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Pumping Test - Evaluation of Rehabilitation on water wells

Diploma thesis

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DIPLOMA THESIS TOPIC

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Thesis title: **Evaluation of regenerations on water wells**

Objectives of thesis: The aim of this work is based on regeneration of wells and the evaluation of hydrodynamic tests (pumping tests before and after regeneration) on the borehole which compares and observes the change of the additonal resistances on the well.
One regeneratioin is by means of ultrasound technology.

Methodology: The study of this paper concerning the evaluaton of hydrodynamic tests performed under the regime - descripton of the investgated site-evaluaton of the hydrodynamic tests on the borehole discussion and conclusion.

The proposed extent of the thesis: 50 pages

Keywords: well, pumping test, regeneration, ultrasound,skin factor

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1. Agarwal, R.G.; Al-Hussainy R.; Ramey, H.J. An investigation of wellbore storage and skin effect in unsteady liquid flow: I. Analytical treatment. Society of Petroleum Engineers Journal 1970, 10, 279-291.
2. BATU, V. *Acquifer hydraulics : a comprehensive guide to hydrogeologic data analysis*. New York: Wiley, 1998. ISBN 0471185027.
3. Cooper, H. H.; Jacob,C. E. A generalized graphical method for evaluating formation constants and summarizing well-field history. Transactions, American Geophysical Union 1946, 27, 526-534.
4. Kruseman, G.P.; de Ridder, N.A. Analysis and evaluation of pumping test data, 2nd ed.; IILRI: Wageningen, The Netherlands, 2008; pp. 1- 372.

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DECLARATION.

I hereby declare that this thesis was carried out independently with the use of the cited literatures and under the supervision and guidance of prof. Ing. Pavel Pech, CSc.

In Prague, 26.03.2021 John Marfo

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ABSTRACT

During the entire life of drinking water wells, formation damage due to natural ageing process is one of the most common causes of reduction in well productivity. This well ageing process, that is, material deterioration and the performance of the well is caused by physical, chemical, and biological processes acting on the well and its immediate surroundings. However, with the introduction of few cleaning or regeneration strategies, the decline in the well efficiency can be improved to such an extent that the well is once again able to function for a longer time in almost its new or original state. Acidizing and hydraulic fracturing are two well conventional treatment methods that are commonly used to address the issues of formation damage. Nevertheless, because of the harmful side effects of these approaches, the relatively new technique of ultrasonic regeneration, which has also been used in recent years has emerged to alleviate these challenges. The effectiveness of this approach has been previously demonstrated experimentally and operationally considered by many water well and oil well operators because no chemical solvents must be eliminated from the groundwater.

This study is based on the regenerations of water wells and the evaluation of hydrodynamic tests (pumping tests) before and after regeneration on some of the boreholes in the Czech Republic which compares and observes the changes of the additional resistances on the well. One of the wells regenerations is utilized by ultrasound technology. The additional resistance of the wells was evaluated by both the slope and the Jacob methods. Comparatively, both approach produce almost the same results. The results showed that the coefficient of additional resistance of the wells were smaller after the regeneration. The wells considered are RD2, KV2, KV9, MO1 and HV5 whose regeneration was utilized by ultrasonic technology.

Keywords: well; puumping test; regeneration; ultrasound; skin factor

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LIST OF SYMBOLS

W_P Well productivity using exponential distribution function.

h Hydraulic head or piezometric head, L

z Elevation head, L

J Hydraulic gradient, unitless

p Fluid pressure, $ML^{-1}T^{-2}$

ρ Density, ML^{-3}

µ Dynamic viscosity, $ML^{-1}T^{-1}$

v Velocity of groundwater, LT^{-1}

h_p Pressure head, L

g Gravitational acceleration $L\ T^{-2}$

Q Flow rate or discharge rate, L^3T^{-1}

q Specific discharge, LT^{-1}

K Hydraulic conductivity, LT^{-1}

K Permeability, L^2

T Transmissivity, L^2T^{-1}

S Storage Coefficient or Storativity,

S_s Specific storage, L^{-1}

S_y Specific yield, unitless

r Distance from pumping well to observation well, L

s Drawdown, L

b Thickness of an aquifer, L

W(u) Theis well function

u Dimensionless Theis parameter of well function.

r_w Radius of pumping well, L

A Cross-sectional area in the direction of flow, L^2

W Additional resistances, L

s_w Drawdown, L

h_0 The equilibrium water level before pumping starts, L

h_1, h_2 Water level during pumping, L

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

1. INTRODUCTION

Larger section of the groundwater extraction takes place by using vertical filter wells. Water components in the groundwater such as iron and manganese as well as microorganisms causes a natural ageing process in the well pipes and the filter gravel during water pumping. These often decrease the output ability of the wells and occasionally damage the producing well (van der Bas et al., 2004). There is the need to regenerate the wells to restore its authentic capacity. Conventional regeneration techniques use mechanical and chemical methods, such as acid washing, acid fracture, and hydraulic fracture to treat damages, both of which have positive effect on the well output. The primary risks of traditional methods particularly the acidizing technique include safety and environmental issues, well corrosion, and decreased efficiency over the course of treatment repetition. Moreover, the need for lots of surface facilities, the necessity of high energy pumps for injection mainly all through fracturing methods, significant working costs, and lengthy downtimes (several days) of the wells to be cleaned and operational problems of proppant are regarded as risks of conventional methods (van der Bas et al., 2004) & (Lim & Okada, 2005). In addition to that, the traditional well stimulation methods, as an alternative of doing away with the primary causes of the damage open new paths for fluid flow in the reservoir which restricts the opportunity of repeating the stimulation of the wells (Abramov et al., 2013).
In recent years, researchers have focused on developing less-expensive treatment methods to eliminate potential sources of production reduction and the risks associated with the conventional approaches. One of the promising techniques is based on ultrasonic wave technology. The monetary comparison between the conventional methods and the ultrasonic wave method suggests that this method might be appropriate (Table 1) (Abramov et al., 2013; Sander, 2007).

Table 1 Economic comparison between treatments methods

No.	Method	Production Enhancement relating to the initial production	Cost (Euro)	Proficiency $\left(\frac{Euro}{Production\ Enhancement}\right)$
1	Acidizing	2.5	12,400	4960
2	Hydraulic fracturing	6	22,350	3725
3	Ultrasound	2.4	8,200	3417

The use of ultrasound in well regeneration in recent years has proven that this new technique can compete with the earlier mentioned purposes and can be categorized as an environmentally friendly method, because none of the chemical solvents used must be eliminated from the groundwater. Moreover, the quick remedy time of a few hours drastically reduces the downtime of the wells.
The quality of drinking water wells, which has been reduced due to natural ageing processes, can be improved by using a variety of cleansing or restoration techniques to the point that the well can be used for longer periods of time in its original or nearly new

condition. For this purpose, the comparatively new approach of ultrasonic regeneration has also been used in recent years. The use of ultrasonic technolgy in many applications had provided accurate to very precise results. For this reason, the environmentally pleasant technology (Ultrasonic technique) is considered highly by many well operators than the traditional mechanical and chemical techniques. Despite the numerous advantages of the ultrasonic method, the issue that not all cleanings are now effective still remain a concern.

2. OBJECTIVE

The aim of this work is based on regenerations of wells and the evaluation of hydrodynamic tests (pumping tests before and after regeneration) on the borehole which compares and observes the change of the additional resistances on the well. Ultrasound technology is one approach of the regeneration.

The practical assessments in the context of this study will be monitored in addition to short pumping tests with borehole geophysical methods.
These measurements will be carried out in two stages.

1. Pumping test before regeneration.
2. Pumping test after regeneration.

3. LITERATURE REVIEW

This section elaborates some information on groundwater hydraulics and its application to the hydrodynamic test, overviews of ultrasound cleaning, well test and hydrological system which will help us to understand more about the importance of groundwater.

3.1 WELL AGEING

As provided by Houben. (2007) and Wolfgang Bott et al.(2003) the mean service life of a well is about a duration of 25 years. In the route of this operating time, there is a gradual minimization in the well delivery rate (Fig.1), which will become important throughout the pumping operation in an increasing and decreasing of the process water level with the same still water level and the same withdrawal volume. This reduce in delivery rate is due to an increase in the flow resistance and is often referred to as well ageing. Further warning signs of well ageing are an enlarge in the power consumption of the underwater pump, a change in the hydro chemical and / or biological water quality and the entrainment of turbid matter and sand in the pumped water.

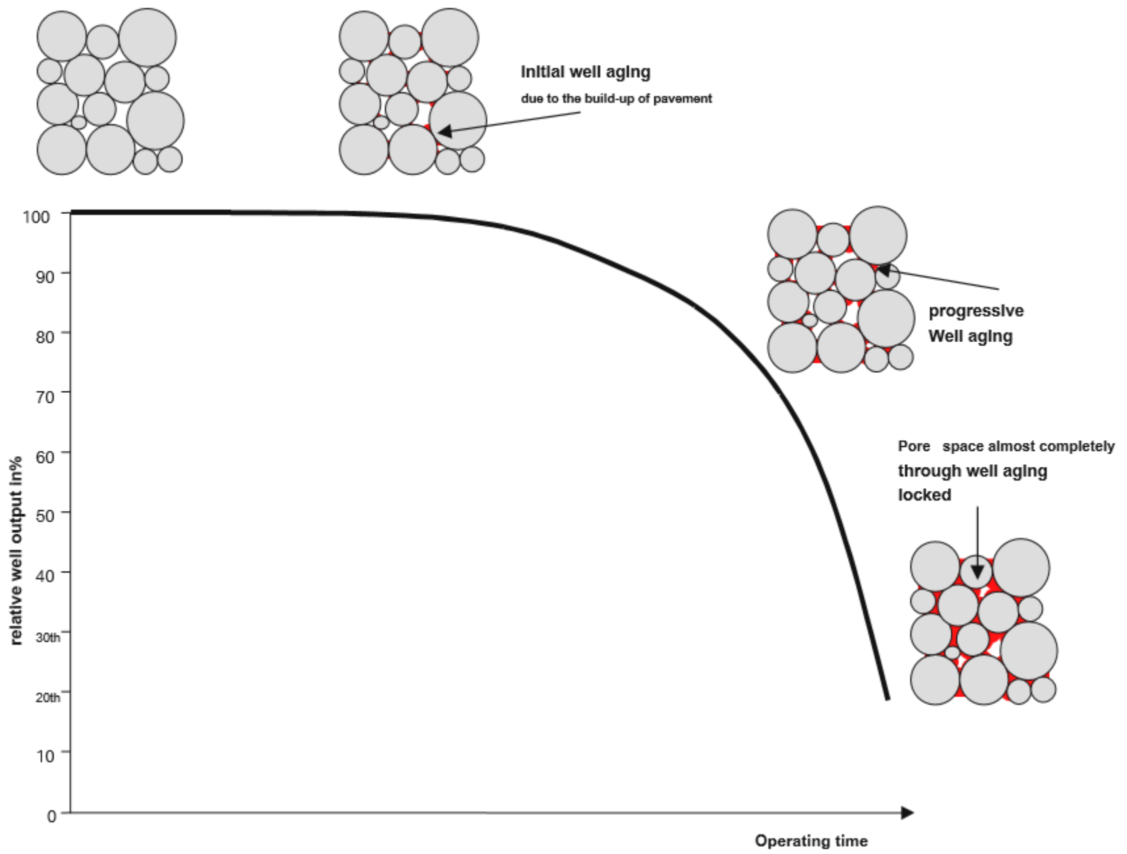


Figure 1: Dynamics deposition of sedimentation products in the filter gravel and the resulting Course of the relative well output (WIACEK, 2003).

