standards restrict the attraction of particles by limiting the flow velocity at the borehole wall. The corresponding limitation of the well capacity is especially problematic for the feasibility of projects in aquifers consisting of fine sand. To investigate the possibility of extending the current design standards, the real flow velocities in a number of wells were analyzed, using data from vertical flowmeter logs. Groundwater models were used to deduce a simulated flowmeter log. Comparing the simulated flowmeter log to the measured flowmeter log, provides information on the performance of different parts of the well screen. For a number of wells, the measured and simulated flowmeter logs agree quite well, which gives confidence in the approach. In a number of other wells parts of the well screen did not contribute or appeared to underperform significantly (in most cases the lower part), which is in accordance with experiences from contractors that perform vertical flowmeter logs. Since underperformance of one part of the well screen must be compensated by the other part, design flow velocities are more likely to be exceeded in the other part in that case (especially in the upper screen section). Design exceeding in part of the well screen could not be correlated with sand production. It is more likely that sand production is caused by the (unintentional) screening of sand layers that are too fine in comparison to the grain size of the gravel pack.

Possible causes for an uneven flow distribution were investigated. Partial well screens produce more water from the end of the well screen than from the middle part, because water can approach the well screen from more directions (i.e. laterally and vertically). The potential influence of head losses due to friction is usually minimized by choosing a sufficiently large well screen diameter. The most important reasons for underperforming well screen sections appear to be differences in the grade of clogging of the concerning part of the borehole. These differences are initiated during the procedure of well construction and well development. Due to an increase in the overpressure with depth inside the borehole during the drilling procedure (density of drilling fluid with suspended sediments is relatively high), more persistent filter cakes are formed in the deeper parts of the well. Well development techniques that treat the whole well, are therefore likely to be more successful in the upper part. This is enhanced when extreme flow velocities occur during well development, leading to significant head losses due to friction and thereby reducing the effectiveness in the lower part of the screen. When partial removal of the filter cake is achieved, preferential flow paths are created which subsequently complicate the treatment of other parts of the borehole. This can explain why techniques like overpumping and surging tend to be more effective in the upper part of the well screen, especially when long well screens are concerned. Wells in aquifers consisting of fine sand seem to be more likely to end up with an uneven flow distribution than wells in coarse sand. In one well, sectional surging proved to be effective to treat the underperforming lower part of the well screen, suggesting a more frequent use of this technique.

Acknowledgements

First of all I would like to express my sincere thanks to Benno Drijver without whom I would not been able to carry out this research. The fact that he has been by my side through the whole research to correct and advise me, has been proved to be of great value. I think we managed to produce some nice and useful results for the further future of (HT-)ATES.

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Further on I would express my thanks to companies which supplied data for the research: Deltares (Pieter Doornenbal and Rein van Schrojenstein Lantman), Haitjema (Kor Reinink) and Evides (Rob Lafort). Special thanks go out to Pieter Doornenbal from Deltares who provided data and a working place for several days. Also Ton Timmermans (Terratech), who presented his ideas regarding drilling fluids and well clogging, has been of great importance for this research.

During the days I have spent at the office of IF Technology, every day the daily grind was interrupted by a few thrilling games of ping-pong. I would like to thank Kees and Bernd for the exciting matches, and I am grateful to Chris and Arjen for the easy wins.

Table of Contents

1. Introduction

Aquifer Thermal Energy Storage (ATES) Systems are currently in use for almost thirty years. These systems offer a relatively cheap way of storing excess energy in aquifers during time of abundance and retrieving this energy in times of need. Cold energy saved up in the winter months can be produced during warmer periods to cool buildings. This technique saves a lot of energy and therefore has significant economical (cost savings) and environmental advantages (reduction of energy use and related greenhouse gas emissions). The number of ATES systems has been growing exponentially and this trend is expected to continue in the future. Cooling buildings with groundwater is a very energy efficient way of lowering temperatures inside a building compared to the reference technology, air-conditioning. The heating of buildings is also more energy efficient compared to its reference technique, the combustion of natural gas. However due to the electricity consumption of the pumping installation and the required heat pumps, the overall efficiency differences are not big and sometimes (when the system is not functioning properly) even negative.

ATES systems cannot be installed simply in every place, extensive analysis has to be done over a certain aquifer. Extraction and infiltration with a certain discharge requires a suitable aquifer, with a transmissivity high enough to be able to produce and inject the required amount of water. Additionally these installations have to be designed in a way that its lifetime is long enough to make it profitable. Generally systems are designed for 20 to 30 years of lifetime.

IF Technology is an engineering-consultancy company, specialized in renewable energy solutions, and is the leading consultant for the development of ATES systems in the Netherlands. It uses certain design standards to ensure good functioning of the installed system and the drilled wells. These standards prevent sand production and the clogging of wells by small particles which will decrease permeability around the wellbore and eventually cause mechanical well clogging. Medium to coarse grained sand aquifers are broadly considered to be suitable for ATES. Fine sand aquifers are often found to be less suitable regarding the present standards, because the capacity of the wells is relatively low leading to relatively high investment costs and a negative impact on (economical) feasibility. But there are indications which make it worth investigating the possibility of altering the standards. When design capacities grow, the feasibility of a project increases. High Temperature ATES (HT-ATES) is presumed to be efficient only when hot water can be stored in aquifers with low permeability and high insulation to prevent large heat losses and water movement due to density differences. The aquifers at the depths where temperatures are high enough for geothermal heat production also have low permeability values. Using the current design standards would make these projects unfeasible from an economical point of view.

These topics make it useful to examine the well design standards for infiltration and extraction in fine grained sand aquifers. A lot of factors have to be taken into account when a good analysis has to be made. Soil properties like hydraulic conductivity, permeability, porosity, grain size distribution and pore diameter have to be investigated. Existing methods and equations to determine these properties are examined to search for improvement.

1.1 Research motive

Despite this, the most important motives of this research are indications both from literature and from the field, which tell that velocity distributions along the length of the well screen are not constant. The experience is that some parts of the well screen, the upper section in particular, often provides more water than the remaining parts. When this is in fact true, flow velocities in these parts of the screen compensate for less contributing parts and are expected to exceed the design standards without causing major problems. This could mean that higher flow velocities and pumping capacities could be allowed, when the flow distribution along the length of the well screen can be improved. Theoretically higher capacities in fine grained aquifers can then be allowed, making HT-ATES systems more feasible.

Another reason to investigate the current design standards is the fact that only very few projects of IF Technology suffer from (serious) well clogging or sand production. When problems are scarce, it suggests the possibility of achieving higher flow rates per well to eventually come to an improvement of the feasibility of these types of systems.

Models of simple well construction theoretically picture the vertical flow-distribution. The flow meter logs of different wells will be used to analyze the flow distribution. Relations between field data and theoretical data are exposed. Because of the heterogeneity in aquifers, trends in practical datasets can be explained by multiple factors.

Ultimately real projects, both successful and unsuccessful, are simulated to find out whether and in which degree flow velocities exceed the design. Likewise these models can be used to investigate whether the expected discharges for a simulated well screen segment is concurrent with the measured values. By using real projects, theories from the field and from literature will be tested and compared to practical observations. The output of this research can lead to a positive change in the treatment of the current design standards IF Technology makes use of.

1.2 Studied Projects

As mentioned, both successful and unsuccessful projects will be investigated. First it has been tried to simulate wells which are functioning as desired. When the base model will be developed to a level where this works properly, unsuccessful wells can be simulated to see in what screen segments problems are appearing. From this point on, an extensive analysis can be done for each situation.

To implement this research, real projects are requisite. IF Technology is involved in many well-construction projects throughout The Netherlands. In total, 13 wells are analyzed extensively in order to investigate possible problems occurring in pumping wells. A wide variety of motives will be described, just as possible measures that can be taken to prevent well malfunctioning.

Essential for good analysis of a production well, is a vertical flow log. Unfortunately this is no standard procedure of a project. This is why finding complete datasets of projects has not been the easiest thing to accomplice. Despite this, multiple projects had the required data available in order to make an extensive analysis.

The projects studied are situated at different locations in The Netherlands:

Fig. 1. Analyzed projects are distributed through the middle and southern regions of The Netherlands (Google Maps, 2012).

2. Theoretical Background

2.1 Aquifer Capacity Parameters

Every aquifer has different properties which determine the suitability for ATES purposes. The main aspect is the hydraulic conductivity of the soil, which is determined by other factors. Some of these characteristics can be approximated quite well. Others remain difficult to determine, obviously this has to do with the high grade of heterogeneity of most aquifers.

2.1.1. Hydraulic conductivity

Hydraulic conductivity is an important characteristic of an aquifer. It is essential in the process of deciding whether to place a pumping and/or infiltration device in an aquifer.
The hydraulic conductivity of a soil is determined by multiple factors:

- Permeability
    - Average grain size
    - Grain size distribution
    - Porosity
- Dynamic viscosity of the fluid
- Density of the fluid

These factors are also depth dependent, however considering only shallow depths; the effects can be neglected in most cases. But when one looks at aquifers situated at large depths (500 m or deeper), it is important to take these effects into account. Systems in this depth category are almost always designed for geothermal heat production installations.

Hydraulic conductivity is given by:

$$k = \frac{\rho_f \cdot g}{\mu} \cdot K_i$$

k = hydraulic conductivity (m/s)
ρ_f *= density of fluid (kg/m^3)*
g = gravitational constant (m/s^2)
μ *= dynamic viscosity (Pa.s or kg/(m.s))*
K_i *= intrinsic permeability (m^2)*

Shepherd equation

In most practical situations, approximating a proper value for the intrinsic permeability is the biggest obstacle to calculate the hydraulic conductivity of an aquifer. Therefore only approximations can be made. IF Technology uses the Shepherd equation (1989) to estimate hydraulic conductivity.

$$k_i = cd^{(1.65\ to\ 1.85)}$$

k = hydraulic conductivity (m/d)
c = constant
d = particle diameter (mm) (approximated by the D50 value)

Values of c and the exponent both generally decrease with decreasing textural maturity and increasing induration (Fig. 2). IF Technology uses the following formula to calculate the expected hydraulic conductivity (for an ambient temperature of ± 11 °C):

$$k_i = 150 * D50^{1.65}$$

D50 = median particle diameter (mm)

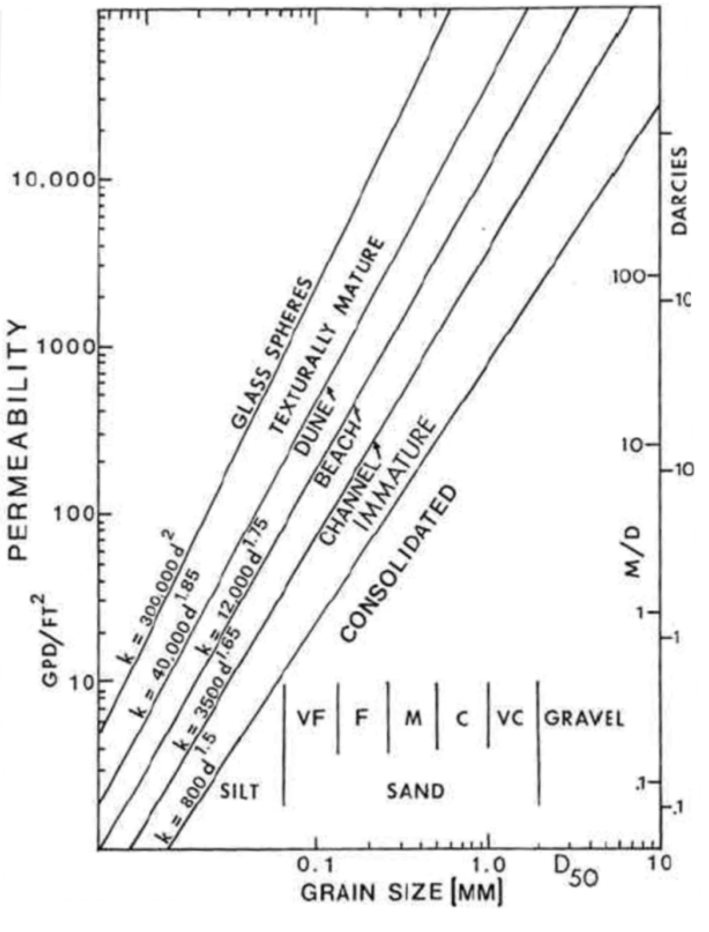
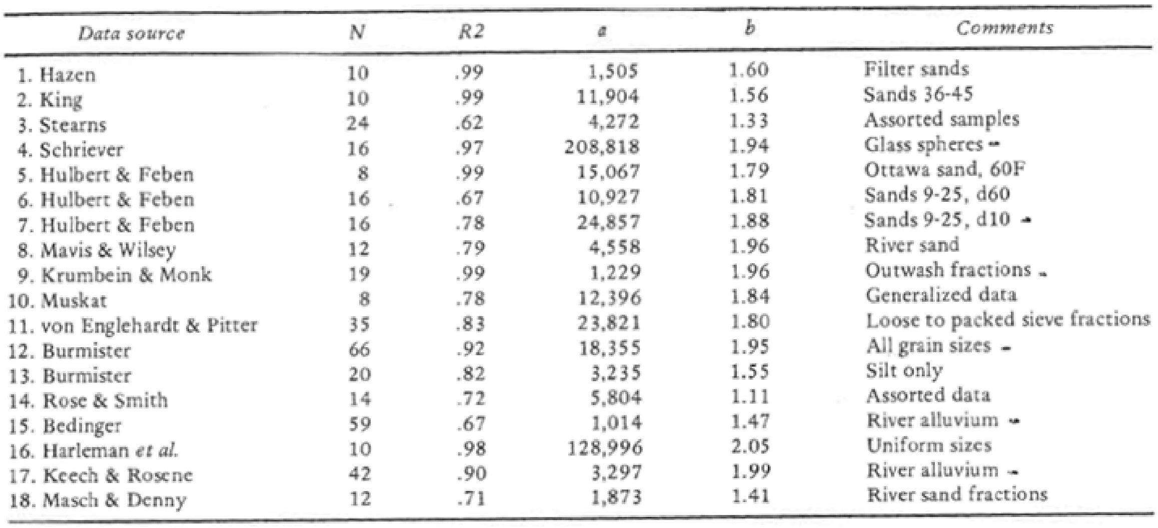


Fig. 2. Graph of permeability against grain size. The units are gpd/ft² on one side and m/d on the other side. Application for different depositional environments are tentatively compared according to their grain sizes and degree of textural maturity (Shepherd, 1989).

This equation relates grain sizes to hydraulic conductivity; porosity and temperature (significantly different than 11 °C) are not included. One has to bear in mind that this is only an approximation of the hydraulic conductivity. Because aquifers are very heterogeneous and complex, it is impossible to get to the real numbers of the required parameters without doing a field pumping test. The average grain size can't even be determined; therefore a D50 value of a soil sample is used to approximate the grain size of that soil layer.

Mostly coarse aquifers are used for well screen installations. This could mean that the constants in the altered Shepherd equation are not suitable for approaching good k values for fine sand aquifers. Somewhat lower values for c and for the coefficient the 'Silt only' formation comes closest to what one expects of a fine sand aquifer: $k = 132 * D50^{1,55}$ (Table 1). At a D50 of 280 µm this formula gives the same hydraulic conductivity as the formula used by IF Technology. At smaller grain sizes the hydraulic conductivity calculation with the latter formula is somewhat higher: 5% at 170 µm and 10% at 110 µm.



Data source	*N*	*R2*	*a*	*b*	*Comments*
1. Hazen	10	.99	1,505	1.60	Filter sands
2. King	10	.99	11,904	1.56	Sands 36-45
3. Stearns	24	.62	4,272	1.33	Assorted samples
4. Schriever	16	.97	208,818	1.94	Glass spheres
5. Hulbert & Feben	8	.99	15,067	1.79	Ottawa sand, 60F
6. Hulbert & Feben	16	.67	10,927	1.81	Sands 9-25, d60
7. Hulbert & Feben	16	.78	24,857	1.88	Sands 9-25, d10
8. Mavis & Wilsey	12	.79	4,558	1.96	River sand
9. Krumbein & Monk	19	.99	1,229	1.96	Outwash fractions
10. Muskat	8	.78	12,396	1.84	Generalized data
11. von Englehardt & Pitter	35	.83	23,821	1.80	Loose to packed sieve fractions
12. Burmister	66	.92	18,355	1.95	All grain sizes
13. Burmister	20	.82	3,235	1.55	Silt only
14. Rose & Smith	14	.72	5,804	1.11	Assorted data
15. Bedinger	59	.67	1,014	1.47	River alluvium
16. Harleman *et al.*	10	.98	128,996	2.05	Uniform sizes
17. Keech & Rosene	42	.90	3,297	1.99	River alluvium
18. Masch & Denny	12	.71	1,873	1.41	River sand fractions

Table 1. Summary of data and results of regression analyses from different authors (Shepherd, 1989).
N = Number of data points.
R2 = Coefficient of determination for regression
a = a (gpd/ft^2) in equation '$y = a*x^b$'
b = b in equation '$y = a*x^b$'

Kozeny-Carman equation

One of the disadvantages of the Shepherd equation is the fact that it does not take into account some very important parameters like porosity. The Kozeny-Carman equations approximate the hydraulic conductivity by taking into account the median grain size and the porosity, both important factors. A common form of this equations is:

$$k = \frac{\rho_f g}{\mu}[K_i]$$

In which:

$$K_i = \left(\frac{n^3}{(1-n)^2}\right)\left(\frac{D50^2}{180}\right)$$

n = porosity (-)

D50 = median grain size (m)

There are many forms of the Kozeny-Carman equation. Some of them take more parameters into account like tortuosity and effective pore radius. In the equation above, these parameters are assumed to be constant and are enclosed into a constant.

2.1.2 Porosity

Porosity is a fraction between 0 and 1, typically ranging from less than 0.01 for solid granite to more than 0.5 for peat and clay. Recently deposited clay can even have porosity values of 0.9. There are different ways to approach and 'determine' the porosity in a sand formation. Nevertheless it is impossible to determine the real, exact value of the porosity. Heterogeneity of sand formations is the reason for this. In the literature some methods can be found to determine porosity.

Archie method (1942)

Archie found the next relationship regarding determining porosity by the use of electric resistances within aquifers:

$$\left(\frac{1}{Ro}\right) = \left(\frac{1}{an^{-m}Rw}\right)$$

Ro = electric resistance aquifer [Ohms m]

Rw = electric resistance water [Ohms m]

a = clay factor, between 1,00 and 1,09 (0% clay to 75% clay) [-]

m = cementation factor, between 1,3 and 2.0 (unconsolidated to completely consolidated)[-]

n = porosity [-]

This method uses electrical resistance measurements that will not be available in many cases. It includes a cementation factor, which is an indication of the consolidation of the formation. Depth is an important factor, because pressure increases with depth. And with increased pressure, the same amounts of grains occupy less space. This means porosity decreases. Also related to this depth dependent porosity value, is the geologic history of a formation. When a formation is old enough, it is possible that because of geological events, the depth has varied through time. It could be that a formation had a depth of a kilometer and was subsequently lifted up. This might result in a different level of consolidation than one would expect, based solely on the current depth of a formation (Fig. 3).

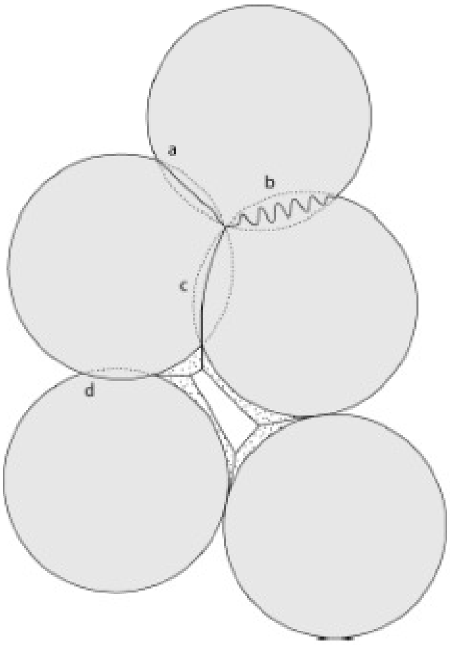


Fig. 3. Schematic image of porosity decrease as consequence of dissolution caused by pressure (increases). Quartzite is pictured as the dotted areas. The dotted lines show the original grain boundaries. (a) Contact with even dissolution of both grains. (b) Contact with even dissolution along boundary. (c) Contact with uneven dissolution of two grains. (d) Contact with dissolution of only one of the two grains (Houseknecht, 1984).

The next equations include depth as an important factor.

Athy method (1930)

Athy 1930 defined this exponential relationship between porosity and depth.

$$\emptyset(z) = \emptyset_0 e^{-kz}$$

z = depth (m)

$\emptyset_0$ = surface porosity

k = compaction coefficient (m^{-1})

Bahr Method (2001)

This equation shows a linear behavior at shallow depths and an exponential behavior at greater burial depths (Bahr et al., 2001):

$$\emptyset(z) = \frac{e^{-cg(\rho_s-\rho_w)z}}{e^{-cg(\rho_s-\rho_w)z} + k_1}$$

$k_1 = (1 - \emptyset_0) / \emptyset_0$

ρ_s = grain density

ρ_w = water density

g = gravity acceleration

c = a constant

Bahr et al. (2001) demonstrate that this exponential behavior accurately fits a large worldwide collection of porosity data from compacted shale, silt and sandstone formations. Both methods assume that the current depth of the formation is equal to the maximum burial depth. For overconsolidated aquifers this assumption is not correct and the maximum burial depth (which will be unknown in most cases) should be used.

2.1.3 Dynamic Viscosity

Temperature increase with depth is a familiar phenomenon. The rate of this increase can be as much as 30 ^{0}C per kilometer in The Netherlands. In Fig. 4 the dynamic viscosity has been set out against temperature. Increasing temperature causes a decrease in viscosity.

When estimating hydraulic conductivity at large depths, viscosity is an important factor. The viscosity of 12 ^{0}C water is 4 times as high as the 100 ^{0}C water viscosity. A lower viscosity means that the fluid moves more easily through the porous medium, and will give a higher hydraulic conductivity. With a decrease in Temperature of 10 ^{0}C, the hydraulic conductivity decreases with about 25% because of the viscosity increase.

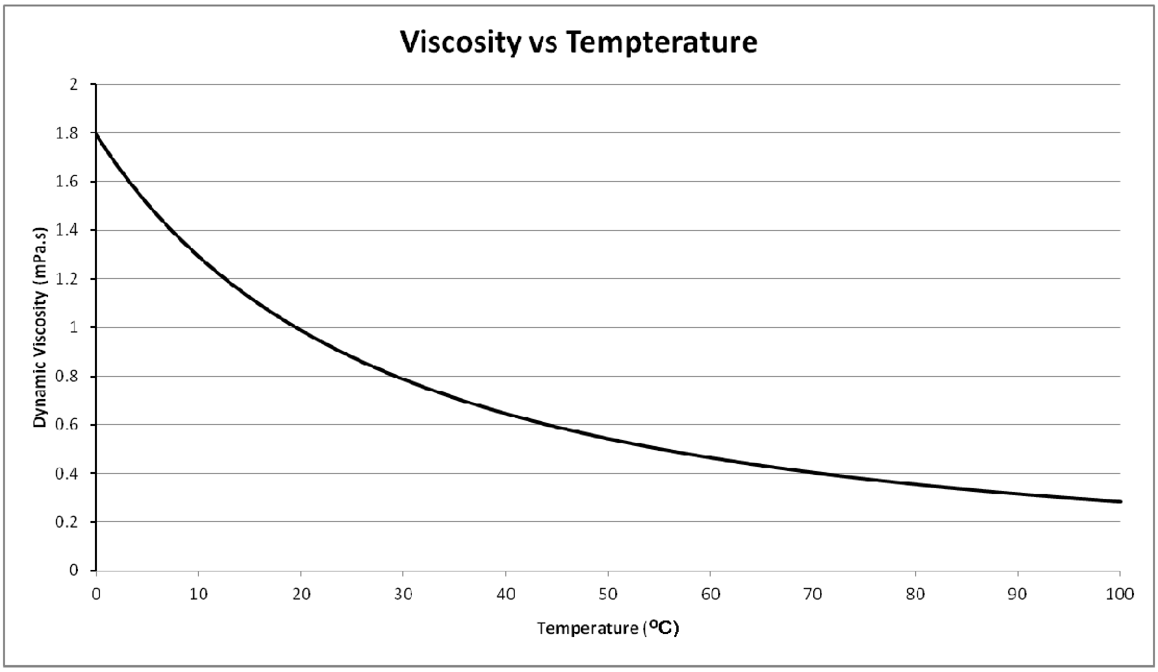


Fig. 4. Viscosity set out against Temperature to determine the change of viscosity through depth.

2.1.4 Density

Density is also a characteristic of a fluid which is closely related to Temperature:

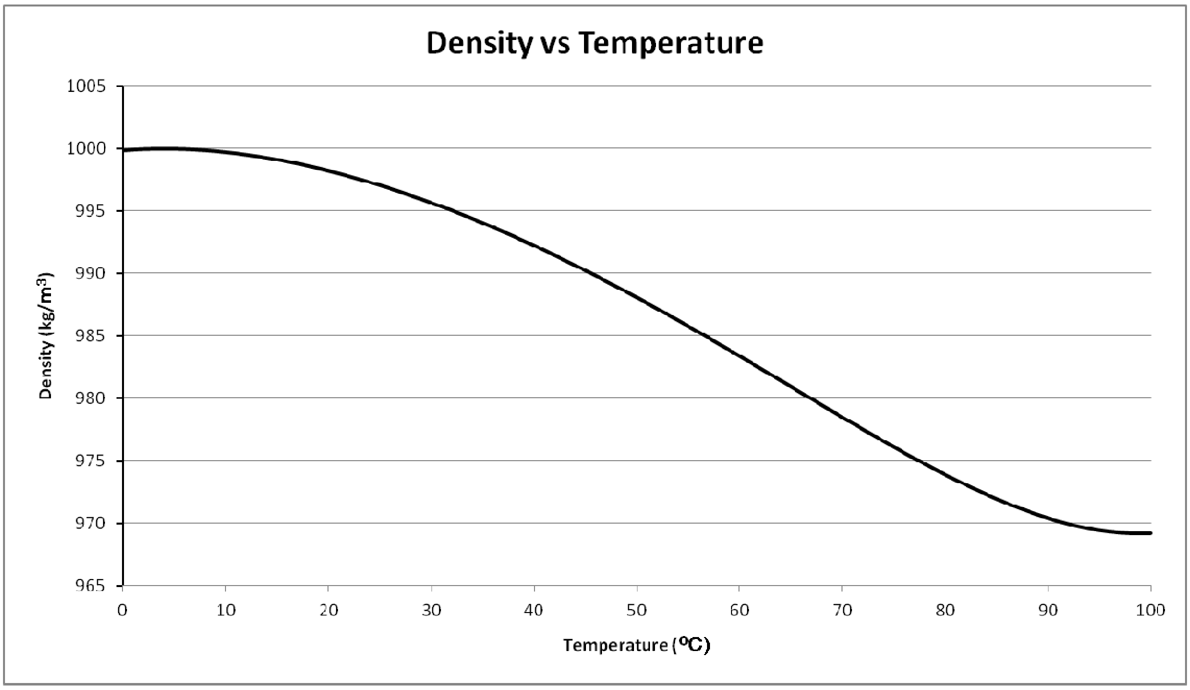


Fig. 5. Density set out against Temperature.

The Temperature effect on density is relatively small compared to the temperature effect on viscosity. A 3% decrease can be observed when water heats up from 10 ^{0}C to 90 ^{0}C. Salt concentration also influences the density of water in the subsurface. An increase in salt concentration results in a higher fluid density.

2.1.5 Pore diameter

Pore diameters are important, the diameter of a pore simply determines whether a particle can move through it or not. It is an important factor in the mobilization of particles.

The average pore diameter is often approximated by (Holtz en Kovacs, 1982):

$$d_p = 1/6 * D50$$

d_p = average pore diameter (µm)
D50 = median particle diameter (µm)

The pore diameter can also be estimated by a simple method, using a triangular constriction of three touching spheres. This results in a relation to estimate the size pore constriction:

$$d_p = d_{grain}/6.49$$

Both methods give similar results.

A porous medium with an average grain diameter of 500 µm has a theoretical average pore throat of 77 µm. Particles larger than this size will not be transported. A real aquifer is not homogeneous and has therefore different pore sizes. In general, based on average grain diameters, it is expected that a coarse aquifer will contain larger particles then a fine aquifer. From measurements reported in the literature (Hofmann 1998), it is known that small particles are abundant in all aquifers and that the number of particles in suspension decreases with increasing particle diameter.

McDowell-Boyer, L.M. et al. (1986) identified four particle filtration mechanisms, based on injection of a fluid with particles in a porous medium (Fig. 6).

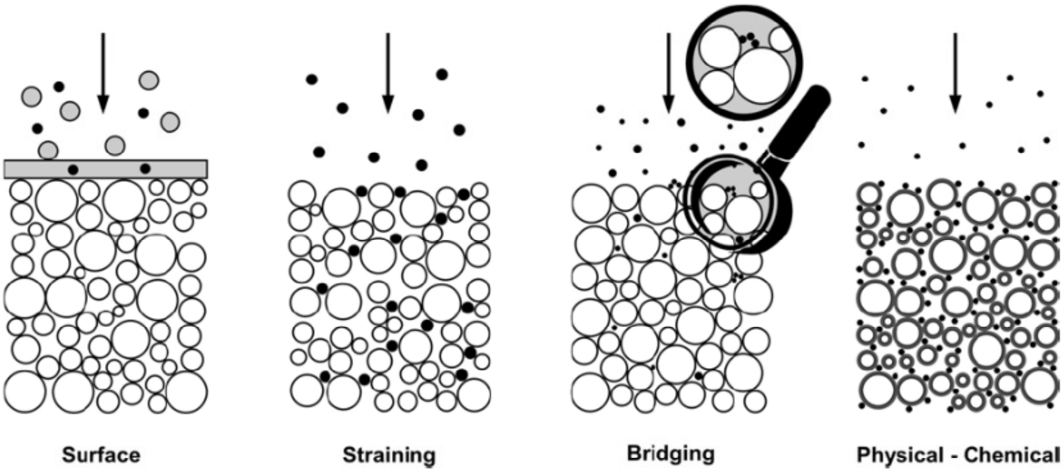


Fig. 6. Filtration mechanisms which are generally considered. Note the particle size dependence and difference in deposit morphology (McDowell-Boyer et al., 1986).

The classification of these processes is related to the ratio of particle sizes (in suspension) and the pore size distribution of the porous medium. If the average suspended particle size is smaller than the average pore size, particles will be able to flow through the porous medium. Depending on grain size and particle size distribution, larger particles will be trapped in smaller pores, because these particles are too large to pass through. This mechanism is known as straining or size exclusion.

Barkman and Davidson (1972) state that the largest particle that can pass through pores is conservatively estimated to be 10% of the average pore diameter. Combined with the Holtz and Kovacs equation this tells that particles moving successfully trough a porous medium have maximum sizes comparable with:

$$d_{particle} = \frac{d_{medium}}{6 * 10}$$

In an aquifer with an average grain size of 300 µm (medium sand) this infers that the ‘sand’ that is able to be transported successfully through the aquifer has a size of 5 µm. In the Wentworth grain size chart this represents very fine silt. So the question raises whether sand can be transported through a porous medium.

McDowell-Boyer et al. (1986) predict something different regarding particle sizes able to be transported through the pores.

$$\frac{d_{medium}}{d_{particle}} = 10$$

The three particle filtration mechanisms depicted in Fig. 6 can be categorized in medium- / particle-grain diameter ratios (d_m/d_p). Below 10, no transport is possible and a filter cake will be developed at the surface of the porous medium. Within the narrow window of particle size $10 < d_m/d_p < 20$, McDowell-Boyer (1986) found permeability reductions by a factor of 7-15, and deposited particles occupied greater than 30% of the pore volume. This window can be attributed to the process of straining. For relative small particles, $d_m/d_p > 20$, only 2-5% of the pore volumes were occupied by retained particles under equilibrium conditions. Permeability reductions were limited to only 10-50% of the clean porous media value. Xu (2006) approves this factor of ~20 and states that the effects of straining should be reconsidered when it is exceeded. When $d_p/d_m < 0.008$ ($d_m/d_p > 125$) he states that there is no straining. Choosing another fit would result in $d_m/d_p \approx 60$ which is equal to the formula based on Barkman and Davidson. Based on literature it is safe to say that filtered water does not sand grains of significant sizes.

Physical-Chemical filtration is only successful when the much smaller particles are retained by the media grains through electrostatic forces in the events of particles colliding with the media. Since particulate pollutants (bacteria, viruses, asbestos fibers) and colloidal matter which has a high sorption capacity for pollutants are micrometers and smaller in size, the ratio of media size to particle size, d_m/d_p, for sand and gravel aquifers exceeds 1000 when physical-chemical filtration is successful.

Whether a suspended particle travels successfully through a porous medium also depends on collision mechanisms. Yao et al. (1971) illustrate three dominant transport mechanisms of suspended particles flowing through porous media, ultimately leading to collision:

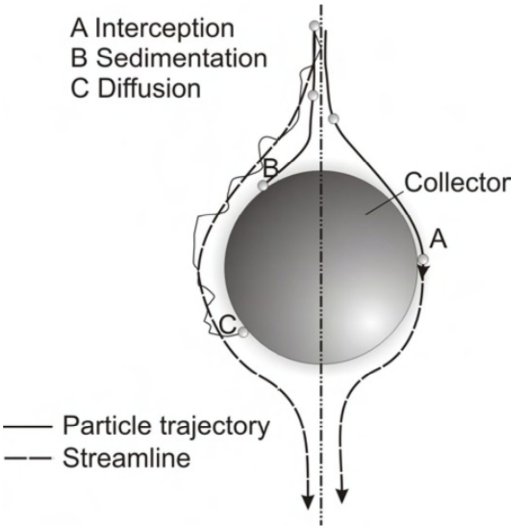


Fig. 7. Three dominant transport mechanisms of suspended particle transport to a collector surface (Yao et al., 1971).

Grain packing is an important factor in pore dimensions. The simplest grain structures are simple cubic and tetrahedral. These structures are pictured below including an equation of the pore dimension:

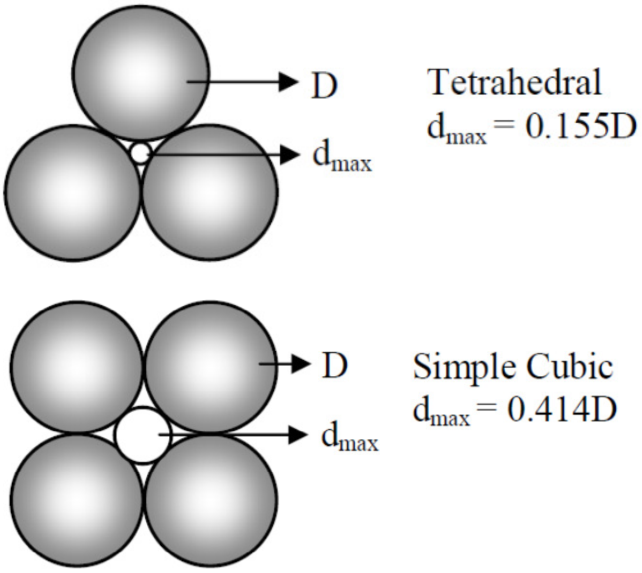


Fig. 8. **Pore throat sizes (i.e., diameter of largest spherical particle that can pass through the pore throat) for simple cubic and tetrahedral packings (Valdes and Santamarina, 2003).**

However in reality there are a lot of packing structures, each one of them creating different pores and pore dimensions. Tung (2004) explains the pore constriction of a body centered cube lattice is not formed by three tangential spheres but by two tangential spheres and two spheres being separated by a small distance as shown in Fig. 9. The pore space can be split up into two circular pores; a larger primary pore with radius r_p and a smaller secondary pore with radius r_s, shown in red in Fig. 9. The pore radius and diameter can be calculated using trigonometry.

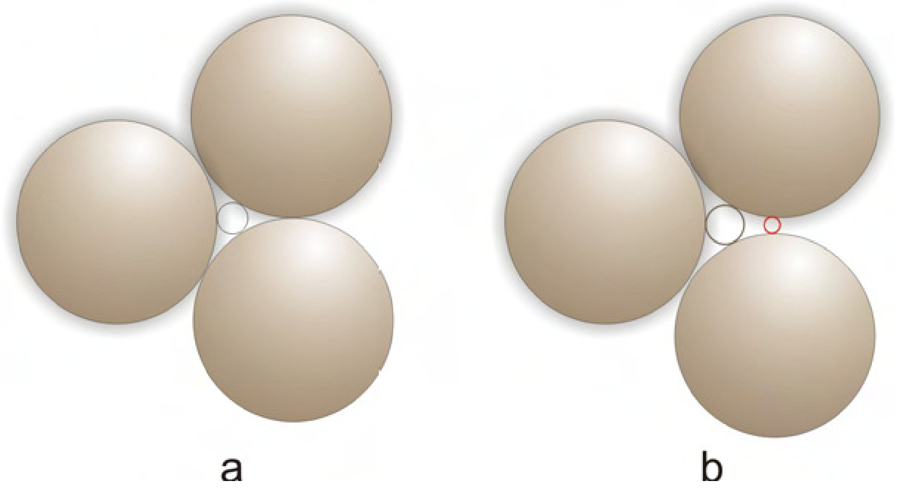


Fig. 9. Primary and secondary pore radii (Tung, 2004).

The mathematical approximations of the primary and respectively secondary pore radii are (Tung 2004):

$$r_p = \frac{\frac{4R(\tan(55^0)^2 + 1)}{3}}{\frac{4}{\sqrt{3}}\tan(55^0)} - R$$

$$r_s = \frac{2R}{\sqrt{3}} - R = R(\frac{2}{\sqrt{3}} - 1)$$

R = Grain radius (µm)

The primary pore will determine whether the secondary pore will clog or not. Colloids will be free to cross the pore constrictions until the amount of colloids flowing through the primary pore constriction is equal to or larger than the amount of particles needed to clog the pore. Once the primary pore is clogged, colloids approaching the primary pore will be diverted towards the smaller secondary pore, which will on its turn get clogged.

2.1.6 Grain size distribution

Porosity is not only dependent on grain size, shape and depth. It also depends on the grain size distribution (Fig. 10). An aquifer never consists of grains all with the same size. A homogeneous medium will always have a higher porosity compared to systems with varying grain sizes. Fraser (1935) explained this unambiguously:

- A very large grain (internal porosity = 0) replaces space which otherwise would be filled with smaller grains and pores between them. Porosity will decrease because of this.
- It disturbs the stacking of the smaller grains, which results in a looser stacking of the small grains close to a big grain. This tends to increase in porosity.

The negative effect on porosity of the first phenomenon increases when the grain size ratio increases, while the positive effect of the second phenomenon decreases with increasing grain size ratios. Until a certain point where the small grains won't be able to keep the big grains separated from each other anymore, increasing grain size ratio has a negative influence on porosity. After this point is reached, porosity starts to increase with bigger size ratios.

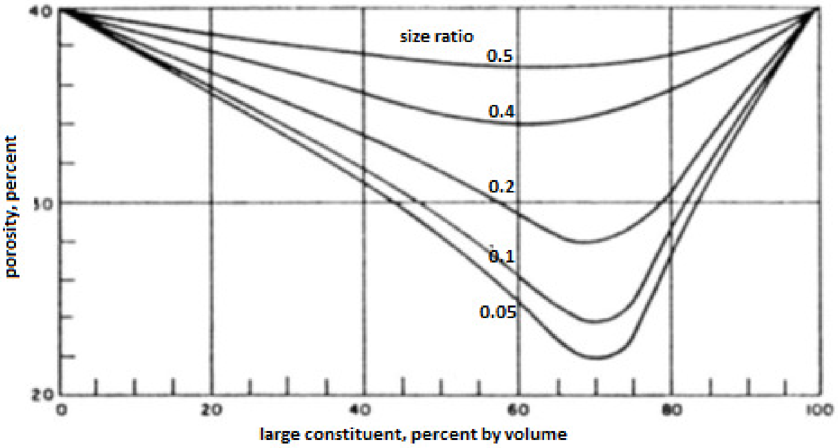


Fig. 10. Porosity of a sediment with grains of two different grain sizes (Furnas, 1929).

Despite the fact that the process discussed above describes a system with only two different grain sizes, the same reasoning can be used for sediments with a wide grain size distribution. Porosity will decrease with decreasing uniformity; but an unanimously quantitative equation will never be derived. (Alberts, 2005).

Fig. 11 shows typical grain size distribution graphs of different kinds of soils.

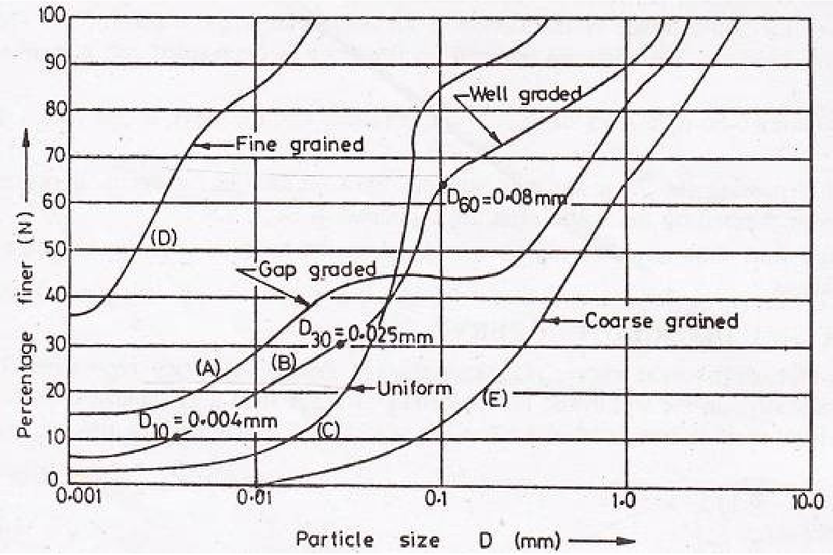


Fig. 11. Typical grain size distribution graphs of different kinds of soils (Mishra, 2012).