As a result of the well ageing processes, the void quantity in the location of the well - pore spaces and pore channels of the gravel bed and filter slots - is increasingly more and decreased by deposits. If steps are taken to clean the well, the well will be fully "closed" in the final stage.
A distinction is usually made between different kinds of ageing, which regularly occurr together (DVGW, 2001; Houben, 2003; Paul, 1994): silting up (deposit of sand and silt in the cavities), corrosion of the well pipes and different metal well components, mucus build-up (reduction of the void volume due to the activity of mucus-forming bacteria and fungi), deposition of aluminium compounds after their chemical precipitation, sintering (deposition or incrustation of carbonates), ochre (precipitation and deposition of iron and manganese compounds).
Well ageing due to clogging collectively with bacterial slime formation occurs according to Abramova et al.(2017); Houben (2003) give the compositions of the most frequent well coverings in their article. The awesome importance of biologically induced clogging is emphasized by Kerms G. (1979); Wolfgang Bott et al.(2003).

3.2 WELL PRODUCTIVITY

The Well performance is indicated by rate of pumping or discharge flow rate per unit drawdown. Each aquifer is produced by several wells with unique drainage. The well performance or productivity rely on lineament distribution in an aquifer. The geologic lineament can be described as assumed origin of linear characteristic (Sander, 2007) and the assumption of lineament is a characteristic which indicates vertical area of fracture concentration (Lattman, 1958) and permeability depends on fracturing in an aquifer (Davis, 1988). However, the fractured aquifer’s properties are difficult to relate with well productiveness quantitatively. The impact of excessive permeability on well productiveness can be calculated by way of spatially distributed exponential function distance to the lineament. For the estimation of well productivity, the form of lineament is changed into circular computational domain. Figure 2 indicates the transformation to unit radii circle.

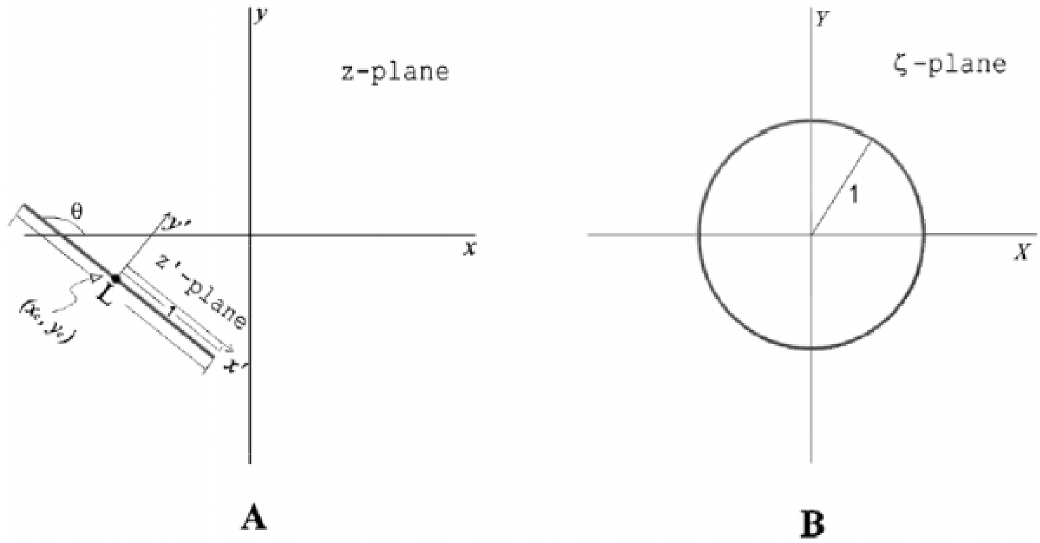


Figure 2a: Transformation of liner lineament to circular domain (Park et al., 2000).

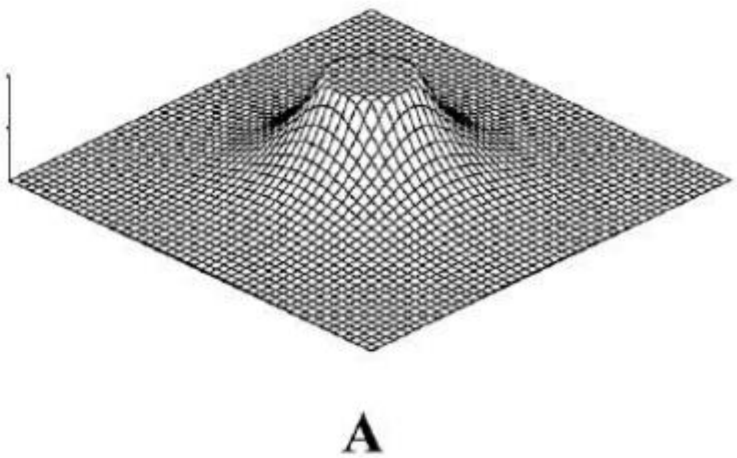


Figure 2b: Distribution of well productivity using exponential distribution function (Park et al., 2000; p.608)

The productivity round the unit circle is assumed to limit exponentially as shown in figure 2b. The well productivity distribution (WP) is indicated from the distance of (r-1) to the unit circle and well productivity (WP0) as following (Park et al., 2000)

$$WP = WP_o * e^{\frac{1-r}{\lambda}} \qquad (1)$$

3.3 GROUNDWATER CHARACTERISTICS

The three principal traits of aquifers are transmissivity, storage coefficient, and storativity. Transmissivity is ability of expressing permeability, the rate at which water can flow through the aquifer fabric. Storage coefficient and storativity express the volume of water that can be released from an aquifer (Soulsby, 2010).

The Characteristics of Groundwater are observed before implementation of big well set up for water extraction such as location of well, quality of water, flow and availability and source of water.

3.3.1 LOCATION

The flow of Water and surface reservoir follow a specific flow path; however, groundwater cannot be described in the same manner as surface flow pattern. Since it is extended in large area which is difficult to define. There is no need of dams and different infrastructures which are constructed for surface water use for the extraction of groundwater. On the other hand, wells are dug in an aquifer to pump out water as required where it is accessible beneath the ground (Bear & Cheng, 2010). There is no need to construct reservoir as in case of surface water system because an aquifer itself works as conduit and reservoir.

3.3.2 GROUNDWATER OCCURRENCE

The seasonal fluctuation in the flow of surface water, however, does not occurred in the groundwater flow. The quantity of water which is stored in an aquifer acts as buffer that will also be available in the draught condition. The principal sources of inland groundwater are rainfall. Groundwater flow is essentially an important part of hydrologic cycle. Rainwaters from the surface percolate downwards into an aquifer in the ground through infiltration and percolation developing saturated zone that acts as a medium for groundwater flow (Soulsby, 2010; Todd David Keith & Larry W. Mays, 2005).

3.3.3 GROUNDWATER DISTRIBUTION

Water penetrates underground mainly present in two zones: unsaturated and saturated zones, each separate according to air and water filled in the pore space in the soil. The pore space which is filled only with water is known as saturated zone and the pore space which is filled with air as well as water is called as unsaturated zone. The unsaturated zone is the largest reservoir of groundwater. The upper layer of ground serves as unsaturated zone consisting root zone, intermediate zone, and capillary fringe zone. Water enters in this zone or the unsaturated zone gets recharged, and water moves to the deep saturated zone gradually (Nielsen et al., 1986). This zone faces fluctuation in water storage due to plant uptake, precipitation, and evapotranspiration (Figure 3).

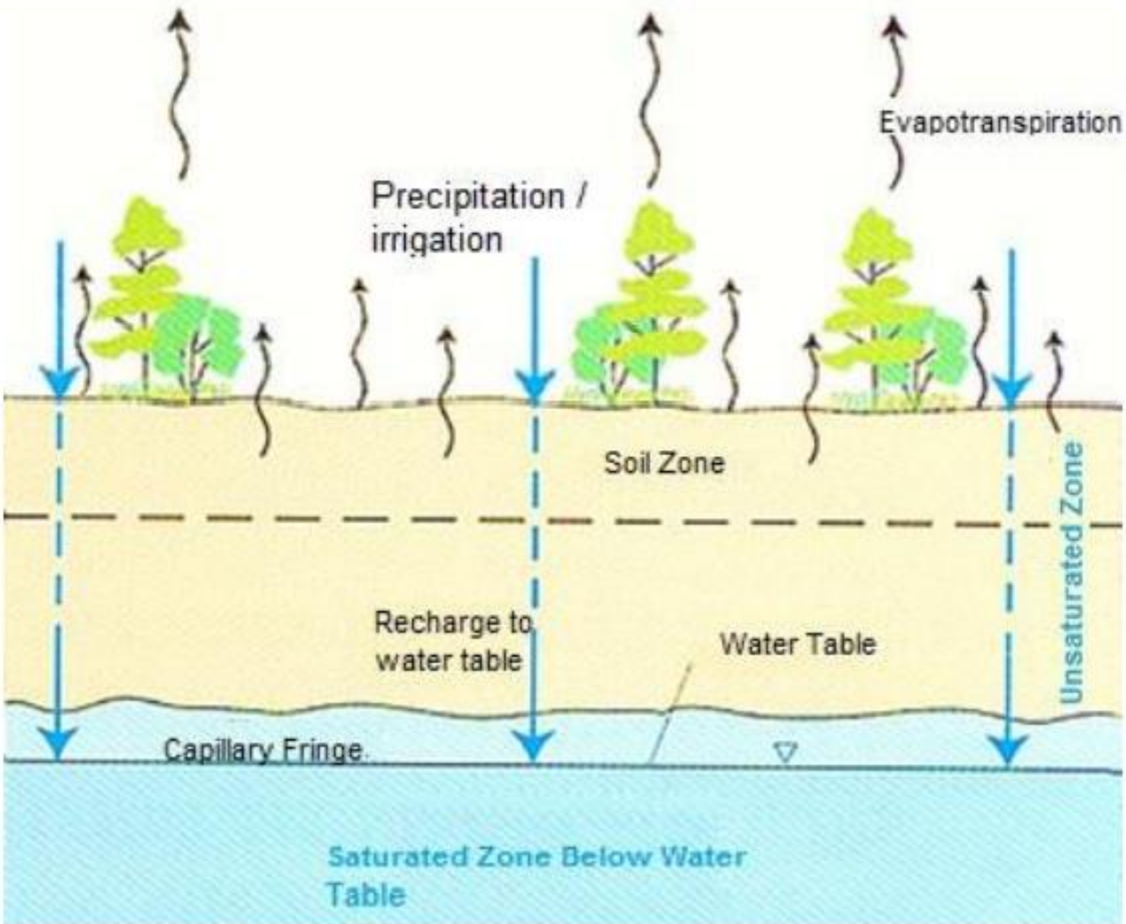


Figure 3: Shows Saturated and Unsaturated Zones (source: US geological survey)

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

3.4 BASICS OF GROUNDWATER FORCES AND HYDRAULIC HEAD

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

Hydraulic head or piezometric head can be defined as a specific measurement of water pressure above a vertical datum. It is usually measured as a liquid surface elevation, expressed in units of length, at the entrance (or bottom) of a piezometric. In an aquifer, it can be calculated from the depth to water in a piezometric well (a specialized water well), and given information of the piezometer's elevation and screen depth. Hydraulic head can similarly be measured in a column of water using a standpipe piezometer by measuring the height of the water surface in the tube relative to a common datum. The hydraulic head can be used to determine a hydraulic gradient between two or more points.