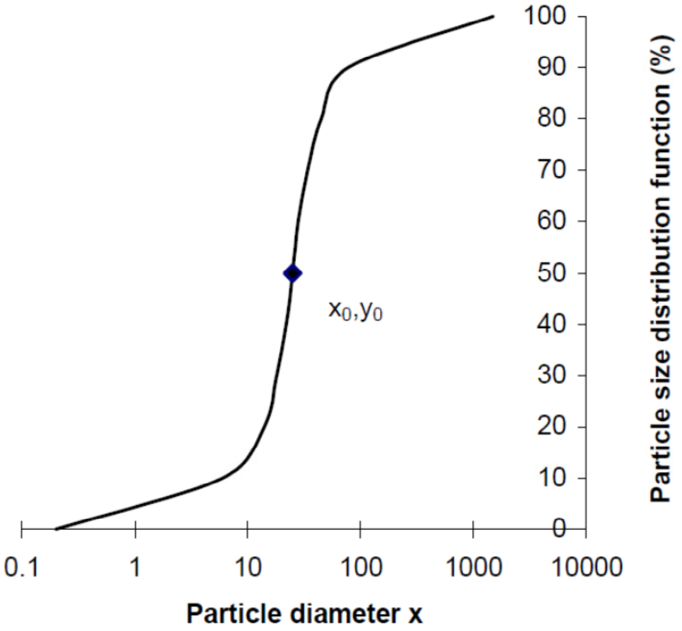


Fig. 12. Schematic curve of Andersson's particle size distribution function for an almost uniform soil (1990).

Grain size distribution also plays a major role in the internal soil stability of a porous medium. When big particles are surrounded by smaller particles it is not hard to imagine that the potential of the smallest particles to move through the pores is high.

The internal stability of a porous medium defines the possibility of a particle escaping from its 'fixed' position towards being a suspended particle going along with the flow. Li (2008) explains that the onset of internal instability is governed by: the grain size distribution curve; porosity and particle shape of the soil; and a combination of effective stress and critical hydraulic gradient.

When the structure becomes unstable because, for example the hydraulic gradient becomes too high, particles will be moved by the water which can lead to instability of the soil. Therefore the mobilization of particles has to be constrained to acceptable values. These aspects have been investigated in relation to the stability of soils below structures that retain water and are related to the risk of failure due to seepage. Knowledge from this field might be useful and is worth investigating.

2.2 Well Clogging

Well Clogging is defined as a decrease over time of the specific discharge rate, where the specific discharge rate equals the discharge rate over drawdown, and where drawdown is defined as the difference in water level during abstraction and during rest. Two types may be distinguished: screen slot (chemical) and well bore (mechanical) clogging (Van Beek, 2010). Wells can clog because of multiple reasons, disabling the water to be infiltrated or extracted out of/into an aquifer. A clogged well is characterized by a change in the injection/extraction head, together with a decrease in specific discharge.

Most of the time the first problems in ATES systems occur at the infiltration well, multiple causes of well clogging are:

- The presence of gas- or air bubbles in the injection water
- The growth of bacteria in the filter-slots, in the gravel pack and in the surrounding formation
- Reactions due to differences in groundwater composition in the aquifer between the top and the bottom of the well screen.
- Swelling and dispersion of clay by interaction between the aquifer material and the recharge water
- Sand production in the extraction well, followed by the infiltration of these particles in the infiltration well

These various clogging processes can support each other in the deterioration of pumping capacities. A good example of this is the interaction between suspended particles and bacterial growth at the well slots. Bacterial slime can function as an assemblage point for these particles, eventually leading to clogged well slots.

Clogging by gas bubbles can be prevented relatively easy by a proper design of the groundwater system meant to keep the pumped groundwater under sufficient pressure.

Bacterial growth and biological precipitation are harder to control and therefore they can cause problems. The determination of the assimilable organic carbon (AOC) content can give good indications of the clogging potential of a well. This level indicates how much substances are present that are useful for bacteria in the groundwater. If this value is low, it is unlikely that bacterial growth can cause well glogging. On the other hand it will be more likely that a well will clog with high AOC content. In general groundwater has lows AOC contents and bacterial clogging will not play a big role.

Chemical precipitation is also a potential danger that can be excluded in projects where sufficient subsurface analysis has been done. It is important that the water that is extracted from different depths is compatible. The well doublets are preferably located in the same aquifer to prevent any difficulties.

Temperature difference is also unlikely to play a big role in chemical clogging processes, because in normal ATES systems these differences are not big. In high temperature systems, where temperature differences are bigger, it is known that problems can occur inside porous media due to the temperature dependence of the solubility of (mainly) carbonates. The most common chemical problem in an ATES system is the clogging by Fe precipitation because of simultaneous production of oxic and anoxic groundwater. Deep ground water does usually not contain oxygen, hence the Fe atoms will remain in the solution. However when this water is pumped up and is mixed with O_2-rich water inside the extraction well or in the process of infiltration, this can cause great problems for an ATES system. Chemical processes like this should be avoided by all means. For the same reason it is essential to keep the system strictly air-tight (to prevent entrance of oxygen).

Variation in the grain structure of an aquifer can theoretically play a role, when the (shifting) flow processes cause a change in grain positioning. But the small changes in local porosity will not play a big role on the permeability and hydraulic conductivity of an aquifer formation.

Other features which influences the permeability of a porous medium are fluctuations in pH and salinity. According to Valdya (1992) formation damage can occur when water with a lower salinity is injected. This results into in-situ release of naturally existing attached fines (fine particles, generally clay) and it can cause permeability reduction in sandstones, thereby reducing water production. Infiltrating fresh water causes higher pH values, because of cation exchange. The repulsive forces between negatively charged clay particles will increase, resulting in release of fines. An abrupt change in salinity that leads to this decline in permeability is called a ‘water shock’. These processes can be prevented by avoiding large salinity contrasts in the aquifers that are used in ATES systems. When this is not prevented, the extracted water will mix and obtain new salt concentrations, which eventually can cause clay swelling and formation damage on the infiltration end of the system. In this case the part of the formation containing relatively salt water (usually the lower part) will clog.

Another major danger is the drilling fluid used during the well development process. Because of the overpressure used to prevent boreholes to collapse, part of these drilling fluids infiltrate in the aquifer. Theoretically this can cause problems which will be further discussed in the ‘Well development’ part.

The information above shows that accumulation of suspended material on the well bore is the most important process in well clogging processes. Main subject in this thesis will therefore be mechanical clogging by particles.

2.2.1 Mechanical Clogging

The particle load on a well bore can cause the clogging of the pores on and around the wellbore. The velocity of the clogging process is determined by this load on one hand and the filtering characteristics of the well bore on the other hand (Breedveld et al. 2007). The load on the well bore is equal to:

$$L_N = Q * C_N$$

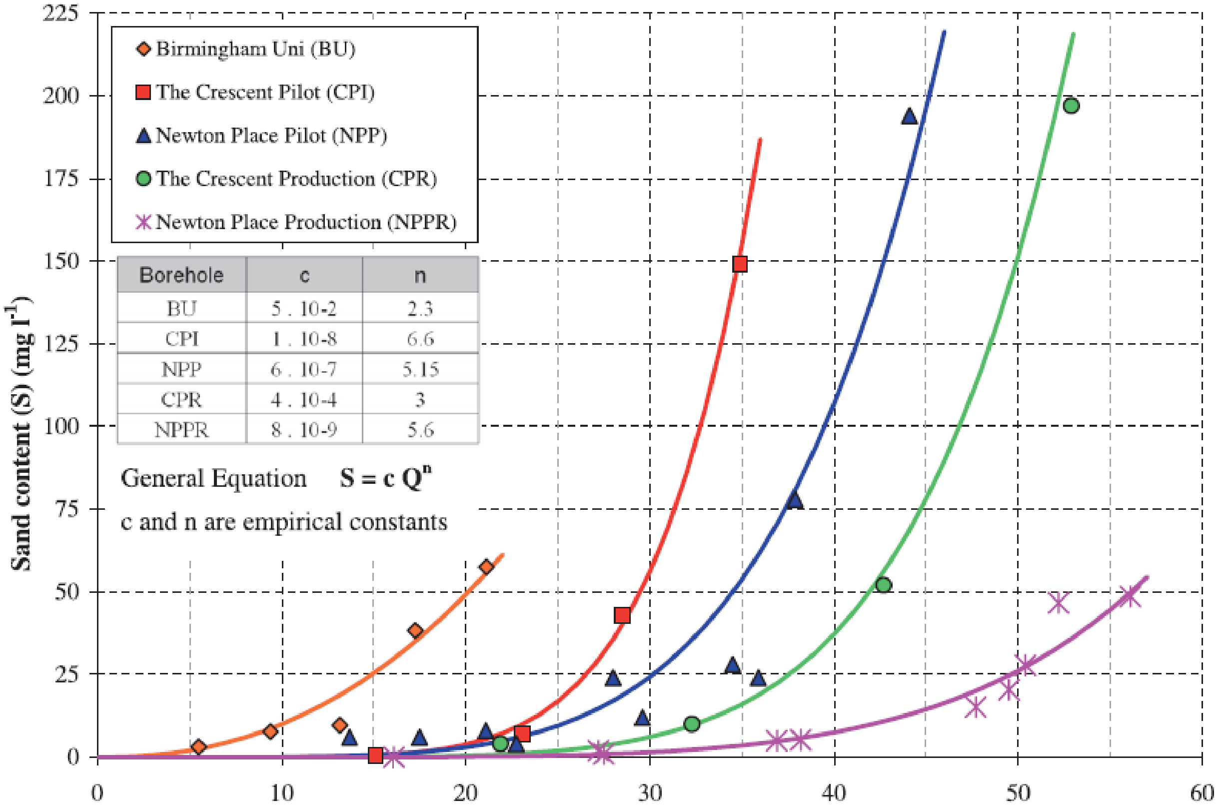
L_N = Particle load on well bore (#/hr)

Q = Pumping discharge (m^3/hr)

C_N = Concentration of particles in water moving toward the well (#/m^3)

The filtering character of the well bore is determined by its resistance. The smaller the well bore surface area, the higher the particle load per m^2. A higher C_N will cause difficulty for all the particles to pass through the pores close to the well bore. A big resistance of the wellbore causes more particles to accumulate on and around the wellbore.

The experience in extraction wells is that as the abstraction rate increases, so does the particle content. This is of course to be expected, as fluid velocities are directly proportional to abstraction rate. In Fig. 13 the sand content has been plotted against abstraction rate for a selected number of water wells in an open construction. Obviously this cannot be compared to the backfilled and screened wells that are constructed in aquifer thermal energy storage. But it certainly pictures the effect of the influence of flow velocity on particle mobilization and transport (Charalambous et al., 2012).



Borehole	c	n
BU	5 . 10-2	2.3
CPI	1 . 10-8	6.6
NPP	6 . 10-7	5.15
CPR	4 . 10-4	3
NPPR	8 . 10-9	5.6

Fig. 13. Sand content in relation to abstraction rate in an open (unscreened) well (Charalambous, 2012).

Resistance at the wellbore has been largely determined by unsuccessful removal of the filter cake from the wellbore during the well development process. Both natural substances like clay and added substances like bentonite act as particles which infiltrate into the aquifer and increase resistance (or reduce hydraulic conductivity) at the wellbore (Fig. 14). With a chosen well design, referring to well diameter and capacity, the particle load on the wellbore can be determined if the particle concentration is known. A closer look to this processes can be found in Paragraph 2.4.

Fig. 14. The typical location of a filtercake. The gravel pack on the left and the aquifer on the right.

Another problem that can occur with a mechanical cause is the production of water with a high particle concentration from an extraction well. When this happens it can have multiple causes which will be discussed later on in this thesis. Particles from the surrounding formation that reach the well interior have been transported through a part of the porous medium, the wellbore, the filter gravel and the well screen slot. As described before sand is too usually too large to pass through the pores of the aquifer. Sand can therefore only come from the borehole wall.

Possible reasons for sand production are:

- High flow velocities around the well
- Screen damage
- Backfilling material is too coarse compared to surrounding layers
- The lack of backfill between the well screen and the formation, which could be the consequence of a backfilling collapse or cavity
- Bad centering of the well tube in the drilling hole

Sand production can reduce the lifetime of the pump and other important accessories of the installation. Another problem with sand production is the chance of infiltrating these particles on the injection side, which can cause blockage of the pores there, ultimately leading to a growing infiltration pressure.

2.2.2 Drawdown

Drawdown in a well drives the water in the aquifer to flow towards the well. The higher the drawdown, the more water can be produced from a well. The caused head gradient determines whether and at what rate flow will take place through the soil matrix.

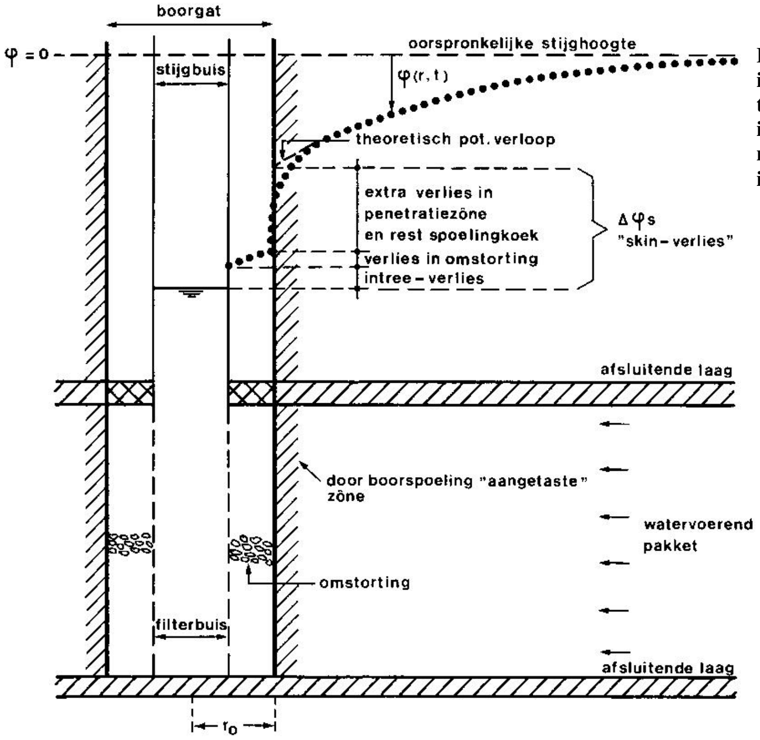


Fig. 15. Schematic situation of the total drawdown is pictured. Multiple constituents comprise the total drawdown. Total head loss can be subdivided into head losses taking place in the formation, the mud cake, the gravel pack, the screen slots and inside the (screened) well tube.

In Fig. 15 a schematic situation of the total drawdown is pictured. Multiple constituents comprise the total drawdown. First there is the drawdown caused by the sand of the aquifer itself, this depends on the hydraulic conductivity of the aquifer and the flow velocity. The resistance on the wellbore is influenced by the presence of accumulated particles which block the pores close to the wellbore. These particles came along with infiltration periods or are present due to the drilling fluid intruding the aquifer during drilling and well construction. The gravel pack around the well screen has a high permeability, due to its large grains and its well distributed grains. The well screen entrance is the final hurdle that has to be overcome for the water to enter the actual well tube.

Unacceptable drawdown levels can cause flow velocities inside the pores to grow to unintended velocities. This can lead to the attraction of particles and a further clogging of the pores around the well. This critical flow velocity should be avoided to prevent mechanical well clogging.

2.3 Sand Production in Extraction Wells

Extracting groundwater from an aquifer always implies the production of some concentration of suspended particles like clay, silt and fine sand. The mobilization of particles depends on media size, flow rate and particle size. It is obvious that this phenomenon has to be limited to an acceptable level, since negative effects like installation damage; polluted water; sand collection in the well; well clogging and soil instability have to be prevented or at least minimized. In order for the particles to reach the well interior, they have to travel through a part of the aquifer and through the gravel pack of the developed well.

According to McDowell-Boyer et al (1986) particles with a size of $d_p/10$ are the biggest particles that can be transported through a porous medium. If this is true, this would mean that sand that comes with extracted water was situated at or at a small distance from the wellbore. Another plausible explanation of sand production can be some thin fine grained layers that were not noticed during the drilling process. Normally clay and fine sand layers are excluded by putting unscreened pieces in the well tube at those depths, combined with clay backfill material. When this does not happen there is a risk that the chosen backfill material is not able to keep the fine material into place. The grain size of the backfill material will be based on the grain size of the aquifer. As well as the aquifer, the screen slots need to be taken into account. It has to be impossible for the backfill material to fit through the screen slots or even get in the way of them.

Mentioned above is the possibility of missing small layers of very fine material during the development of the lithology log. In most cases small samples of every meter that has been drilled are collected, therefore not every single fraction of a meter of soil is represented in such a sample.

Another risk with backfill material is the possibility of subsidence of the backfill column caused by rearranging gravel particles due to vibrations or pumping forces. When this happens, open spaces can develop between the clay ball (which is less likely to subside because of its strong contact with the formation due to swelling) and the top of the gravel pack which will be filled by aquifer material. This helps bringing the formation sands closer to the well screen. When this happens it is more likely that sand grains will be transported through the backfill medium.

What is stated above indicates the importance of accurate preparation, backfilling and well development, before taking a well in use. More on these subjects will be explained in the next paragraph.

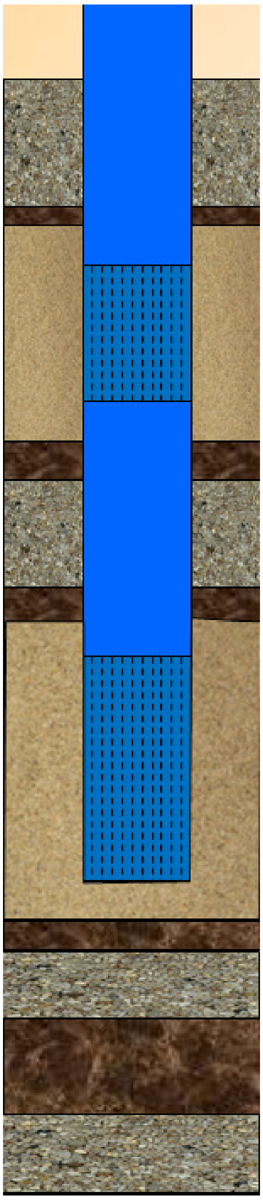


Fig. 16. Typical well penetrating two aquifers. Notice the space between the top of the well screen and the confining layer.

2.4 Well construction, back filling and well development

In the process of realizing a good functioning production/infiltration well, multiple procedures have to be carried out well. The total process can be divided in three major sub-activities:

- Well construction, including the drilling process, the filter placement and the effects of drilling fluids
- The back filling phase, around the well tube backfill material will be placed to provide well stability and keep finer formation material away from the screen slots
- Well development will clean the borehole wall and the pores around it in the screened area by one or various possible treatments

2.4.1 Well construction

The drilling process determines for a large share whether a well performs as expected. This mainly has to do with the formation of the filter cake at the wellbore. Overpressures are necessity to guarantee borehole stability during the drilling. The consequence is the infiltration of drilling fluid into the wellbore. Yet one can imagine that the infiltration of water and, most important, fine particles into the formation has to be limited, since they will have to be removed as much as possible later on.

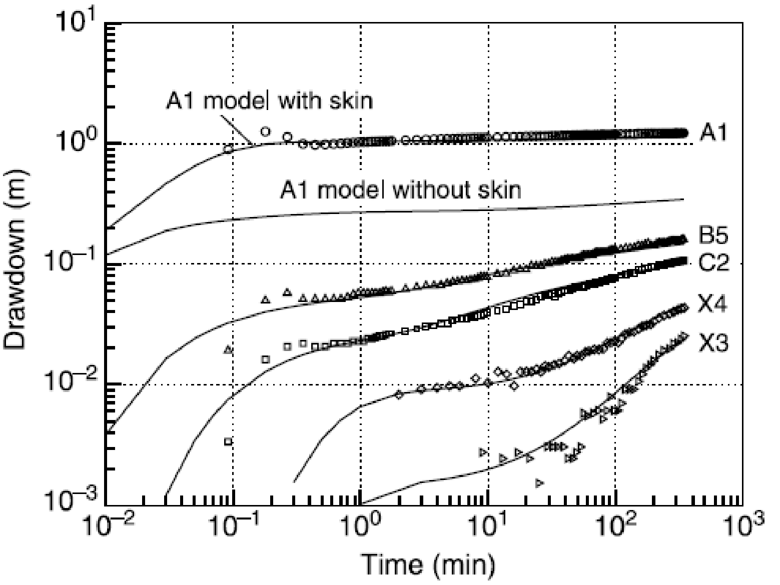


Fig. 17. Barrash (2006) proved that models with 'skin' (increased resistance at the wellbore) go together with bad performance wells. The comparison between graph 'A1 model with skin' and 'A1 model without skin' show this relation. Clearly it is important to clean and develop a well properly.

In general two main drilling processes can be distinguished:

Reverse circulation rotary drilling in combination with air lifting

In this drilling method the flow of the drilling fluid is reversed and the drilling fluid moves upward inside the drill pipe and discharges at the surface, typically into one or more settling pits. The air lifting promotes the water in its upward movement by adding air into the drill pipe. The air bubbles force the water to move upward by its low density (Fig. 18). The circulation rate during drilling commonly is 2,700 m^3/day or greater. By using this drilling method, it is possible to collect soil samples of for example each meter of soil.

Straight flush drilling

This cheaper, but also less prudent method works the other way around. Drilling fluid is pumped into the drill stem taking the dirt along the wellbore side of the drill stem upwards out of the drilling well. This method of drilling is less clean, whereas the loosened soil particles are smeared out over the wellbore to cause a more extensive filter cake. Soil samples are much less reliable compared to reverse rotary drilling soil samples.

After the drilling process, the depth of the well screen (segments) will be determined. Blinded well parts will correspond to low conductive formation layers, where the screened parts will match the productive layers.

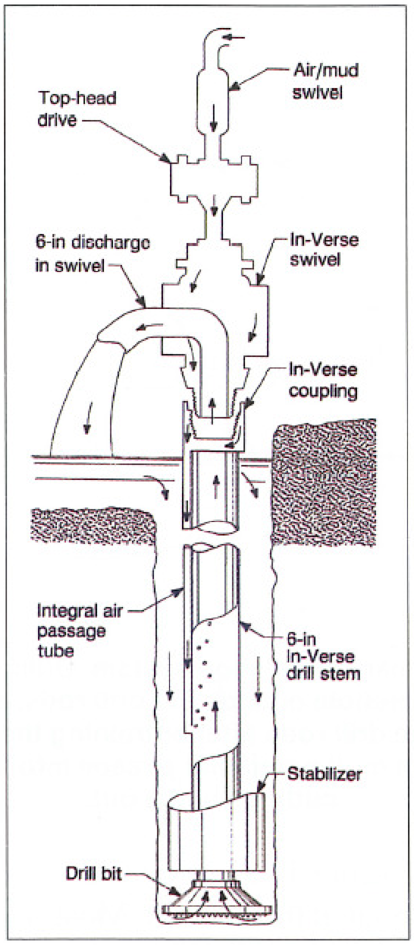


Fig. 18. A diagram of a reverse circulation rotary drilling in combination with air lifting (Driscoll, 2007).

2.4.2. Drilling fluids

In order to keep the borehole from collapsing during the drilling process, overpressure must be achieved and retained. The water level inside the borehole casing often extends the ground(water) level up to a few meters. Overpressure will be reached when this distance above groundwater level is sufficient and/or the density of the fluid is high enough. Drilling fluids sometimes contain some additives to 'enhance' its properties. The main properties that are enhanced by using additives like bentonite and polymers are the viscosity, density and the potential to smear the wellbore which limits the fluid penetration into the aquifer. This way less water will be lost during the process of drilling. Raising viscosity makes the suspension and transport of sand grains easier, but also reduces settlement. However, higher density of the drilling fluid due to additives also raises the overpressure, especially in the deeper regions of the borehole. Normally in the Netherlands, there is only a limited use of these additives because this can have a bad influence on the well development later on. Persistent mud cakes are harder to remove during development.

Despite the frequent choice of adding no additives, the drilling fluid will always have higher density compared to the water inside the aquifer. During drilling, aquifer material becomes suspended in the drilling fluid. Depending on whether the material is fine or coarse, one can determine whether the material settles at a quick rate or not. One can imagine that during drilling in an aquifer which mainly consists of fine material, or when it includes a large number of clay layers for example, the drilling fluid can have large concentrations of suspended material for a long time. This could consequently lead to persistent plugging of the wellbore in large sections of wellbore, especially in lower regions because overpressures can reach significantly high values there.

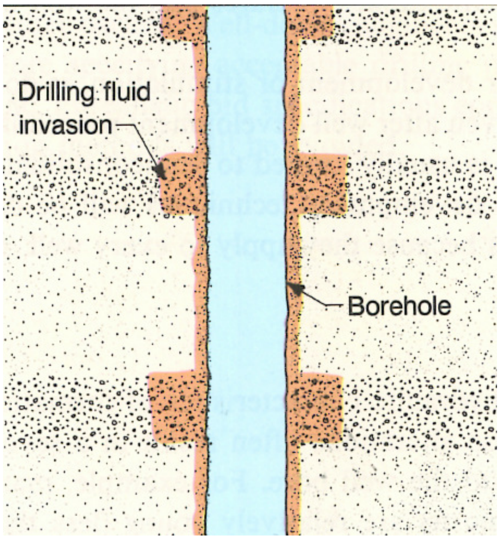


Fig. 19. When drilling with water-based drilling fluids, some of the fluid will flow into the most pervious parts of the formation, taking suspended particles into the formation (Driscoll, 1989).

During the well development, both chemical and physical measures can be taken to remove the drilling fluid remnants from the borehole wall and out of the formation. The rate of drilling fluid removal depends not only on the type of additive used but also on the physical character of the aquifer, the depth of the well, and the characteristics of the drilling fluid. A lot of extra energy is required in the cleaning process when clay additives are used during drilling (Driscoll, 1989). One has to keep in mind that fine material can also enter the drilling fluid, when clay (or other fine) layers are penetrated during drilling.

2.4.3 Backfill

After lowering the actual well tube into the borehole according to the well design, the space between the wellbore and the well screen has to be filled to assure well stability. This process has to be executed accurately to make sure a few essential properties are minded. The backfill has multiple important functions beside acting as filling material. These aspects will be discussed in this paragraph, together with the choice regarding grain sizes of the backfilling material.

The backfill material is required to be placed carefully to prevent damage on the wellbore or poor grain packing. When this is achieved, the removal of the drilling fluid remnants and of other fine material can be started. However in the process of placing the backfill material, the distribution of sand/gravel backfill versus clay backfill has to be determined in a way that the most conductive formation layers are exploited. These swelling clay balls (often mikolite or bentonite) also limit vertical movement of attracted water in the gravel pack.

A typical design of the well together with the gravel pack is depicted in Fig. 16 Usually a distance of one or two meters has been kept between the screened boundary and the clay backfill. The placing of these clay layers at the depth of (relative) low permeability layers (e.g. clay or very fine sand) corresponding with blinded parts of the well tube, prevent finer material of these layers to be attracted to the well.

The size of the backfill grains is based on the median grain size (D50) of the finest layer in the aquifer formation. One can imagine that selecting a grain size too big, may have serious consequences for sand production potential and well screen plugging. On the other hand, choosing a grain size too small has bad influence on specific capacity. Obviously the choice in grain size and build up of the backfill is essential in the ultimate well performance.

The currently used rule of thumb for backfill grain size have been used for many decades (KIWA, 1976):

$$4 < \frac{D_{50}}{d_{50}} < 5$$

D_{50} = median gravel pack grain size
d_{50} = median aquifer grain size

The thickness of the gravel pack commonly lies between 12 and 20 cm. The minimum distance is based on the thickness of the tube which depositor tube of the gravel into the well. Further on the gravel pack has to be compact enough to protect the cleaning potential of the well. A thick gravel pack is harder to clean successfully.

Both from literature and from the field there are examples of failing wells after well development, which in this case means a failure (settlement) of the backfill. Apparently there are processes which compact the backfill column during well development and after commissioning. One can imagine that grains are exposed to different stresses during activity, this can cause grains to rearrange to a more compact texture causing a net lowering of the backfill column. However this effect does not result in serious compaction. Vibrations caused by constructional piling can have a much bigger impact on grain rearrangement and settlement of the well. According to Hericks (2011) the backfill material can settle up to 17% of the backfill length due to extensive vibrations. Another possible process is the phenomenon of gravel sinking into swelling clay, this can be prevented by putting some sand between the clay and the gravel pack during the backfilling process.

The consequences of a significant decrease can be serious. When the swelling clay remains at its original depth, cavities will arise allowing the aquifer material to intrude the production well. When the swelling clays also sink into the borehole, there is a possibility that the clay gets to interfere with the well screen which will also lead to particle production in the well. Another issue could be that the clay layers won't cover the low permeability layers anymore, leaving a hole in the confining layer.

2.4.4 Well development

Various techniques can be applied to 'develop' a well to its desired level of performance. Based on the nature and the purpose of a well, choices have to be made in the process of well development. Besides, there are often certain constraints regarding the drilling company; some companies apply techniques which other firms do not perform in the process of well development.

Basically these processes take care of removing as much of the drilling mud from the wellbore and out of the borehole as possible to improve the specific discharge value of the well. The better the result, the less susceptible the well will be for clogging and the longer the lifetime will be. Lowering this value to a minimum saves a lot of energy later on and it protects the well from aging processes and plugging. In section *'2.6 Specific Discharge'*, table 2 shows a selection of development techniques.

In The Netherlands a variety of mechanical techniques are put in practice. Figures 20-22 show the most important activities, being sectional pumping, air surging and sectional circulation pumping. These three are usually accompanied by increasing-capacity pumping and switching the installation on and off (intermittent pumping).

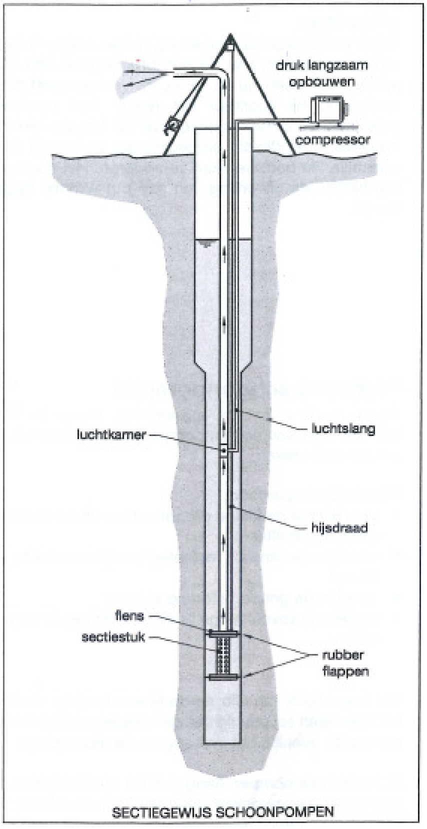


Fig. 20. Schematic picture of sectional pumping (IF Technology).

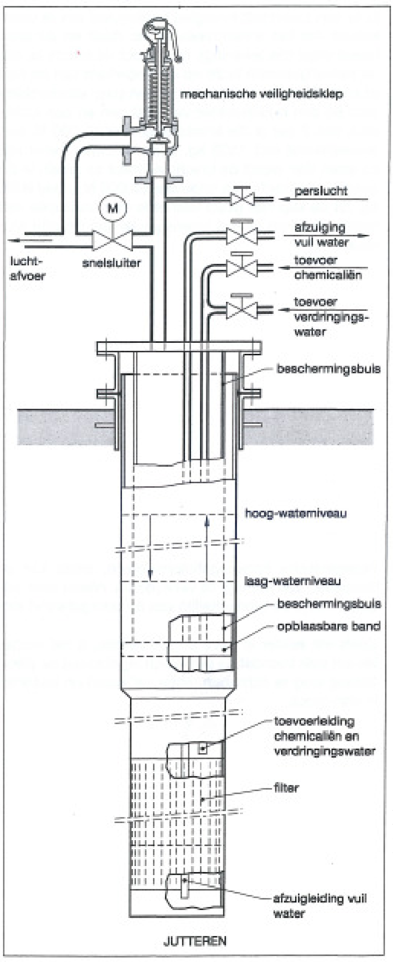


Fig. 21. Schematic picture of air surging (IF Technology).

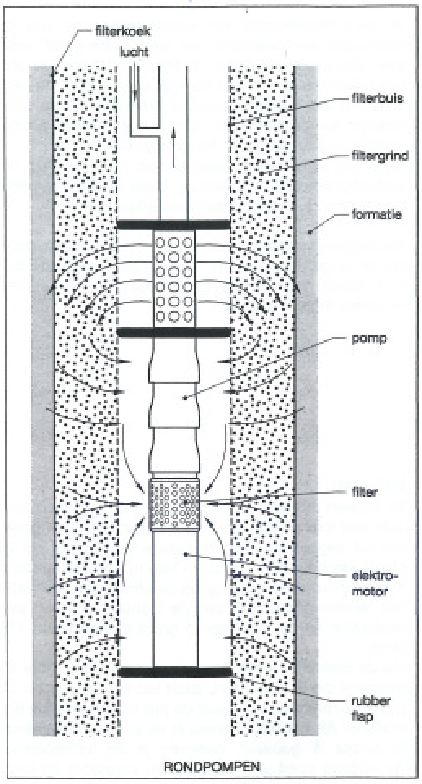


Fig. 22. Schematic picture of sectional Round pumping (IF Technology).

When the backfilling material has been placed around the PVC well tube, in every case the well will be taken into use with a slowly increasing capacity. This build-up starts with a discharge of 10% of the desired capacity, ultimately reaching the design capacity. This is the first step in the process of cleaning a well properly. After that it is decided what extra measures will be taken to remove the filter cake from the wellbore. Sectional pumping (Fig. 20) concentrates the development action on small sections of the well screen when pumping at a certain discharge. The rubber flaps insure the sectional activity of the device, this way the backfill material and wellbore at this depth are addressed.

A resembling development technique which is also widely used, is sectional round pumping (Fig. 22). It is similar to the sectional pumping technique, only now part of the extracted water is injected at the same time above the extraction part to create a circulating water trend. This intensive circulation thoroughly cleans the backfill material, and at the same time it removes fines from the wellbore. The flow is concentrated in the gravel pack and in the first centimeters of the formation material.

Air surging is the most effective physical development technique (Fig. 21). Surging is a repetition of a certain cycle. The first phase of the procedure is compressing air into the well tube to force the water level down to the requested level. In most cases the water is forced down 10-20 m, which corresponds with pressures of 1 to respectively 2 Bar. After the pressure build-up, which usually takes about 5 minutes, the pressure will be released. When this happens the water from the formation and the gravel pack will be pressed through the pores around the well inside the well tube. Because of the high velocities, clogging particles are removed and taken into the well tube. The observed time of the violent part of the pressure release is just a matter of seconds. After 30 seconds this process is repeated. This cycle will be executed a few times, before the pump is turned on to extract the removed particles from the well. From then on the whole process starts over until the engineer thinks the well satisfies the desired capacity.

Some drilling companies apply a more specialized form of surging called sectional surging. The name already tells what the technique implies. This technique is developed because people working in the field generally think that ordinary surging is not equally efficient in all parts of the well screen. It is known that surging effects may be concentrated near the top part of the screen, which might be explained by high head losses inside the well during the process of surging, related with the brief ‘mega-discharge rates’ that will be achieved right after the pressure release. Especially in longer well screens this can form a problem. Pressure loss inside wells, also during surging, will be further explained in the next paragraph.

Effective development procedures should include reverse of flow through the screen openings that will agitate the sediment, remove the finer fraction, and then rearrange the remaining formation particles (Fig. 23). Reversing the direction of flow normally breaks down the bridging between large particles and across screen openings. The backflow portion of a backwashing cycle breaks down bridging, and the inflow then moves the fine material towards the screen and into the well.

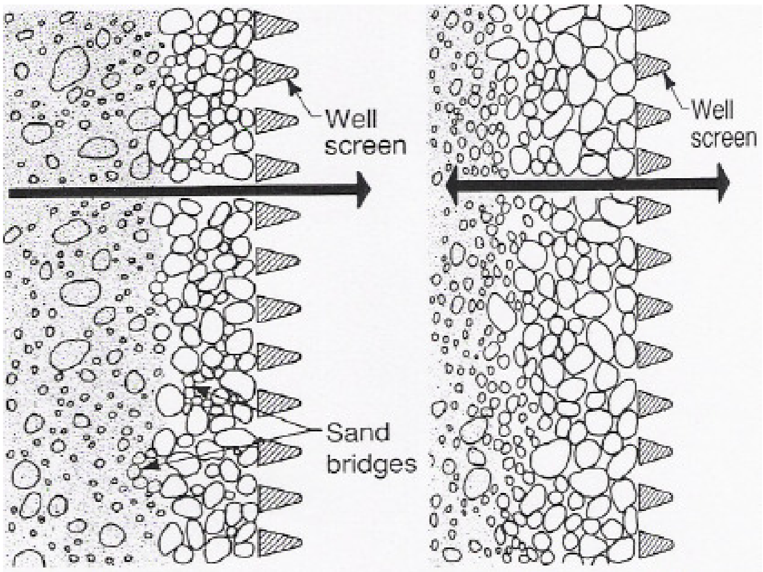


Fig. 23. Back washing effect on breaking down particle bridges (Aliewi).

A hydraulic surging action consists of alternately lifting a column of water a significant distance above the pumping water level and letting the water fall back into the well. The pump should be started at reduced capacity and gradually increased to full capacity to minimize the danger of sand-locking the pump. As soon as water is lifted to the surface the pump is shutoff; the water in the pump column pipe then falls back into the well and oscillates to the situation at rest.

Although these methods seem effective in theory. The results are often disappointing in reality (Breedveld et al. 2007). These observations can presumably be explained by the fact that once a part of a well becomes or already is well developed and cleaned; water will preferably choose its path through the best developed part during later development activities because these areas offer the lowest resistance, therefore the under developed parts remain inactive. Especially during non-sectional development activities this seems to be a real problem. Sectional development techniques appear to be most effective regarding large scale well improvements. Sectional round pumping is already a developed and commonly used technique. Sectional surging however, has not been performed often. The lower parts of the well can be developed significantly better when the latter technique will be developed, mainly because of the aggressive reversal of the flow direction which appears to be effective on particle removal from the wellbore.

The usual order in the use of these explained mechanical development methods is as follows:

1. Pumping clean by increasing discharge from 10% to 100%
2. Hydrological-/Air-Surging
3. Sectional (round) pumping
4. Intermittent pumping

2.5 Flow resistance inside pumping well

Due to extraction of water from an aquifer, a certain head difference will be created between the inside of the well and the surrounding formation. The drawdown inside the well depends on well development, formation hydraulic conductivity, and the flow rate. Additionally there are head losses inside the well tube which can be attributed to the turbulent character of the vertical water movement inside the well, combined with the frictional losses at the well casing.

2.5.1. Formulation of borehole flow equations

By creating a model which simulates head losses inside an extraction well, the relation of the significant parameters discharge (Q), screen length (L) and welltube diameter (ø) to head loss can be studied. For these calculations, some essential equations are required:

$$Re = \frac{\rho v L}{\mu}$$

Re = Reynolds number (-)
ρ = Fluid density (kg/m^3)
v = Mean velocity (m/s)
*μ = Dynamic viscosity (kg/(m*s))*

On the basis of the Reynolds number it can be determined whether the flow regime in a (well) tube is turbulent or laminar:

Laminar flow: $Re \leq 2260$
Turbulent flow: $Re \geq 3400$

When one is dealing with laminar flow this equation should be used to calculate the friction factor:

$$f_{lam} = \frac{64}{Re} = \frac{64\mu}{\rho v L}$$

f_{lam} = Darcy friction factor for laminar flow regime (-)

A common equation to calculate the turbulent friction factor is by using the Colebrook-White equation (Parker et al. 1969; Kaleris 1989):

$$f_{tur} = (-2 * \log(\frac{\epsilon_p}{3.71 D_h} + \frac{2.51}{Re * \sqrt{f_{tur}}}))^{-2}$$

Because the friction factor term is on both sides, this equation needs to be solved iteratively. Therefore another approach for the friction term has been chosen in the calculation of this factor: the Haaland equation (Haaland,1983).

$$f_{tur} = (-1.8 * \log((\frac{\epsilon_p}{3.7D_h})^{1.1} + \frac{6.9}{Re}))^{-2}$$

f_{tur} *= Darcy friction factor for turbulent flow regime+*

$\epsilon_p = \epsilon/D_h$ *= Relative roughness (-)*

ϵ *= Absolute roughness (m)*

D_h *= Internal hydraulic diameter of the well screen (m)*

Ultimately when a good approximation of the Darcy friction factor has been found, the head loss can be calculated by:

$$h_f = f * \frac{L}{D_h} * \frac{v^2}{2g}$$

h_f *= Head loss due to friction (m)*

g *= Gravitational constant (9.81 m/s*^{2}*)*

2.5.2. Model

By using these equations, the head loss due to friction in a closed tube can be calculated. However, a few important factors are not yet included:

A. The discharge, and corresponding flow velocity within the tube, is not constant. The fact is that the volume of water flowing through the well is increasing from the bottom to the top of the well screen, which is simply due to the accumulation of the contributions of every part of the well screen section.

B. The wall roughness of a screened tube is bigger than for a closed tube. Siwon (1987) developed a relation for the friction factor for perforated PVC pipe as:

$$f = f_0 + f_t$$

Where $f_0 = 0.0106*\phi^{0.413}$ *and* f_t is given by the implementation of $\epsilon = \epsilon_p + 0.282\phi^{2.4}$ into either the Haaland or the Colebrook-White equation (Clemo, 2010). ϕ Represents the perforation density (fraction of the screen open to radial flow).

C. The inflow of water through the screen slots reduces the wall friction.

Keeping this in mind, the model is extended to simulate more realistic head loss estimates. The upward flow velocity inside the well is assumed to increase linearly. The total head loss is then calculated by dividing the screen into small sections, each of them with a vertically constant average discharge. The head loss values for each section are summed up to the total head loss. It will not correspond to practical values, but at least it will give an idea of the overall influence of the slots and inflowing water compared to the simplified assumption of a closed tube.

Water inflow through the slots is assumed to decrease the head loss inside the well up to 30% (Clemo, 2010), therefore the friction factor decreases in areas of inflow. This can be clarified by lateral flowing water forming a thin fluid wall along the well screen reducing the wall friction of the water that is flowing upward through the well screen. As this effect was not included, the calculated head loss will turn out to be less than calculated using this model.

The outcome of the model could explain what influence the head loss inside the well has on the vertical flow distribution over the well screen. For clarification: assume a head loss in the well of 1 meter over the whole well screen length. In case of an extraction well with a drawdown of 10m, this effect is relatively small (10%); in the top of the screen the drawdown is 10 m, and it is 9 m in the bottom. But in case of a well with a drawdown of +/- 2m, this effect is big (50%); in this case the upper part of a well produces twice the amount of water compared to the lower part. So for each system the head loss inside a well varies relatively, this tells us that it could be a major influence on the flow distribution logs.

The relation of the important variables determining the head loss inside a tube is depicted in Fig. 24:

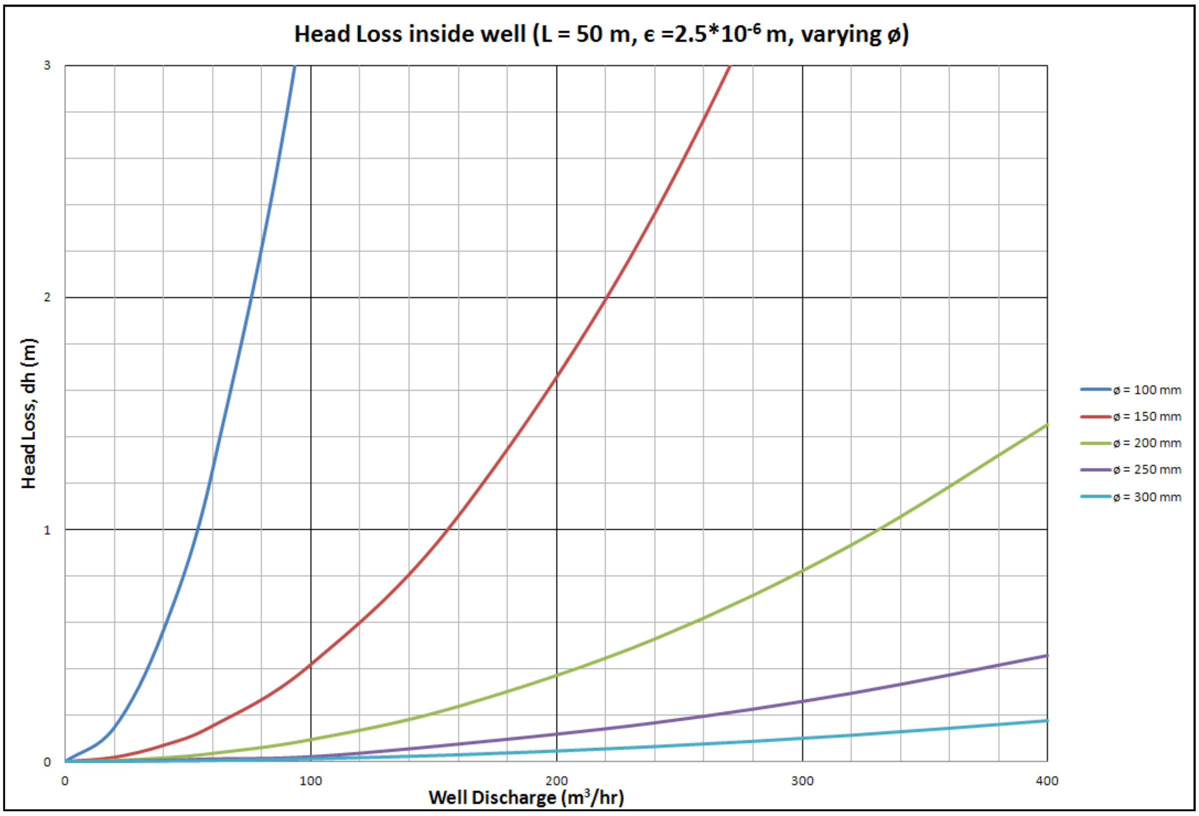


Fig. 24. Head loss set out against discharge; the screen length is constant (50 m), while the inner well diameter varies between 100-300 mm. It is assumed that the discharge is increasing linearly over the length of the well screen.

A constant filter length is taken and the flow rate inside the well screen is assumed to increase linearly from 0 m^3/h at the bottom of screen to the well discharge at the top of the screen. The absolute roughness (ϵ) of the pipe wall in this figure is also set to a constant level, 0.0025 mm; this is a typical value for PVC roughness (Moody Diagram, Fig. 25). The welltube diameter appears to be the most important factor of influence on head loss, followed by the flow rate that has to travel through a pipe.

From figure 24 it can be concluded that the welltube diameter is of major influence in the amount of head loss that is observed. Mathematically one can also easily see that the well diameter and the inversely proportional flow velocity are significant factors in the given equations.

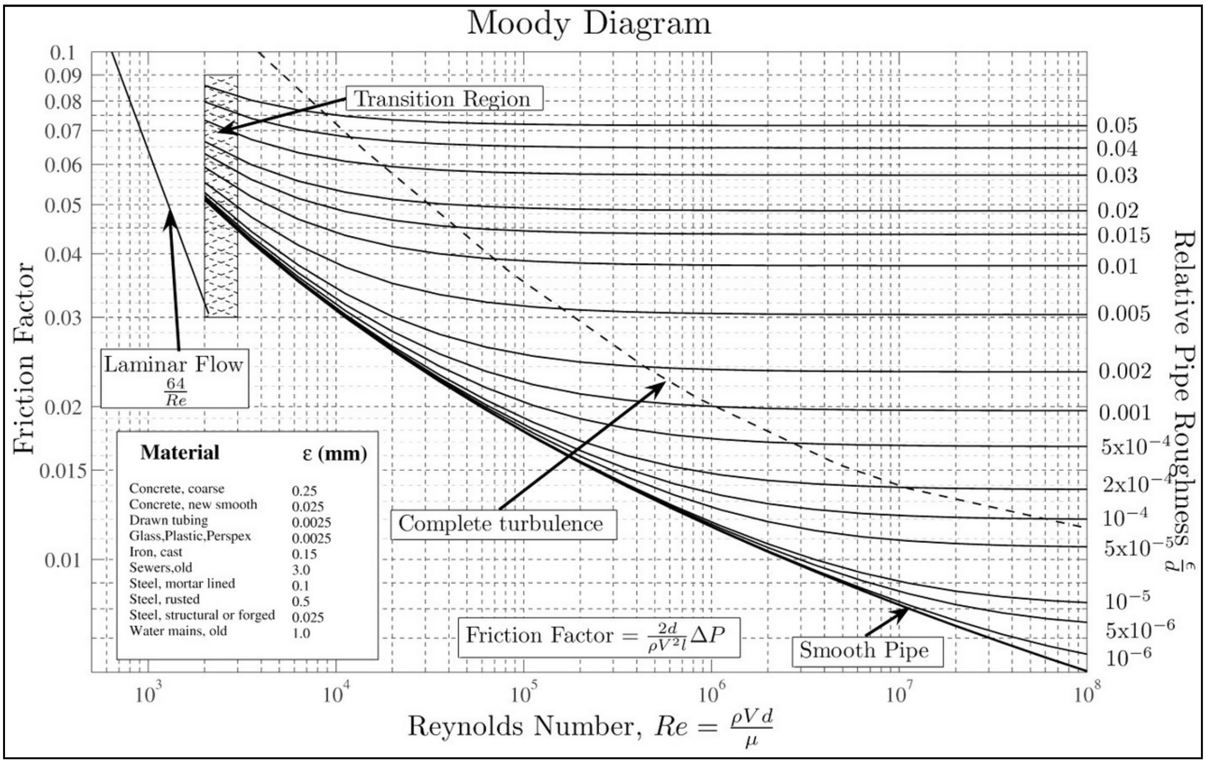


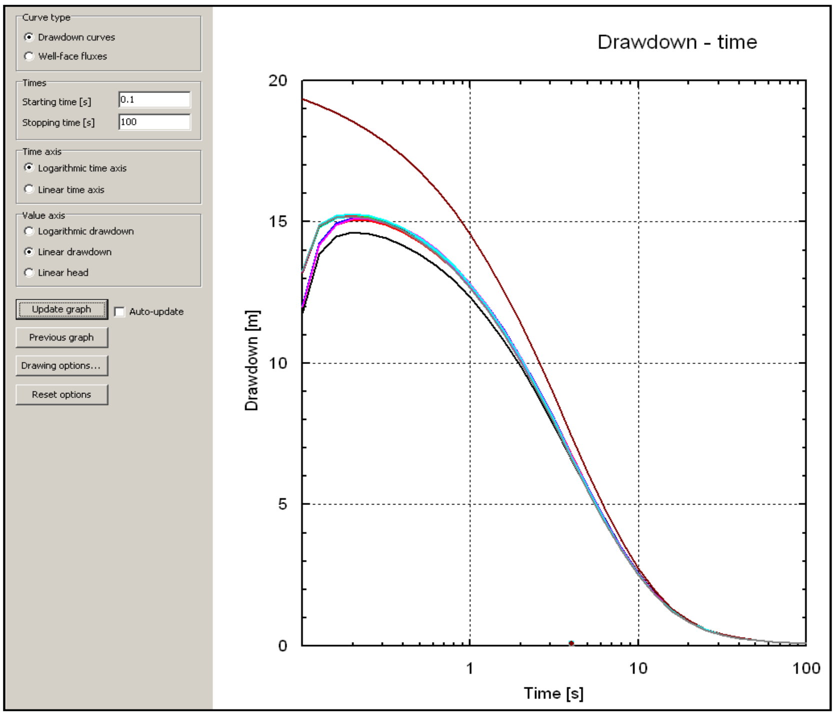
Fig. 25. Moody Diagram. In this diagram the friction factor in both laminar and turbulent flow regimes can be found back when the (relative) roughness of a pipe is known (Moody, 1940).

2.5.3. Head loss during surging

It's a widespread conception in the field, that air surging (2.4.4.) is often not effective over the whole screen length during well development. The impression is that the upper part of a well screen is improving, while lower parts are not influenced by the treatment. By using the model we can make a good approximation of the magnitude of head loss inside the well tube. In order to get a picture of this, it has to be clear how much water flows through the pipe at the moment of pressure release in the surging cycle. Therefore a simple MLU model of a project in Arnhem (NL) was produced which shows both drawdown through time inside the well and the drawdown 0.2 meters outside the wellbore (Fig. 27). Using this data a certain discharge can be derived for each moment in time using Darcy. Right after the pressure release, the model predicts that a discharge of 2160 m^3/hr will be reached, naturally corresponding with great resistance to flow inside the well tube.

Fig. 24. Pressure release during the process of surging.

The MLU model produced in order to create figure 27 has got a few shortcomings when it is compared to reality. One thing is that the model always assumes laminar flow and additionally it doesn't take mass inertia or head losses due to friction inside the well into account. The field observation that has been done during the surging process of this well, was a pressure release which could be heard for 5 seconds. After these 5 seconds the rebounding water table probably was not in rest yet, the amount of air replaced at that moment was simply not enough to cause the sharp sound coming out the valve (Fig. 26). According to the model it takes about 10 seconds for most of the drawdown to be compensated. The field data suggest that in practice it might occur up to twice as fast, corresponding to a maximum flow rate of 4320 m³/h.



Curve type
● Drawdown curves
○ Well-face fluxes

Times
Starting time [s] 0.1
Stopping time [s] 100

Time axis
● Logarithmic time axis
○ Linear time axis

Value axis
○ Logarithmic drawdown
● Linear drawdown
○ Linear head

☐ Auto-update

Fig. 27. Simulation of the pressure release during well development (surging). The drawdown is set out against time. The upper line represents the drawdown inside the well from the moment of pressure release in the surging cycle. The water level inside the well is forced down almost 20 m by the air compressor before the pressure will be released. By calculation it appears that 0.1 s after releasing the pressure, a discharge of 2160 m^3/hr will be reached. This value can be approximated by using the head gradient simulated in MLU. In the calculation of the frictional head losses it is assumed that the discharge inside the well increases linearly. The graph is made in MLU.

According to the model a head loss inside the well of 5.9 m can be expected, which leads to the pressure distribution inside the well depicted in Fig. 28. When the field observations are used, the real flow velocity might be up to twice as high. In that case the calculated head loss is 23 m. It is immediately apparent that a head loss of 23 m is impossible, since the maximum drawdown at the start was only 20 m. The head losses are overestimated because of the assumption of a linearly increasing flow velocity inside the well screen, which is not true since there will hardly be any drawdown at the bottom of the screen. This means that the lower part of the screen will hardly produce any water. One can imagine that this has great consequences on the well screen inflow distribution during the rebound phase of surging. Water strongly prefers to flow into the upper part of the well screen, and this will remain the case in the subsequent phases of the surging process. Once this part has been developed better than the rest of the well, water will keep choosing the way of lowest resistance. Finally, in the process of surging there remains a high risk of poor development in the deeper parts of a well. Longer well screens and small diameter will be more sensitive to this problem.

Solutions to this problem can be sectional treatment or maybe it is useful to slowly increase surging pressures to slowly develop larger pieces of a well instead of only forcing the water through the upper part.

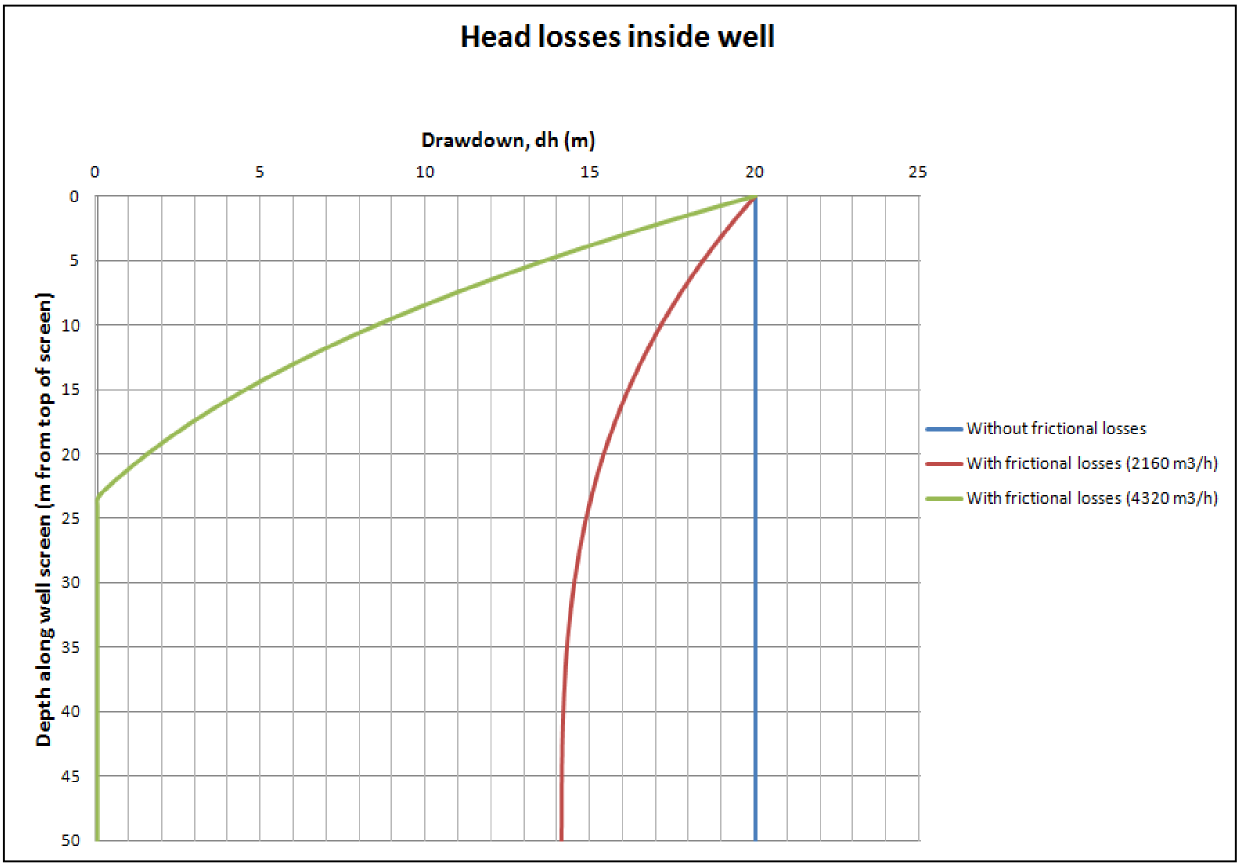


Fig. 28. By simulation, this could be a good portrait of what goes on during the process of surging. Because high discharges during surging, the hydraulic gradient in the top of the aquifer can be much bigger than it is in the lowest part. Head losses are bigger in the upper part. In reality the assumed linear cumulative discharge cannot be reality, where varying head losses and evenly distributed water intakes contradict one another.

2.6 Specific Discharge

The specific discharge (SD) or specific capacity (SC) of a well is its yield per unit of drawdown, usually expressed in cubic meters per day per meter of drawdown. Dividing the yield/discharge of a well by the drawdown, when each is measured at the same time, gives the specific capacity at that time. Since the drawdown generally increases with pumping time, the specific capacity would be dependent on time of measurement of the drawdown. It is therefore important to wait until the drawdown has stabilized.

Specific discharge is a variable which is often used for aquifer analysis. High specific capacities generally indicate a high transmissivity, and low specific capacities generally indicate a low coefficient of transmissivity. Theoretically this is true, but in the field the specific capacity of a well cannot be an exact criterion of the of transmissivity. Specific capacity is often adversely affected by partial penetration, well losses and hydro-geologic boundaries. This leads to frequent underestimation of transmissivity (Walton, 1962). Despite this, rough estimates of transmissivity are very useful for an examination between the transmissivity and specific capacity. Experimentally the relation between these two aquifer characteristics can be determined and plotted into a graph (Fig. 29). While time as a negative influence on the drawdown, the well radius has a positive influence:

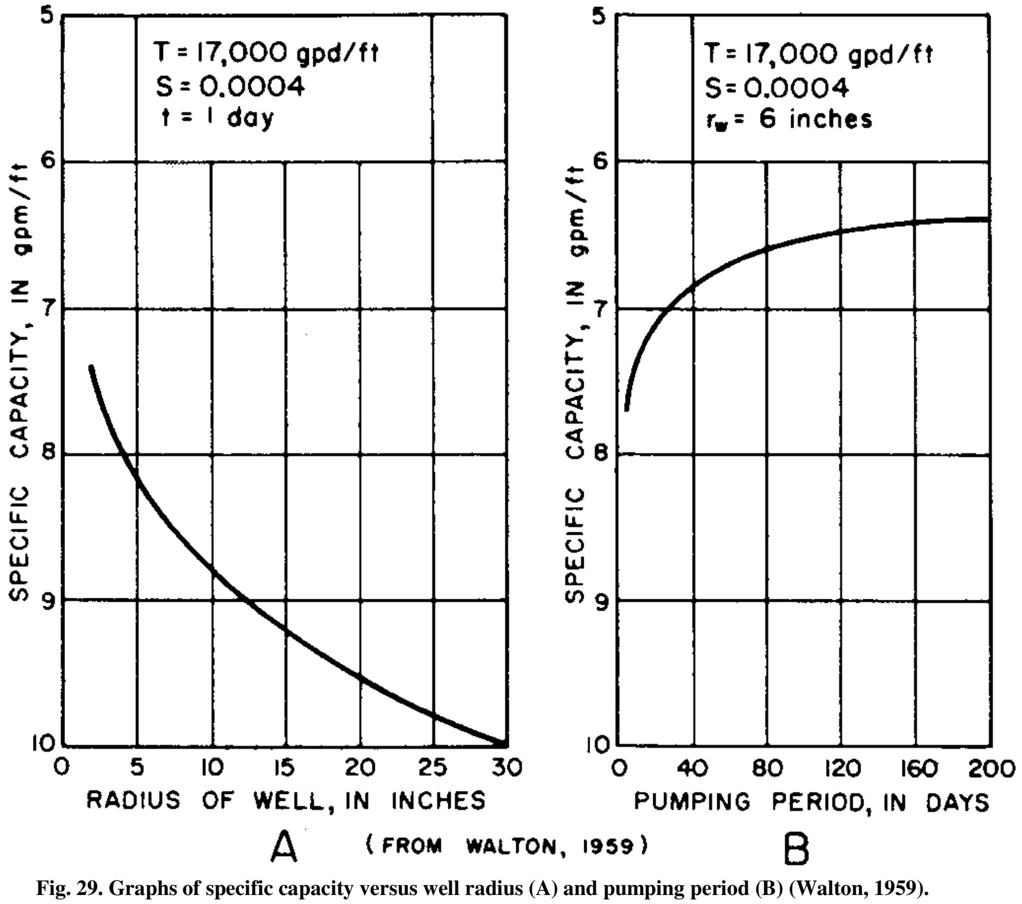


Fig. 29. Graphs of specific capacity versus well radius (A) and pumping period (B) (Walton, 1959).

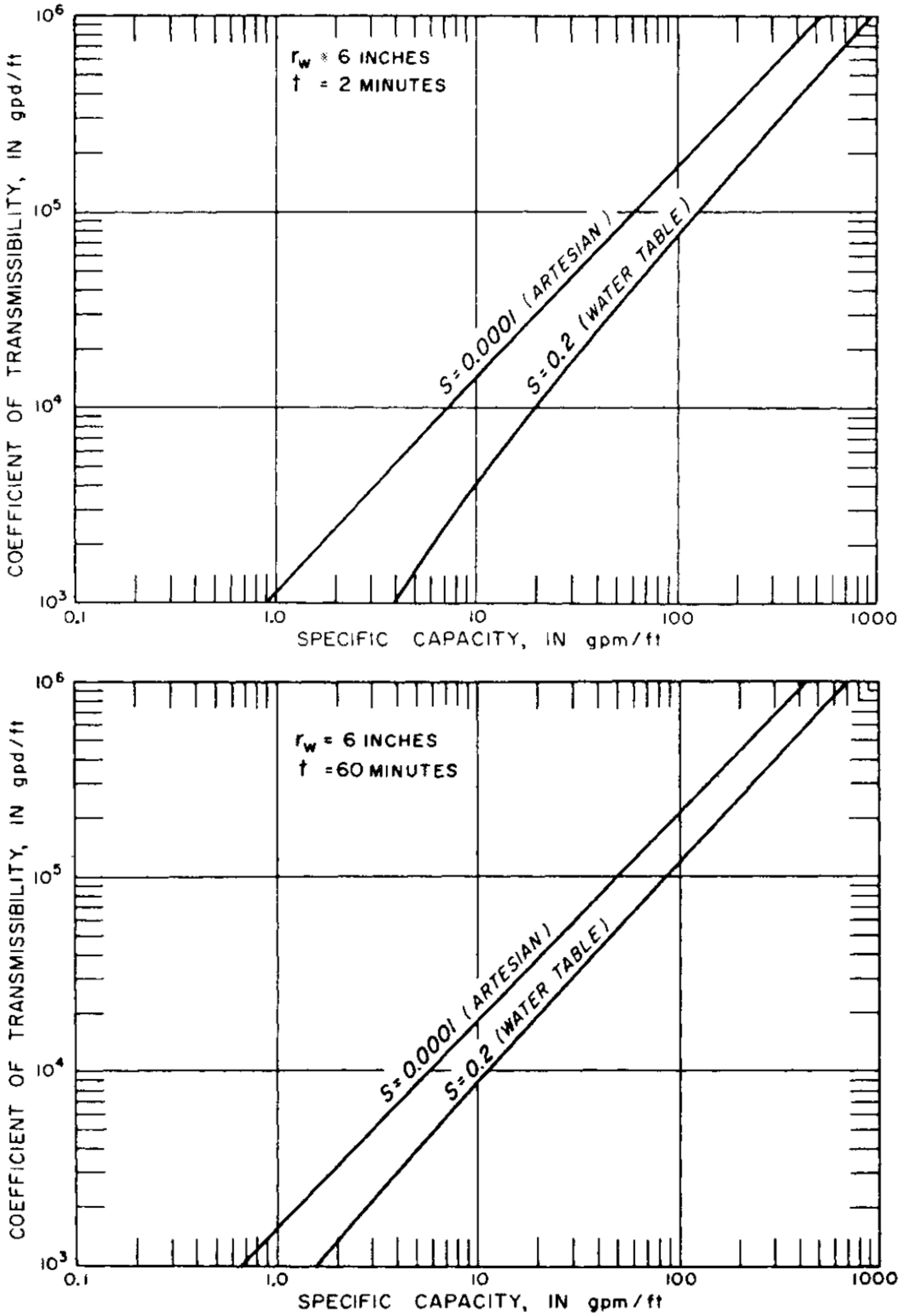


Fig. 30. Graphs of specific capacity versus coefficient of transmissivity after respectively 2 and 60 minutes. A clear decrease in specific capacity can be observed through time (Walton, 1962).

In practice, SC measurements are used in the process of well monitoring. Capacity tests are frequently performed to observe trends in the SC of the well. A decrease indicates well clogging and an increase indicates improvement due to removal of clogging material. These data show that well performance often increases shortly after taking a system into use, followed by a steady decrease through time. Short term increase after well development tells something about the well construction, well development, the gravel pack, well bore and/or the aquifer have not been cleaned optimally. Remaining particles are apparently removed in the first period of activity of the well. Fig. 31 shows a typical declining specific capacity trend through time.

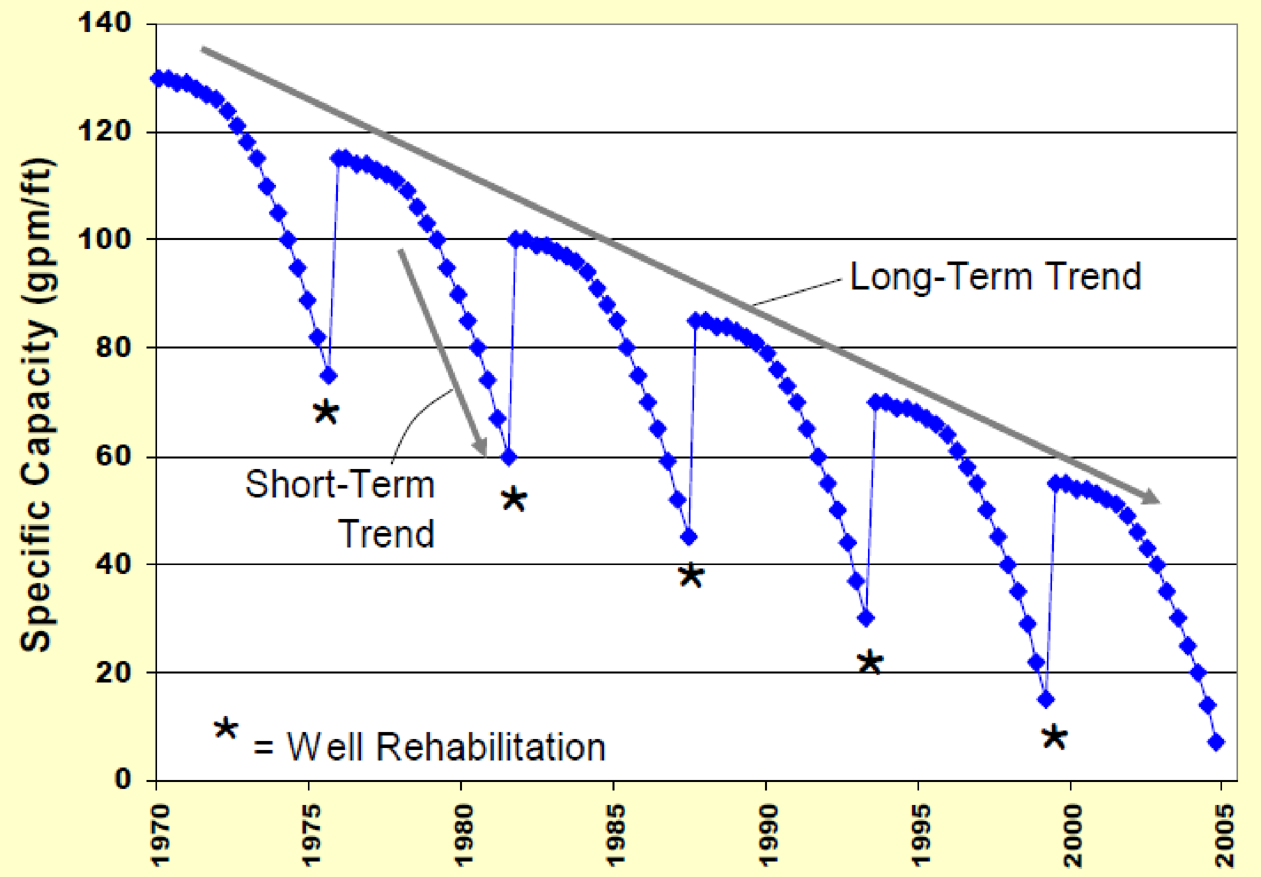


Fig. 31. Typical SC graph showing the difference in short term trends and long term trends (Johnson 2005).

Striking is the repeating exponential decrease in the short term trend. These appearances are a representative of a positive feedback in the blocking of pores. Imagine that pores in/around the wellbore are clogging one by one. The flow velocity in the remaining pores will increase since the discharge of the well remains constant. The consequence of the higher flow rates within pores an increase in the particle load flowing through the pores which increases the chance of clogging of the pores and bridge forming in the pores. Similar trends can be recognized in development of mineral incrustations or biological blockings of the well screen.

The asterisks represent rehabilitation events, these events can range from chemical techniques to mechanical rehabilitation techniques. The treatments show a significant improvement in well performance, translated in the appearance of an increase in SC.

As mentioned a well will start to lose SC as soon as it is put into service. Although the rate of this deterioration will vary from well to well, good record-keeping will allow declining performance to be recognized so that proper evaluation can be made and maintenance or rehabilitation performed. Decline in SC occurs when the well screen, filter pack, or near-well aquifer becomes plugged from physical, chemical or biological sources. The rehabilitation treatments are performed to remove these blockages and restore the well's SC and improve the well's efficiency.

Record keeping and maintenance

A well should be on a program of regular preventative maintenance like any other piece of equipment to assure that it is kept in good working conditions. Accurate and consistent record-keeping is one of the easiest and most important programs to implement. Record-keeping at a minimum should consist of measuring parameters that are needed for calculation of the SC of the well: non-pumping (static) and pumping water levels and pumping rates. The translation of these data into graphs should make the identification of well, pump or aquifer problems easier.

Simple, inexpensive methods can also help to tie down the required frequency of time and money consuming rehabilitation methods. Simply switching on and of the pumps several times can create a positive effect on overall permeability. Intermittent pumping has positive consequences for extraction wells (Breedveld et al., 2007). Switching the flow direction (injection well becomes extraction well) has also positive effects on cleaning pores, mainly by breaking down bridges which remain their strength to constant flow direction and flow velocity.

A preventative maintenance program will not always exclude the need of more aggressive and expensive rehabilitation efforts. Johnson (2005) suggests that these efforts are best timed at the moment when SC falls by 25% or more from the original value. There is a danger of an irreversible SC drop when the SC value has descended too far. The rehabilitation techniques generally fall into two broad categories: mechanical and chemical techniques (Table 2).

Mechanical Techniques	Chemical Techniques
Pump On/Off	Acids (for mineral deposits)
Bailing	- Hydrochloric (muriatic),
Surging / Surge Block	- Phosphoric, Sulfamic
Overpumping / Rawhiding	Acids (for organic biofilms)
Airlift Pumping	- Hydroxyacetic (Glycolic),
Brushing (steel or nylon)	- Glacial acetic, Oxalic
Swabbing (single or dual swabs)	Carbon Dioxide (AquaFreed)
Acoustic Shock/Fluid Displacement	Caustics (for organic biofilms)
Vibratory Explosive Shock	- Sodium/Potassium Hydroxide
Air Displacement Surging (juttering)	Chlorine Dioxide
Single Shot Explosives (primer cord)	Dispersants, Sufactants
Jetting (high-pressure air or water)	Sodium or Calcium Hypochlorite

Table 2. List of mechanical and chemical regeneration techniques, not all of them are used in The Netherlands.

The main focus in this thesis research will be on the well losses, which cause different specific capacities than the values expected from using models. The goal with the specific discharge data will be to determine whether well efficiency can be predicted using models. When predictions do not fit with the capacity tests, there has to be something that is overseen. An important share of this discussion will be about possible explanation factors considering the aquifer, development of the well, backfill material and particle attraction.

In each project the simulated specific discharge will be compared with the measured specific discharge using the factor: modeled SD / calculated SD. In an ideal situation the number would be one. In that case the measured value fits to the number the model has simulated. The probability that one is dealing with a successfully developed well without significant problems, is eminent. In the case of small deviations, values < 1 indicate that a well is better than you would expect from the model. This can mean that aquifer hydraulic conductivity is underestimated when using Shepherd (1989). Values > 1 however, mean that a well achieves less than one would expect from the given data:

1. Through clogging. In the case of a new developed well, values as much as 2 could be explained by this process.
2. Values >2 point to an overestimation of the hydraulic conductivity which can (partly) explain the lower measured value of the SC. In the case of overconsolidated sediments, large deviations can be expected.

2.7 Vertical Flow-Logs

Vertical flow-velocity-logs collected using flow meters are commonly used to determine the quantity and distribution of ground water flow in a screened well. Flowmeter data collected within wells under pumped conditions can be used to determine the contribution of different parts of the well screen to total discharge (Newhouse et al., 2005).

In most cases a flow distribution is pictured as a cumulative graph, where the depth of a well tube has been set out against the local discharge inside that tube. At the bottom of the well screen the discharge is 0, while this value reaches its maximum value at the top of the well screen. From the sectional contribution both the (darcy-) velocity on the well screen and the velocity on the wellbore can be approximated. Eventually calculated values can be compared to certain design standards which act as a target in the process of a well design.

The problem however in this process, is the assumption that over the whole depth of the well screen, the same amounts of water infiltrate into the well relative to the local horizontal hydraulic conductivity. In designing a well, an average hydraulic conductivity value is estimated. Though from information in former paragraphs, one can imagine that these assumptions are rarely reality. Constructing and developing a perfect well seems to be impossible. This means that it is not unlikely that in some cases, for a variety of possible reasons, the well does not perform just as well in each section as one would expect. This means that good functioning parts have to compensate for worse parts, which can lead to exceeding of the determined design standards. Obviously this can eventually lead to problems regarding well performance and clogging mechanisms.

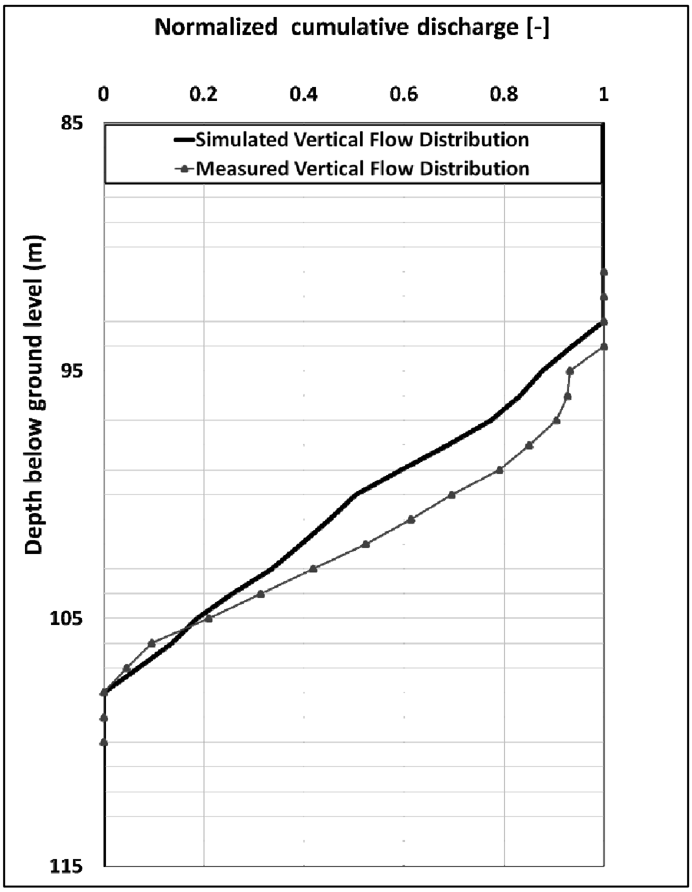


Fig. 32. Expected vertical flow distribution versus the measurements that have been done at the site. This graph comes from project 10a that among others, will be studied and analyzed later on in this thesis. The well screen is situated between 93 and 108 m below ground level.

Let's take a real case of a constructed well inside a close to homogeneous aquifer. Pictured are two graphs which indicate both what is assumed in calculation with respect to the design standards, and what is in fact the real flow distribution measurement. Note that the discharge is depicted as normalized discharge, it goes from 0 at the bottom of the screen to 1 at the top of the screen.

When the aquifer would really be homogeneous, the expected graph would be a straight, linearly increasing line, meaning each section produces the same amount of water. In this project there are relative small vertical differences in hydraulic conductivity which are translated in the wobbling slope. The measured data deviate from the theoretical data, because some factors apparently cuase different water inflow rates at the well screen than expected. Striking are the upper meters of the well screen, in which some parts don't seem to contribute. A more extensive analysis of this project can be found in the results sector.

The principle of more water flowing through high hydraulic conductivity layers is quite self evident, for a clear picture one can take a look at Fig. 33.

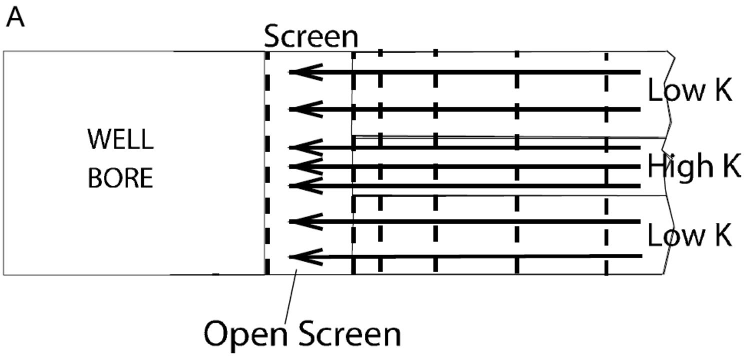


Fig. 33. High hydraulic conductivity act as path of lowest resistance for the water, therefore 'high K' layers will act as major contributor for water production in a well (Barrash et al., 2006).

Influence of well penetration on vertical flow distribution

Not only clogged wellbores, well screens or adjacent aquifer material have influence on vertical flow distributions along the depth of a well screen. From both literature and the field it is stated that well penetration is important in the vertical flow distribution. One can depict a situation of a partially penetrating well, which means that the top and/or bottom of the well screen are not bounded by an impermeable layer like clay, silt or loam. In this case one or both ends of the screened wells

can extract more water from the aquifer because water will be conducted not only from the horizontal direction, but also from the vertical direction. Houben (2006) produced a simple PMWIN model to model the flow path lines (Fig. 34).

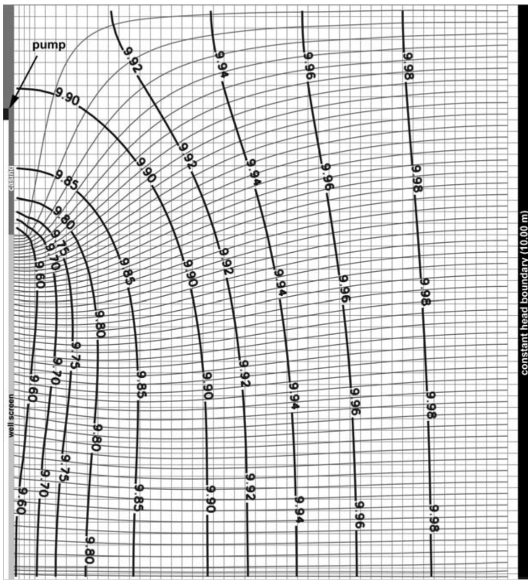


Fig. 34. (a) Contours and flow paths of vertical flow to a well (cross sectional view). The square cells have an edge length of 1 m. Modeled using PMWIN (Houben, 2006).

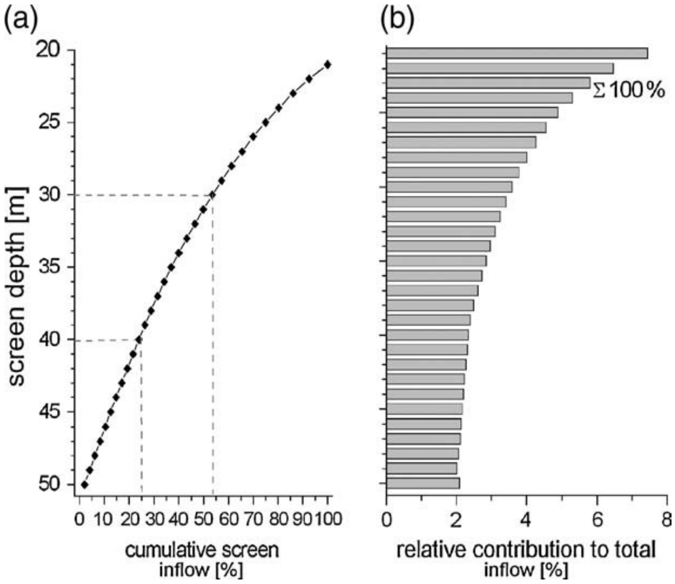


Fig. 35. Vertical distribution of inflow rates into the screen. (a) cumulative and (b) relative proportion of individual screen sections. The dashed lines separate the three thirds of the screen length. Data extracted from model calculated using PMWIN.

Hemker (1999) also explains that it is almost always assumed that the flow into a well from each layer intersecting the well screen is proportional to the transmissivity of that layer. In essence this means that a uniform radial hydraulic gradient is assumed at the well face. But even if the well is screened in a homogeneous part of the aquifer, the assumed uniform gradient (and uniform flux) at the well face is not correct in general, vertical flow components near the well will always play a role in partially penetrated wells. In Fig. 36 a typical conception of the lateral net flow regime is pictured. Through vertical flow components the upper and lower sub layers that intersect the well screen will provide more water.