The Bernoulli Equation that defines hydraulic head is as shown below:

$$h = z + \frac{p}{\rho g} + \frac{v2}{2g} \qquad (3.0)$$

Where, h is the hydraulic head (m), z is the elevation above datum (m), p fluid pressure (Pa), ρ is the density of water ($kg.m^{-3}$), v is the velocity of water ($m.s^{-1}$) and g is the gravitational acceleration ($m.s^{-2}$).

Pressure head (hp) is defined as follows from the equation (3.0).

$$h_p = \frac{p}{\rho g} \qquad (3.1)$$

Since the groundwater velocity is extremely low, hence it is neglected.

Then the hydraulic head, $h_p = z + \frac{p}{\rho g}$

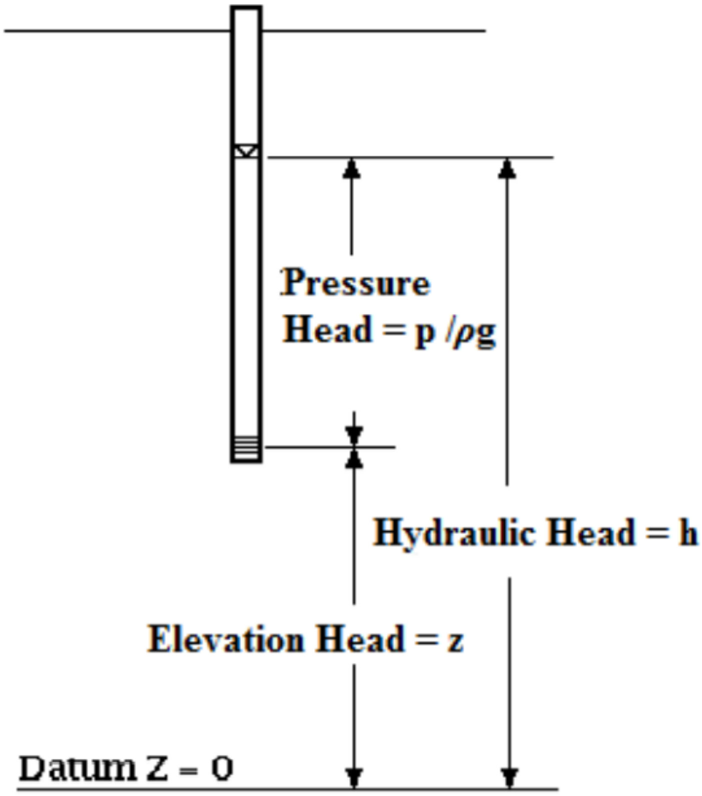


Figure 4: Shows the hydraulic head, pressure head and elevation head.

3.5 GROUNDWATER TABLE

Water table is the height of water in and around the well summing of pressure head and elevation above datum. It is the water level where water pressure in pores is equal to the atmospheric pressure (Holzer, 2010). Figure 4 shows water table above the screen of well which is equal to pressure head above the well screen.

3.6 AQUIFERS

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

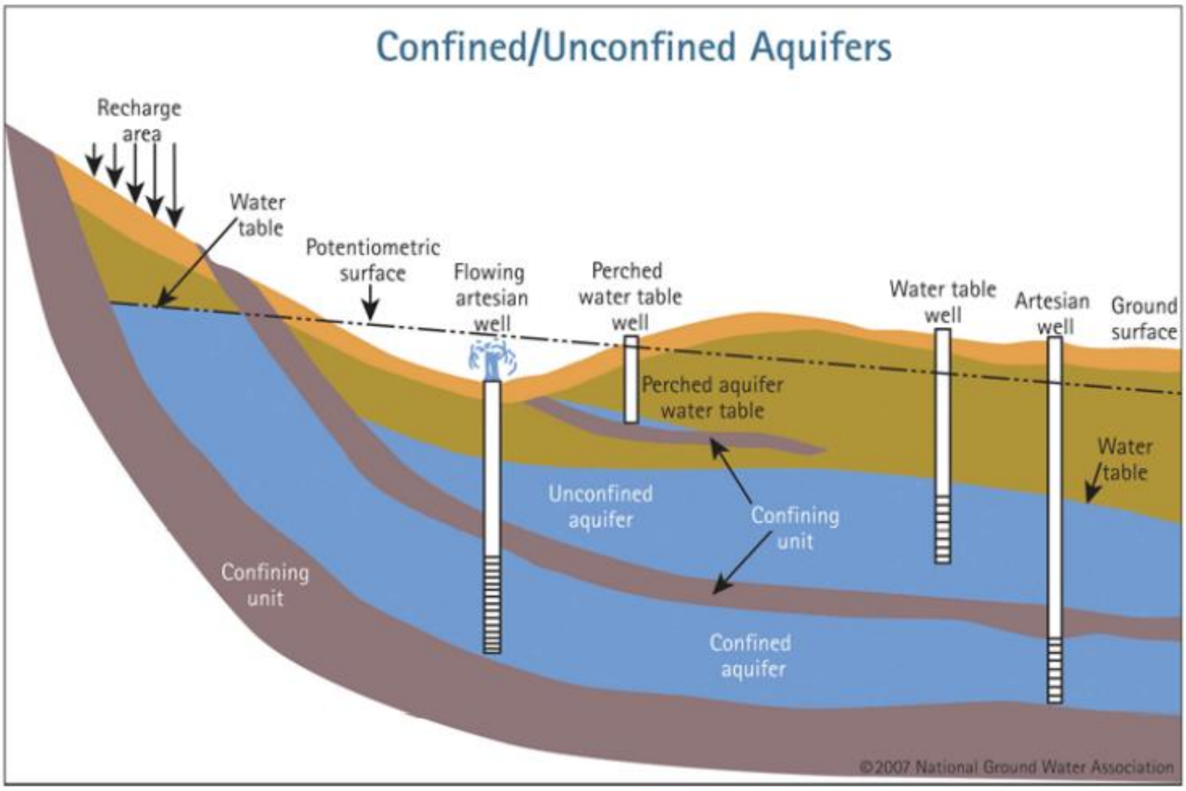


Figure 5: Types of Aquifer (Smith Stuart, 1982)

Unconfined aquifer is not compacted by impervious layers (confined layer) from the upper side. It is mostly held near to the ground level and water table does not change due to atmospheric pressure effect. An inverted cone of depression occurs while pumping out water from an unconfined aquifer and water is filled in the depression of cone after pumping stops. Pumping out water depends on gravity drainage principle (Smith Stuart, 1982). The confined aquifer occurs between aquitards or extremely low permeable layers. The confined aquifer is under pressure due to overlain layers than atmospheric pressure and water table rises above the aquifer in the well. The pumping from confined aquifer is not due to gravity discharge. A semi confined and a leaky aquifer occurs in strata type semi pervious layer while pumping out water from the well, water moves horizontal as well as vertical direction in a semi-confined aquifer (Hemker, 1984).

3.7 GROUNDWATER MOVEMENT

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

3.7.1 DARCY'S LAW

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

$$Q = -KA\frac{dh}{dI} \qquad (3.2)$$

Where, Q is the flow rate, A is the cross-sectional area through which fluid passes, K is the hydraulic conductivity, h is the piezometric head and I is the distance between two observing points. Darcy's law is generally valid for laminar flow and small Reynold's number of Newtonian fluids in a porous aquifer, the flow is one dimensional in a homogenous porous media (Neuman, 1977). The extension of Darcy's law in three dimensions (Bear & Cheng, 2010) can be written with parameters shown in Figure 6 as follow:

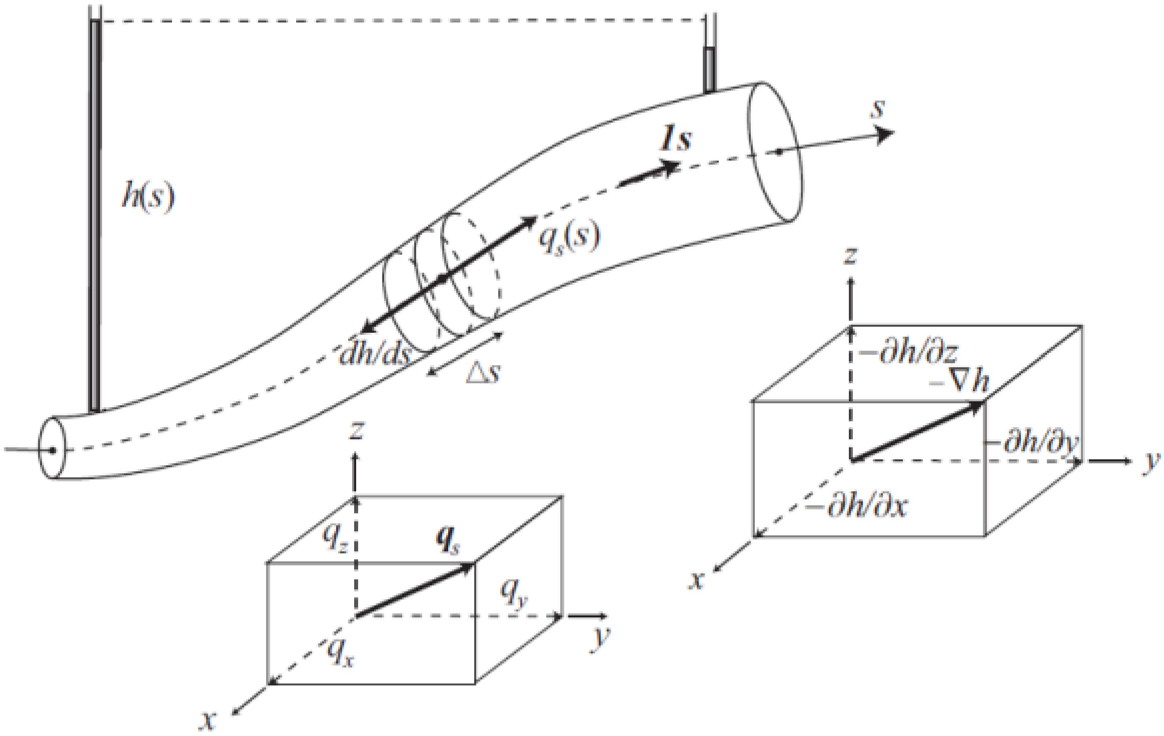


Figure 6: Three-dimensional stream tube of flow. (Bear & Cheng, 2010; p. 114)

$$q = -K(x, y, z)\frac{\partial h}{\partial x} + \frac{\partial h}{\partial y} + \frac{\partial h}{\partial z} \qquad (3.3)$$