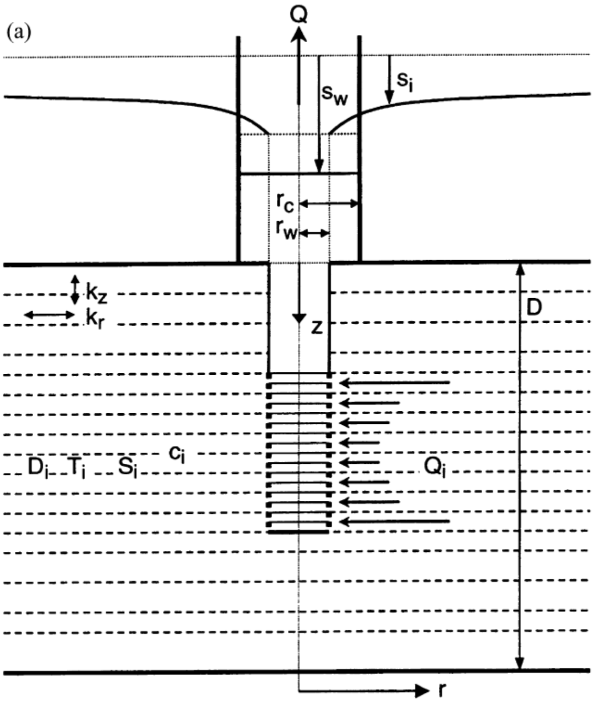


Fig. 36. Schematic diagram of a partially penetrating well in a horizontally layered aquifer. Each layer has a specific: Depth (D_i), Transmissivity (T_i), Storage coefficient (S_i) and Discharge (Q_i); whereas the c_i stands for vertical resistance between two sub layers (Hemker, 1999).

Hemker also shows that in the first time phase of an active well, the flow distribution is iniform. After a short period of time a new constant distribution is approximated which is not uniform anymore but discharge increases exponentially towards the end(s) of the well screen (Fig. 37).

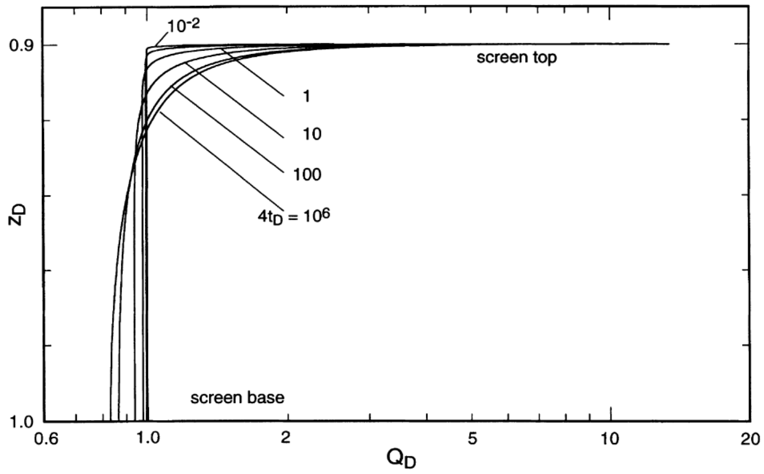


Fig. 37. Dimensionless well-face flux versus dimensionless depth for a partially penetrating (0.9-1.0D) well with a finite diameter ($r_w/D = 10^{-2}$) at different dimensionless times (Hemker, 1999).

Unlike the factor time, the well diameter seems to have a permanent influence on the vertical flow distribution (Fig. 38). According to the model of Hemker, a smaller well radius has positive influence on the distribution.

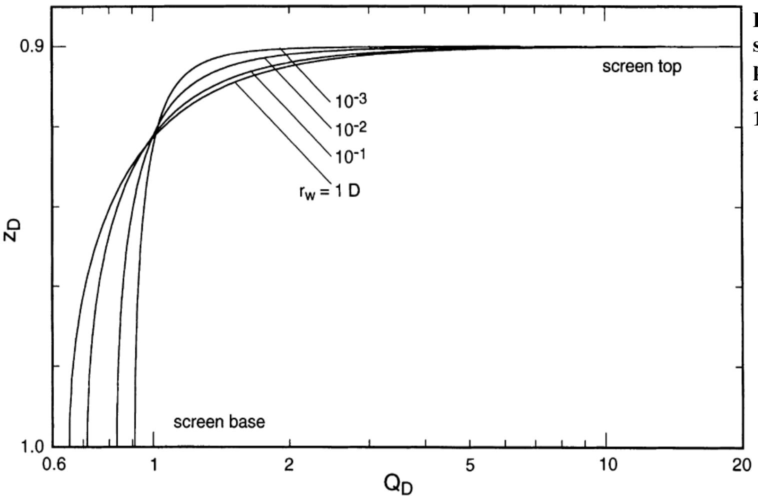


Fig. 38. Dimensionless well-face flux versus dimensionless depth for different diameters of a partially penetrating (0.9-1.0D) well: $r_w = 10^{-3}$D, 10^{-2}D, 10^{-1}D and 1D, where D is the aquifer thickness (Hemker, 1999).

However, when one analyses the radii that are plotted, only one realistic value is present. That is the 10^{-2}*D factor. When assuming an aquifer with a thickness of: D = 30m: $r_w = 10^{-2}*30 = 0.3$ m. Increasing or decreasing with a factor 10 is unrealistic, since wells do not have radii of that size. So when putting these results into perspective, choosing a smaller radius does not cause great improvements regarding the flow distribution.

Houben (2006) also states that the uppermost part of a well screen also receives much more inflow than the deeper screen sections in the case of a partially penetrating well. Motivation for his research regarding vertical flow distribution is the phenomenon of well incrustations accumulating on the upper part of well screens, indicating higher flow rates in that part. Using PMWIN he tries to numerically describe the influence of partially penetrating wells on flow distribution, thereby an isotropic formation is assumed with an adjacent impermeable layer at the depth of the bottom of the well screen (Fig. 35).

In this situation, the upper screened part seems to produce more a volume of water that is 3 times as high as the lowest screened part. Whether this is realistic or not, it certainly gives rise to doing some extra research regarding these kind of phenomena in real case wells. Just like anisotropy and well radius, there should be multiple other factors in an aquifer or in the well that have influence on the vertical flow intake distribution. Houben and Hauschild (2011) investigated the influence of well screen hydraulic conductivity and pump position inside the well (Fig. 39 and 40).

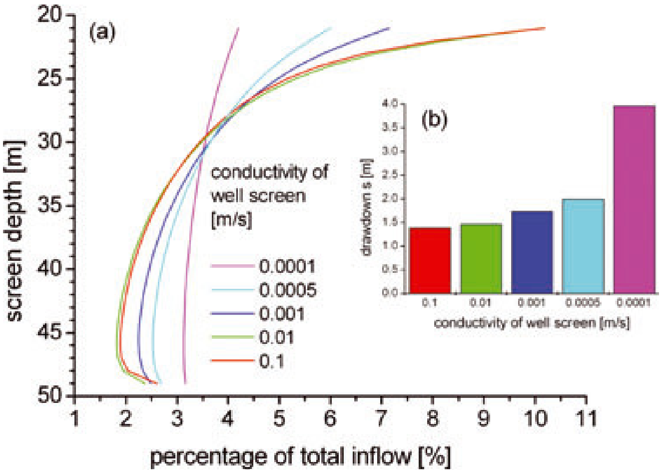


Fig. 39. Vertical distribution of inflow rates depending on the hydraulic hydraulic conductivity of the well screen. The lower the resistance of the well screen, the worse the distribution (Houben and Hauschild, 2011).

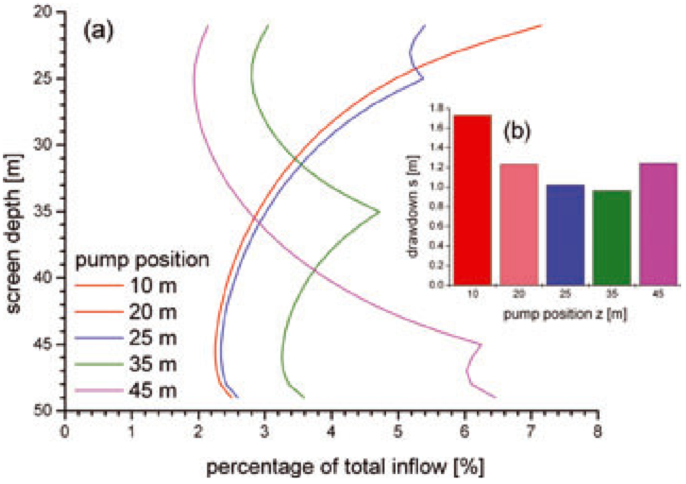


Fig. 40. Vertical distribution of (a) inflow rates at the screen and (b) total drawdown in the pump as a function of pump position. The inflow curves for 10 and 20 m are practically identical, whereas drawdown is different (Houben and Hauschild, 2011).

Pump inlet positioning seems to have significant influence whenever the pump is situated in the depth range of the screened well. A tube can be installed below the pump which reaches into the screen section. Further analysis of this measure and other measures will be done later on in this thesis. In the modeling part, a sensitivity analysis has been described to find out which parameters in a well have influence on the vertical distribution.

2.8 Design Standards

Consultancy corporations act on the basis of certain design standards in the process of preparing an advice for their clients. Commonly, existing design standards are not discussed when there is no motive. Taking into account that ATES systems are growing in popularity and the fact that not every location has a 'suited' extraction aquifer available, make it useful to revisit these standards.

'Suited' in this case means: an aquifer out of which a certain amount of water can be extracted without exceeding the design standards. This is mainly based on the grain size values in the formation, together with the porosity and grain size distribution. In areas where coarse formations are scarce in the shallow subsurface, options have to be studied to use finer grained formations. Since the current design standards seriously limit the capacity of a well in fine sand, it is valuable to take a close look at these design standards and where they could be adjusted in such a way that it will be more interesting to use fine sand aquifers.

2.8.1 Extraction standards

Maximum pumping rates that can be achieved depend on the well radius, screen length and the flow velocity at the wellbore (v_b). The v_b value has been determined empirically in 1997 (IF Technology):

$$v_b = 2k$$

V_b = flow velocity at the wellbore (m/h)

k = hydraulic conductivity (m/h)

This relation assumes a linear relation between the allowed v_b and the hydraulic conductivity of the aquifer. Using this standard, wells have been designed successfully over a period of at least 15 years (Buik, 2001). Buik (2001) compared this approximation for the velocity on the wellbore, with various other relations regarding the relation of v_b with hydraulic conductivity. In the hydraulic conductivity range of fine sand aquifers (0 – 20 m/d), the IF design standard is relatively conservative to three other methods, with differences up to a factor 2 (below 10 m/d) (Fig. 41).

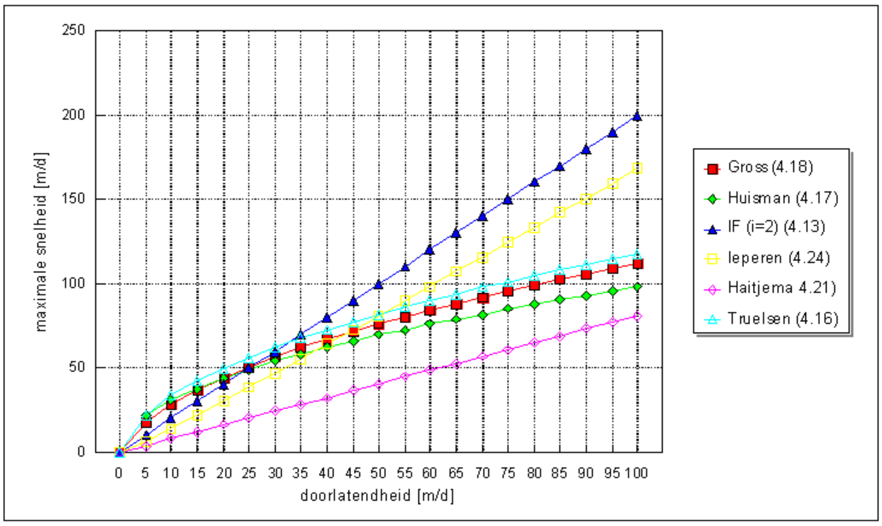


Fig. 41. Various design standards regarding the flow velocity on the wellbore (Buik, 2001).

2.8.2 Injection standards

Infiltrating ground water sets requirements to the well design. The most important requirement is the prevention of an unacceptable rise of the injection pressure due to clogging particles in the groundwater. If the injection pressure rises to a critical level in a well, there is a chance of fracturing of the adjacent formation. A rule of thumb is formulated for the maximum allowed pressure rise in the well (NVOE/BodemenergieNL) :

$$h_{max} = 0.2 * z$$

z = distance from the ground surface to the top of the well screen (m)
h_{max} = maximum allowed hydrostatic pressure in the well

For critical situations a more accurate calculation of h_{max} is needed, based on soil properties, depth and hydraulic head in the aquifer. Well designs should be based on the following rule:

$$1.5 * \Delta h \leq h_{max}$$

Δh = injection pressure (m)

When it is assumed that particle clogging is the most important clogging mechanism, the next equation can be used to approximate the maximum allowed velocity on the wellbore. This formula comes forth out a quadratic relation between clogging rate and the velocity on the wellbore:

$$v_0 = {v_0}' * \sqrt{\frac{8760}{u_{eq}}}$$

v_0 = acceptable velocity on the wellbore (m/h), based on 8760 load hours per year
v_0' = acceptable velocity at a number of 8760 equivalent full load hours (m/h)
IF Technology uses 0.5 m/h as value for v_0'
U_{eq} = number of equivalent full load hours

U_{eq} is calculated using:

$$U_{eq} = \frac{\Sigma Q}{Q_{max}}$$

ΣQ = total amount of water pumped per season (m^3)
Q_{max} = maximum discharge of the system (m^3/h)

2.9 Flow meter, reliability and uncertainties

To obtain a vertical flow log of a well, one has got to measure the flow velocity inside a well which is being pumped at a certain discharge. Although several methods of measuring flow within wells are available, the impeller flowmeter (Fig. 42) is the most common tool used to measure flow within production wells under pumped conditions (Hill, 1990). The impeller flowmeter relies on a mechanical impeller that turns as water flows past the impeller vanes. The number of revolutions is transmitted to the surface by electrical impulses triggered by mechanical, electrical, or magnetic counters. Impeller flowmeters are useful in higher flow velocities typically encountered in pumped wells but lack the sensitivity to low-velocity flow found in the deeper parts of some wells or in unpumped wells. The most commonly used impeller flowmeters are not accurate to velocities < 1.2-1.5 m/min. Impeller flowmeters are sensitive to mechanical interference from debris in the well. The electromagnetic flowmeter measures the rate of flow on the inside of a hollow, cylindrical measurement section built into a borehole-logging probe (Paillet 2000). Electromagnets inside the cylinder create a strong magnetic field across the hollow of the sampling cylinder. According to Faraday's law of induction, the voltage generated by water (electrical conductor) passing through the sampling volume is directly proportional to the average water velocity moving through the magnetic field (Young and Pearson 1995). Electromagnetic flowmeters enable measurements of velocities <0.1 m/min.

Fig. 42. Impeller flowmeter used by Q-flow, Rabobank Utrecht project.

The gathered results will add up to give shape to a cumulative graph, using this graph the discharge per screen section can be calculated (Terwey, 1971). This can tell a lot about the location of possible unproductive well sections (clogged parts) and aquifer hydraulic conductivity. Additionally the technique is sometimes used to test whether performed rehabilitation techniques are effective considering well improvement. Flow meters can also be used to prove the water transport from one water bearing formation to the other, this can be measured when the pump is at rest. However, an impeller flowmeter will probably not be suited for this because it is not sensitive enough to detect the relative low flow velocities. Signs of this worse sensibility can be found back in the PV-02 well in Fig. 43.

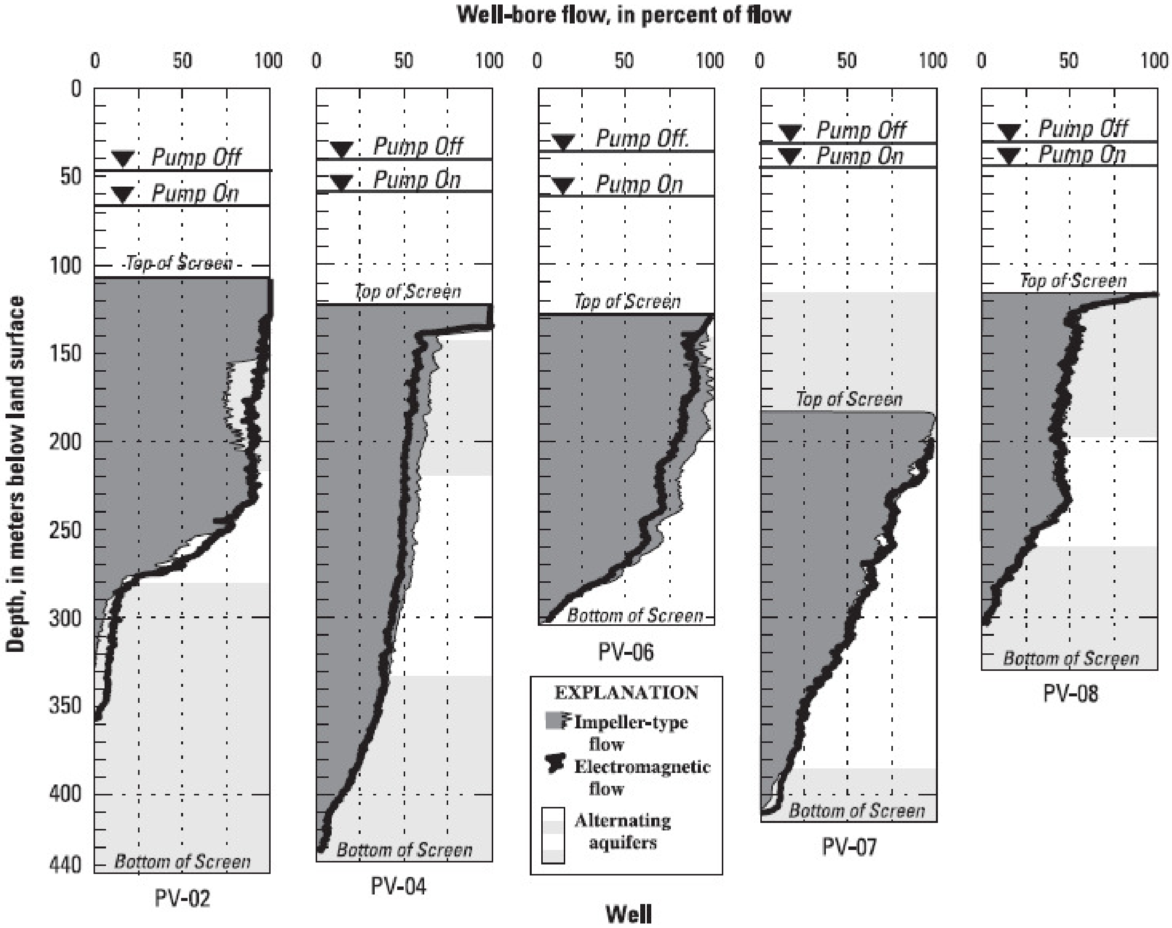


Fig. 43. Newhouse et al. Did experiments in Pleasant Valley, California, to compare the data collection of an impeller flowmeter with a electromagnetic flowmeter. The results are quite familiar. The lower part of the PV-02 well proves that an impeller flowmeter is less accurate for low flow velocities (Newhouse et al., 2005).

Reliabitity

A common problem in the collected data is the reliability of the exact propeller location in the cross section of the well. The problem with wells is that they are never 100 percent straight, especially in the case of deeper wells. An unwanted consequence is that the propeller moves laterally through the well in this case. Obviously this influences the results in a bad way, since flow velocities vary from highest in the centre of the well tube to zero at the wall of the well tube (Fig. 44).

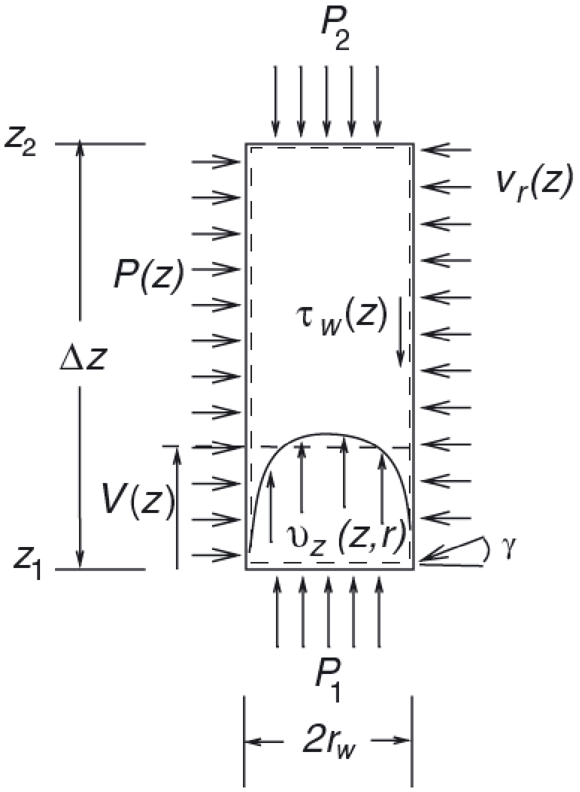


Fig. 44. Lateral flow distribution in a slotted well tube under laminar flow. Momentum balance control volume for a wellbore (Clemo, 2010).

In fact flow velocity is not zero at the well screen; the flow direction is perpendicular compared to the overall flow direction inside the well tube because water penetrates through the screen slots. The inflowing water forms a vertical no flow layer close to the well screen; this can be seen effectively as a small decrease in well radius. Keeping this in mind, one can imagine that locations which relatively contribute a lot of water show velocity values in the centre of a well tube which are too high. This is a phenomenon that can be detected often at the boundaries of a screened well part with a blinded part.

Regarding the impeller accuracy, a graph has been produced where in the flowmeter accuracy can be observed as a function of discharge (Fig. 45). Each line represents a realistic (commonly used) inner well tube diameter. The ratio Q_accurate represents the discharge at a flow velocity of 1.2 m/min, according to the article from Newhouse et al. (2005), this is the minimum flow velocity for reliable velocities.

Especially low discharge wells are more likely to show questionable flow velocities in the lower sections of a well. In this research only a few wells are dealing with unreliable results when compared with this graph (well 4a, 4b, and 5 in Appendix A).

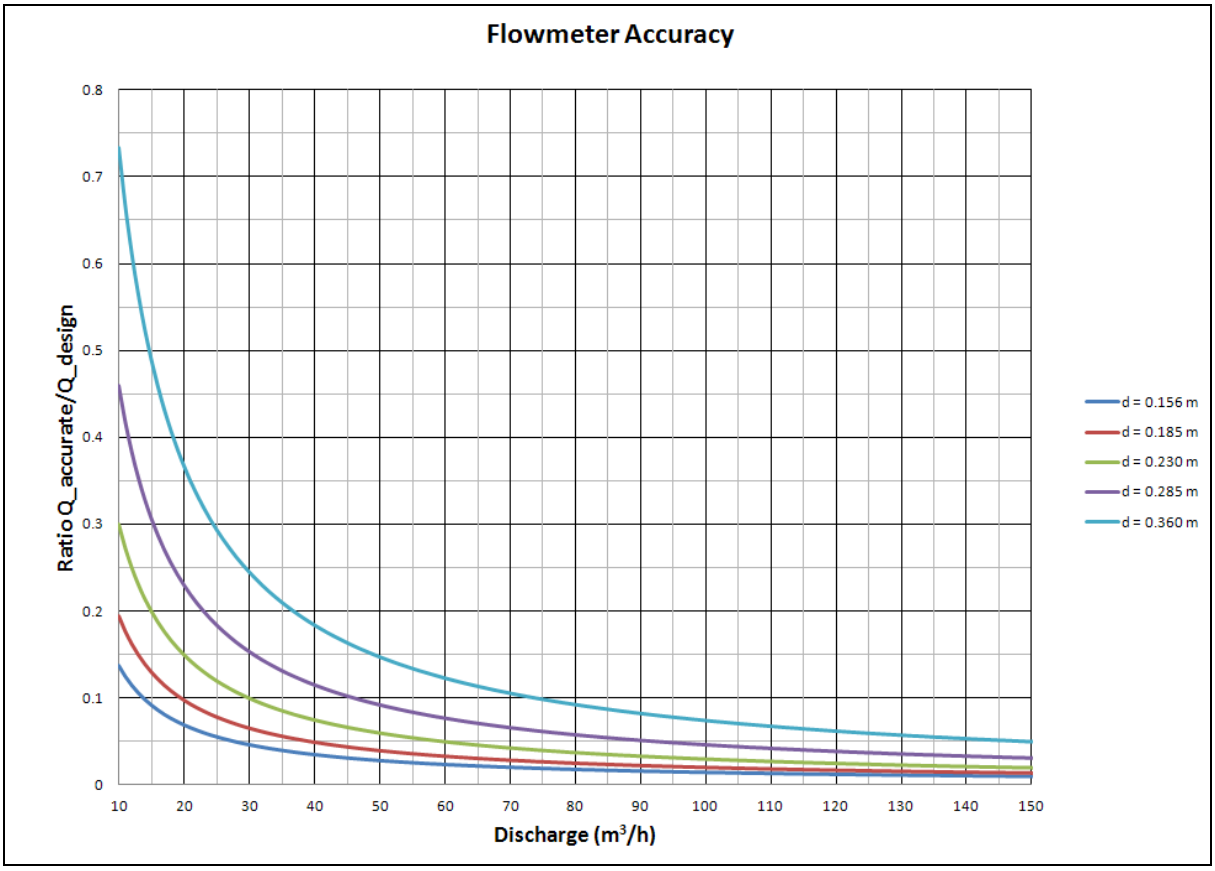


Fig. 45. Flowmeter accuracy plot. The higher the ratio, the worse the accuracy of the flowmeter. Each line represents a realistic (commonly used) inner well tube diameter. The ratio Q_accurate represents the discharge at a flow velocity of 1.2 m/min, according to the article from Newhouse et al. (2005). This is the minimum flow velocity for reliable velocities.

Conclusively it is clear that there can be some uncertainties and false trends in vertical flow distribution logs. Despite this, it does not make the flow distributions useless. The graphs can have significant value in showing the relative contribution of each well section and tracing clogged parts; and thus it is also useful in checking the effectiveness of development techniques in different parts of the well screen. Important to keep in mind is that velocities in the lowest section of the well could be unreliable because of the flowmeter sensitivity, also radial well positioning is significantly important in the reliability of the measured values.

3. Methodology

3.1 Ground Water Flow Models

To study ground water flow patterns around a well or within a system of wells, IF Technology uses a program called MLU. This aquifer test analysis (pumping tests) program calculates drawdown at different locations (x, y, z) in time due to infiltration and/or extraction activities. Hydraulic conductivity, aquifer thickness, vertical anisotropy, storage coefficient, discharges and well diameter can be altered for a maximum of 40 layers. In the research this modeling program has been used for a sensitivity analysis of these varying factors on the vertical velocity distribution over the well screen length. More importantly it also acts as simulator for real projects to simulate and predict flow distributions.

MLU-built drawdown models can be exported to a more advanced model called MicroFEM. This is a computer program for multiple-aquifer steady-state and transient groundwater flow modeling. Instead of model grids with squared cells (like the grids in PMWIN), this program uses triangle shaped cells. Therefore of this it is more efficient in producing a detailed raster at the locations of interest, close to a well for example. The visualization functions are rather enhanced; flow lines, drawdown graphs, contour lines, fluxes and water balances are easy to study. Using MicroFEM one can examine the effects and the magnitude of well interference on flow patterns and the water intake distribution.

In MLU, the output data exists of the calculated hydraulic head (in meters) at a given location, with a punctuality of three decimals (mm accurate). Using Darcy's law, the flow velocities can be calculated at the wellbore when both hydraulic head inside the well and at a certain distance from the well are known. After normalizing these velocities for each meter of the well screen, a vertical flow meter log can be produced. MicroFEM offers a function which calculates the horizontal flux at each node in the model. For each layer, this value can be translated to a normalized flow velocity at the wellbore.

3. 2 Model Build-Up

3.2.1 MLU-Sensitivity analysis

The sensitivity analysis has been performed by creating a simple semi-partial model of a 40 m thick aquifer, consisting out of 40 layers of 1 m in thickness. The upper and lower boundaries are impermeable. An extraction well is situated in the lower 8 m of the aquifer. A qualitative sensitivity analysis has been executed for four parameters:

- Well radii
- Vertical anisotropy
- Horizontal hydraulic conductivity
- Discharge

During the model runs all but the tested parameters are kept at constant, realistic levels. The tests run with a flow rate of 800 m³/d, well radius of 0.2 m, homogeneous hydraulic conductivity of 10 m/d and a vertical anisotropy of 1.

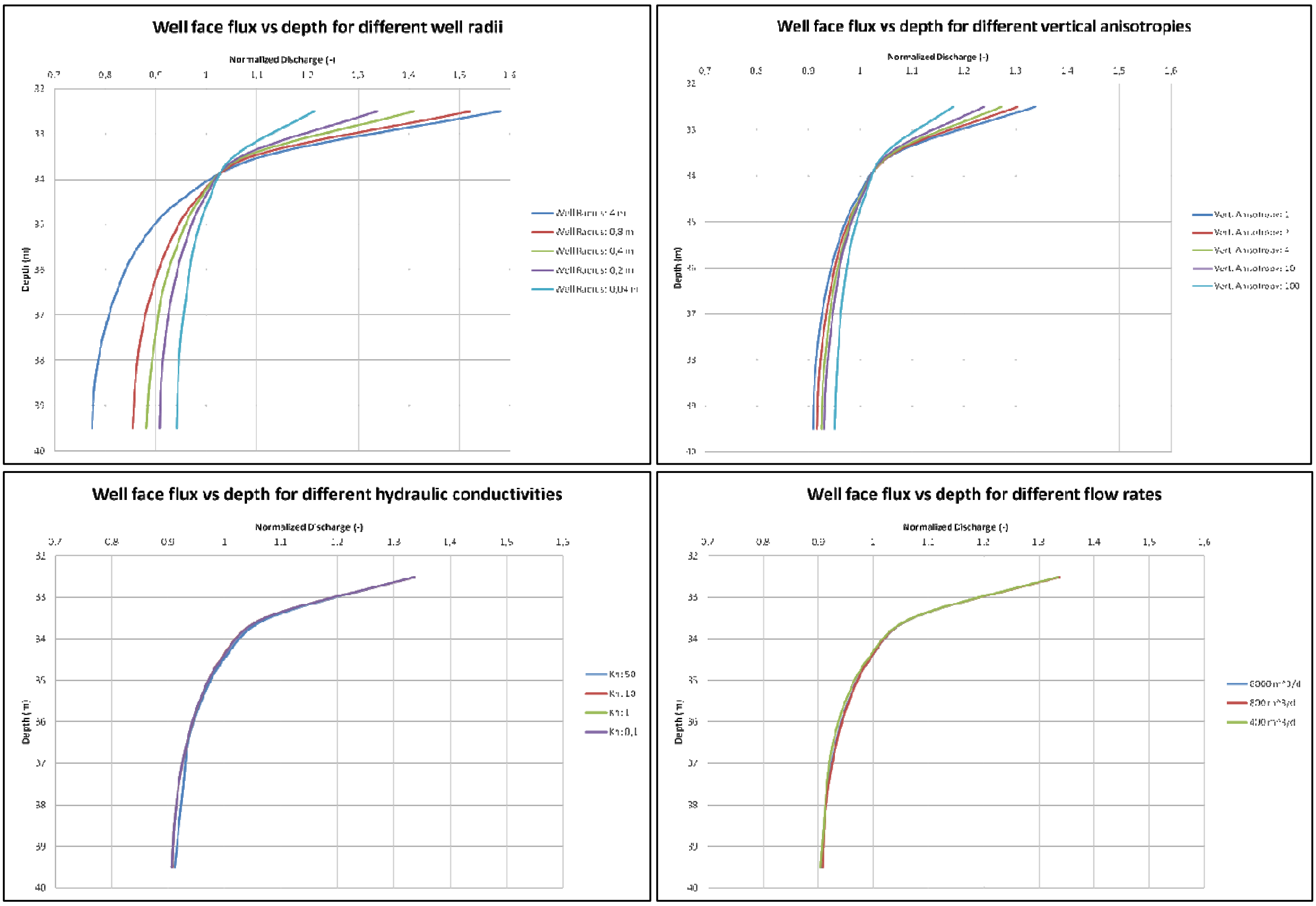


Fig. 46. Qualitative sensitivity analysis for four parameters on the subject of well performance. It appears that the well radius has most prominent influence on vertical flow distribution. Anisotropy variance has minor influence while both hydraulic hydraulic conductivity and flow rates in a homogeneous aquifer do not have any influence on the flow distribution.

The main conclusion of this sensitivity analysis is that the most important factor regarding vertical flow distribution is the well radius. The vertical anisotropy logically also plays a role, while neither the hydraulic conductivity nor the discharge is of any influence on relative differences in the uneven flow intake (Fig. 46).

3.2.2. MicroFEM Well interference analysis

Within certain distances, active wells can interfere with other active wells. In most extreme case, infiltrated water gets extracted in the production well. In practice this will not happen often, because great care goes to optimal well location. Despite this, changes in hydraulic gradients will occur to some extent, which will on its turn lead to changes in ground water flow patterns. To investigate these phenomena, a MicroFEM model has been developed. The influence of head losses due to friction in the well tube are not taken into account by the model. Furthermore the well is assumed to be clean; variations in the inflow due to relative differences in clogging are therefore neglected

Realistic distances between an infiltration and an extraction well are in the order of 150 m. Typical distance between two wells of the same character, for example two extraction wells, is in the order of 20 to 30 m. Bearing these numbers in mind, the well positioning is build around the central modeling well, as it is pictured below (Fig. 47).

MicroFEM offers the possibility of modeling a maximum of 20 layers with variable thickness. The depth

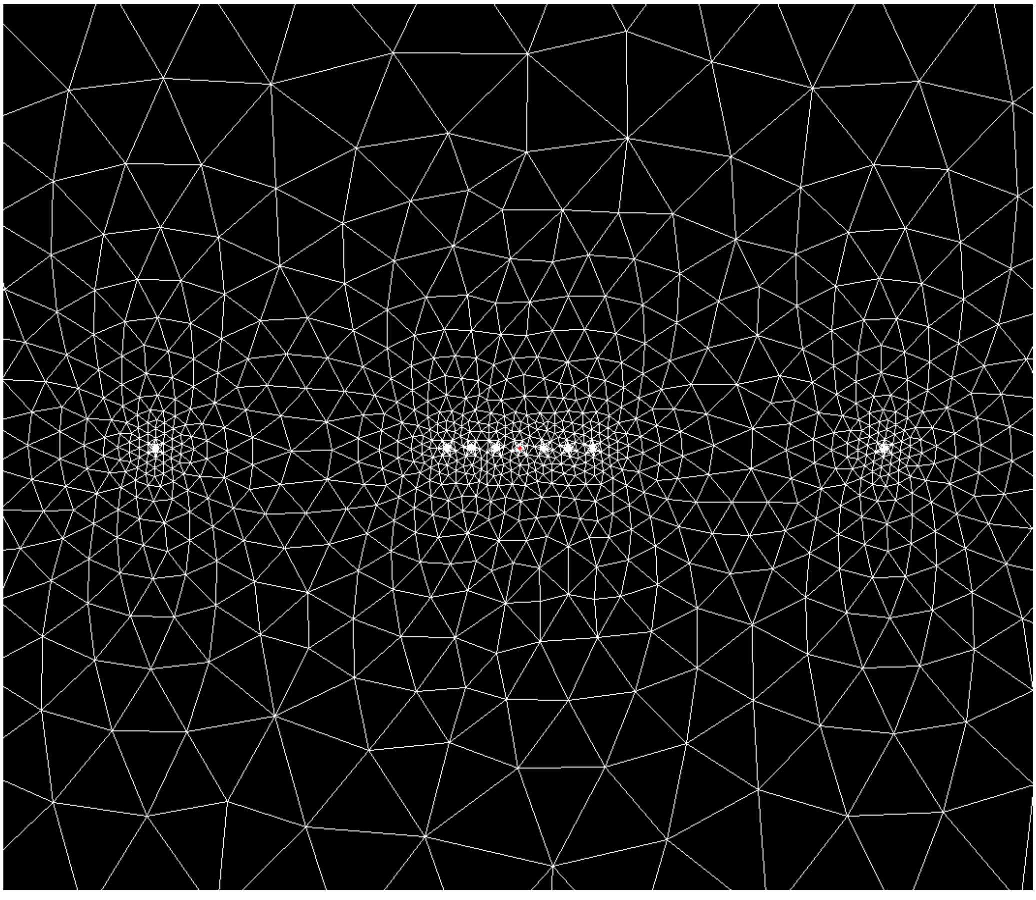


Fig. 47. Well build-up. The inner group of wells represent potential extraction wells, which have a mutual distance of 10 m. The two remaining wells represent potential infiltration wells, situated 150 m from the central well. Mesh image from MicroFEM.

of the layers is translated through varying transmissivity (T [m^2/d]) per layer. The bottom of the model is defined by an aquitard at -60 m; the top is also confined by an impermeable boundary. The well has a total depth of 60 m of which the lowest 10 m are screened. The lowest 10 meters of the model are constituted of 10 layers of 1 meter thickness. The upper 50 meters of the model are represented by 10 layers of 5 meters thickness.

The well diameter is 0.45 m; the nodes within the (active) wells are assigned with a constant head which simulates a certain discharge. The lateral model boundary is also assigned with a constant head; this head value is 0.0 m. One meter of the formation has a vertical resistance of 0.2 days. Hydraulic conductivity in the horizontal direction is uniform with k = 10 m/d. Consequently the upper 10 layers are indicated by a transmissivity of 50 m^2/d (T [m^2/d] = k [m/d] * D [m], D represents thickness).

In order to perform a sensitivity analysis which pictures the influence of well screen positioning with respect to clay layers, each well situation is modeled for four different depths of a confining clay layer:

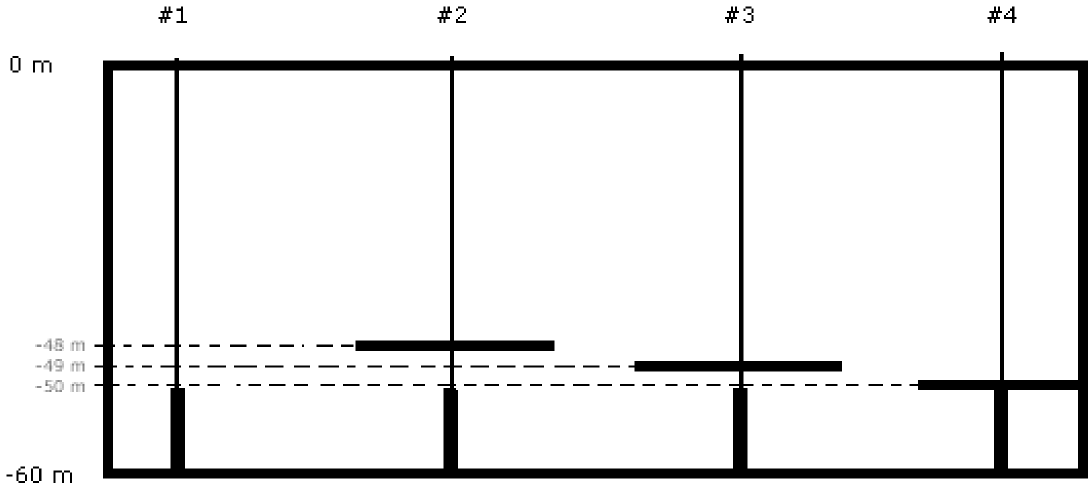


Fig. 45. Four well situations which have been simulated. The thick black horizontal lines represent confining clay layers. Later on it can be seen that these layers could be of great importance in the flow distribution.

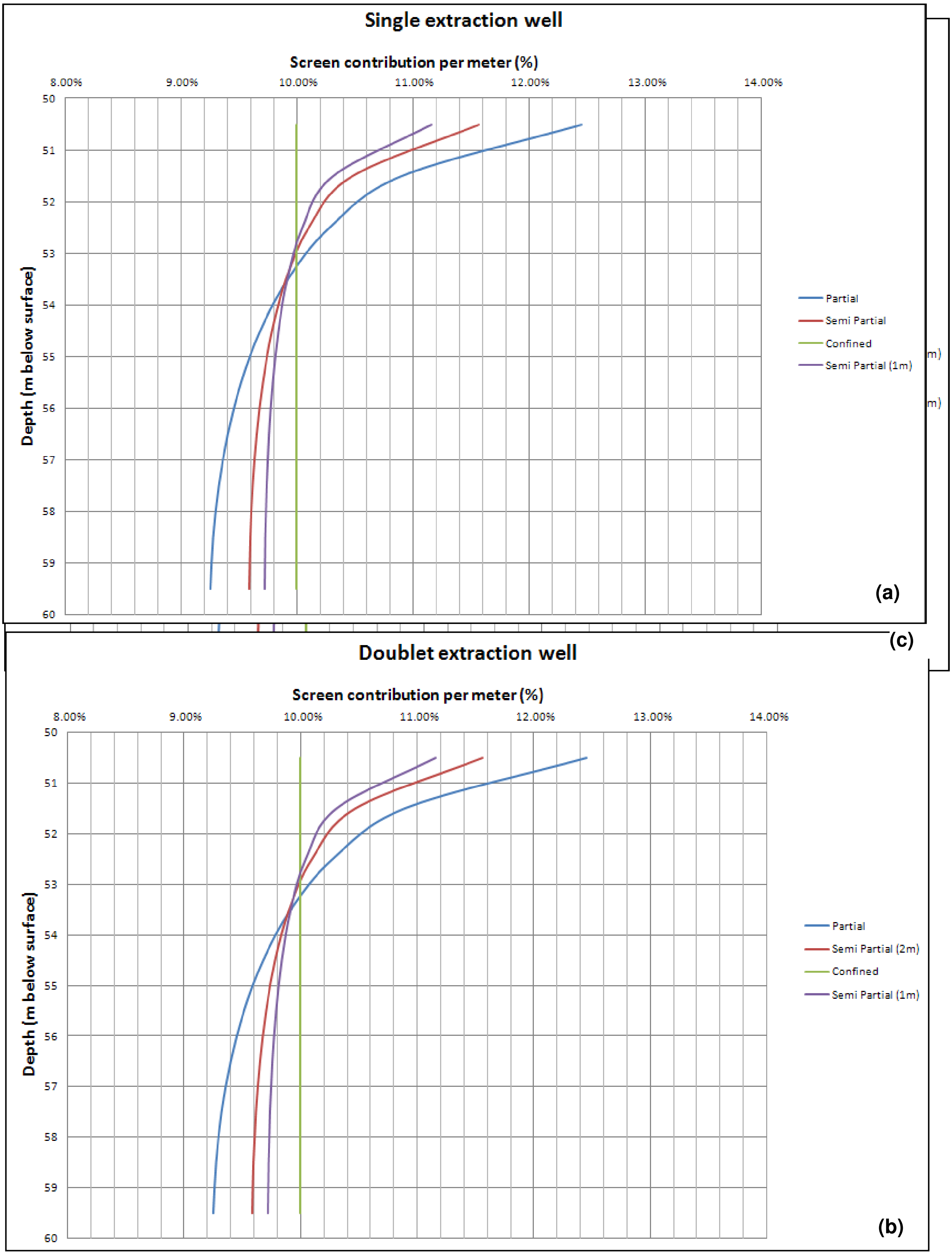
#1: Partial
#2: Semi partial (2 m)
#3: Semi partial (3 m)
#4: Confined

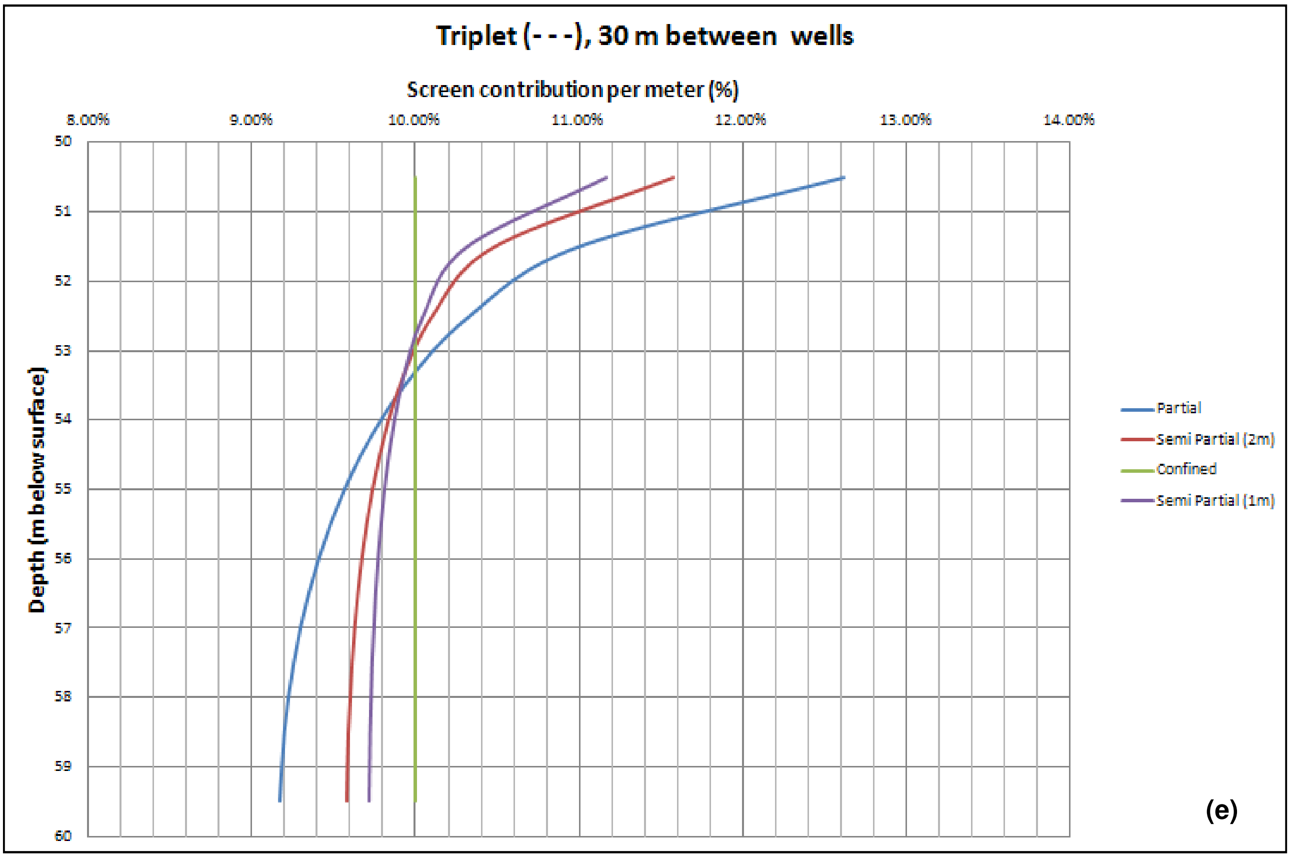
For each of these four situations, the model ran for the following well situations:

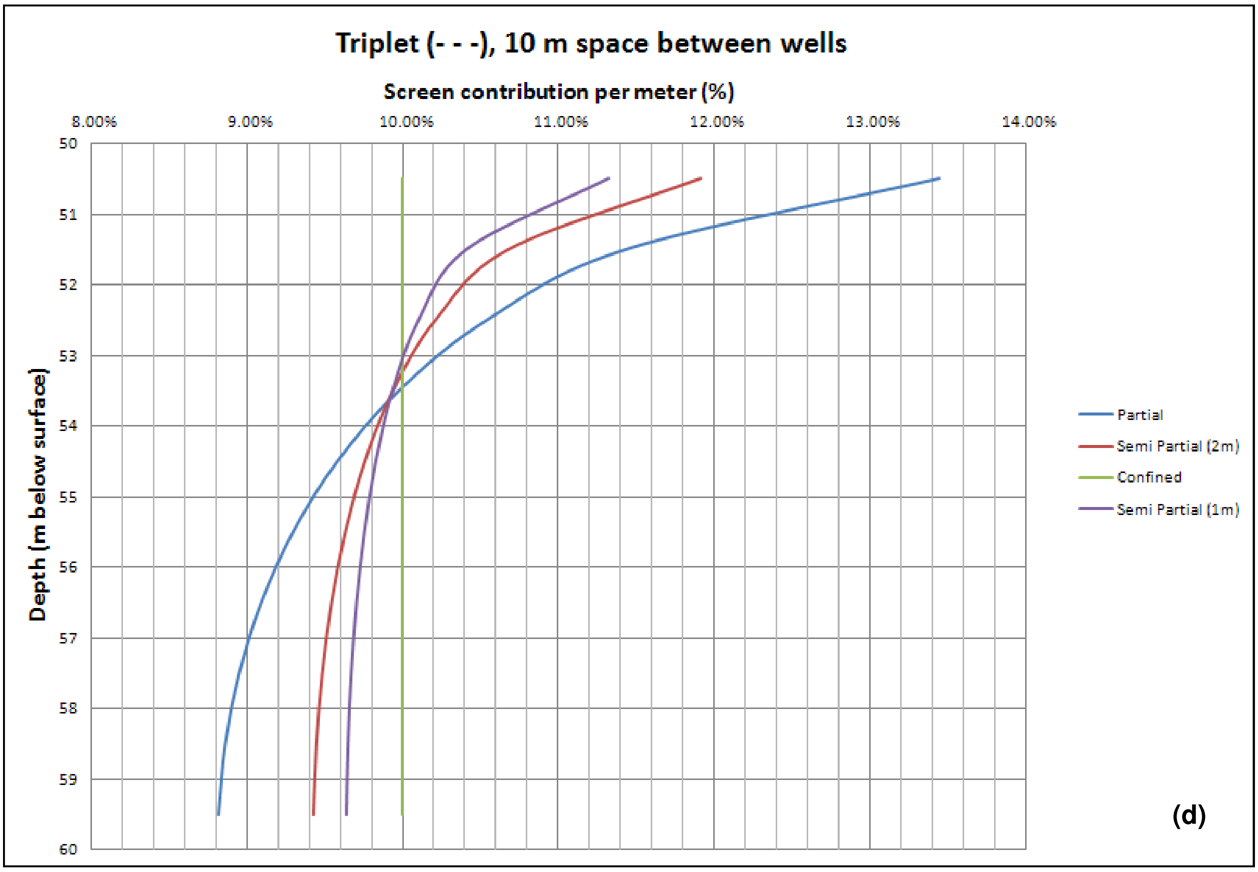
-Single extraction well	(-)
-Doublet	(- +)
-Triplet	(+ - +)
-Triplet with 10m between extraction wells	(- - -)
-Triplet with 30m between extraction wells	(- - -)

Well location and interference sensitivity results are represented below in figure 49:

Fig. 49. Visualization of the difference between situated confining layers in an aquifer. Each graph (a-e) contains 4 different 'confinement cases' (Fig. 42) and represents varying well interference cases.




Triplet (- - -), 30 m between wells
Screen contribution per meter (%)
8.00%
9.00%
10.00%
11.00%
12.00%
13.00%
14.00%
Depth (m below surface)
50
51
52
53
54
55
56
57
58
59
60
Partial
Semi Partial (2m)
Confined
Semi Partial (1m)
(e)


Triplet (- - -), 10 m space between wells
Screen contribution per meter (%)
8.00%
9.00%
10.00%
11.00%
12.00%
13.00%
14.00%
Depth (m below surface)
50
51
52
53
54
55
56
57
58
59
60
Partial
Semi Partial (2m)
Confined
Semi Partial (1m)
(d)

The results of the well interference test show that well interference does not play a significant role in the vertical flow distribution in case of a realistic distance between an injection and an extraction well (Fig. 49 a, b and c). When wells are more closely situated to one another, as in (d), well interference is slightly increasing the difference in contribution between the top and the bottom of the screen. Water is in lesser extend coming from the directions of the adjacent wells (E- and W- directions), the hydraulic gradient is relative low there (Fig. 50).

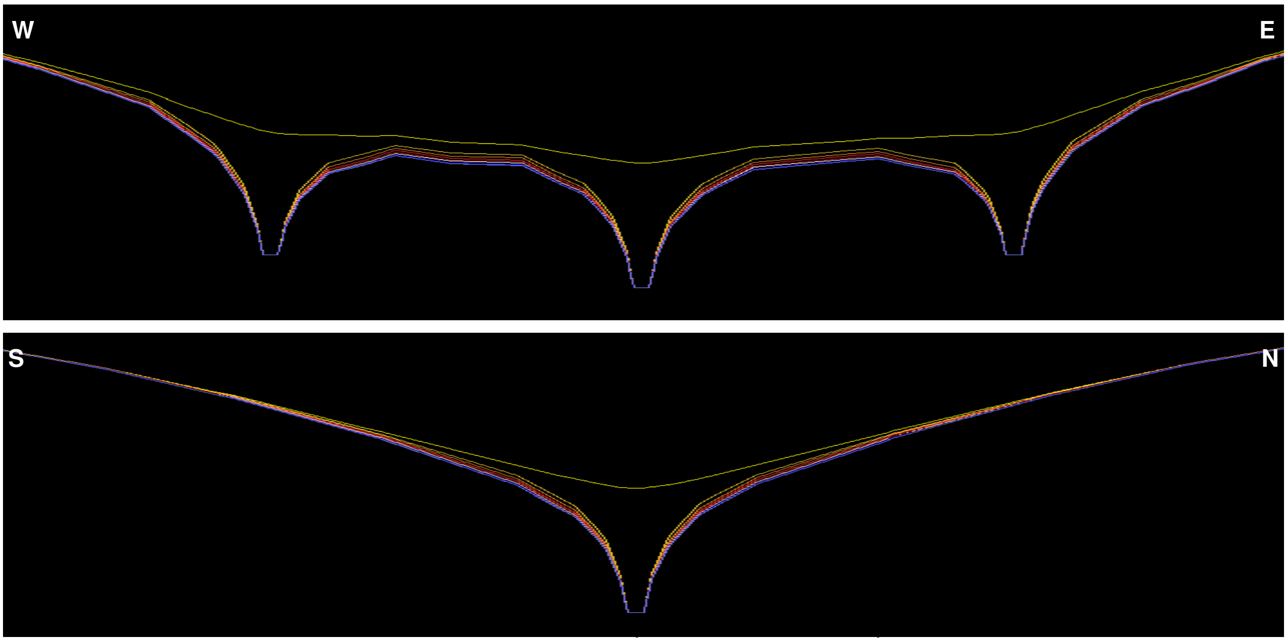


Fig. 50. Cross section of the hydraulic head in E-W respectively N-S directions. When one takes a close look, the hydraulic gradient is bigger in the N-S direction. More water is supplied from these directions. Graph is taken from MicroFEM (Hemker and De Boer).

From comparing Fig. 49e with 49a we can see that the effect of well interference is almost negligible in case of a mutual distance of 30 m between extraction wells. The N-S:E-W ratio is only 1.06 for a confined aquifer. In Fig. 51 this becomes clear, because the flow paths show where the water is coming from. The flow from the North and South directions is not as dominant in (b) as it is in (a).

It seems that well interference is not likely to have great influence on the vertical or horizontal flow distribution in ordinary well design. What does matter is the grade of confinement of a well. When it is perfectly confined at the bottom and at the top, flow logs are more likely to have a well-balanced distribution. When this is not the case, one can expect relative large amounts of water intake at the end(s) of the well screen; that is at least in the case of a clean, well developed well in a nearly homogeneous aquifer.

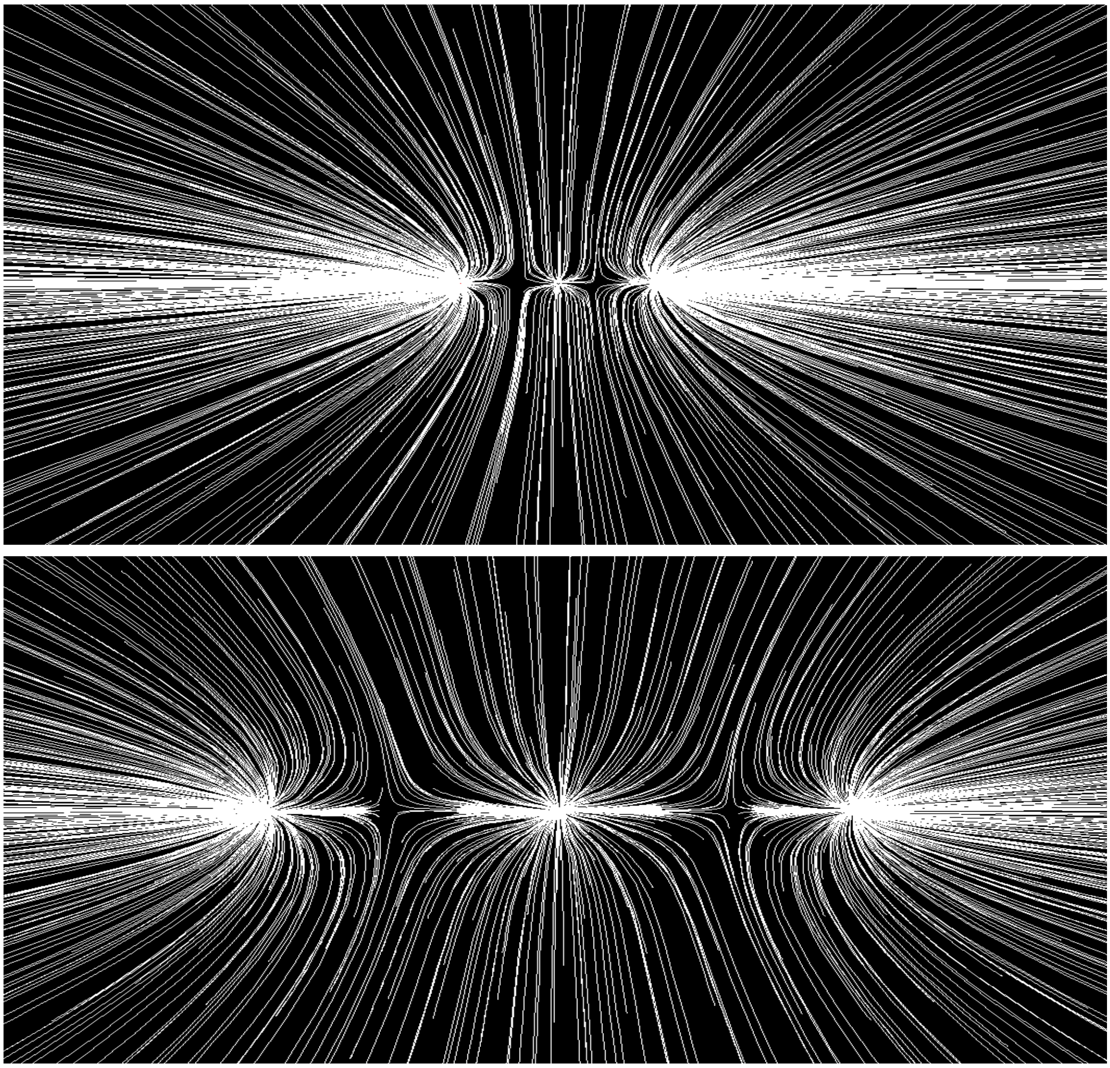


Fig. 51. Flow path diagrams with mutual distances of (a) 10 m and (b) 30 m, respectively (MicroFEM).

3.3 Data collection and selection

In theory the vertical flow logs show an irregular flow velocity pattern on the well screen, especially in partial well screens. In the models, most expectations were unanimous with the literature and experiences from people working in the field. However, models reflect only a theoretical approach to the problem. Using vertical flow meter logs, practical data can be analyzed to weigh observations in the field to theoretical expectations.

In order for practical flow data to be suited for proper, significant analysis, it has to contain all the essential pieces of information like: screen positioning, lithology, well diameter, maximum discharge, gravel pack and specific capacities. In the results part of this thesis extensively studied projects will be treated, in almost all of the treated cases IF Technology supplied the data. However Deltares also contributed to the research with a selection of raw data regarding flow meter tests. Unfortunately the lack of some essential information made it not suitable for extensive analysis. Furthermore drinking water company Evides and drilling company Haitjema also assisted in gathering relevant information.

3.3.1 Deltares datasets

Collecting flow measurements, the institute ‘Deltares’ was approached to supply a part of these measurements. They made a selection of roughly 70 flow logs. They also offered a working place to make a selection out of the datasets, and to process them to useful, visual supporting files. After the selection, the accompanying local lithology data has been downloaded from ‘DINO Loket’. These files are essential in clarifying features that are observed in the vertical flow distribution graphs that are the result of the selection and processing.

The software used to process the data was also provided by Deltares, the program is used is ‘Strater 2’. It is used to translate raw text documents to more visual adjusted graphs and lithology logs.
First the text data is loaded into two worksheets. One sheet for the well (lithology) and one for the required parameters like flow velocity. Making use of a template, a separate sheet with multiple graphs has been displayed. Depth was set out against gamma rays (CPS), Resistance (Ohm.m), Lithology, Grain Size and Flow (m/s or %) respectively.

The gamma rays that are emitted by different lithological fragments of the soil indicate whether one is dealing with clay or sand. It is measured in ‘counts per second’ (CPS). Clay emits more gamma rays compared to sands because of the elements that it is constituted of. Together with soil samples that are gathered during the drilling process, it determines where the well screens can be placed.

The resistance can be measured in short normal waves (16N) or long normal waves (64N) and the unit is Ohm*m. The short normal waves give a view on the electrical resistance in the well tube itself and the long normal waves are more representative for the properties in a wider radius. The resistance plots can be used (among others) to show exactly where the well screens are situated in the well. Unfortunately in most datasets the resistance measurements are not available.

Long normal waves (64N) make it possible to look in the formation adjacent to the well. It roughly gives the same image as the 16N plots. Where possible the 16N plots are pictured. Lithology has been subdivided into coarseness of the grains, from clay to coarse sand and gravel. Electric sensitivity measurements can also be used to trace transitions between fresh water and salt water.

Because essential data regarding screen locations, backfilling material, discharges and lithological features are frequently missing in the datasets, the flow distribution graphs are not used in the analysis in this thesis. However, these graphs do give an impression concerning the influence of for example lithological variance. In Appendix B, these graphs can be consulted. Fig. 52 shows a nice example of a processed dataset. Striking is the steeping of the graph near the bottom and the top of the screen (119-95 m below surface). Also the unproductivity of the screen part correlating with the medium sand layer is interesting to observe. Clearly the water much rather chooses its way through relative high conductive layers.

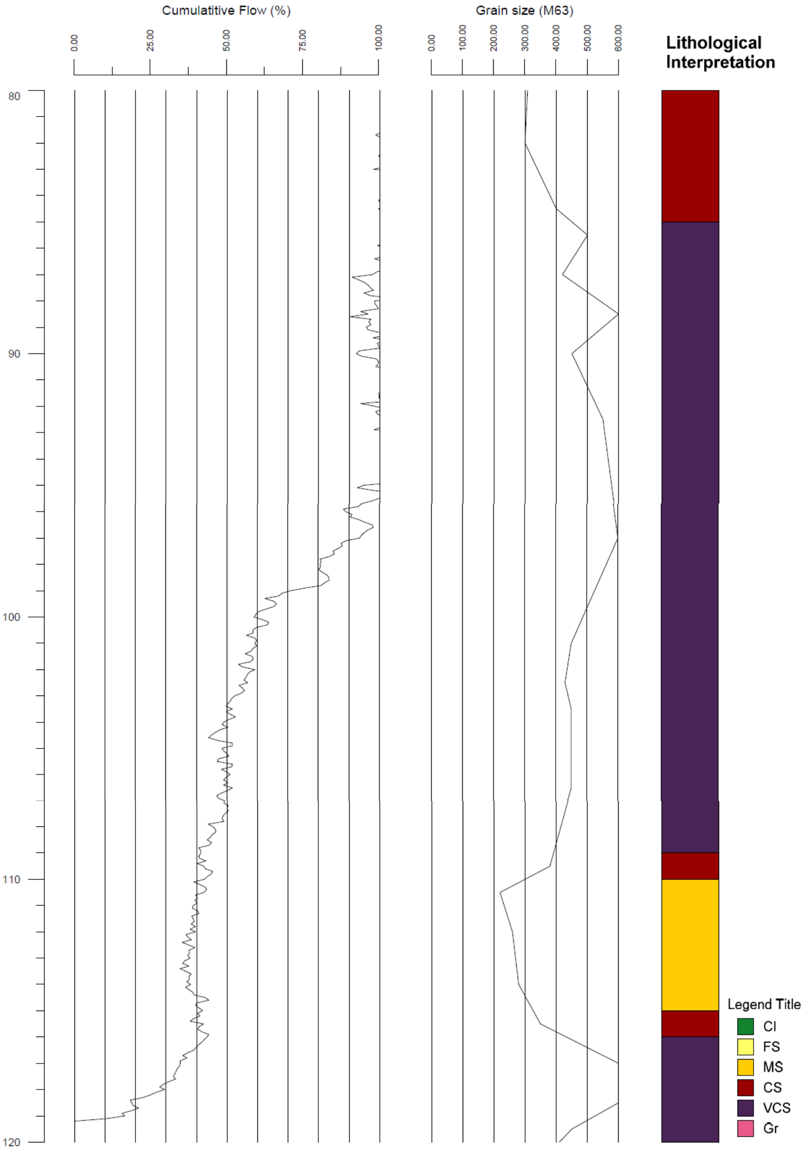


Fig. 52. This is one of the +/- 20 datasets processed with Strater 2. This is the same well as Project 7, analysed in the results part. In Appendix B, the rest of the graphs can be found back (Deltares).

3.3.2. Data used for main analysis

In the past, performing flow measurements in newly produced wells was something that did not occur on a regular basis. This made the process of collecting useful data for a significant amount of projects not easy. Most of the projects which are suited for the research are relatively young; some of them are not even taken into use yet. Despite this, some interesting observations have been done while studying the available projects. In the next part the results of this study will be shown and discussed.

4. Results & Discussion

In order to get a grip on processes and phenomena taking place inside a well when problems occur, different points of view are taken during the analysis. A clarifying table containing relevant data of all the studied wells will be presented. The actual visual supporting results are shown in Appendix A, so that a detailed look can be taken on specific details. The current design standards have been proved to be safe, since only a small fraction of the developed wells perform below expectations when living up to these standards.

Further on it has to be mentioned that information about well location, client and contractor cannot be released. That is the reason that the wells have numbers instead of location or names.

4.1 The table of results

Every studied well has a collection of essential properties regarding well design and activity. Screen positioning, backfill material, formation lithology and well discharges are some of these properties. By calculating wellbore flow velocities, it is assumed that the filter pack has the same extension (length) as the well screen sections. In reality this is not true, because the gravel pack exceeds the screen section by one or more meters.

To make it all easy accessible, a table is given below (table 3) in which the most relevant properties are displayed. Colors have been used to identify important similarities between wells, these colors are also used to identify trends and relations between certain characteristics:

Well #	Discharge (m^3/h)	Distribution: Model vs. Measured	Average formation grain size	Screen confinement	Screen Length: top-bottom (m)	Borehole-/Inner well-diameter (mm)	Backfilling material (mm)	Wellbore flow: Model/ Design	Sand Production	SC Calculated/ SC Measured	Under-performing screen sections	Well Development
1	160	medium/good	coarse	partial	71	600/230.8	0.8-1.2	0.2	no	1.0	small parts	a, b, d, f
2a	105	bad	fine-medium	semi-confined	107	700/291	0.8-1.2	1.5	no	1.1	lowest 30%	a, e, f
2b	105	medium	fine-medium	confined	103	700/291	0.8-1.25/0.4-0.6	1.2	no	1.4	lowest 25-30%	a, e, f
3	24	very bad	fine	partial	75	500/156	0.2-0.63	0.6	no	6.3	lowest 60%	a, b, d, f
4a	25	medium	medium	semi-confined	15	700/291	0.63-1.0	0.5	yes	4.1	screen top	a, b, e, f
4b	24	medium	medium	confined	17	700/291	0.63-1.0	0.5	yes	6.8	bott. upper section	a, b, d, f
5	15	very bad	fine-medium	partial	35	600/360	0.5-0.8	0.3	no	5.2	lowest 30%	a, b, d, f
6	200	medium	medium-coarse	partial	26	700/285	1.0-2.0	1.0	plausible	0.5	in fine layer	?
7	30	?	coarse	semi-confined	17	500/-	?	0.2	yes	?	?	a, b, d, f
8	98	?	medium	partial	24	500/230	1.0-1.6	1.9	yes	0.5	?	a, b, d, f, g
9	100	?	medium	confined	53	600/235	0.8-1.25	0.7	yes	0.8	?	a, b, d, f
10a1	22	bad	fine-medium	confined	15	600/185	0.5-1.0	1.0	no	1.1	lowest 40%	a, b, d, f
10a2	22	medium/good	fine-medium	confined	15	600/185	0.5-1.0	1.0	no	1.0	no	a, b, d, f, c
10b	22	medium/good	fine-medium	confined	27	600/185	0.5-1.1	0.9	no	1.0	no	a, c, d, f

Table 3. Results table: every relevant well has been simulated. Important factors have been determined in both in the process of simulation as in the analysis. To clarify and visualize some important similarities between wells, colors have been used.

Well development:
a = Build-up Discharge (from 10%-100% of well capacity)
b = Air-Surging (applied pressure normally between 1,0 and 2,0 bar)
c = Sectional Surging
d = Sectional Pumping
e = Sectional Circulation Pumping
f = Intermittent Pumping
g = Chemical Treatment

The marked project wells represent wells in which the measured flow velocity at the borehole wall exceeds the design standard. This is at least, when assuming that the Shepherd approach for estimating the hydraulic conductivity is accurate. In some cases the usual approach of hydraulic conductivity does not seem to be the proper method because other variables, e.g. geologic history influencing porosity, appear to have influenced the formation permeability. Comparing these wells with other columns in the table, design-exceeding wells can be coupled to relative fine formations and large unproductive screen segments in the lower regions of a well (leading to extra flow from the productive segments).

The high numbers in the specific capacity column are varying significantly from ideal values. When this ‘Calculated Specific Capacity : Measured Specific Capacity’ –ratio lies close to 1.0, the simulated and measured specific capacities are similar. This suggests that the model approach is a good simulation of reality. When this number varies a up to a factor 1.5-2, it could indicate partial clogging of the well. In case of an even bigger deviation, like in the cases of the orange marked wells, there is more going on. The most likely cause is a significant difference between the estimated hydraulic conductivity and the real hydraulic conductivity. Based on the D50 grain size combined with the Shepherd equation, the hydraulic conductivity has been estimated. But it has to be mentioned that a number of relevant aspects, like geological history, grain size distribution or clay content have not been taken into account in this approximation.

If one takes a look at the four wells with a SC ratio ranging from 4.1 to 6.8, it is striking that these wells are all situated in the Eastern part of The Netherlands. Geologically this part is rising 2-4 mm (Fig. 54) each year. This indicates that maximum burial depth of the employed formations might differ significantly from the current burial depth. As a consequence the formation could be overconsolidated. This could easily affect the porosity and the related hydraulic conductivity due to higher pressures deeper inside the Earth, while grain size remains constant over time (Fig. 53).

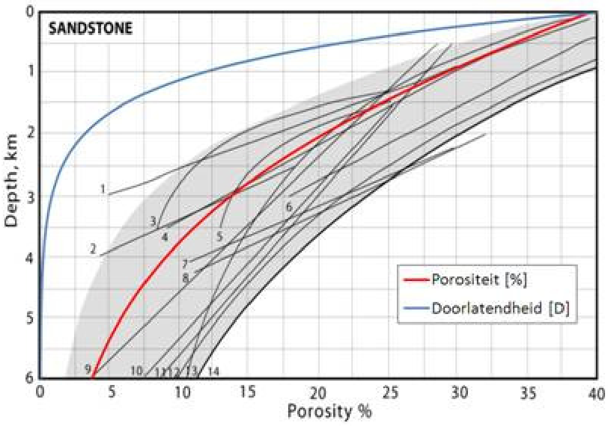


Fig. 53. Depth vs. Porosity graph. Here the red line shows an averaged approximation of the porosity behavior through depth. The blue line represents the estimated variation in hydraulic conductivity based on Kozeny-Carman. Just below the surface (0-2 km) the porosity is most sensible to depth changes (Alberts, 2005).

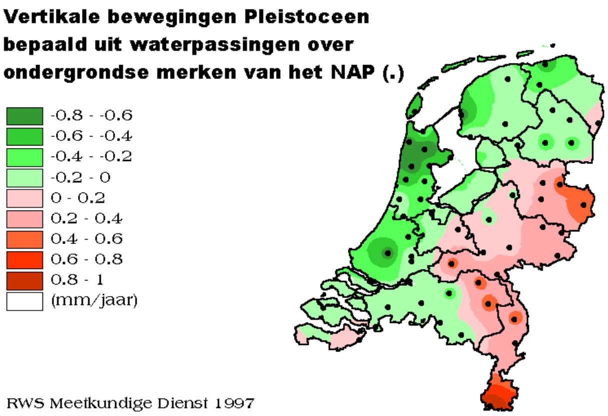


Fig. 54. Vertical movements of the Pleistocene bedrock. In the eastern part there is a clear uplift, while the western part of The Netherlands appears to subside (RWS Meetkundige Dienst, 1997).

Additionally faults and fractures can play a role in formations of this age and geologic history. Wells 4a and 4b suffered major difficulties in sustaining overpressure during the well drilling procedure, which is indicated by great amounts of water loss. This indicates that some part of the drilled formations have a very high hydraulic conductivity which can be explained by the intersection of one or more faults which are known to be present in the aquifer that has been used. Initially this all means that it is hard to perform accurate estimates and calculations for natural formations, since they are all heterogeneous. It is simply impossible to take everything into account, therefore in some cases errors are inevitable. Despite this, it is relatively safe to say that relative permeability has been estimated to a more accurate level.

Clay swelling can also be of big influence on hydraulic conductivity around a well, a big gradient in salinity underlies this phenomenon. Therefore this feature has also been examined in some problematic wells; especially in well 3, where large shares of the screen do not contribute.

The most important finding appears to be that the Shepherd equation is not always accurate to interpret and analyze aquifer hydraulic conductivity. The 4 wells mentioned above evidently indicate this, which on its turn implies that the calculated maximum flow velocity according to design is too high. A wrong estimation of the hydraulic conductivity gives the impression of a well system in which actual flow velocities are far below the design velocities, while in reality these values will presumably exceed the ´design safe velocities´. By using the specific capacity ratio, the design velocities graph can be corrected. When doing this, the Model/Design ratio changes from < 1 (safe) to >>1 (significant exceeding of the design standard).

Well #	Wellbore flow ratio (model/design)	SC-ratio	Wellbore flow ratio corrected for SC-ratio
1	0.2	1.0	0.2
2a	1.5	1.1	1.7
2b	1.2	1.4	1.7
3	0.6	6.3	3.8
4a	0.5	4.1	2.1
4b	0.5	6.8	3.4
5	0.3	5.2	1.6
6	1.0	0.5	0.5
7	0.2	?	?
8	1.9	0.5	1.0
9	0.7	0.8	0.6
10a1	1.0	1.1	1.1
10a2	1.0	1.0	1.0
10b	0.9	1.0	0.9

Table 4. The simulated wellbore flow to design standard flow ratio can be corrected for situations in which the expected (calculated) SC differs from the measured SC. Hereby it is assumed that the deviating ratio is completely caused by wrong hydraulic conductivity estimation.

By multiplying the first two columns, a corrected wellbore flow ratio can be achieved. Assumed here is that the real hydraulic conductivity is equal to the estimated value divided by the SC-ratio. Obviously the design velocity changes with the same factor. One has to keep in mind that this correction assumes that the full difference in SC-ratio is the consequence of an inaccurate estimate of the hydraulic conductivity (and not caused by, for instance, clogging of the well). As mentioned before, SC-ratios up to a factor 1.5-2.0 could be the consequence of well clogging caused by remains of drilling fluid. For higher ratios this is considered unlikely and at least part of the difference must be the consequence of a wrong estimate of the hydraulic conductivity.

The wells that ‘produce’ sand do not seem to be correlated to an exceeding of the design standard, this even holds after the SC-ratio correction. Both extremes are observed; i.e. there are wells that significantly exceed the design standards while they do not produce sand, and on the other hand we find wells that stay within the standards while producing sand. Sand production can however be related to a relatively coarse choice in grain size of the backfilling material compared to the grain size of the aquifer. These wells share a minimal backfill grain size of 0.63 mm (table 3). Further on another conclusion can be made about the failing screen sections. It appears that wells with large parts of the well screen that do not contribute are all recent wells. This indicates that the reason for the poor performance can almost certainly be assigned to aspects related to the drilling and well development procedures.

Calculation of the head losses as a consequence of friction inside the screens, indicate a relatively small effect of internal friction on vertical flow distribution at maximum well capacity. Therefore there is no column showing the internal head loss in the results table.

The last column shows which development techniques were used to develop the well before taking it in use. The most common development process not only consists of pumping the well with a gradually increasing flow rate after the well has been fully installed. Commonly the drilling firms apply air-surging, sectional (circulation-)pumping and intermittent pumping to a well. But in some cases another procedure has been chosen, also depending on which firm took care of the well development and in what year the well was constructed.

4.2 Well Analyses

4.2.1 Well data presentation

The results of this research consists of 13 wells that have been simulated and analyzed extensively. For 10 of these 13 wells, vertical flow logs are available. The other 3 wells which lack a flow measurement were simulated because these wells are problematic in the sense that they produce sand after the well has been developed. Flow measurements are usually not performed in every well; mostly only problematic wells undergo a flow measurement to establish clarity about poorly performing screen sections.

The most clear proof of this statement is Well 10a, which is shown below (Fig. 55). This well is special because there are two flow logs exposed in the analysis; one dating from after the regular well development (10a1) and one which has been taken after an extra rehabilitation action, sectional surging (10a2). The essence of proper wellbore cleaning can be seen very well in this figure:

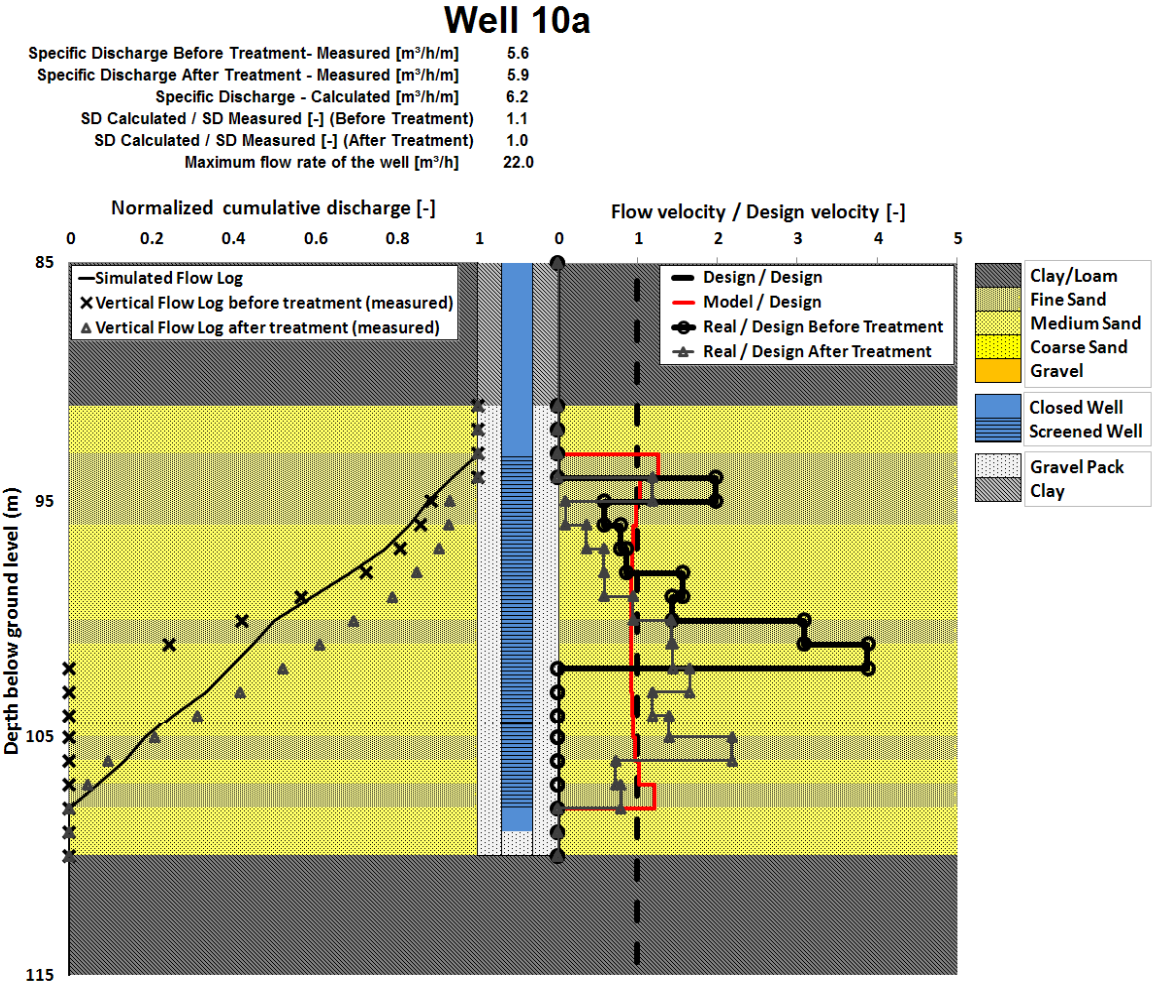


Fig. 55. Before treatment the lower section of the well screen does not produce any water according to the flow log (crosses). During well development, which includes sectional surging, this part of the well has been cleaned. The consequence is a relatively good flow distribution over the whole screen length (triangles). Results of the other wells can befound back in Appendix A.

The first flow log shows that the bottom part does not contribute and in the second flow log the flow over the length is much more evenly distributed. This is a strong indication that the development/rehabilitation technique used in between both flow logs was able to effectively treat the lower part of the well screen, while the other development techniques were much less effective.

For now the focus is restricted to a broad analysis and discussion of relationships and trends for the complete dataset:

4.2.2. Common trends and observations

Throughout the analysis of the processed wells, some frequently observed trends and relationships can be distinguished:

- Increasing flow velocities at both ends of the well screen section. Houben (2006) stated this phenomenon, and the modeling part of this research confirms this. The major part of the flow logs show similar trends, both for multiple section- as for continuous-well screens. Even the restrictive effect of close confining layers can be pointed out.
- Coarse formations have a relatively larger share in total water production, because they share higher hydraulic conductivities. This discharge – hydraulic conductivity relation can also be revealed in some wells.
- Wells including large failing well sections (2a, 2b, 3, 5, 10a1) share similarities regarding the location of the failing sections. These are all in the bottom part of the well.
- Consequence of a failing well screen section is that it forces the better-developed part of a well screen to compensate for the poor well section. This compensation often leads to an exceeding of the design standard.
- Wells with large parts of the screen failing can be related to fine grained soils and large distances between the top of the screened part to the bottom.
- It appears that well development is not effective/extensive enough in lower parts of the deeper/longer well screens in fine grained aquifers.
- Sand production in wells can be correlated with the choice of a coarse gravel pack, which has pore diameters large enough for fine particles to be able to penetrate into the well screen.
- No clear relation can be detected between flow velocity compared to the design standard and sand production.

4.2.3 Identification well problems – Failure

In the course of the past decades, models and field observations point out some problems appearing repeatedly in constructed systems. The most prominent problems, well section failure and sand production, have already been discussed in this report. Focusing on inactive well screen sections, hydraulic conductivity variations in the wellbore are the main reason for unproductive screen segments. This problem presumably starts during the drilling process. The overpressure in a well is essential to prevent collapse of the borehole. However, the overpressure becomes extra high in the lower sections of deeper wells because of the large - relatively dense - water column above. The concentration of suspended material (sometimes partly consisting of additives like bentonite or polymers) in the drilling fluid causes a difference in density between the drilling fluid and the aquifer water. One can imagine that at greater depths, the overpressure can therefore rise to a level which is significantly higher than the overpressure in the more shallow sections of the borehole (Fig 56). Density of the drilling fluid especially is high when fine material becomes suspended in the drilling fluid, this material does not precipitate out of the fluid at a fast rate, while coarse material does. The overpressure in combination with the small pore size in these formations, make fine sand aquifers sensitive to form persistent wellbore clogging. This is a phenomenon that act as a good explanation for the poor flow distributions in the fine grained aquifers (wells 2a, 2b, 3, 5 and 10a1). The grade of filter cake development determines the effort that has to be done to remove it properly during well development.

These screen sections obviously need more attention during the process of development in order to properly develop a well. Supposedly a good way to achieve a properly developed lower screen section is to apply sectional development techniques to successfully remove fines from the borehole.