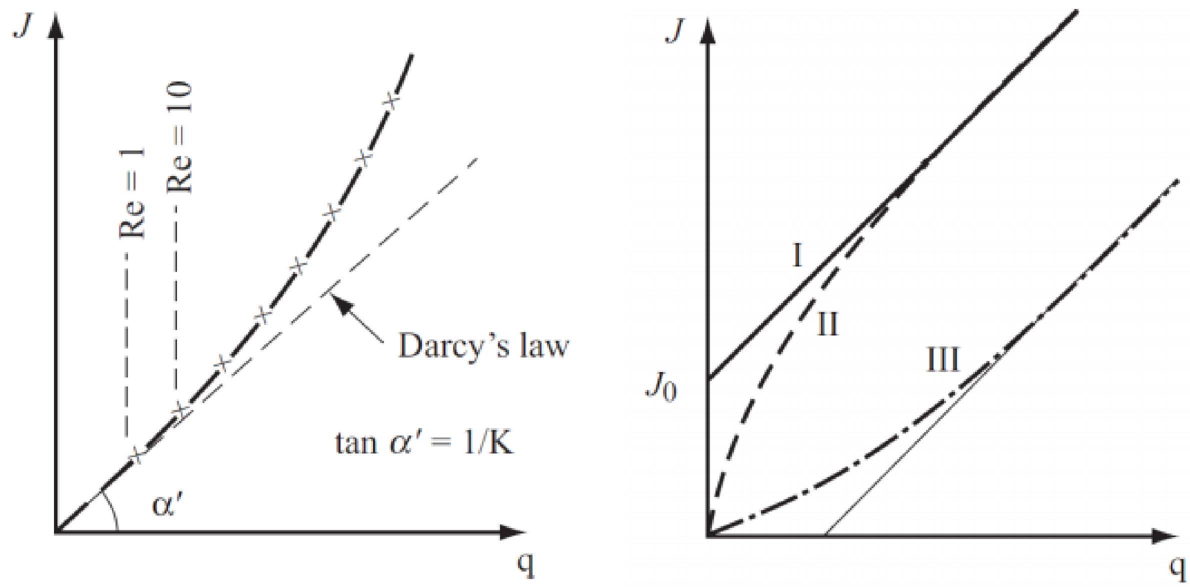
Where q is specific discharge and $\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}$ & $\frac{\partial h}{\partial z}$ are three dimensional components of the hydraulic gradient vector.

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

$$q_x = K_x \cdot \frac{\partial h}{\partial x} \quad , \quad q_y = K_y \cdot \frac{\partial h}{\partial y} \quad and \quad q_z = K_z \cdot \frac{\partial h}{\partial z}$$

3.7.2 NON DARCIAN GROUNDWATER MOTION

Darcy's law shows liner relationship between specific discharge (q) and hydraulic gradient (J) but this situation exits at low Reynolds number (Re < 1). But the liner relation between specific storage (q) and hydraulic gradient (J) is not linear in some cases as shown in Figure 7.



A-Sand B-Clay

Figure 7: Relationship between hydraulic gradient (J) and specific discharge (q). (Bear & Cheng, 2010)

The Reynolds number is used to indicate the type of flow such as laminar, turbulent, or transient flow of fluid. Most of the groundwater flow in a porous media has a Reynolds number less than 1 but, in some cases of high pumping rate and recharging, the Reynolds number is not less than 1. High Re exists in a high porous media including lime stones (Firdaaouss Mouaouia et al., 1997). Non Darcian law for a leaky aquifer can be derived by analytical solution of the cone of depression and drawdown changes in the observation well (ŞEN, 2000). Darcy´s law is valid for Re <10.

3.7.3 HYDRAULIC CONDUCTIVITY

The hydraulic conductivity (K) is defined as the ability of soil media to transmit water which is used as a boundary condition in the soil-water relation study (Klute & Dirksen, 2018). The hydraulic conductivity (K) depends on the shape and the size of soil particles (geometry and packing factor of pore space), the diameter of pores and the permeability of an intrinsic medium (Fair & Hatch, 1933). The hydraulic conductivity can be expressed as follow:

$$K = k \cdot \frac{\rho g}{\mu} \tag{3.4}$$

Where, ρ is the density of a fluid ($kg.m^{-3}$), μ is the dynamic viscosity of fluid (Pa.s), g is the gravitational acceleration ($m.s^{-2}$) and k is the permeability (m^2). The permeability is the function which depends on the shape and the size of a pore space of the porous media. The permeability can be expressed below as:

$$k = Cd^2 \tag{3.5}$$

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

3.7.4 TRANSMISSIVITY OF AN AQUIFER

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

$$T = bK \tag{3.6}$$

Where, b is the thickness of an aquifer (m) and K is the hydraulic conductivity ($m.s^{-1}$). The transmissivity (T) depends on the heterogeneity of the porous media and interconnectedness of voids (Richard et al., 2016).

3.7.5 STORAGE COEFFICIENT OR STORATIVITY

The Storativity (S) can be defined as the volume of water which is drained from an aquifer at a unit difference in the hydraulic head through unit the area by the gravity flow at water table. Water is drained due to hydrostatic pressure in the voids below the water table from an aquifer (Wu et al., 2005). The specific storage (Ss) is the volume of water in a formation, it is drained from the storage at a change in a unit hydraulic head per unit height of aquifer (Helm, 1975). The storage coefficient (storativity) S of a saturated confined aquifer or confined layer with thickness b can be expressed as (Batu Vetat, 1998):

$$S = b.S_s \tag{3.7}$$

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

$$S = S_y + b.S_S \tag{3.8}$$

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

3.7.6 GROUNDWATER EQUATION FOR AN IDEAL AQUIFER

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

$$Q = -2\pi r T \frac{\partial h}{\partial r} \tag{3.9}$$

Where T is the transmissivity ($m^2.s^{-1}$), r is the radial distance of pumping well at a given point in an aquifer and h is the hydraulic head in an aquifer (m).

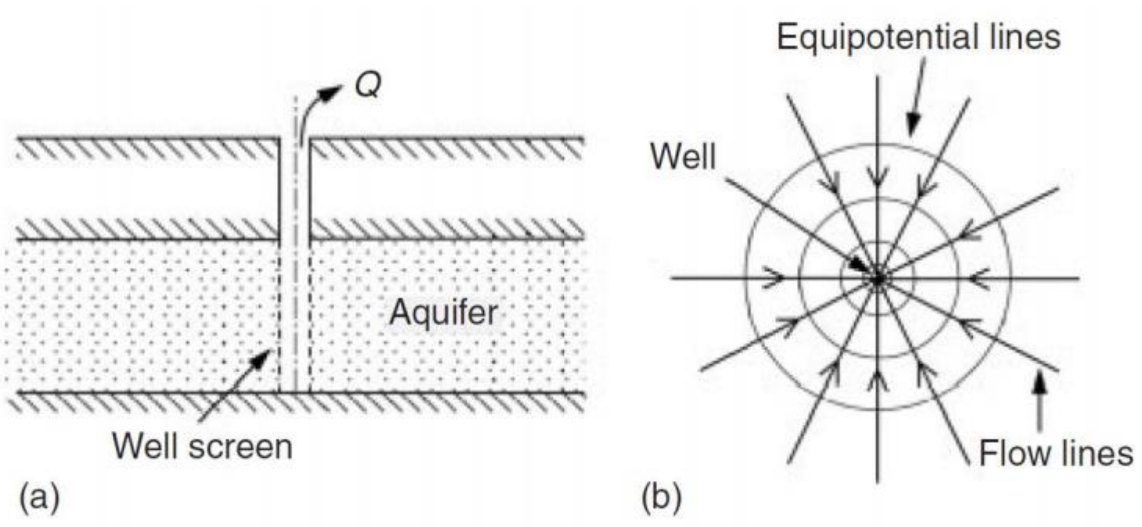


Figure: 8 (a) Ideal Confined Aquifer and (b) Radial water flow to the well penetrating completely (Renard, 2006)

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

$$\frac{\partial Q}{\partial r} = -2\pi r S \frac{\partial h}{\partial t} \qquad (3.10)$$

Where S is the Storativity of a confined aquifer. The general equation can be derived from the two equations above as,

$$\frac{1}{r}\frac{\partial h}{\partial r} + \frac{\partial^2 h}{\partial r^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (3.11)$$

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

3.7.7 THEIS SOLUTION FOR AN IDEAL WELL

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

$$T = \frac{Q}{2\pi(s_2 - s_1)} \cdot \ln\frac{r_1}{r_2} \qquad (3.12)$$

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

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

$$u = \frac{r^2 S}{4tT} \qquad (3.14)$$

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

$$W(u) = \int_u^\infty \frac{e^{-u}}{u} du \qquad (3.15)$$

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

$$\lim_{r \to \infty} s = 0 \qquad (3.16)$$

$$\lim_{r \to 0} 2\pi Tr \frac{\partial s}{\partial r} = -Q \qquad (3.17)$$

Theis derived solution from the equation (3.11) with the initial and given boundary condition (Equation 3.16) and (Equation 3.17) which is expressed as follows (Renard, 2006)

$$s = \frac{Q}{4\,\pi\,T} W(u) \qquad (3.18)$$

Where W(u) is Theis well function and u is argument of well function.

$$u = \frac{r^2\,S}{4\,T\,t}$$

This Equation (3.18) express drawdown with time and space including an aquifer's storativity S and transmissivity T.

3.8 PUMPING TEST

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

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

The quality of well is estimated while comparing real well with ideal well parameters but this comparison may lead to increase or decrease the performance of real well. This stimulation and damage are evaluated by skin factors. The resistance as the pressure drops due to the skin of real well (composition and properties of soil around real well). These additional resistances and wellbore storage affect pumping test at real well. The pressure drop is due to resistance formation, viscosity of liquid, skin zone and the additional resistance concentrated arround the real well (Pech Pavel, 2004; van Everdingen, 1953).

3.8.1 ADDITIONAL RESISTANCE

As a rule, it is accepted that well infiltrates all through the thickness of an aquifer, however, it does not happen in real condition. Well, is in part entering into an aquifer with a finite thickness of the skin. Well-bore has also some diameter which allows to store water in well-bore. This well-bore prolongs the movement of water to enter in the well from an aquifer. In addition to this effect, the damaged or the material left while drilling of the well, affects water movement which is called skin effect (Moench, 1985). While drilling well-bore, mud amasses around well screens which change permeability around the well walls compare to the surrounding aquifer. According to changed permeability, skin effect can be positive or negative (Chen & Chang, 2006). Hence, it is assumed that well-bore storage and skin effect are insignificantly thin for pumping, observation well and skin has no storability to be convenient for mathematical solution (Pasandi et al., 2008). Another assumption is the homogeneity of porous encompassing skin which is used in steady rate of pumping and it does not discontinue head at the opening of drilled well (Chen & Chang, 2002).