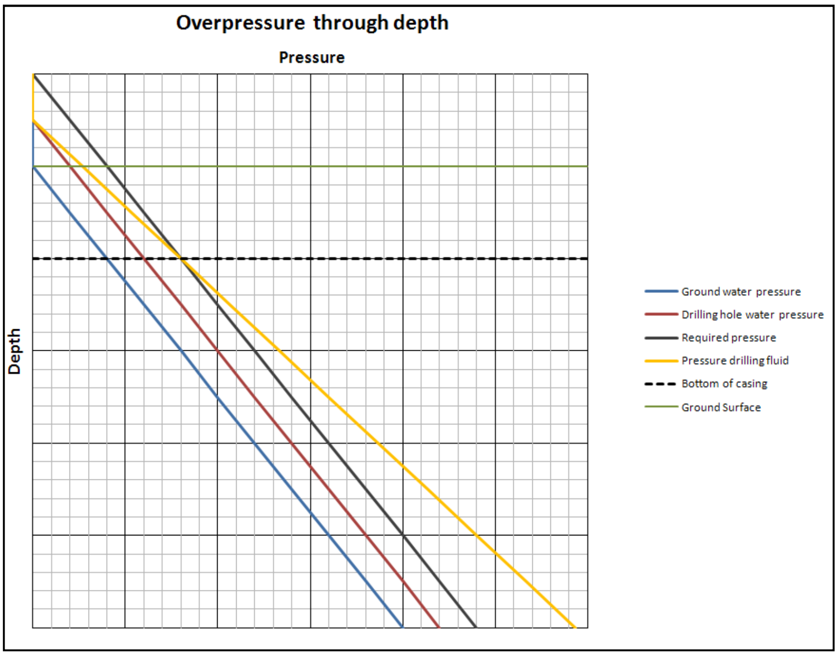


Fig. 56. The development of the overpressure in a well. To obtain overpressure, one must either keep the water level in the casing far enough above the ground water level, or the density of the drilling fluid has to be increased. The difference between the orange and the black line indicate the overpressure exerted on the wellbore. Furthermore this thicker filter cake experiences a higher pressure and is therefore pushed more tightly into the borehole wall.

Smaller scale clay (and other fine material) lenses in coarse formations can easily be overlooked during drilling. This can cause small scale clogging at depths which can sometimes be correlated to these clay lenses. A good example of this is well 1, where clay lenses are encountered at depths of: 123, 135 and 150 m. Directly below these clay lenses, the well screen is under performing.

Theoretically, sinking (failure) of the backfill material can also be of influence on the contribution of well screen sections. Imagine that a clay backfill part descends to the depth of the well screen, the consequences could be drastic. Yet this is not likely to happen often, since the clay backfill is jammed tightly in the borehole because of the clay swelling it undergoes after implementation. If the gravel pack sinks and the clay ball on top remains in place, a cavity might be created which could also lead to sand invasion. It is therefore important to prevent settling of the backfill material as much as possible. Additionally safety margins have been implemented in the well design, which have to minimize the risk.

4.2.4. Identification of well problems – Sand production

Sand production is a phenomenon that should be minimized in the field of ATES. When sand is produced during water extraction, particles are someway enabled to be mobilized from the well-aquifer boundary and to penetrate the gravel pack and well screen. When the water is not filtered before it is injected in the other well, well clogging might occur in the injection well.

The most common cause of sand production is the implementation of backfill gravel that is too coarse compared to the porous medium grain size. Or the other way around: screening layers with a grain size that is too small for the gravel pack that has been applied. However, design standards have been developed to implement the right grain sizes in the backfilling material. A mistake regarding gravel pack appears to be unlikely to be made; therefore it is more likely that inaccurate soil sampling is leading to the incomplete or wrong recording of clay-, loam-, silt- and fine sand- layers. This shortcoming can be attributed to the fact that most drilling logs are based on one soil sample for each meter of soil. Screen depths and backfill designs can be incompatible because of this.

Further on, the D50 number is not incorporating the grain size distribution. It is just (an estimate of) the median grain size. The choice of the screened layers is based upon this value, while it does not take the grain size distribution into account. Consequently it is possible that the finest fraction of the formation is able to penetrate the gravel pack. It seems no coincidence that every sand-producing well studied, has a medium to coarse character; the finer fractions in these aquifers are more likely to cause problems. In practice, when a well produces amounts of sand that exceed the design standards, eventually the particle concentration is expected to decrease through the formation of a ‘natural gravel pack’ around the well. Wells 7 and 4 for example have not been taken in use because of long lasting, continuous sand production. This could infer defects in the gravel pack, which allow the aquifer material to come into contact with the well screen.

Unforeseen contact of the soil and the well screen can occur due to poor well construction and backfilling (when the screen is not properly centered and is in contact with the borehole wall) or due to the sinking of backfill material allowing the soils to intrude the space created. In the production of wells 4a and 4b there have been a lot of issues regarding the well construction. The contractor was dealing with problems regarding the required overpressure, which presumably lead to small scale collapses during the backfilling process.

5. Conclusions

Design standards

Since ATES systems are designed for a lifetime of at least 20 years, it is essential to minimize well clogging. In practice well clogging due to the particles in the extracted water is generally occurring at a very slow rate. Well design standards are meant to prevent (significant) well clogging due to particles by limiting the flow velocity at the borehole wall. When the flow velocity is too high, the risk of well clogging due to high particle concentrations is expected to increase significantly. The current design standard for extraction wells allows a maximum hydraulic gradient at the borehole wall of 2, which means that the maximum capacity of the well is linearly dependent on both the aquifer hydraulic conductivity, the borehole diameter and the length of the well screen. For aquifers with a low hydraulic conductivity (fine sand aquifers), this results in relatively low design well capacities compared to a number of other design standards. This makes it worth investigating whether the permission of higher gradients might be acceptable.

Estimation of essential aquifer properties

An accurate estimate of the aquifer hydraulic conductivity is required since it determines the maximum well capacity according to the well design standards. The hydraulic conductivity is often estimated by using the Shepherd equation in combination with the average grain size (D50) from the borehole log. This method is successful in predicting the relative hydraulic conductivity values of different sand layers. However, the absolute hydraulic conductivity is not always accurate, because essential features like the grain size distribution and the porosity are not taken into account. For overconsolidated aquifers, this can result in significant overestimation of the hydraulic conductivity.

Particle mobilization and transport

Groundwater flowing through the pores of the aquifer can drag particles towards the well screen. The transport potential of a soil grain is dependent on the grain size relative to the pore size of the porous medium:

- The diameter of the sand grains of which the aquifer consists, determines the average pore size. A rule of thumb is that the pore diameter is equal to the average grain diameter divided by 6. This would mean that in an aquifer with grains of 300 um, the pore diameter is about 50 um. Only particles with a smaller grain size can be transported through the porous medium. Since a reduction of the porosity will lead to a reduction of the pore diameter, transport of the same particle will be more difficult at a lower porosity. Because deeper formations generally have a lower porosity, this is expected to be relevant for the design of wells in deep formations.
- Because of the radial groundwater flow to the extraction well, the available pore space gets smaller and smaller. As a result the chance that particles arrive at the same pore at the same time increases. Although the individual particles would have been able to pass the pore, they

will get stuck. This is called particle bridge formation and is considered to be important when the particle grain size is more than 10% of the average pore diameter. For the same aquifer that would mean that particles with grain sizes above 5 um are unlikely to be transported to the well in significant quantities.

- Particles with very small grain sizes (colloids) are susceptible to electrostatic forces that are able to bind the particles to the surface of soil grains. Changes in pH can influence the electrostatic forces and can therefore lead to the release of colloids. When the pH change occurs quickly (e.g. due to a rapid change in salinity) this can result in serious well clogging due to clay dispersion (and/or clay swelling).

Gravel pack

The gravel that has deposited between well tube and the borehole wall is essential in preventing sand production. When the grain size of the screened layers of the aquifer is not smaller than the pore size of the gravel pack, the average sand grain cannot pass through the gravel pack. Therefore the relative grain size of the gravel pack and the screened layers of the aquifer should not differ more than a factor 4 to 5. When this grain size ratio is exceeded (e.g. due to unintentional screening of very fine sand layers) the risk of sand production is increasing significantly. As a consequence it is essential to have an accurate borehole log, based on representative soil samples.

Well screen inflow distribution

An adjustment of the current design standard can only be achieved if it is based on data from real wells that exceed current design standards. The question is if exceeding the design standard (and to what extent) leads to problems like well clogging or not. Since wells are designed according to the current design standards and usually relatively conservative assumptions are made, only few wells are expected to exceed the design standards. However, information from the field indicates that many wells hardly produce water in the bottom part of the well screen and consequently will produce more water than intended from the top part. An uneven distribution of inflow could thus indicate that the flow velocity in part of the well screen that contributes most, is exceeding the design standards. The well inflow distribution of a number of wells was therefore investigated theoretically and based on measurements. In an ideal unclogged well there are a number of factors that influence the flow distribution over the length of the well screen:

Variations in hydraulic conductivity

Layers with a high hydraulic conductivity will produce more water than layers with a lower hydraulic conductivity.

Full or partial penetration

In a homogeneous aquifer the contribution of each meter of well screen will be equal for fully penetrating, confined wells, when head losses inside the well screen are insignificant. Partially penetrating wells do not have an equal flow distribution over the length of the screen. The part of the screen that is bounded by a confining layer will produce less water than the part that ends further from a confining layer. If both ends of the screen end in the aquifer, the middle of the well screen will contribute the least. Conditions that increase the influence of partial penetration on the flow distribution are:

- Large aquifer thickness compared to the screen length
- Large well diameter
- Steady state flow conditions (long pumping time)
- Low vertical anisotropy of the aquifer
- High hydraulic conductivity of the well screen

Head losses inside the well

Head losses that occur inside the well, influence the effective drawdown inside the well screen. Since the drawdown inside the well screen is the driving force for the inflow of water from the aquifer, head losses inside the well screen can influence the flow distribution over the length of the screen. Head losses are strongly dependent on the inside diameter of the well screen tube in combination with the extraction rate and the screen length. During well design the tube diameter is chosen large enough to prevent significant influence of these type of head losses.

Analysis of field data

Vertical flowmeter logs

To investigate the flow distribution in practice, a number of vertical flowmeter logs have been analyzed from real (mainly ATES) projects throughout The Netherlands. A tool has been developed that generates input for a groundwater model based on information from the drilling report (soil layers and properties, well screen depth) and the well test (flow rate versus drawdown). The model output is used to create a flowmeter log based on the model results. The simulated flowmeter log can be compared to the real (measured) flowmeter log. For a number of wells the simulated and measured flow logs are in good agreement, which confirms the validity of the method. For other wells the difference between the simulated and measured flow logs indicated that some parts of the well screen (in many cases the bottom part) were significantly underperforming.

Specific capacity

Another indicator of well performance is the specific capacity (SC) which is the ratio of the flow rate divided by the drawdown. High values represent well developed wells and good aquifer hydraulic conductivity. When the SC number is lower than expected, something has to be going on. This could either indicate a wrong estimate of the aquifer hydraulic conductivity or (partial) clogging of the well. Therefore, the ratio of the Calculated SC and the Measured SC have also been analyzed.

Flow velocity compared to design velocity

Actual flow velocities at the borehole wall can be estimated when the water intake in a certain section is divided by the wellbore surface in that section. These flow velocities were compared with the maximum velocity according to the design standard. Together with other information about the well (like length of the well screen, degree of sand production, properties of the aquifer that was used and grain size of the gravel pack) this information was used to look for correlations. During the analysis, certain ideas from the literature and from the field have been proven to be realistic:

- Inflow velocities are relatively high near the well screen ends, especially in the top
- The influence of hydraulic conductivity on the inflow rate was confirmed
- Underperforming well screen sections were mainly found in the bottom part of a well
- Exceeding design standards and sand production could not be correlated
- Sand production mainly depends on the relative grain size of the aquifer and the gravel pack
- The aquifer hydraulic conductivity in some cases seriously differs from the value that was estimated using the Shepherd method, which is suspected to be a result of overconsolidation of the aquifer

Improving the vertical flow distribution

Underperformance of the lower part of the well screen was mainly found in wells with long well screens and in fine grained aquifers. Somehow the lower part of the well screen appears to be more clogged in those cases than the upper part. Since this problem was (also) found in new wells, the cause has to be related to the process of drilling and well development in combination with the well screen length and grain size of the aquifer. The process of well construction includes some essential procedures that might influence the well performance later on.

Drilling procedure

Normally, reverse circulation rotary drilling in combination with air lifting is performed for the construction of ATES wells. This is a relatively clean drilling method, which additionally enables the production of a relatively reliable lithology log. During the drilling process overpressure is required to prevent collapse of the borehole. The overpressure is generated by two aspects. First the hydraulic head in the borehole is higher that the ambient. Second the density of the drilling fluid is higher than of the ambient groundwater, due to the suspended sediments in the fluid. As a result the overpressure increases with depth and the filter cake that develops at the borehole wall is thicker and more tightly pushed into the borehole wall with increasing depth. As a result the filter cake will be more persistent at the bottom of the borehole. This effect is strengthened in the case of fine grained aquifers. Fine material will become suspended in the fluid, therefore overpressures inside the water column (especially in the lower sections) significantly increases. In combination with the small pore sizes of fine formations, this could have significant consequences for the mud cake development. Lower regions of the wellbore are therefore likely to form persistent mud cakes, leading to poor flow distributions along the length of the well screen.

Another aspect is that the coarser part of suspended sediments in the drilling fluid (mainly consisting of the finest fraction) will sink to the bottom of the borehole when the circulation of the drilling fluid is paused. From field observations it is known that the water is at rest for a certain time when the drilling equipment is taken out of the borehole before the water circulation starts. Furthermore the circulation does not always occur over the full length of the borehole, which means that the fluid in the bottom part is not refreshed. The lowest meters of a borehole could effectively be influenced by the precipitation of suspended particles in the drilling fluid. However, the penetration of particles into the borehole wall due to overpressure appears to have a more significant influence looking at a broad extent.

Placing the well tubes

In this phase it is essential to prevent contact between the well screen and the aquifer, using centralizers. When the screen is in contact with the aquifer, sand can directly penetrate the well screen due to the absence of the protection of the gravel pack.

Backfilling

Next step is the deposition of backfill material between the well tube and the borehole wall. At the depth of layers with a high hydraulic conductivity gravel is applied and for layers with a low hydraulic conductivity clay (mikolite or bentonite) ‘balls’ are used to prevent fine materials to reach the well. In order to get a well developed gravel pack, (partial) wellbore collapse has to be prevented during backfilling by using a tremie line. Partial collapse could also cause sand production due direct contact of the collapsed sediment and the well screen. Furthermore effects of possible subsidence of backfilling material after well completion have to be taken into account by maintaining at least 1 or 2 meters between the top of the well screen and the top of the gravel pack.

Well development

In order to remove a (persistent) filter cake, sectional development have proven to be useful to develop the well properly so that every well screen section contributes. Sectional surging seems especially suitable, but not all contractors are able to perform this technique. On the other hand, it could help to change the common sequence of development techniques, which currently is:

1. Pumping clean by increasing discharge from 10% to 100%
2. Hydrological-/Air-Surging
3. Sectional (round) pumping
4. Intermittent pumping

By performing air surging in an early phase of well development, an uneven grade of development in the wellbore can be initiated early in the development process. First the water column is pressed downward by gradually increasing the air pressure above the water level. As a consequence the flow at the borehole wall is reversed in comparison to an extraction situation an particle bridges are broken down. The sudden release of pressure might cause a shock that help destabilizing the mud cake. After pressure release, extreme flow velocities occur during a few seconds. Which results in extreme flow velocities at the borehole wall. Due to the extreme flow velocities, the head losses inside the well tube/screen increase exponentially and will cause an uneven distribution of the inflow. As a result the upper part of the well screen is treated more effectively than the lower part. The zones where the filter cake has been broken down will become preferential flow paths during later stages of the development process, making it more difficult to treat other parts of the borehole wall with non-sectional techniques. By using sectional surging instead, this uneven development of the wellbore will be prevented. Every section of the well screen will be effectively cleaned this way, development of preferential flow paths will be avoided this way.

Although the extreme flow velocities during air surging occur over a very short period of time, apparently there is no permanent damage to the well. This suggests that higher flow velocities do not pose a threat to the well and can be applied without serious risks of spoiling the well.

6. Recommendations

Well design and construction

Design

- During design the well screen pipe diameter has to be chosen sufficiently large to prevent significant head losses due to friction inside the well screen.
- The thickness of the gravel should not be too large to prevent negative impact on the effectiveness of the well development techniques.
- When a system is designed with significant head losses over the length of the well screen, countermeasures can be considered to counteract the resulting uneven flow distribution. Possible countermeasures are an adjustment of the location of the pump intake (e.g. pump intake halfway in the well screen) or adjusting the well screen properties with depth (e.g. making the open (screen slot) area depth dependent).

Drilling and backfilling process

- A detailed lithology log has proven to be essential to prevent unintentional screening of layers that are too fine in comparison to the grain size of the gravel pack.
- During the drilling process standstill of the drilling fluid circulation in the screened part of the aquifer should be prevented as much as possible to minimize deposition of the suspended sediments. When the final depth has been reached the drilling equipment is removed and standstill will occur. After removing the equipment, the drilling fluid circulation can be restarted using the tremie line as pump intake. In this case it is important to take care of fluid circulation over the full length of the borehole by placing the end of the tremie line close to the bottom of the borehole.
- During drilling it should also be possible to separate the suspended material from the circulating drilling fluid above ground. Existing separation techniques are cyclones and ordinary sieves. The refreshed drilling fluid has a lower density, this will consequently limit overpressure.
- Direct contact between the well screen and the aquifer (which can cause sand production) has to be prevented by using centralizers.
- Use of a tremie line is recommended and helps to prevents crumbling/partial collapse of the borehole wall.
- To prevent negative impact in case of subsidence of the backfilling material, the gravel pack should be extended at least 1 or 2 meters above the top of the well screen.
- Applying thin sand layers between the clay balls and the gravel pack is recommended to prevent subsidence due to invasion of gravel in the clay balls or the other way around.

Well development

- Vertical flowmeter logs are recommended to gain insight in the flow distribution in newly constructed wells. The results can be used to focus the appropriate well development techniques on the underperforming parts of the well screen.
- In most cases the underperforming part of the well screen is the lower part. Since sectional surging has proven to be able to effectively develop the deeper part of the well screen, it is considered a promising technique for future well development.

Further research

- Performing and interpreting more flowmeter logs is expected to improve the understanding of the processes that are relevant for the vertical inflow distribution. Performing flowmeter logs in between different well development stages can help to make clear which techniques are effective at which depths.
- To be able to better understand the key factors it is essential to keep record of the most important actions during the well drilling and well development process and the way they were performed.
- The circumstances in which the estimation of hydraulic conductivity using the Shepherd method can be used, should be further investigated.
- Knowledge from the field of soil mechanics related to piping seems interesting and might give insight in the influence of grain size distribution and confining stress on the critical hydraulic gradient.
- Deliberate exceeding of the design standards combined with measurements of particle concentrations can help to find new (extended) design standards.
- The possibilities of the creation of a natural gravel pack by deliberate extraction of the fine fraction from the formation are worth investigating and might help to create wells with a higher capacity (larger effective well radius).
- Further research into controlled sand production, the possible consequences and countermeasures (e.g. filtering before reinjection).

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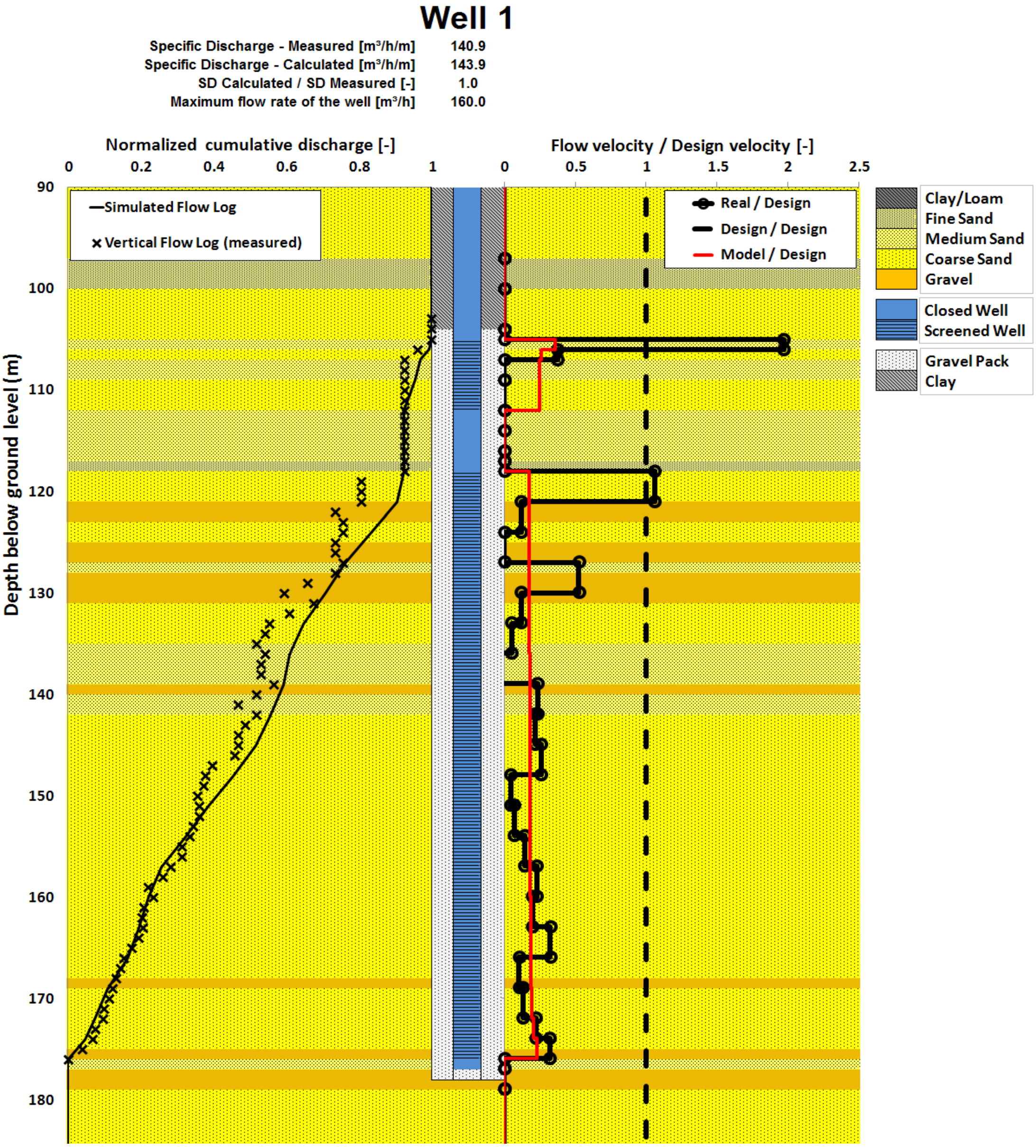
Appendix A

Well1

This well has a very coarse character; therefore one expects no significant problems. The only ‘problem’ that can be pointed is the lower half of the upper well screen section, which does not appear to produce water. This is likely to be the main cause of the strengthening of the design exceeding in the upper part of this screen section. Further on the SC ratio is perfect, so it is very likely that the simulation matches reality to relatively good extent.



Well 2a + 2b

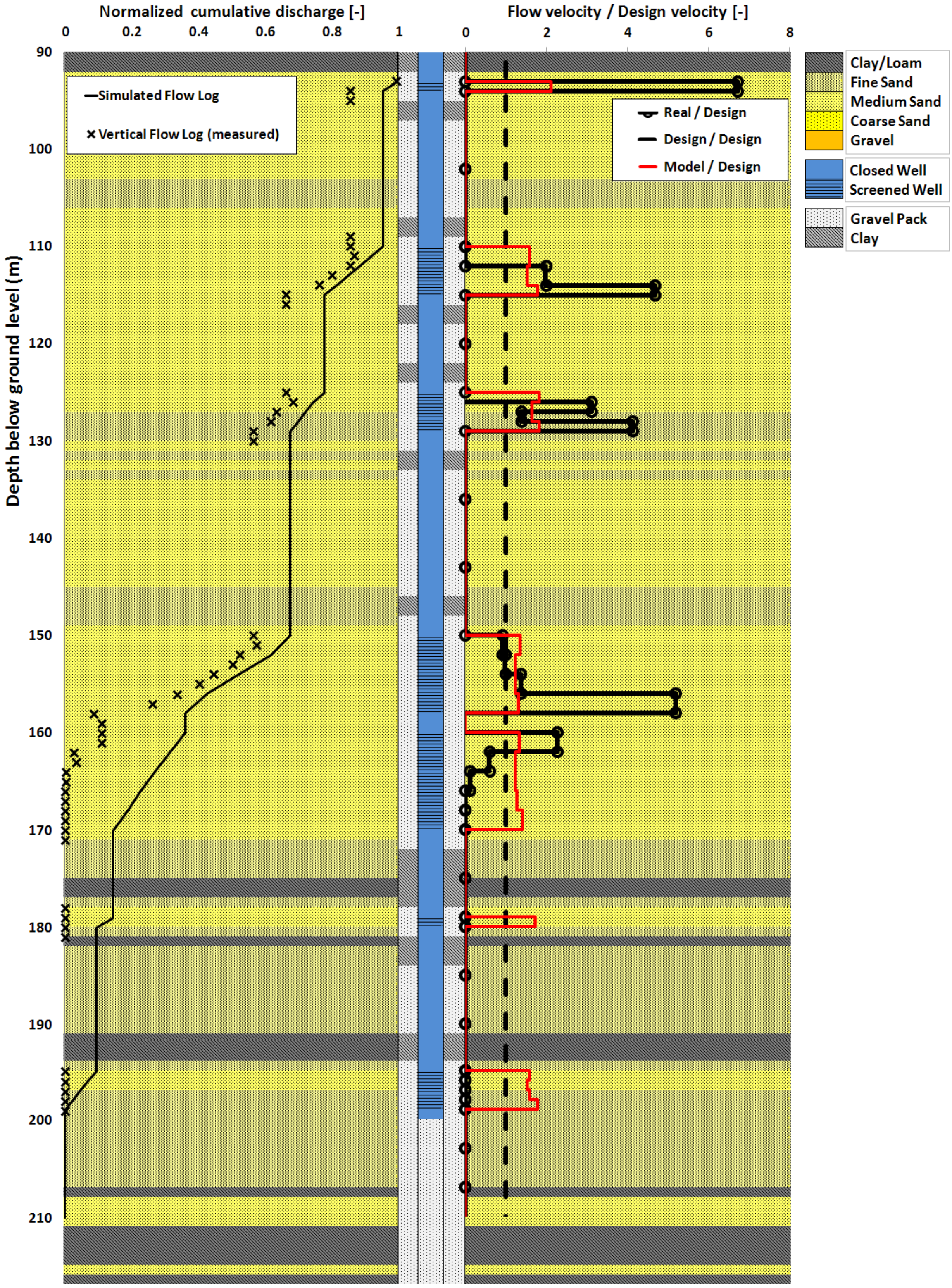
Wells 2a and 2b are part of the same project. The two extraction wells have a lot in common, clearly the lower meters (20-30%) of the well screen do not contribute water. Despite of the clogged lower part, well 2a has a very nice SC-ratio: 1.1. The ratio is 1.4 for well 2b. Striking are the prominent clay layers in the lower sections of the lithology. Also important is the depth of these wells (200+ m). In both cases the surface below the ‘real/design’- and ‘model/design’-ratio graph is not the same. This should be the case, but because the blind parts of the well tube also produced water according to the flow measurement these values were removed. This means that, especially in the case of well 2b, the ‘real/design’ graph is underestimated a little.

It is very likely in the case of these two wells, that unremoved drilling fluid remains are the main cause for the problems in this project. The filter cake could be persistent because of the penetrated clay layers in the soil. The reason for the incomplete removal can partly be declared by the great depth of the wells, the choice of development techniques and maybe also by the fine grained character of the lower section.

Further on it has to be mentioned that there is no reason to expect that salinity has something to do with the well failure. If this would be the case, the plugging depths could have been correlated with each other.

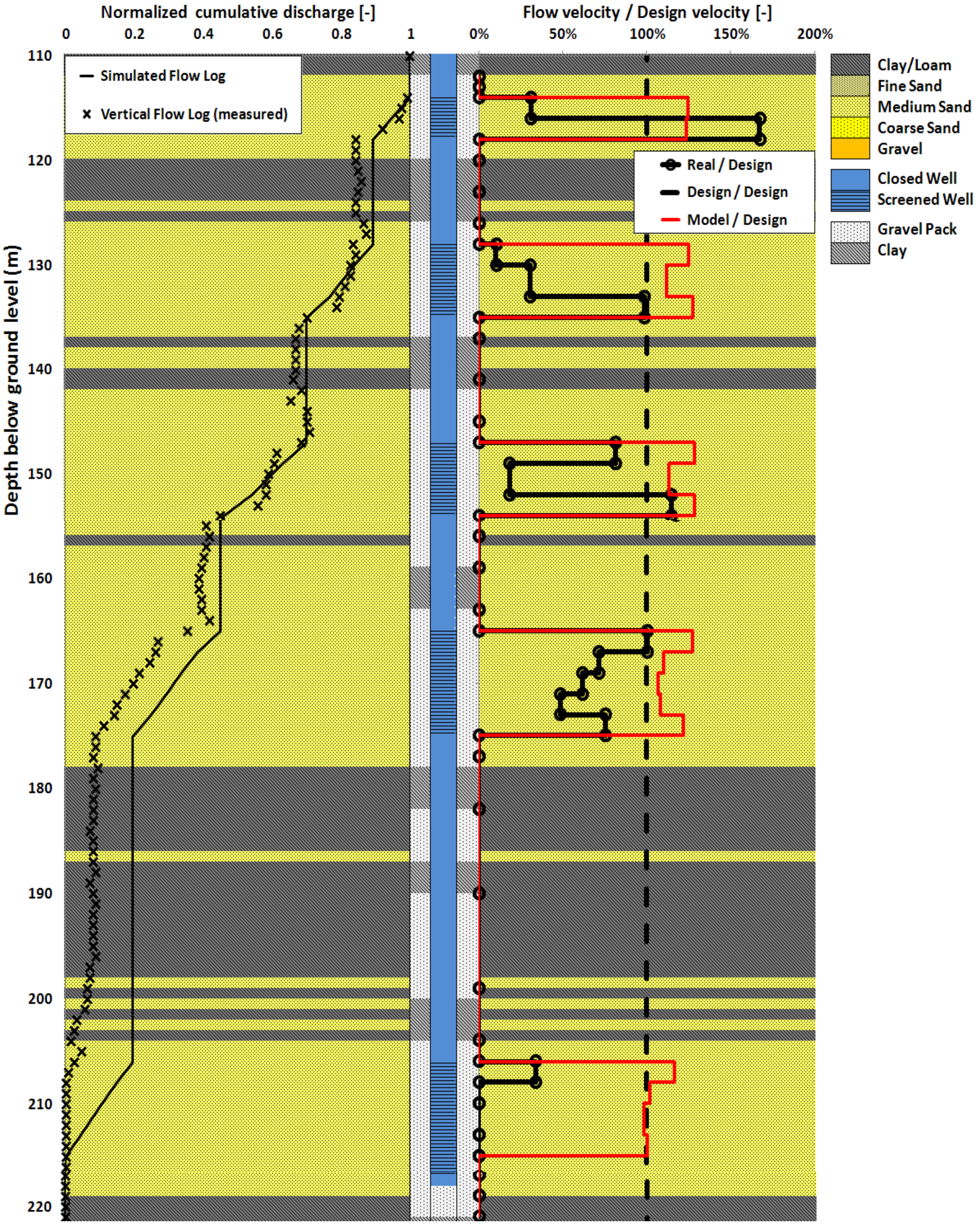
Well 2a

Specific Discharge - Measured [m³/h/m]	21.4
Specific Discharge - Calculated [m³/h/m]	22.5
SD Calculated / SD Measured [-]	1.1
Maximum flow rate of the well [m³/h]	105.0



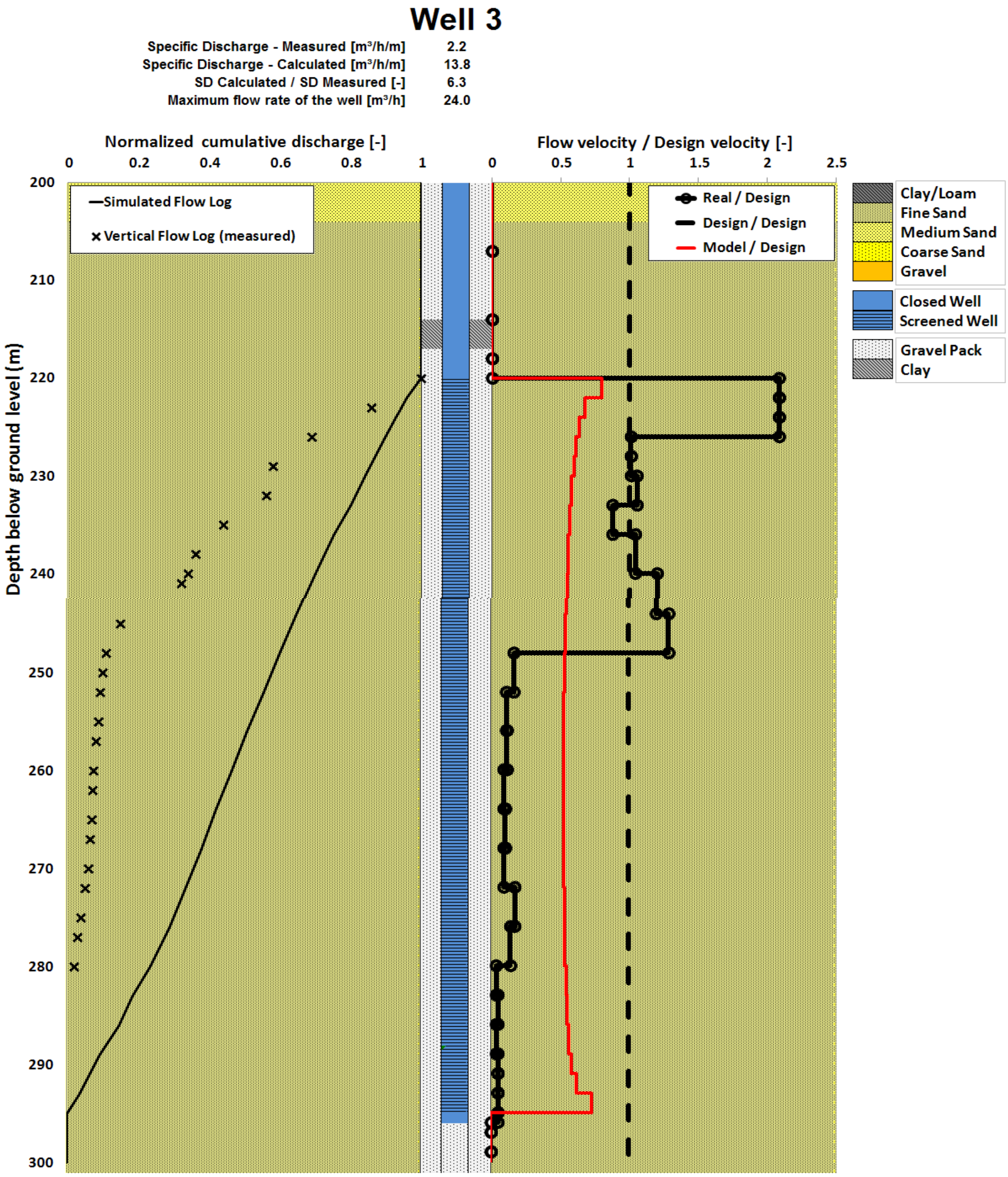
Well 2b

Specific Discharge - Measured [m³/h/m]	17.1
Specific Discharge - Calculated [m³/h/m]	24.2
SD Calculated / SD Measured [-]	1.4
Maximum flow rate of the well [m³/h]	105.0



Well 3

This project is the only High Temperature ATES system that has been investigated in this report. When one takes a look at the depth of the well screen, it is clear that this well has been installed at greater depths than the other wells. The poorly performing lower section of the well can be related to multiple things. Because it is HT ATES, the aquifer D50 values are very small (100-150 µm). Important to mention is the large salinity gradient through the depth of the well screen. The SC ratio is also very disappointing, the hydraulic conductivity has been estimated completely wrong.



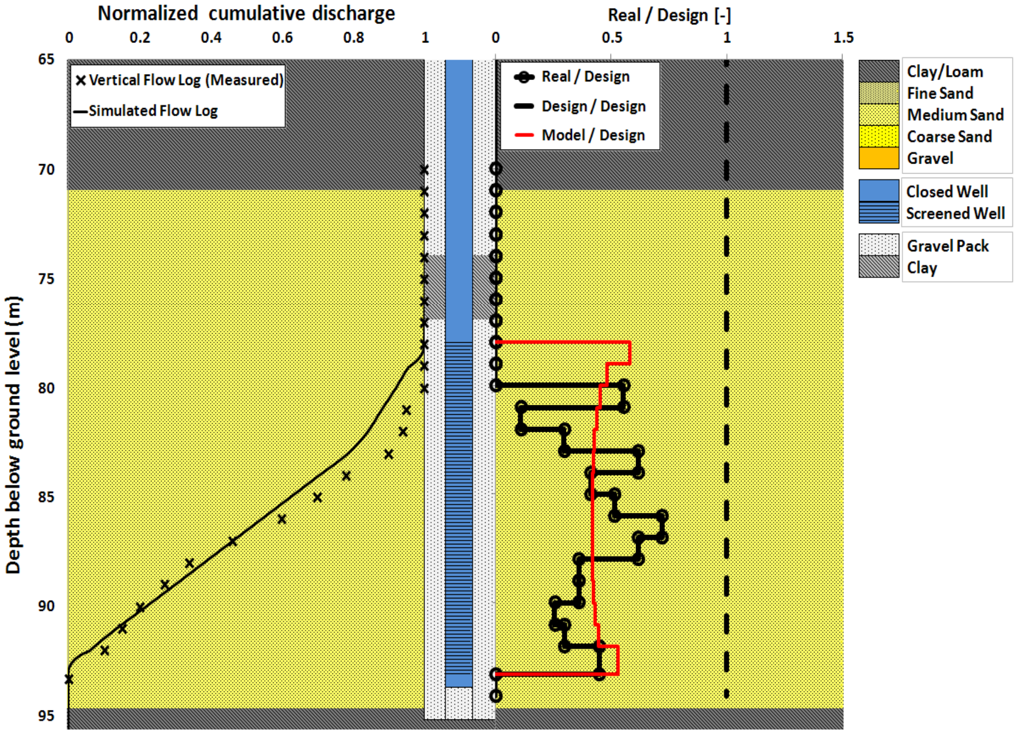
Wells 4a + 4b

Wells 4a and 4b are both problematic wells. In the early phase of well construction it was clear that the formation was not ideal for drilling because a lot of drilling fluids infiltrated in the aquifer. The consequence was that has been almost impossible to keep overpressure during drilling and backfilling. Therefore small scale borehole wall collapse therefore cannot be excluded.

Nevertheless the wells were both finished. Well development however did not seem to help against the sand production. Measured SC values did not match the expectations, therefore the most likely explanation in this case is a poor estimation of the hydraulic conductivity value. Things like overconsolidation and possible fractures around the well could be the reason for the large water losses during well production.

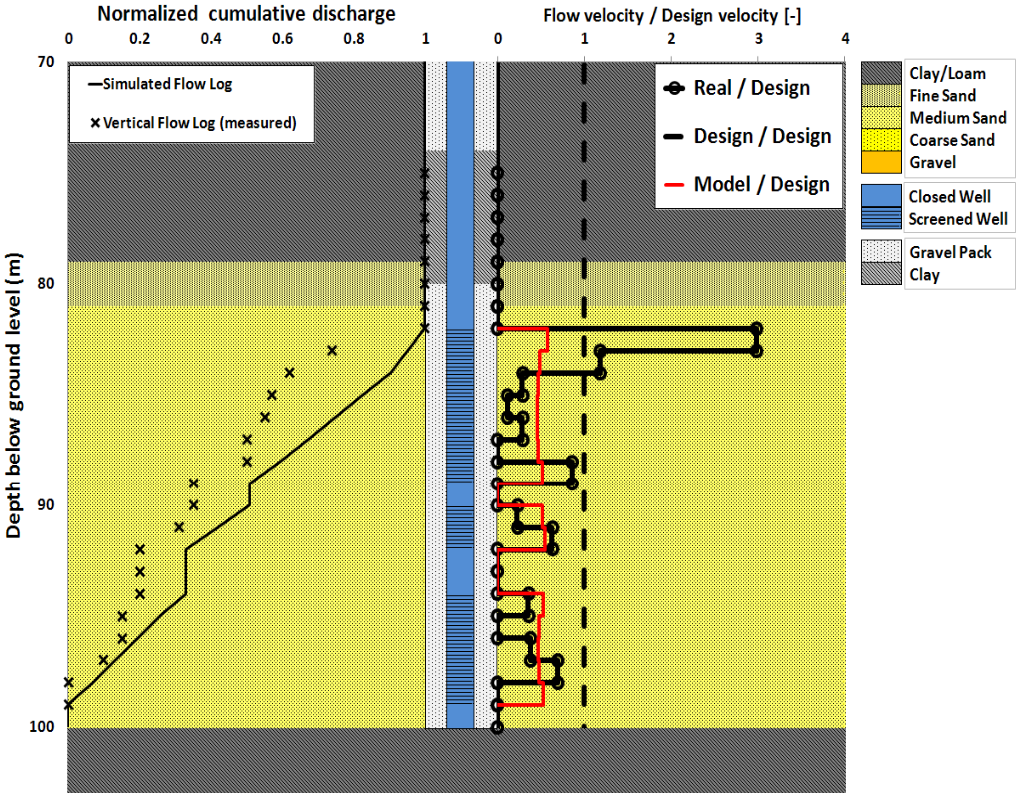
Well 4a

Specific Discharge - Measured [m³/h/m]	2.8
Specific Discharge - Calculated [m³/h/m]	11.5
SD Calculated / SD Measured [-]	4.1
Maximum flow rate of the well [m³/h]	25.0



Well 4b

Specific Discharge - Measured [m³/h/m]	1.5
Specific Discharge - Calculated [m³/h/m]	10.1
SD Calculated / SD Measured [-]	6.8
Maximum flow rate of the well [m³/h]	24.0



Well 5

This project has been, and still is, subject to a lot of discussion and unanswered questions. Assuming that the measurements reflect the real situation inside the pumping well, one sees a poorly performing lower section of the well screen. Water is coming out, but it occurs at significantly lower rates than one would expect.