3.9 ULTRASOUND

Ultrasound is sound waves with frequencies higher than the upper audible limit of human hearing. The limit varies from person to person but is approximately 18KHz to 20KHz (R. Wilken et al., n.d.), at frequencies above 10 GHz the range of hypersonic starts (Kuttruff, 2012). The physical properties of ultrasound are like the normal audible sound. This is because physical laws of sound generation and propagation do no longer rely on the frequency.

However, due to the greater frequencies and the correspondingly smaller wavelengths, there are variations in the technical dealing with ultrasound. In addition, results that occur in the ultrasonic range cannot be determined or can solely be observed very weakly in the audible sound range. These effects include, for example, material erosion due to cavitation (Kuttruff, 2012) & (Noltingk, 1962) and the material destruction or structural change of solid substances, which can be brought about with the aid of ultrasound because of over-elastic stress on the material (Pohlmann R., 1960).

The general fundamentals of acoustics and the distinct physics of ultrasound cannot be discussed in extra detail at this point. They can be found in standard works of physics (in textbooks on the physics of ultrasound by (Kuttruff H., 1988; Kutzner J., 1983). Basic lookup in ultrasound has been carried out for round 50 years. The application of ultrasound in the field of diagnostic and curative medicine, pharmacy, material testing or the use of ultrasonic cleansing baths in industry, in laboratories, at opticians or jewellers is known to many. The application of ultrasound in environmental technology, on the other hand, is still quite new and takes place under distinct boundary conditions (Thiem A. Neis U, 1999; Wolfgang Bott et al., 2003). Depending on the application, large and greater effective reactors are required. Fig. 3.9 indicates the earlier known modes of action for their precise frequencies. The common rule here is that the lower the frequency of the Schaller used, the higher the output of the generators.

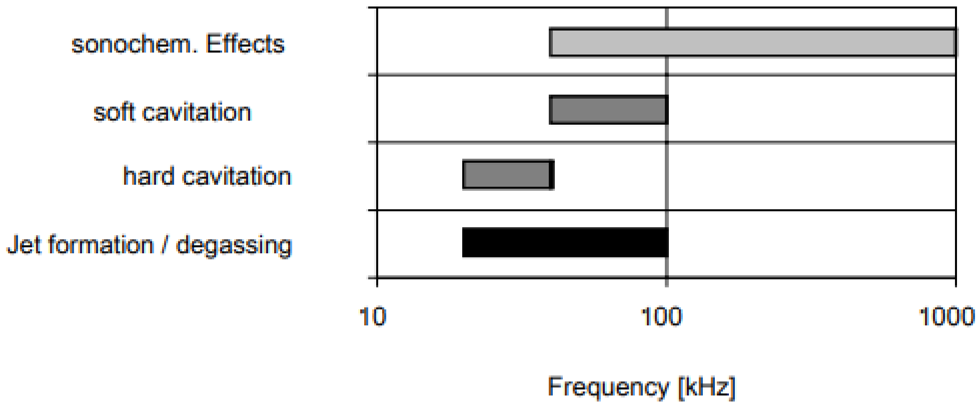


Figure 9: Ultrasonic Frequency Ranges and their corresponding Effects. The frequency is plotted logarithmically.

The fundamental application of ultrasound for surface cleaning is broadly speaking primarily based on the mechanical force brought about by the prevalence of hard cavitation. In addition to hard or actual cavitation, there is also so-called tender cavitation or gas cavitation. The form in which cavitation happens relies upon on the kind and degree of purity of the liquid and on the strength, frequency, and geometry of the sound field. In general, cavitation is understood to imply the formation of cavities in liquids on corresponding cavitation nuclei. This occurs either through the input of energy (e.g., laser radiation) or through pressure drop in hydrodynamic flows (ship's propellers) or sound waves (ultrasound). The gas or liquid bubbles formed in this way oscillate for a certain time, grow, and reduce till they eventually collapse (implode) under sufficiently excessive pressure. Temperatures of about 5000 ° C and pressures of about 500 bars occur.
As it can be considered from Fig. 9, the impact of the high-energy ultrasound at a frequency of 20 kHz, which is used for well regeneration, lies in the mechanical destruction of substances, which is mainly brought on through hard cavitation. However, the statements made regarding cavitation as an effective variable are based totally on the assumption that work is carried out at atmospheric pressure. The one ruling in fountains hydrostatic pressure (overpressure conditions) basically has a cavitation-inhibiting effect, since it makes the formation of cavitation bubbles more difficult. The cavitation threshold additionally will increase linearly with increasing pressure, ie an ever higher alternating sound pressure with higher sound intensities is required. With steady sound intensity and increasing hydrostatic pressure, the cavitation decreases and at some point, it can no longer be detected (Wolfgang Bott et al., 2003).
When cleaning the well behind the filter pipe, cavitation is practically negligible and happens in wells only up to a certain maximum depth (~ 20 m) due to the hydrostatic pressure. However, cleansing outcomes with the use of ultrasound have also been proven substantially in deeper wells (eg; 100 m) with higher water columns (Bott W. Wilken R. D., 2002).

3.9.1 APPLICATION OF ULTRASOUND

Ultrasound is used in many different scientific fields such as navigation, medicine, imaging, cleaning, mixing, communication, resting, etc. Even in nature, bats and porpoises use this technique for location of prey and obstacles.

3.9.2 ULTRSOUND CLEANING:

The process of ultrasonic cleaning is used in objects with parts that are difficult to reach, for example, spiral tubes and electronic components.

The cleaning involves the use of high-frequency sound waves (the upper range above human hearing, or about 18 kHz) to remove different kinds of contaminants from parts immersed in aqueous media. The impressing improvement of ultrasound technology in seismic techniques and other ultrasonic applications in other fields of petroleum engineering have encouraged the study of ultrasonic radiation on asphaltenes removal. Ultrasound requires vibratory waves which are above the detection limits of human ears. The idea of using ultrasound waves to increase well production is not new as some publications have been published under this subject. The main study has been given by (Aarts et al., 1998) presenting a theoretical model and laboratory test results supporting the theory that radiation of ultrasound wave near wellbore region deforms the pore wall thus increasing the flow. Moreover, the ultrasound cleaning technique is reported to be successful in 40 to 50% from the preceding studies, and the results of the improved permeability will last for several months (Champion et al., 2004). Ultrasonic cleaning is powerful enough to remove tough contaminants, yet gentle enough not to damage the substrate. It provides excellent penetration and cleaning in the smallest pore space and between tightly grains. However, most of field tests have given an opposite result, yielding a limited success as little is known about the physical mechanism of the wave interaction with particles trapped and optimum wavefield parameters required to remove these particles. Ultrasound wave is generated through the interaction of positive and negative pressure waves. To produce the positive and negative pressure waves in the aqueous medium, a mechanical vibrating device is required. Ultrasonic manufacturers make use of a diaphragm attached to high-frequency transducers. The transducers, which vibrate at their resonant frequency due to a high-frequency electronic generator source, induce 16 amplified vibration of the diaphragm. This amplified vibration is the source of positive and negative pressure waves that propagate through the solution in the tank. The function is like the function of a loudspeaker except that it occurs at higher frequencies. The resonant frequency of the transducer determines the size and magnitude of the resonant bubbles. Typically, ultrasonic transducers used in the cleaning industry range in frequency from 20 to 80 kHz. The lower frequencies create larger bubbles with more energy, as can be seen by dipping a piece of heavy-duty aluminium foil in a tank. The lower-frequency cleaners will tend to form larger dents, whereas higher-frequency cleaners form much smaller dents. Ultrasonic technology equipment for near wellbore application is made up of the powerful ultrasonic generator and ultrasonic transducer, powered through a standard 3 core logging cable. The whole equipment, realizing the acoustic stimulation technology, is in coordination with the regular equipment’s of geophysical parties which does not cause any difficulty in its adaptation by the regular geophysical personnel. The acoustic stimulation technology consists in the processing of collector layers (in the open bore, filter interval or perforated holes) by powerful ultrasonic field aimed at the restoration of their filtering properties. Processing is carried out point wise (with 0.5-1.0 interval) selectively based on the “inflow stimulation profile” principle. Well and equipment preparation is practically the same as that for standard geophysical research.

Ultrasonic cleaning

Figure10: Cleaning by the use of ultrasoud tecnology

3.9.3 DETECTION OF CRACKS:

Ultrasound is used to detect cracks in the metallic components that are used in the construction of high-rise structures such as buildings and bridges. They generate and display an ultrasonic waveform that interpreted by a trained operator, often with the aid of analysis software, to locate and categorize flaws in test pieces. High-frequency sound reflects from flaws in predictable ways, producing distinctive echo patterns corresponding to the echo response from good parts and from representative flaws. The echo pattern from a test piece may then be compared to the patterns from these calibration standards to determine its condition.

Detection of cracks

Figure 11: Cracks detection in metallic components using ultrasound

3.9.4 ECHOCARDIOGRAPHY

In the process of electrocardiography, the ultrasonic waves are used to form an image of the heart using reflection and detection of these waves from various parts.

3.9.5 ULTRA SONOGRAPHY:

Medical ultrasound is a diagnostic imaging technique based on ultrasound. It is used for the imaging of the internal body structures such as muscles, joints, and internal organs. Ultrasonic images are known as sonograms. In this process, pulses of ultrasound are sent to the tissue using a probe. The sound echoes the off the tissue where different tissues reflect sound varying in degrees. These echoes are recorded and displayed an image.

3.9.6 LITHOTRIPSY:

Ultrasonic waves are used to break stones in kidney. High energy sound waves are passed through the body without injuring it and break the stone into small pieces. These pieces of small stone move through the urinary tract and out of the body more easily than a large stone.

3.9.7 SONAR:

Sonar, sound navigate, and Ranging is a technique in which sound waves are used waves to navigate, detect, and communicate under the surface of water.