The first relevant observation is the fact that this well screen is situated in a very fine grained aquifer. Another important observation is that the well tube inner diameter is the biggest of all the studied wells: 360 mm. Also the system requires a discharge of only 15 m^3/h for a well screen with a length of 35 m. According to Hemker (1999) and model simulations, bad flow distributions are more extensive to occur in well tubes with large diameters.

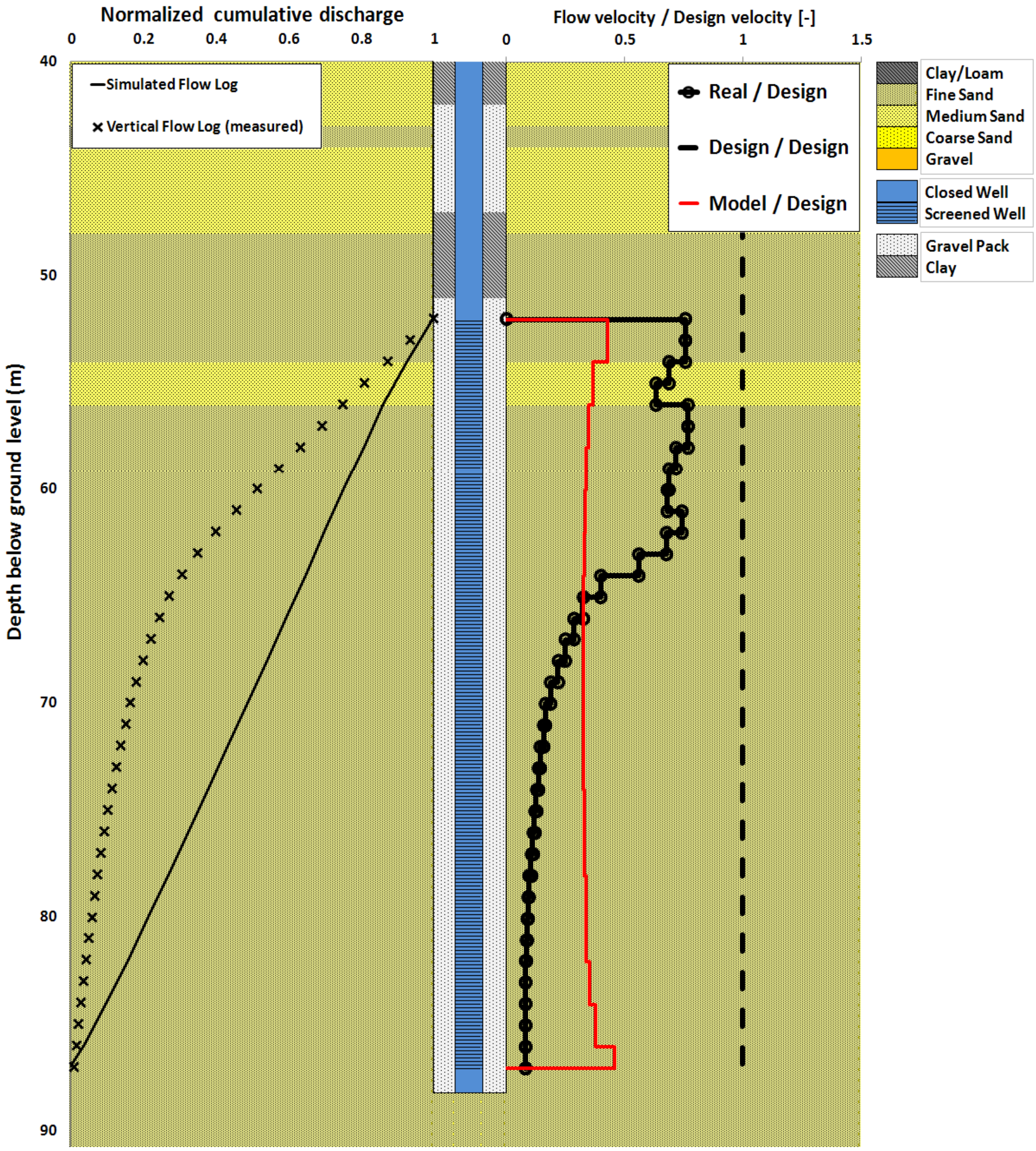
This well appears to suffer from bad well development, which only has cleaned a small part of the wellbore. The reason for this bad well development can be explained by the combination of smearing of drilling fluids over the borehole wall with the fine aquifer grain size. One can imagine that fine material is more sensitive to the formation of persistent mud cakes. During the sectional pumping phase in the process of well development, a large concentration of clay has been measured in the pumped water. It is unknown whether drilling additives like bentonite had been used; though this observation does certainly point to the use of additives during drilling. Considering the coarse gravel layers on top of the aquifer, the usage of additives is very likely. In this case it could be the main cause of the uneven flow distribution in this project.

The SC ratio is very bad for this project, which makes the hydraulic conductivity values that are assumed questionable. Since this project is situated in the eastern part of The Netherlands, overconsolidation and porosity overestimation cannot be excluded.

Additionally the large well diameter provides a large factor of uncertainty in the flow velocity accuracy. Because its low design capacity of 15 m^3/h and the sensitivity/accuracy of the flowmeter, measured velocities in the lower section of this project well are questionable. This could mean that the well does produce water in the parts that now appear to contribute no water.

Well 5

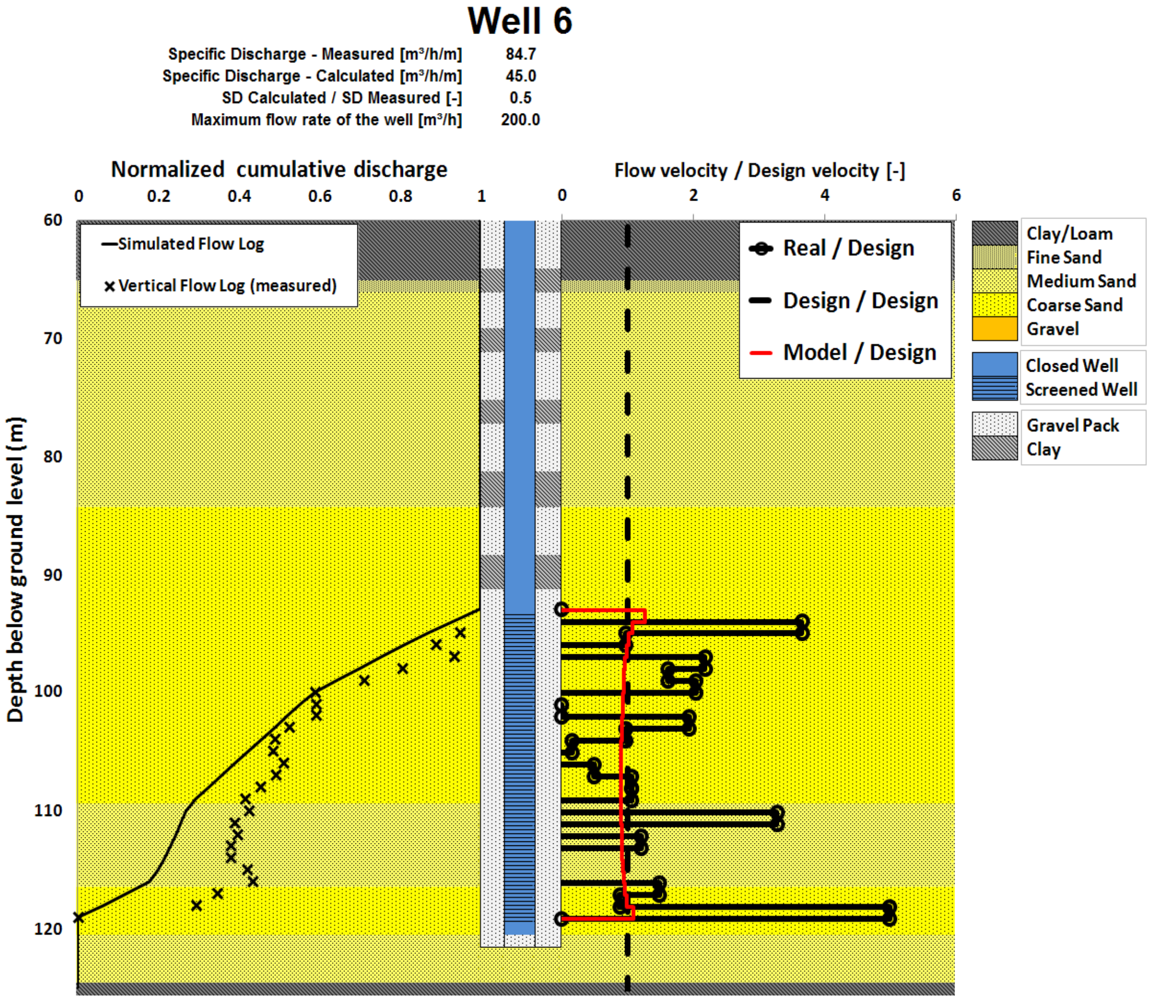
Specific Discharge - Measured [m^3/h/m]	2.4
Specific Discharge - Calculated [m^3/h/m]	12.4
SD Calculated / SD Measured [-]	5.2
Maximum flow rate of the well [m^3/h]	15.0



Well 6

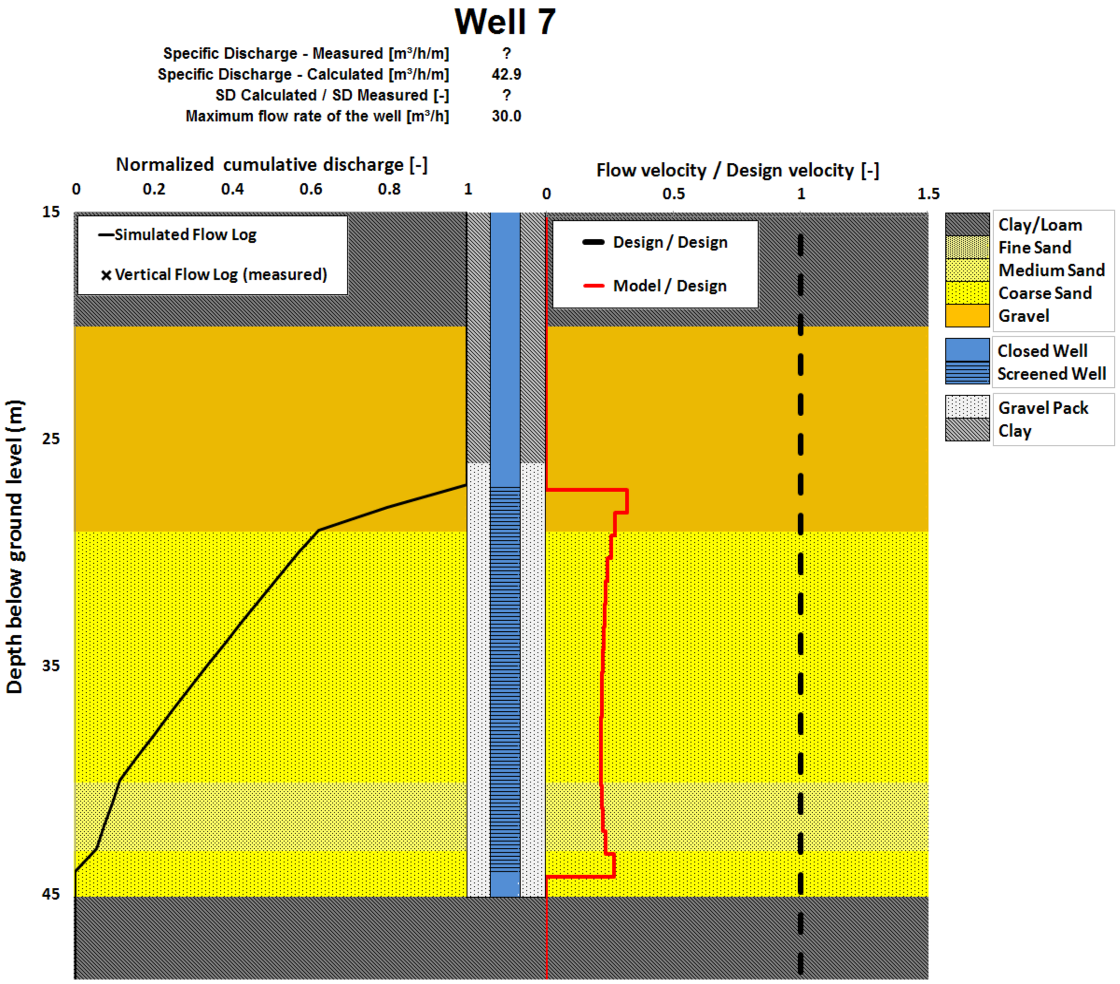
Well 6 acts as a drinking water well. Its function can be recognized easily when one takes a look at the big flow rate and the relatively short well screen length. The flow distribution can be correlated well with the formation grain size. Productive well sections go along with big grain sizes and high conductive layers, while the unproductive part corresponds with a finer grained part in the lower middle part of the formation. The consequences to flow distribution can also be declared by the partial situation of the well screen. The top and bottom part take in almost 80% of the total discharge.

Unfortunately it is unknown whether this well produces sand. However, when looking at the coarse character of the formation combined with the large grain size of the gravel pack, one can suspect sand production. Normally this is not a big problem in drinking water wells, because the water will not be injected at another location.



Well 7

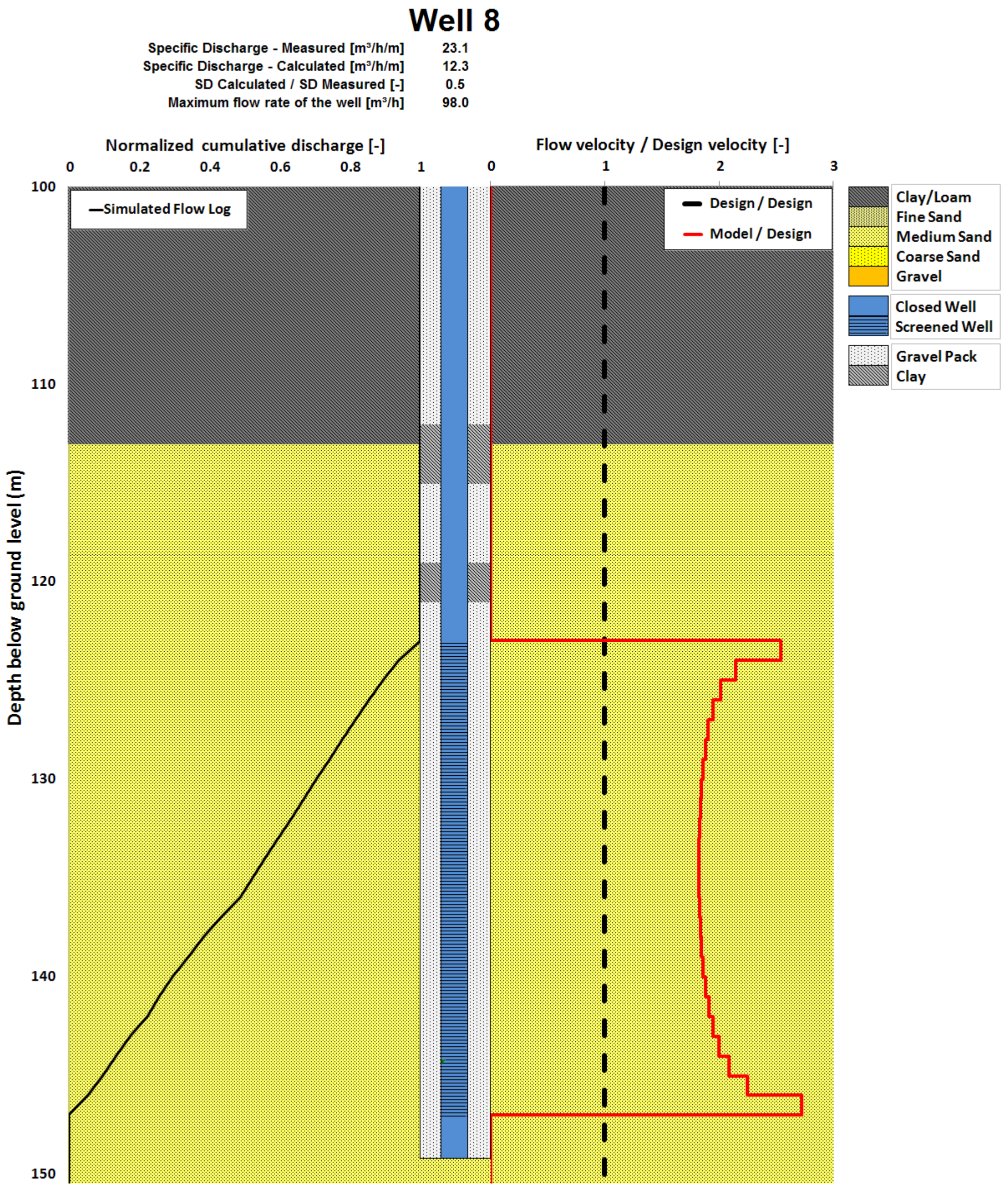
No flow measurement has been performed in well 7; also there are no specific capacity numbers available. Despite this the well has been simulated anyway, because of the known sand production in the lower section (+/- 39m depth). Through the first active period of the well, specific capacity has deteriorated significantly. Presumably this is the consequence of colloids clogging the wellbore. Further on it appears that some fine sand layer have been neglected during the lithology log composition. The coarseness of the gravel pack turns out to be too coarse for these fine layers, the finest particles are able to penetrate through the gravel pack into the well tube.



Well 8

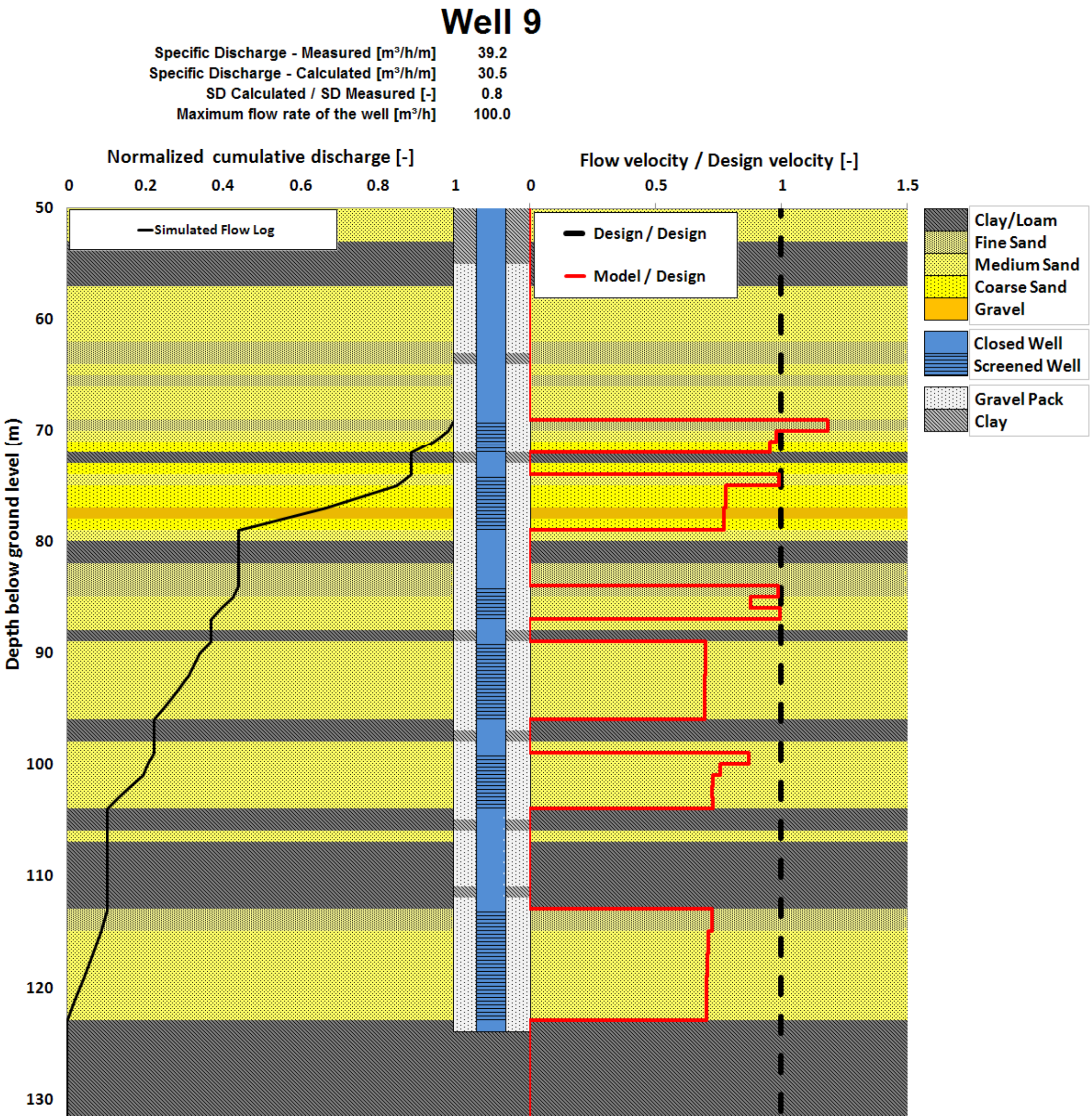
Well 8 can be characterized by a coarse gravel pack in combination with large slot dimensions. At first sight the lithology/grain size appears to be very constant through the length of the aquifer. But fact is that the lowest sections include some layers of relatively finer sand layers, sand production plays a role in this lower section. This problem has been treated with the removal of the sand out of the well tube, followed by the filling the lowest tube section with gravel to prevent more sand production in the extracted water. Also important to mention is that the well performance measured is better than one would expect based on the lithology (SC ratio = 0.5). This could mean that the mean flow velocity does not exceed the reality when it will be based on the real k-value.

Additionally the flow simulation shows that the ends of the well screen will be subject to large flow velocities, due to the partial situation of the well screen. Presumably the flow velocity will be exceeded here.



Well 9

This well produces water with high concentrations of sand. According to the project report, crucial mistakes have been made during well development. After that the project team decided to drill a new well with a bigger diameter, which unfortunately did not help. It is safe to conclude that the finer fractions in the layers have been mobilized and transported through the gravel pack and screen slots. Broad grain size distributions and backfilling material that is too coarse are likely to be the main causes of this, while the overall grain size seems to be medium sized in this aquifer.



Wells 10a + 10b

These two wells comprise one single system in which two wells are installed in one borehole. The upper section (10a) acts as the producer of cold water, while the lower part (10b) acts as infiltration well of warm water. Both wells do not interfere, because there is a thick clay layer between them; vertical water motion therefore is not possible.

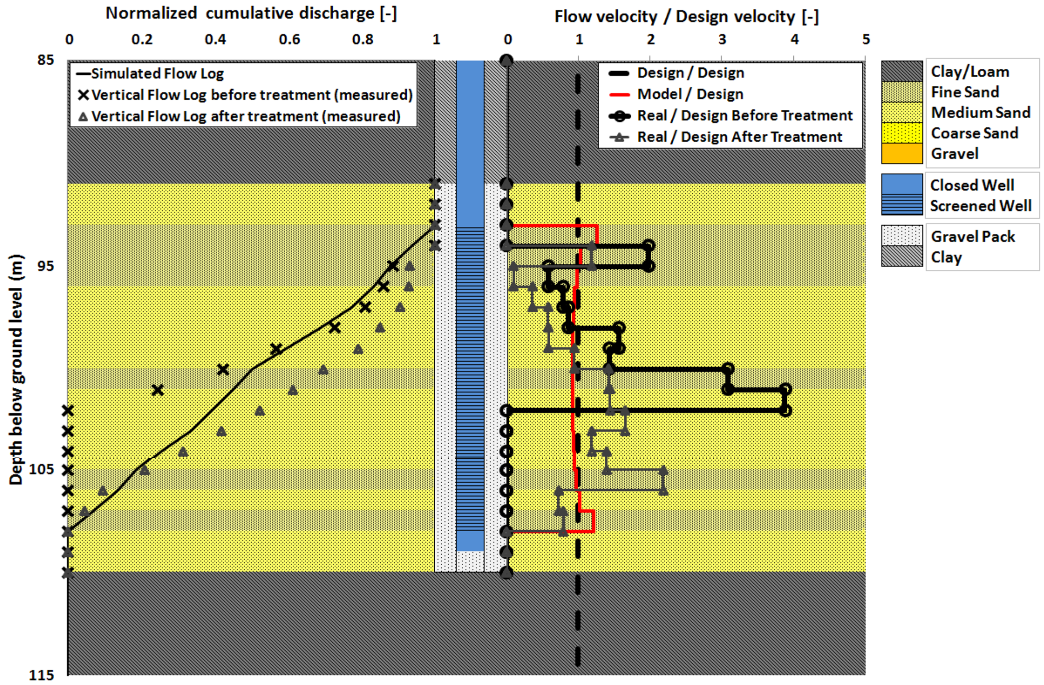
Well 10a has been subject to two flow measurements; one before and one subsequent to additional rehabilitation activities (sectional surging). In 10a the effect of well development can be observed very easily. Before treatment (10a1) the lower half of the well did not contribute any water, which leads to large scale design exceeding. After treatment (10a2), the exceeding was not as explicit as it was before. The sectional surging played a big role in the well-developed character of the well after treatment.

The only thing that cannot be explained in this project is the specific capacity that hardly changes according to the field measurements, despite the strong improvement of the wellbore development. Commonly one would expect the specific capacity to improve when a large share of a plugging develops to a more permeable wellbore.

Well 10b only shows a flow measurement after development, but just as in 10a this graph fits almost perfectly. Both wells have perfect SC ratio values, which indicate well developed wells matching expectations. The most important thing that can be concluded in this project is the effectiveness of sectional development techniques. Especially sectional surging appears to be a good method. The commonly mentioned trend in the field and in literature, is that ordinary surging often is not effective over the whole screen length. This is mainly due to extraordinary head losses inside the well caused by temporarily high discharges that come along with the process. Sectional surging seems a good solution for this problem, the only thing is that not many drilling companies perform this technique during well development. This development/regeneration technique could be the answer for extensive well plugging.

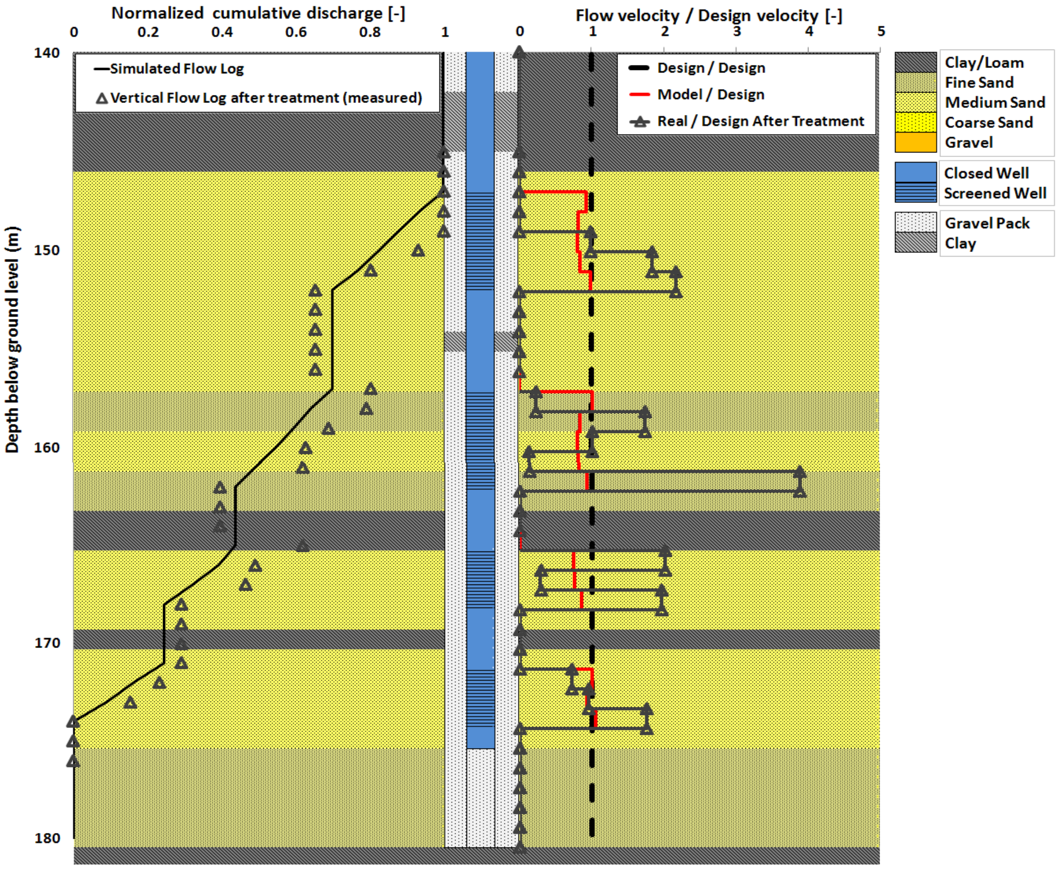
Well 10a

Specific Discharge Before Treatment- Measured [m³/h/m]	5.6
Specific Discharge After Treatment - Measured [m³/h/m]	5.9
Specific Discharge - Calculated [m³/h/m]	6.2
SD Calculated / SD Measured [-] (Before Treatment)	1.1
SD Calculated / SD Measured [-] (After Treatment)	1.0
Maximum flow rate of the well [m³/h]	22.0

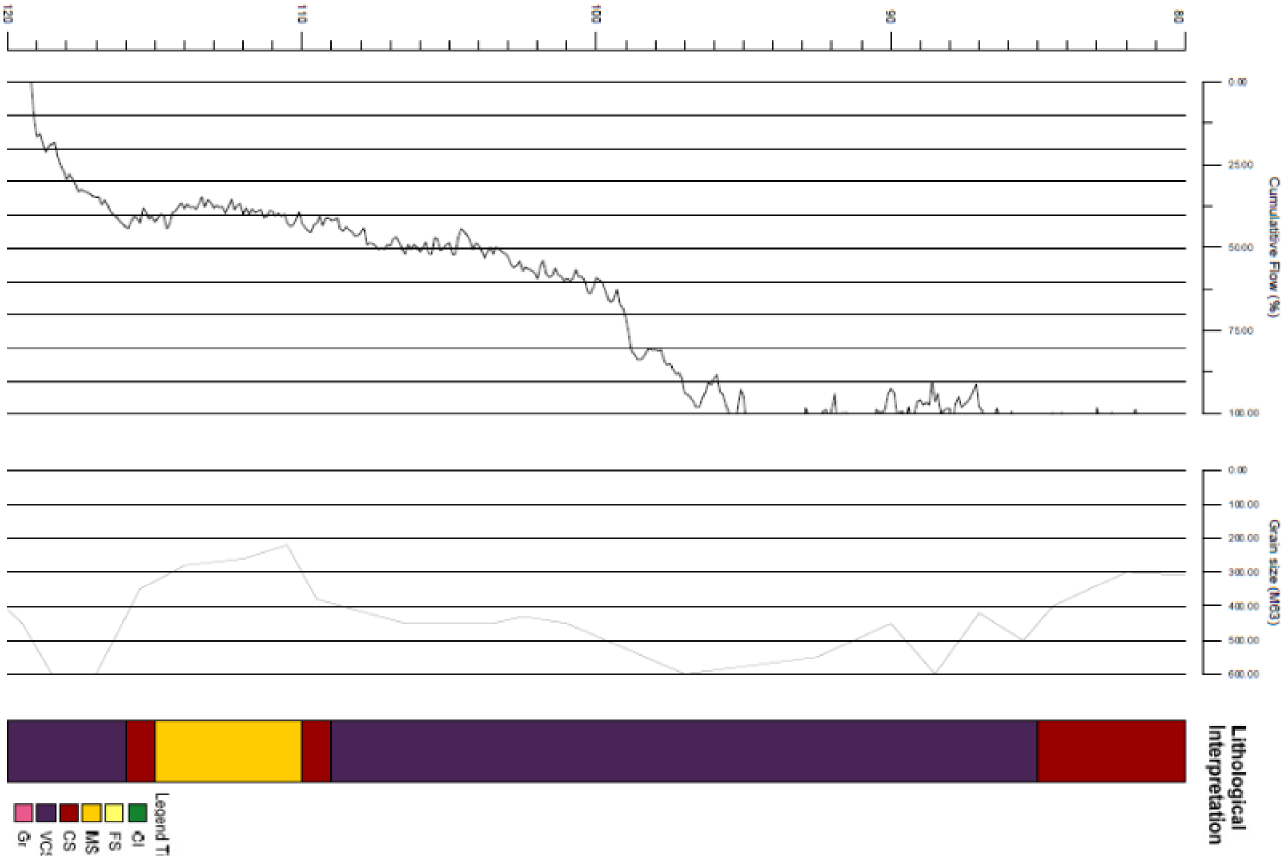


Well 10b

Specific Discharge Before Treatment- Measured [m³/h/m]	4.5
Specific Discharge After Treatment - Measured [m³/h/m]	7.5
Specific Discharge - Calculated [m³/h/m]	7.3
SD Calculated / SD Measured [-] (Before Treatment)	1.6
SD Calculated / SD Measured [-] (After Treatment)	1.0
Maximum flow rate of the well [m³/h]	22.0



Appendix B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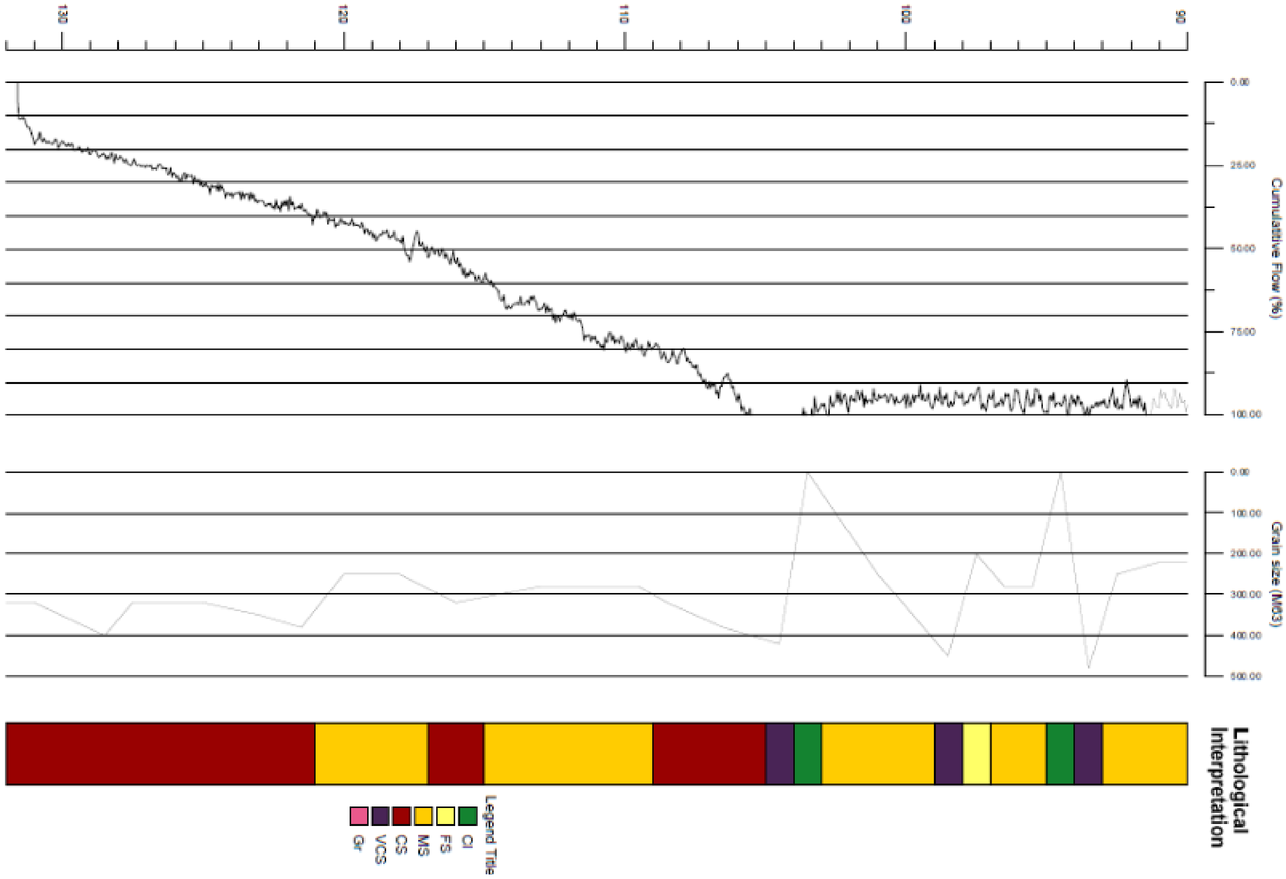
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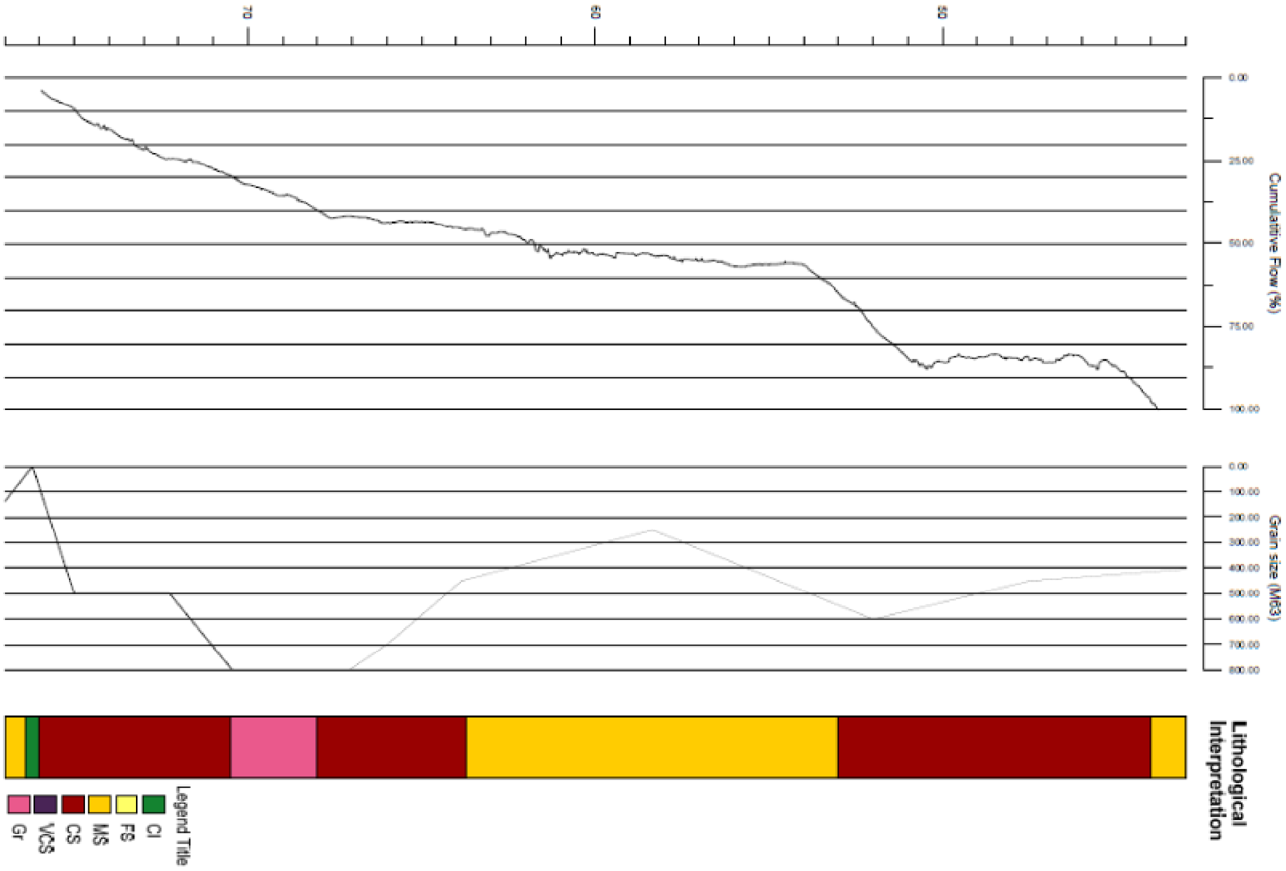
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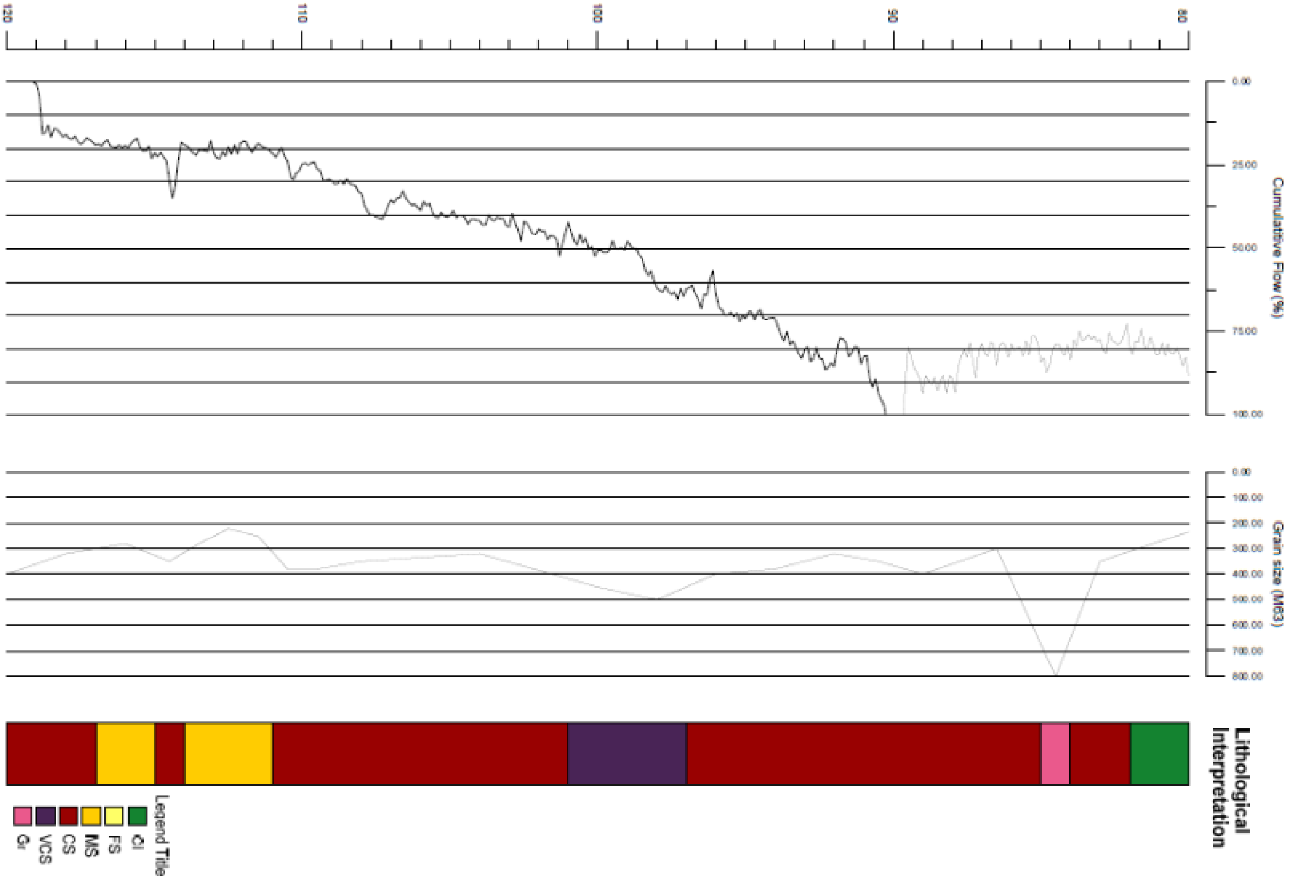
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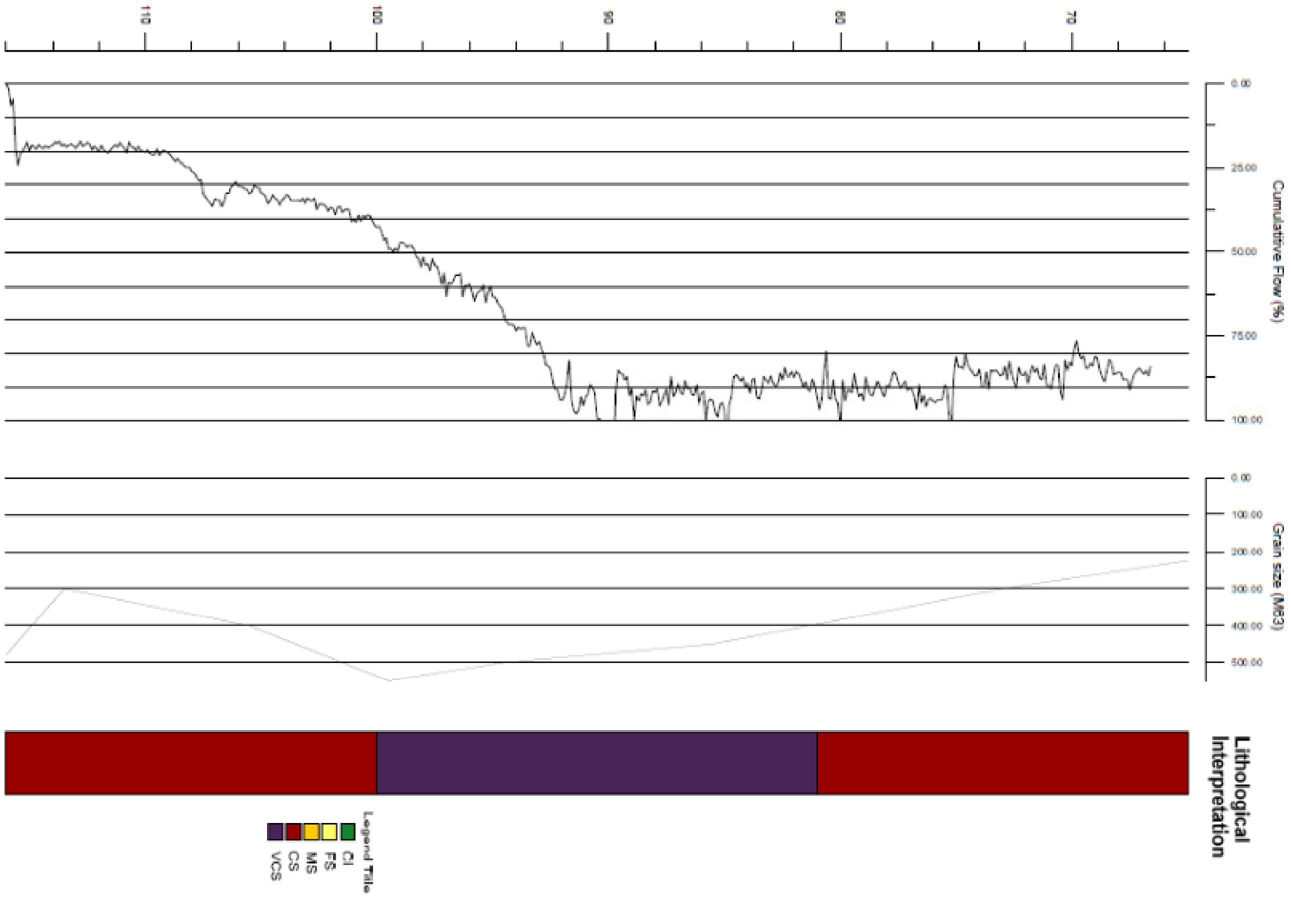
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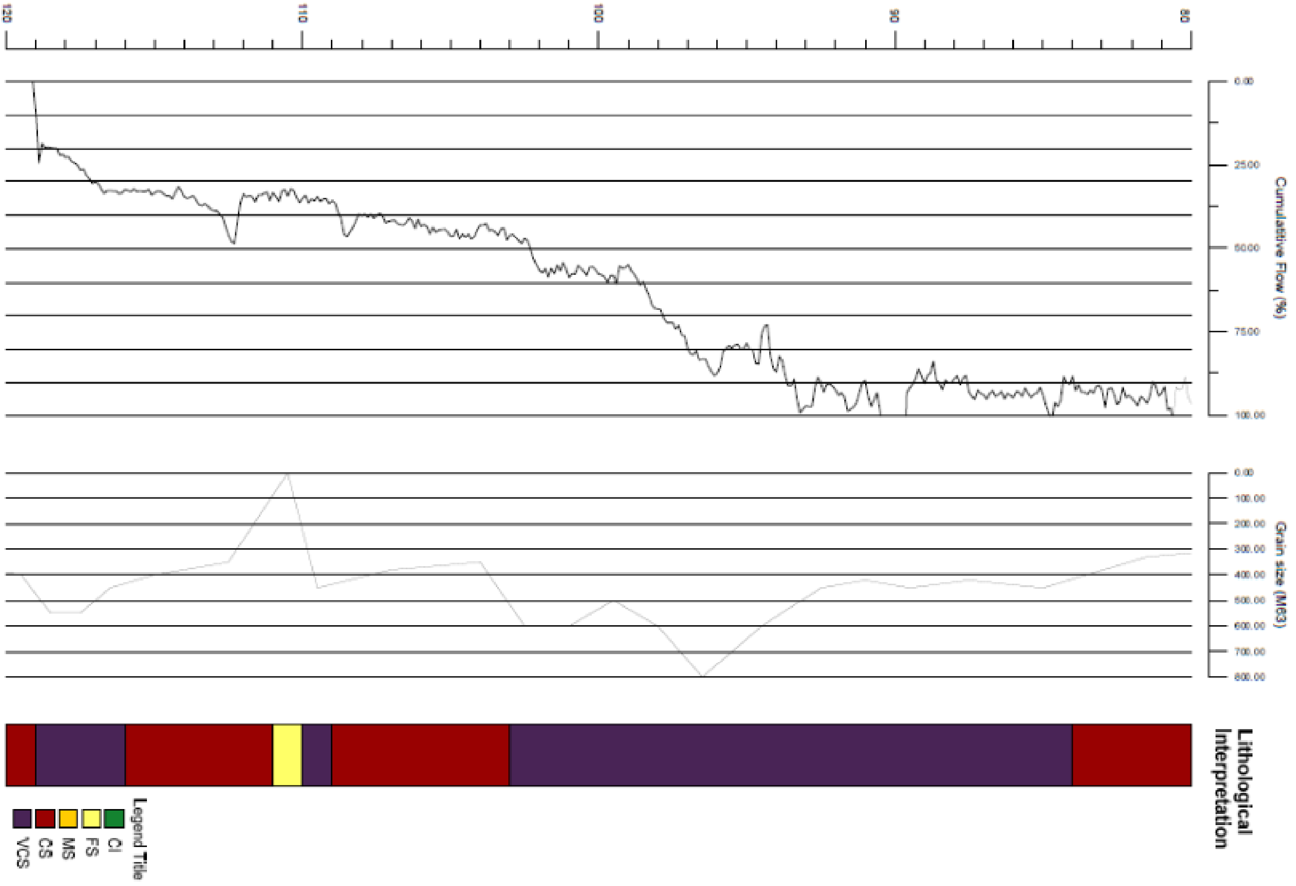
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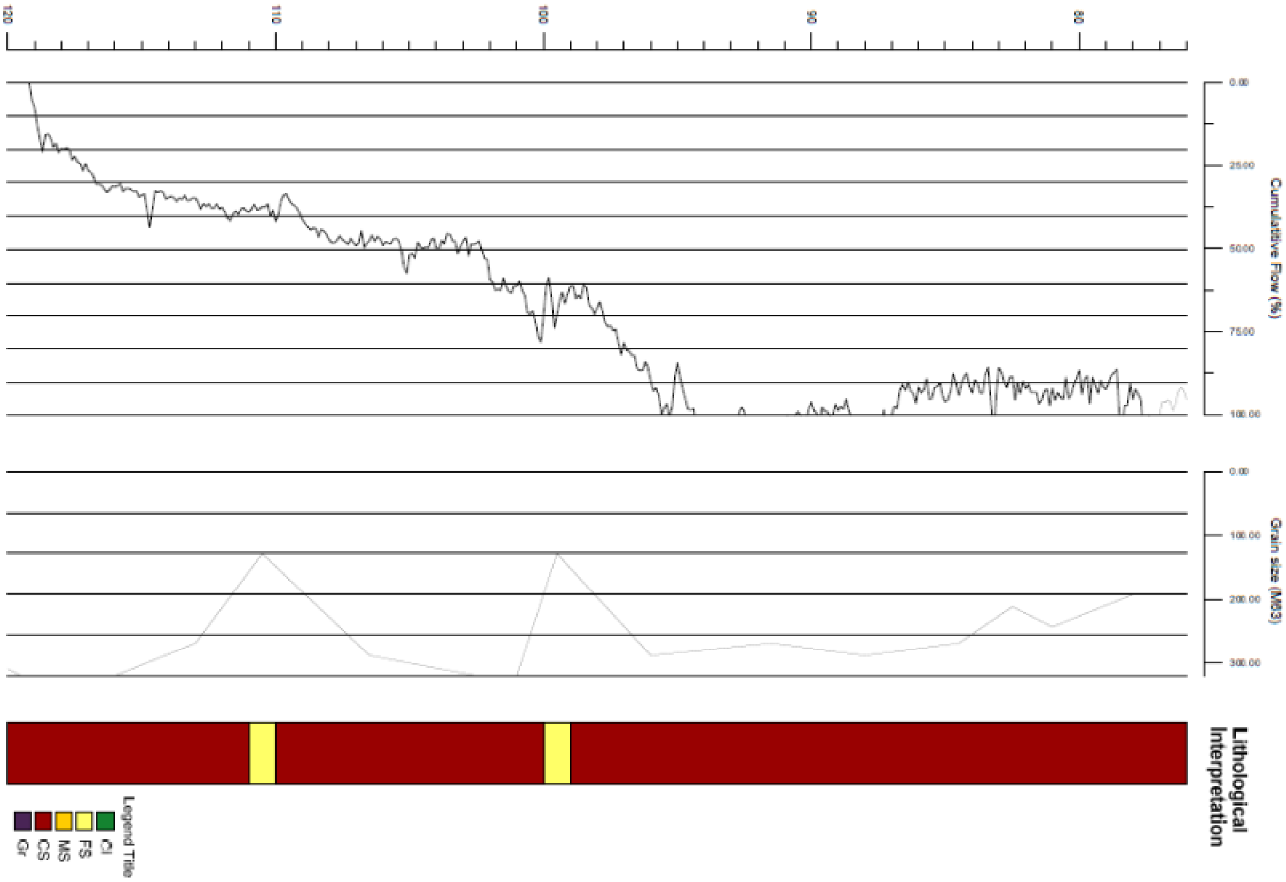
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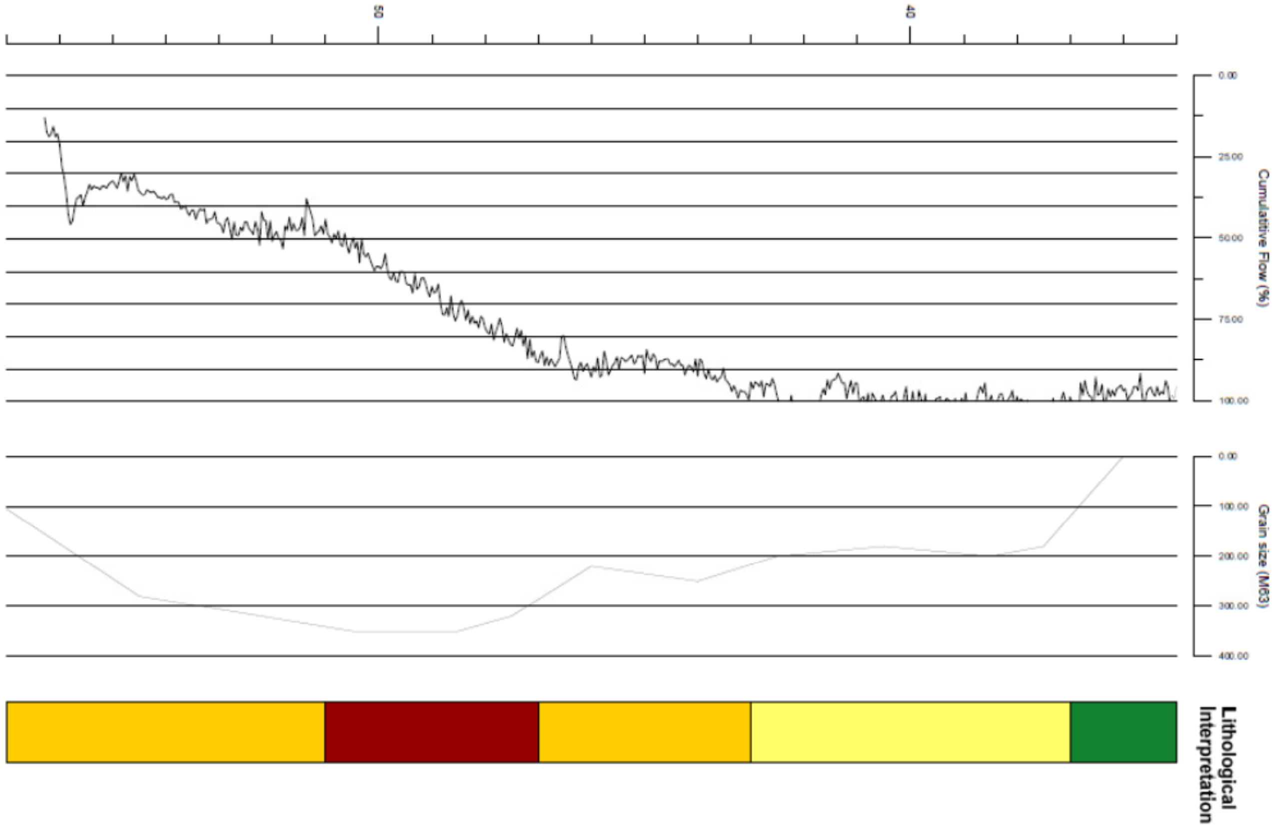
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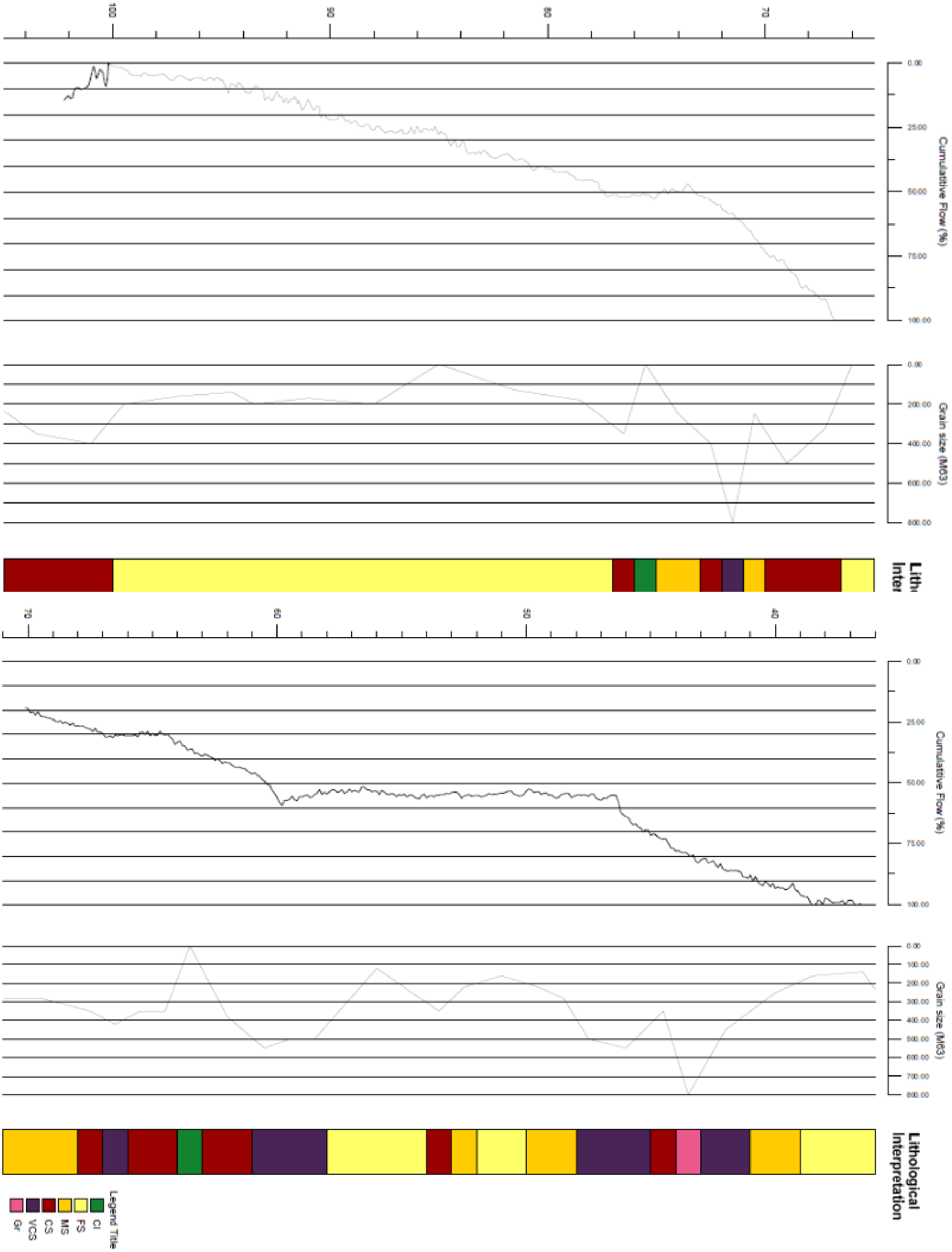
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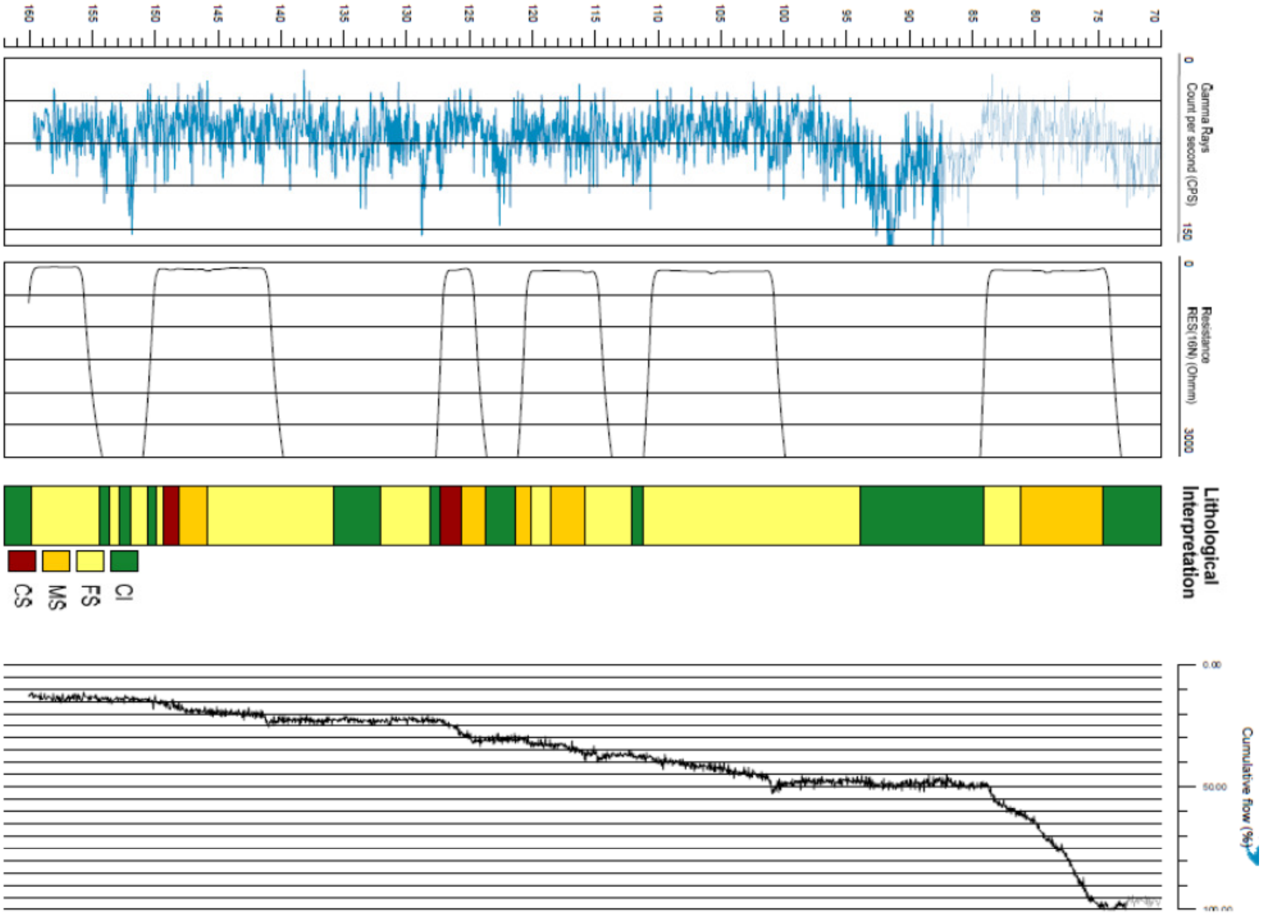
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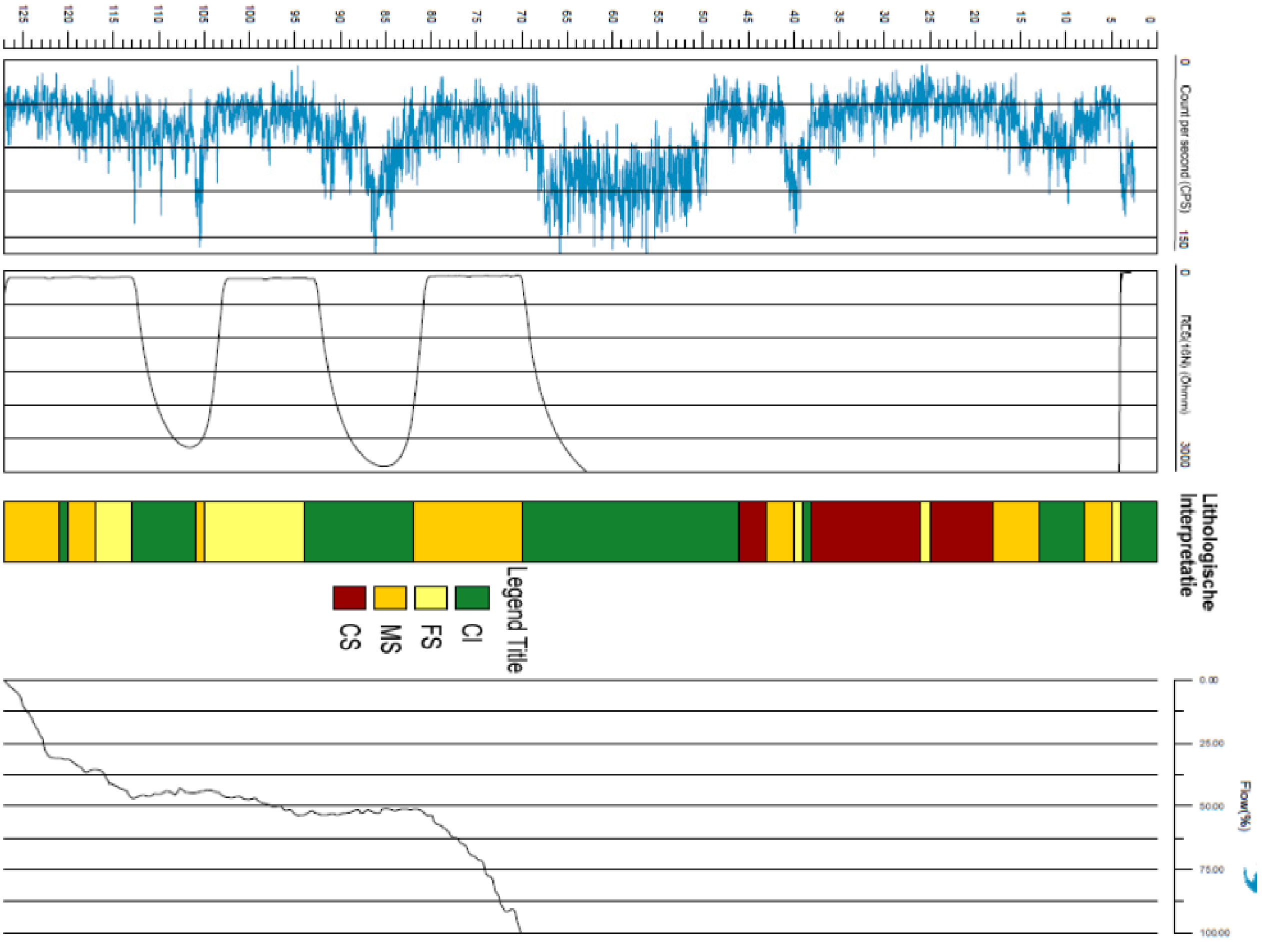
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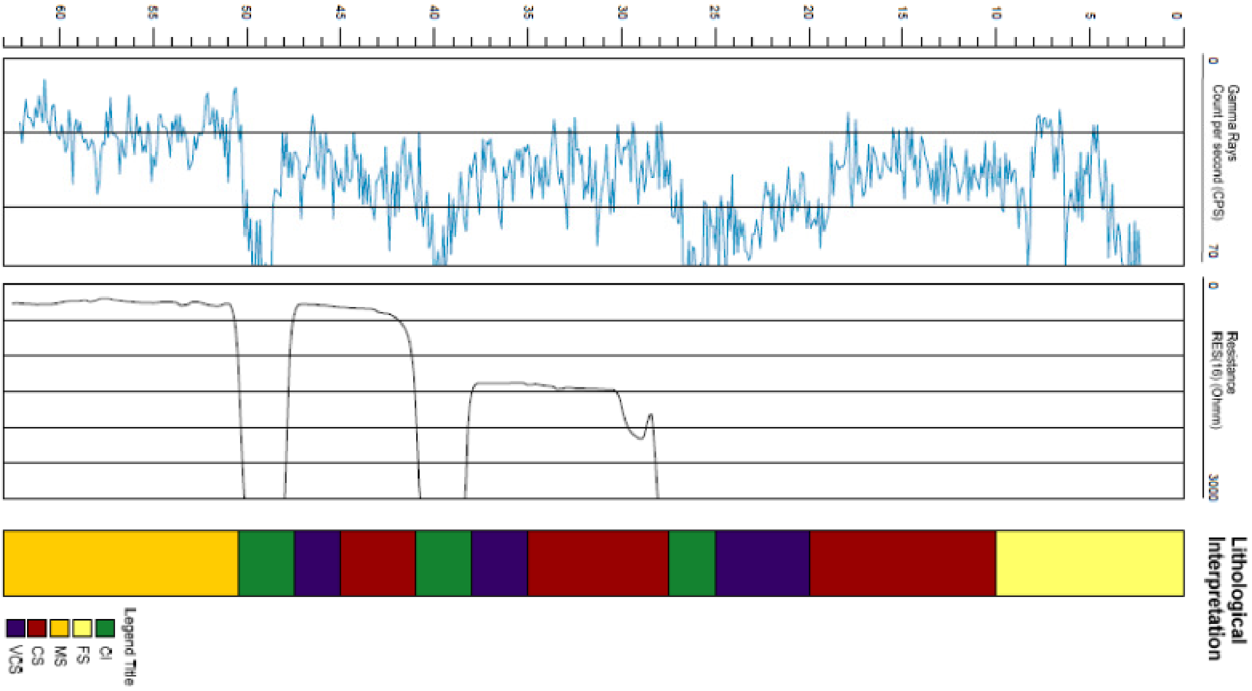
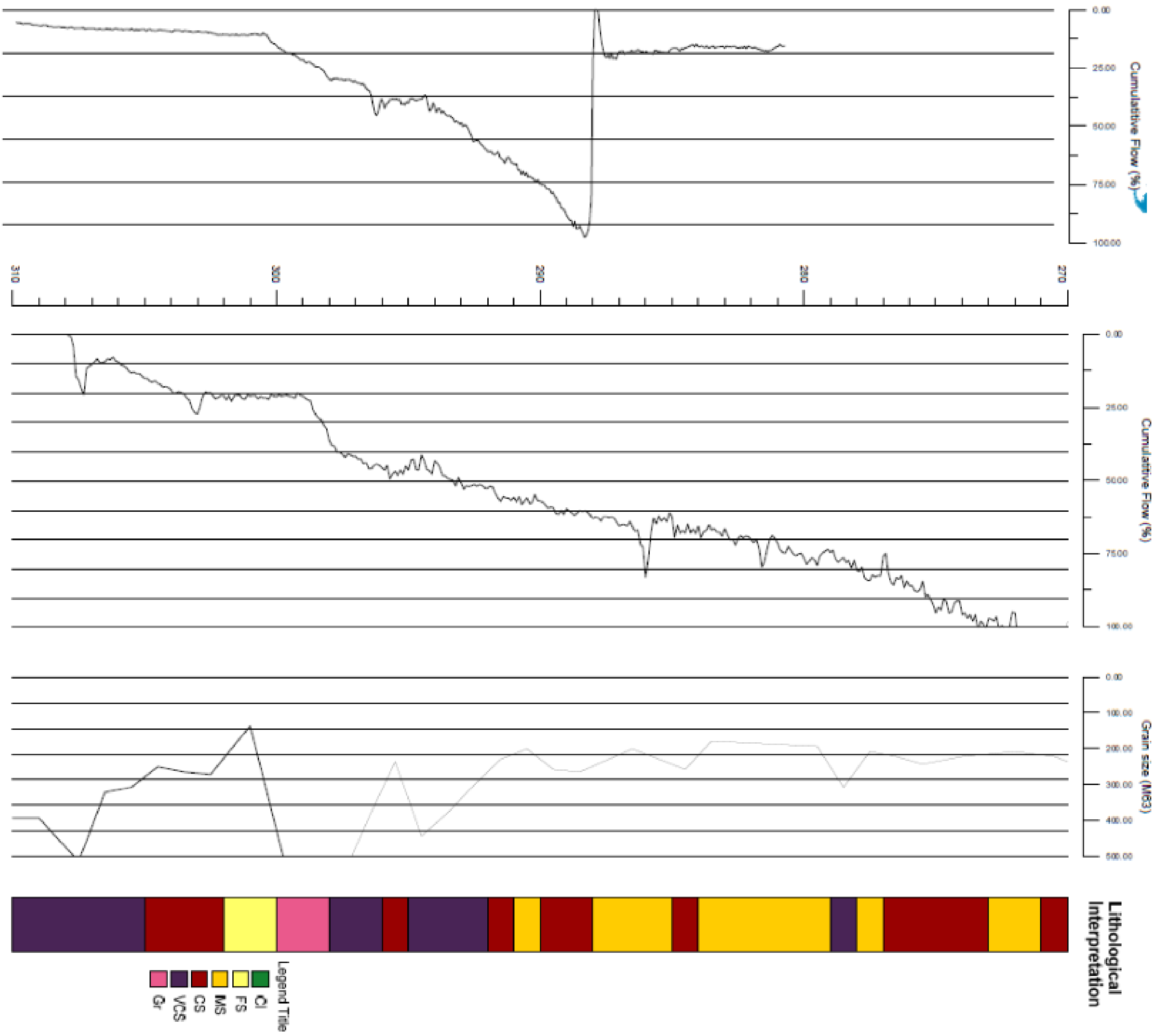
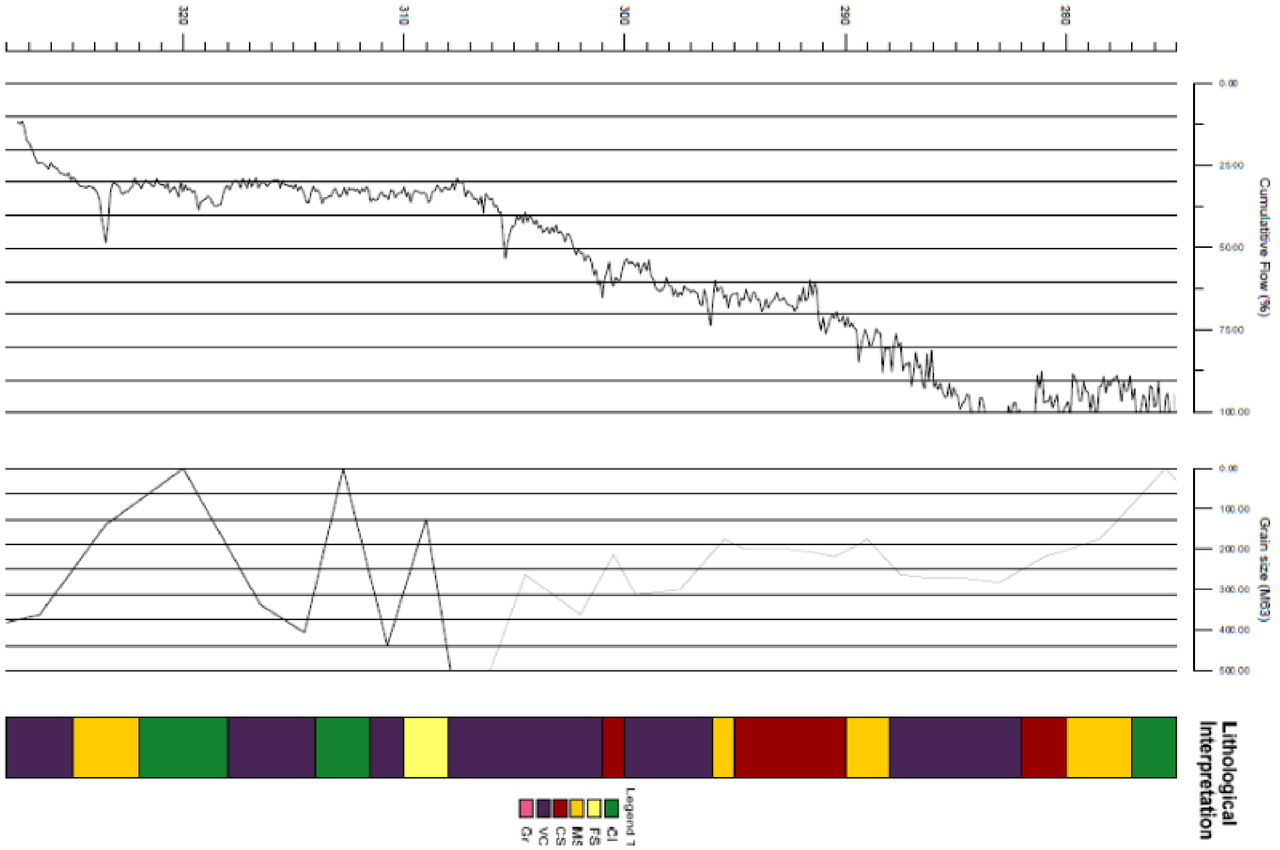
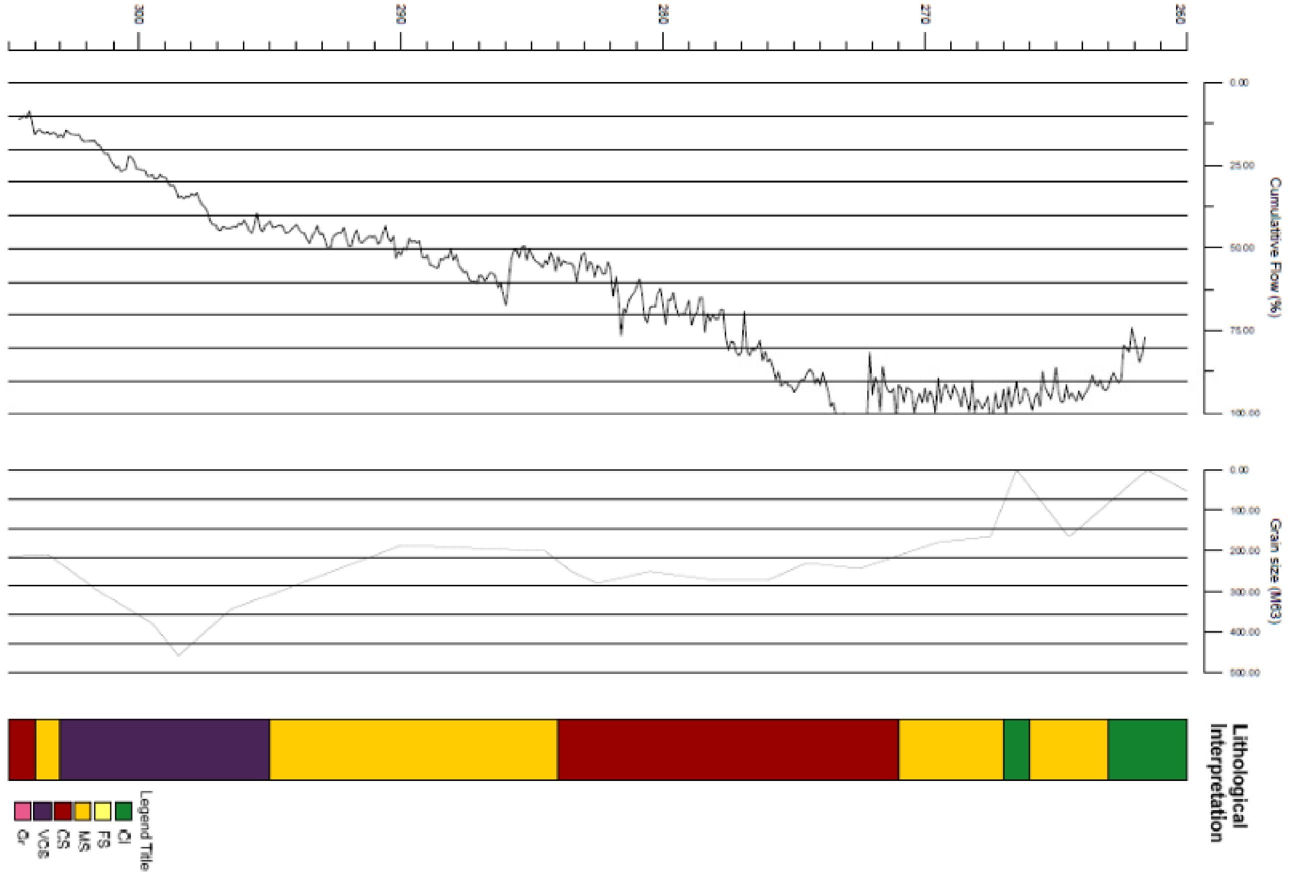
0
150
RES(16N) (Ohmm)
0
3000
Lithologische Interpretatie
Legend Title
CI
FS
MS
CS
Flow(%)
0.00
25.00
50.00
75.00
100.00


0
5
10
15
20
25
30
35
40
45
50
55
60
Gamma Rays
Count per second (CPS)
0
70
Resistance
RES(16) (Ohmm)
0
3000
Lithological Interpretation
Legend Title
Cl
FS
MS
CS
VCS


Cumulative Flow (%)
0.00
25.00
50.00
75.00
100.00
310
300
290
280
270
Cumulative Flow (%)
0.00
25.00
50.00
75.00
100.00
Grain size (M63)
0.00
100.00
200.00
300.00
400.00
500.00
Lithological Interpretation
Legend Title
Cl
FS
MS
CS
VCS
Gr



320
310
300
290
280
0.00
25.00
50.00
75.00
100.00
Cumulative Flow (%)
0.00
100.00
200.00
300.00
400.00
500.00
Grain size (M63)
Lithological Interpretation
Legend 1
Cl
FS
MS
CS
VC
Gr



300
290
280
270
260
0.00
25.00
50.00
75.00
100.00
Cumulative Flow (%)
0.00
100.00
200.00
300.00
400.00
500.00
Grain size (M63)
Lithological Interpretation
Legend Title
Cl
FS
MS
CS
VCS
Gr