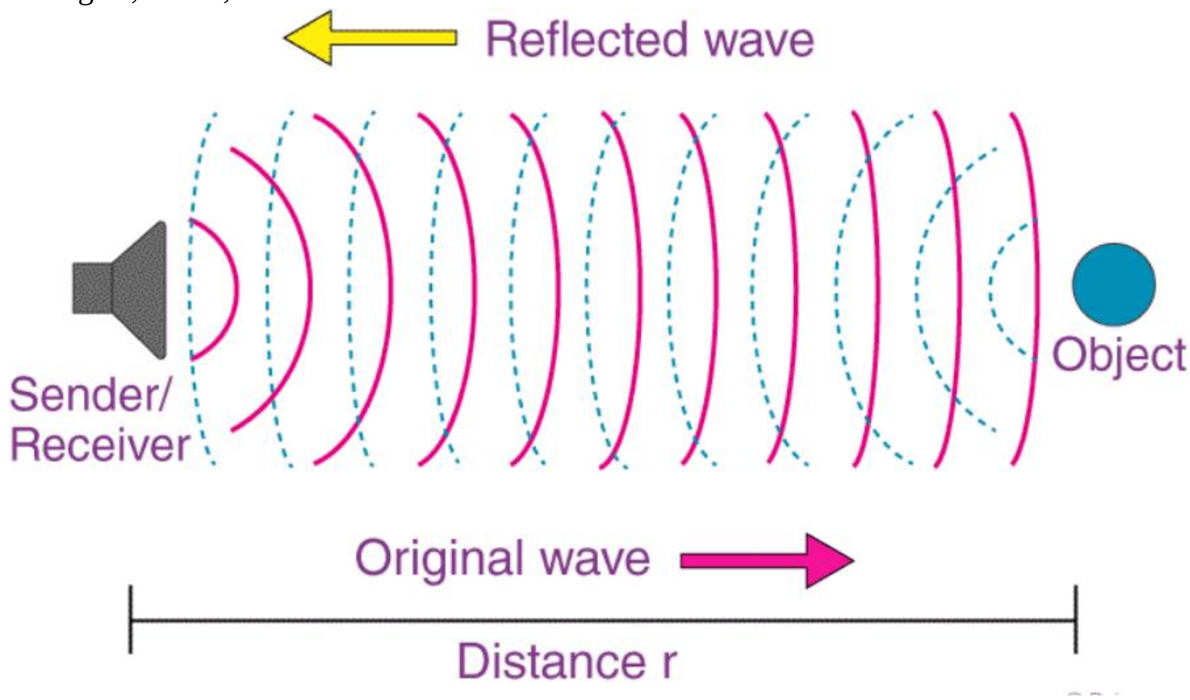


Figure 12: Sonar Sound Navigator

3.9.8 ECHOLOCATION:

Echolocation is the process where sound waves and echoes are used to determine the objects in space. Echolocation is used by bats to navigate and find their food in the dark. Bats send out sound waves from their mouth and nose, which then hit the objects in their vicinity producing echoes which are received by the bats. The nature of the echo helps them determine the size, the shape, and the distance of the object.

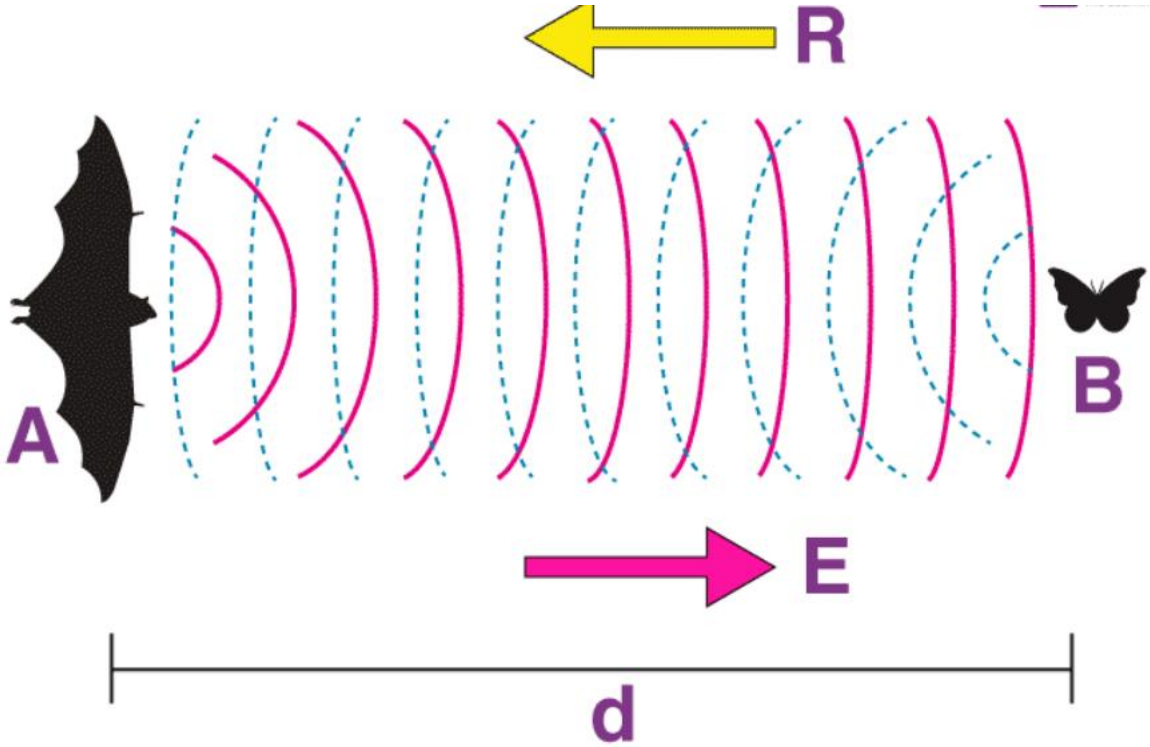


Figure 13: Echolocation

3.10 CLEANING MECHANISM OF ULTRASONIC WAVES

The advantageous result of ultrasound cleaning has been used in numerous applications for quite some time. There are two cleaning mechanism require to explain the cleaning effect of ultrasound, acoustic streaming, and acoustic cavitation (Venkitaraman et al., 1995). In cavitation process, micron-size bubbles form and grow due to alternating positive and negative pressure waves in a solution. The bubbles subjected to these alternating pressure waves continue to grow until they reach resonant size. Just prior to the bubble 17 implosion (Figure 14), there has been a tremendous amount of energy stored inside the bubble itself.

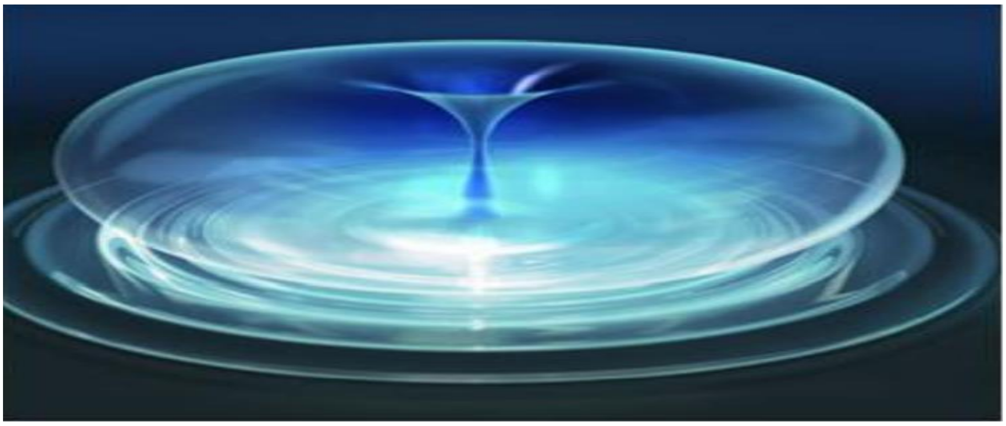


Figure 14: Cavitating Bubble

The temperature inside a cavitating bubble can be extremely high, with pressures up to 500 ATM. The implosion event, when it occurs near a hard surface, changes the bubble into a jet about one-tenth the bubble size, which travels at speeds up to 400 km/hr toward the hard surface. With the combination of pressure, temperature, and velocity, the jet frees contaminants from their bonds with the substrate. Because of the inherently small size of the jet and the relatively large energy, ultrasonic cleaning can reach into small crevices and remove entrapped deposits very effectively. Acoustic streaming is when steady rotational flow is occurring because of the interaction of acoustic waves with physical inhomogeneities in a fluid, such as smooth boundaries and solid particles. Fluid agitation caused by acoustic streaming is not as violent as the one caused by cavitation, but streaming is highly effective for liberating particles attached to the surfaces. However, it is believed that for reservoir formation, cavitation induces further damage to porous medium. Thus, the frequency and power of the ultrasonic wave must be maintained at a level which cavitation does not occur and the primary physical removal mechanism is acoustic streaming. From studies conducted by (Gollapudi et al., 1994), the removal of asphaltenes damage near wellbore is happen when a sound wave passing through viscous crude oil and creates a vibration pattern that set the liquid in motion. The ultrasonic vibration patterns form crude oil molecule layers that stretch, compress, bend, and relax. Interacting layers generate tiny vacuum spaces called cavitation within the liquid. Imploding cavitation scrub part surfaces and pull away foreign materials. The study has concluded that the use of ultrasound wave is a promising and potentially useful since it can be extended to high pressure range wave.

3.11 REGENERATION TECHNIQUES

Since it is difficult to discover new places for well structures and the economic outlay for a new well is no longer insignificant (Wolfgang Bott et al., 2003), maintaining the well overall performance through regeneration measures is of particular importance. Now, often mechanical, and chemical as well as combined cleansing techniques are used (DVGW, 2001; E & F.N. Spon, 1990; R. D. , & B. W. Wilken, 2002; Wolfgang Bott et al., 2003).

Brushes (as pre-cleaning)
Pumping out (as pre-cleaning)
Intensive removal (e.g., intensive de-sanding in sections,) Flask
Injection with CO_2 (gaseous and liquid)
low-pressure water flushing
High pressure water flush
Pressure wave / impulse method, generated by
- High water pressure
- Impulses (e.g., oxyhydrogen, water or air compression, explosive charges)
- Ultrasonic

Mechanical cleaning is primarily based on the impact of high shear forces in the medium. Using brush and high-pressure cleansing systems, deposited materials that have not completely hardened are loosened and then pumped out with the groundwater (DVGW 2001). In a subsequent separation stage, the groundwater loaded with solids is separated. The period of the mechanical regeneration can differ depending on the well depth and Degree of wall coverings on the filter pipes take several days. The risks of this method are regularly damage to the well pipes, the relocation of the filter grain and the compaction of the dust particles in the pore cavities of the gravel packing (BÄCHLE, 1992).

In most cases, mechanical cleansing is followed by chemical cleaning. According to DVGW (2001), the following regenerants are typically used:

Inorganic (acid) mixtures
Organic (acid) mixtures
Combination of inorganic and organic mixtures

These chemical methods (50% share) are subject to a unique permit under water law. The acids are fed to the well till a pH value of approx. 1 is established (Normann-Schmidt S., 1992). After an exposure time of up to forty-eight (48) hours, the acidic groundwater with the deposits dissolved in it is pumped out and should then be disposed of or dealt with in an environmentally pleasant manner.

Both types of technique are characterized by a long downtime of the well and a massive amount of groundwater that must be pumped out. The ultrasound method, which in accordance with DVGW (2001) is counted amongst the mechanical processes, represents an alternative method of cleaning well. Numerous practical applications on a few hundred wells have proven that this treatment can be used to obtain desirable cleaning results. The primary advantage of ultrasonic regeneration is that there are no hazardous chemical substances in the groundwater and that the well pipe and the filter gravel are spared. In addition, there is a doable time saving and as a result shortened downtime of the wells due to the removal of exposure times for chemical cleaning agents and the reduction of manual cleansing work (Allen, 1995). Overall, one can talk of a specially environmentally friendly method (BERLITZ, 1997).

4.1 METHODS OF EVALUATION OF PUMPING TEST

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

4.1.1 PUMPING TEST FOR STEADY-STATE FLOW

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

4.1.2 CONFINED AQUIFERS –THIEM ANALYSIS

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

a) The aquifer is confined from both sides (up and down).

b) The aquifer has infinite aerial extent. Cone of depression does not increase (decrease) with time.
c) The aquifer is homogeneous, isotropic and of uniform thickness.
d) The piezometric surface is horizontal prior to pumping.
e) Water flows radially towards well.
f) Darcy's law is valid.
g) The groundwater level changes due to only pumping.
h) The density and the viscosity of groundwater do not change in space and time.
I) The aquifer is pumped at a constant discharge rate.
j) The well penetrates the full thickness of an aquifer and thus, receives water by horizontal flow (see Figure 15)

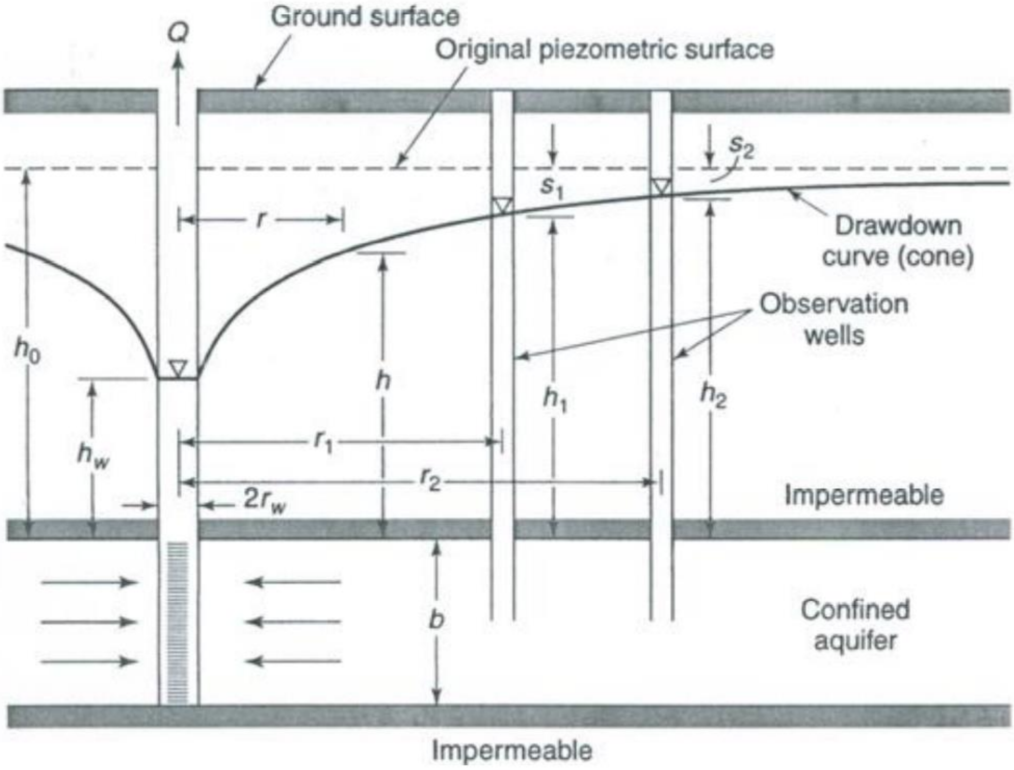


Figure 15: Cross-section of a pumped confined aquifer (Wilson, 2007) & (Todd David Keith, 1980).

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

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

$A = 2\pi r$b

Darcy's Law v_r = -K$\frac{\partial h}{\partial r}$ (4.2)

From the equation 4.1 and 4.2

$$Q = -2\pi K b \frac{\partial h}{\partial r}$$

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

Rearranging the equations while considering two observation wells with hydraulic head of h_1 and h_2 at distance of r_1 and r_2 from pumping well (Figure 15).

$$\frac{Q}{2\pi Kb}\int_{r_1}^{r_2}\frac{1}{r}dr = \int_{h_1}^{h_2}dh \quad (4.3)$$

$$h_2 - h_1 = \frac{Q}{2\pi Kb}ln\frac{r_2}{r_1} \quad (4.4)$$

$$S_1 - S_2 = \frac{Q}{2\pi kb}ln\frac{r_2}{r_1} \quad (4.5)$$

$$T = Kb = \frac{Q}{2\pi(S_1 - S_2)}ln\frac{r_2}{r_1} \quad (4.6)$$

Where, s_1 and s_2 are drawdowns and T is the transmissivity.
Thiem equation at equilibrium shows that the drawdown varies with logarithm of the distance from the pumping well to the observation well.

4.1.3 UNCONFINED AQUIFERS
An aquifer of water is bounded with impermeable or an aquiclude at the bottom is known as the unconfined aquifer. The conditions and the assumptions for an unconfined aquifer are as follows:
a) The well penetrates the full thickness of the aquifer and thus receives water from the entire saturated thickness of the aquifer (seen in Figure 16)
b) The aquifer has the infinite aerial extent
c) The aquifer is a homogeneous, and isotropic and consists of uniform thickness
d) The water table is horizontal prior to pumping, e) An aquifer is pumped at the constant discharge rate

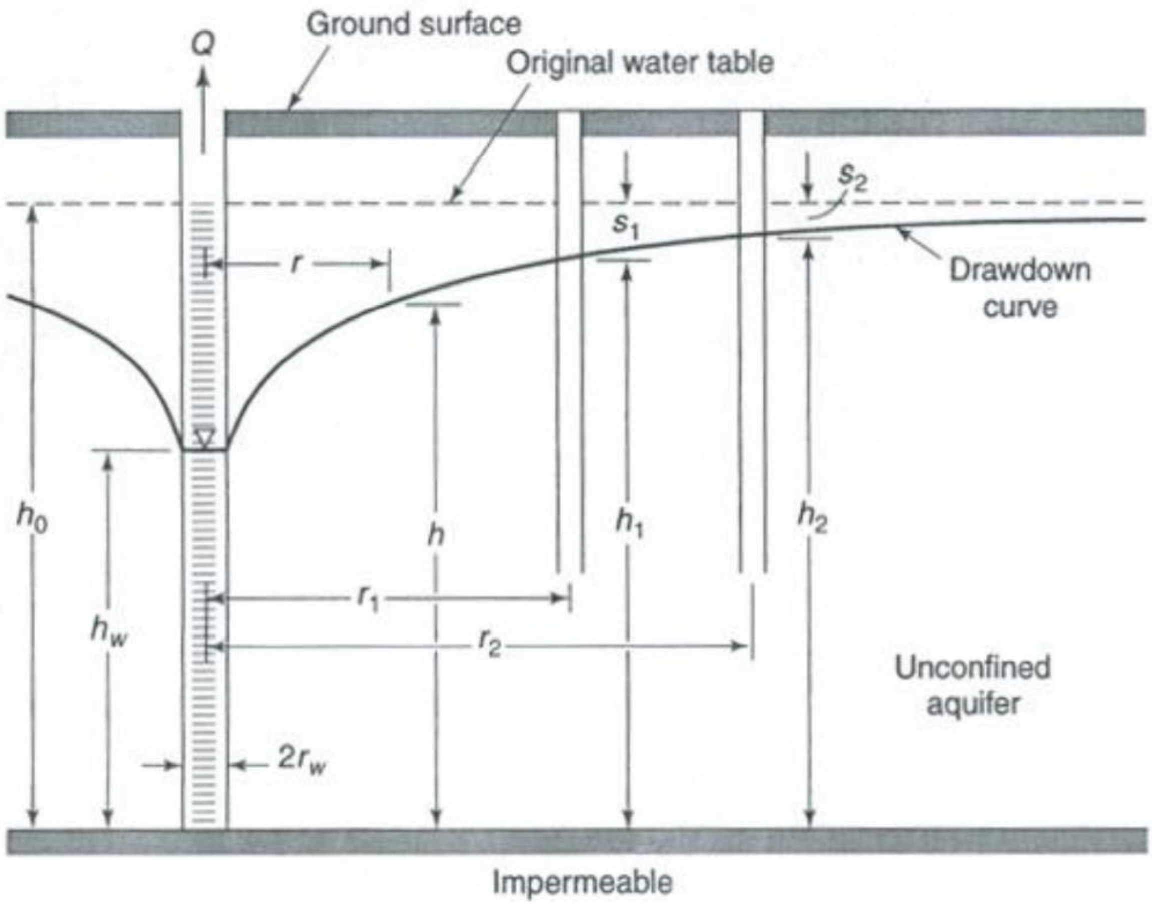


Figure 16: Cross-section of a pumped unconfined aquifer (steady-state flow) (Wilson, 2007) & (Todd David Keith, 1980).

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

Continuity Equation $Q = v_r \cdot A$

Darcy's Law $v = -k\frac{\partial h}{\partial r}$

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

Rearranging the equations

$$\frac{Q}{2\pi Kb}\int_{r_1}^{r_2}\frac{1}{r}dr = \int_{h_1}^{h_2}dh \qquad (4.7)$$

$$h_2^2 - h_1^2 = \frac{Q}{2\pi Kb}ln\frac{r_2}{r_1} \qquad (4.8)$$

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

4.1.4 Pumping Test for Unsteady-State flow

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

4.1.5 CONFINED AQUIFER- THEIS METHOD (UNSTEADY-STATE FLOW)

Water is pumped out at the constant rate through a well that penetrates an extensive confined aquifer, and the radius of impact grows over time due to discharge. The general equation of an unsteady-state flow for a confined aquifer (Mutreja, 1986):

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

Where S is the storativity, T is the transmissivity and h are hydraulic head.
The differential equation can be re-written as

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{y^2} + \frac{\partial^2 h}{z^2} = \frac{S}{Kb}\frac{\partial h}{\partial t} \qquad (4.10)$$

Polar coordinates for plane are reduced to.

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (4.11)$$

Where T is transmissivity, t is the time since pumping starts, b is the thickness of confined aquifer, K is hydraulic conductivity and S is the storage coefficient. Theis presented solution of the equation 4.11 as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial h}{\partial r}\right) = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (4.12)$$

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

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial s}{\partial r}\right) = \frac{S}{T}\frac{\partial s}{\partial t} \qquad (4.13)$$

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

$$s(r,t) = \frac{Q}{4\,\pi T}\int_{u}^{\infty} \frac{e^{-u}}{u}\, du \qquad (4.14)$$

The integral in the equation 4.14 is known as well function and can be re-written as:

$$W(u) = \int_{u}^{\infty} \frac{e^{-u}}{u}\, du \qquad (4.15)$$

$$u = \frac{r^2 S}{4\,T\,t} \qquad (4.16)$$

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

$\log S = \log[W(u)] + \log(\frac{Q}{4\pi T})$

$\log t = \log\frac{1}{u} + \log\frac{r^2 S}{4T}$

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

a) The potentiometric surface is approximately horizontal before pumping begins (No slope).
b) Darcy's equation is valid
c) Storativity (S) and Transmissivity (T) are constant in time and space.
d) The aquifer is a confined.
e) The aquifer is a homogeneous and an isotropic of uniform thickness over the area influenced by pumping.
f) The well is pumped at a constant rate,
g) The well is fully penetrating in a confined aquifer.
h) Water removed from storage is discharged instantaneously with decline in head.
i) The well diameter is small so that well storage is negligible.

The Data Required for the Theis Solution are

a) The drawdown vs. time data at an observation well.
b) Distance from the pumping well to an observation well.
c) The pumping rate of the well.

The procedure for finding parameters by Theis Method.

a) On log-log paper, plot a graph of values of SW against t measured during the pumping test.
b) Theoretical curve W(u) versus 1/u is plotted on a log-log paper. This can be done by using tabulated values of the well function. The ready printed type curves are also available (as seen Figure 15).
c) The field measurements are similarly plotted on a log-log plot with (t) along the xaxis and (sw) along the y-axis (see Figure 18).
d) Keeping the axes correctly aligned, superimposed the type of curve on the plot of the data (i.e. The data analysis is done by matching the observed data to the type curve).

e) Select any convenient point on the graph paper (a match point) and read off the coordinates of the point on both sets of axes. This gives coordinates (1/u, W(u)) and (t, sw) (see Figure 19).
f) Use the previous equations to determine T and S.
The points on the data plot corresponding to early times are the least reliable.
N.B. The match point does not have to be on the type of curve. In fact, calculations are greatly simplified if the point is chosen where W(u) = 1 and 1/u=10.

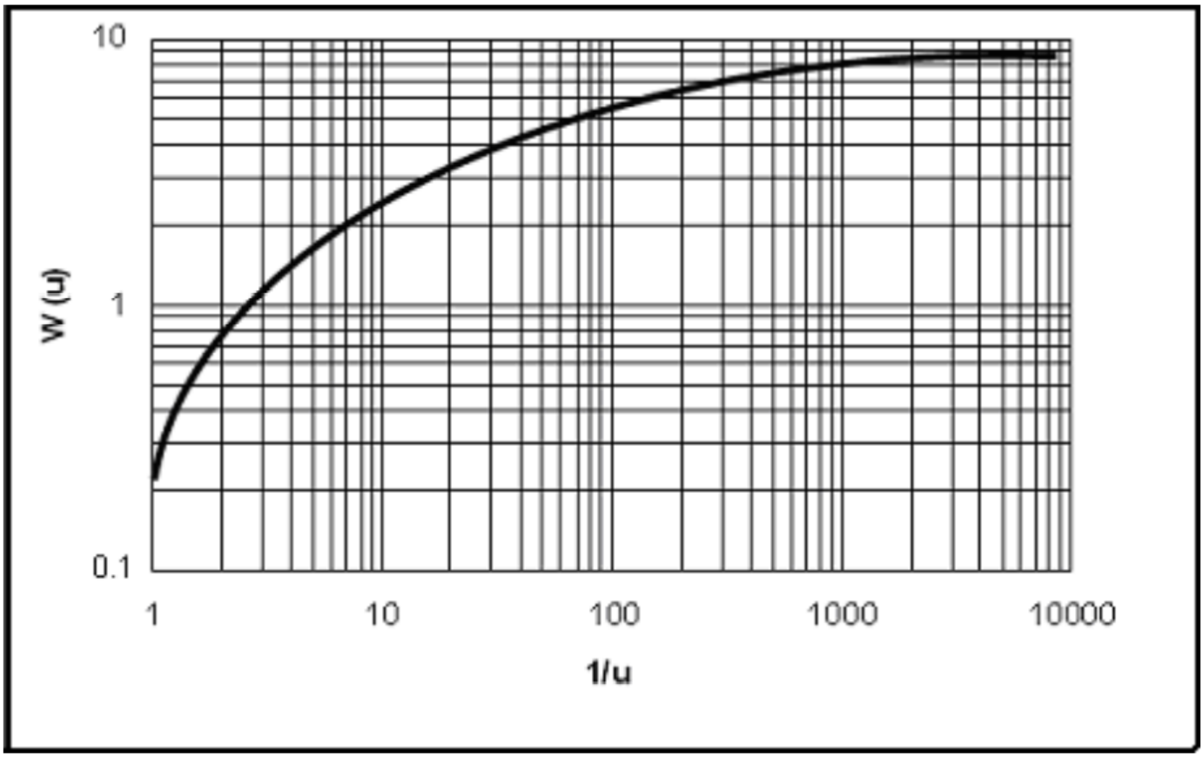


Figure 17: The non-equilibrium reverse type curve (Theis curve) for a fully confined aquifer

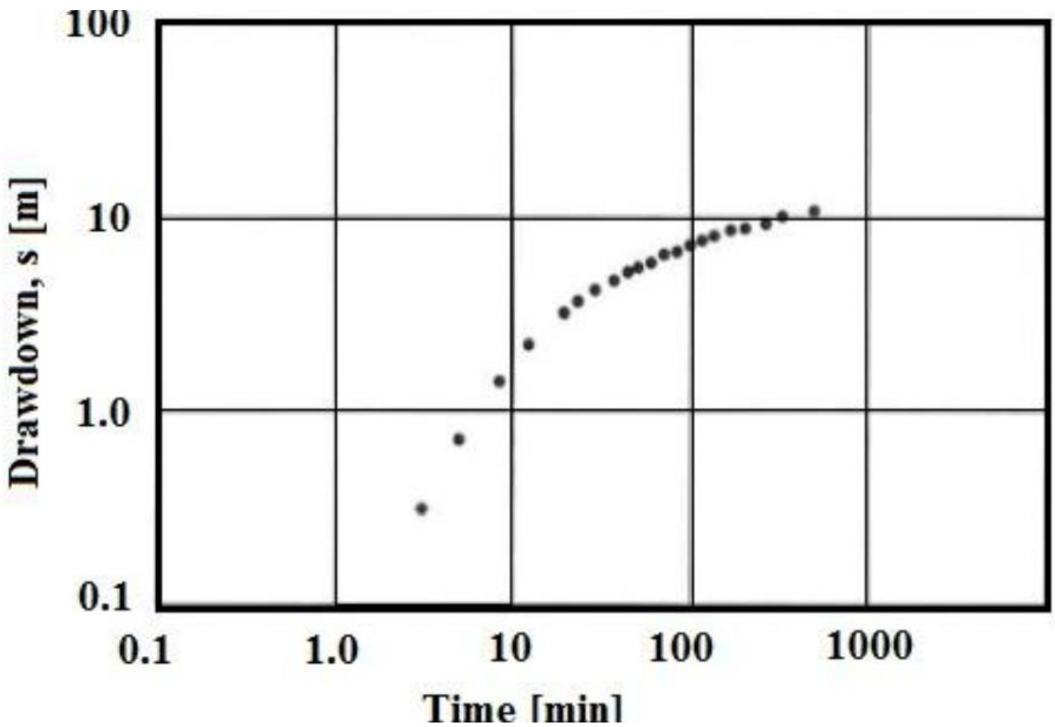


Figure 18: Field data plotted on logarithmic paper for Theis curve-marching technique.

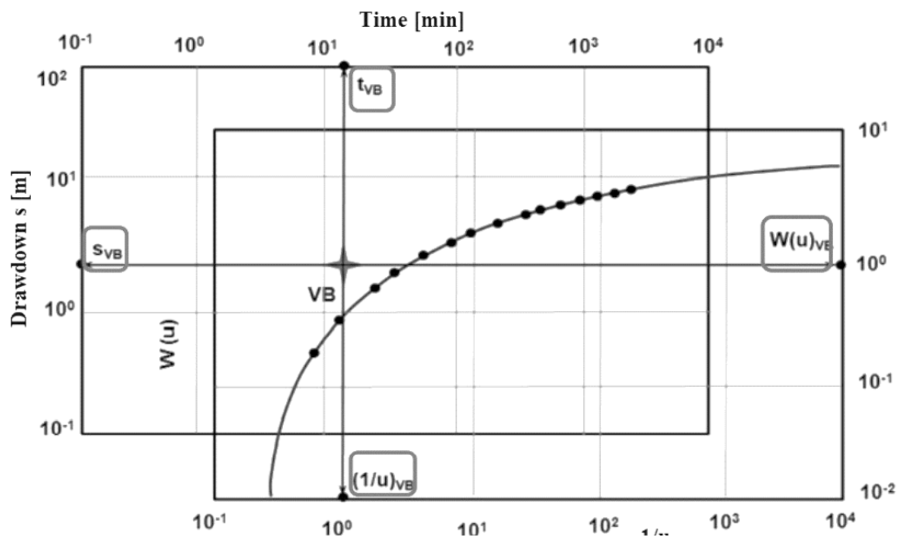


Figure 19: Match of field data plot to Theis Type curve.

The transmissivity (T) and the storativity (S) can be estimated as shown from the equations below using figure 19.

$$T = \frac{Q}{4\pi\, Ts_{VB}} W(u)_{VB} \qquad (4.17)$$

$$S = \frac{4T\, u_{VB}\, t_{VB}}{r^2} \qquad (4.18)$$

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

4.1.6 CONFINED AQUIFER- JACOB METHOD (UNSTEADY-STATE FLOW).

The Theis method is criticised due to subjective procedure for evaluation of aquifer characteristics. The Jacob method is consistent and calculate T and S for pumping well by one observation well (van Everdingen, 1953). The analysis presented here is of a pumping test in which drawdown at a piezometer distance, r from the abstraction well is monitored over time. This is also based upon the Theis analysis. W(u) (equation 4.15) can be expressed by Taylor's series expansion:

$$W(u) = -0.577 - ln\, u + u - \frac{u^2}{2.2!} + \frac{u^2}{3.3!} + \cdots$$
(4.19)

$$s = \frac{Q}{4\pi T} W(u) = \frac{Q}{4\pi T}\left(-0.577 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \cdots\right)$$
(4.20)

From $u = \frac{r^2 S}{4Tt}$, it will be seen that u decreases ($u \leq 0.01$) as the time of pumping increases and as the distance of the piezometer from the well decreases. So, for piezometers close to the pumping well after sufficiently long pumping times, the terms beyond $\ln u$ become negligible. Hence for small values of u, the drawdown from equation 4.20 can be approximated by:

$$h_o - h_1 = s = \frac{Q}{4\pi T} \ln \frac{0{,}562}{u} = \frac{Q}{4\pi T} \ln\left(\frac{2.25T}{Sr^2} t\right) \quad (4.21)$$

The equation 4.18 has transmissivity (T) at multiple location so that transmissivity (T) can be derived though manipulation of equation 4.21. Thus, drawdown s vs t on log graph gives straight line (Figure 20 with drawdown (m) and time (s))

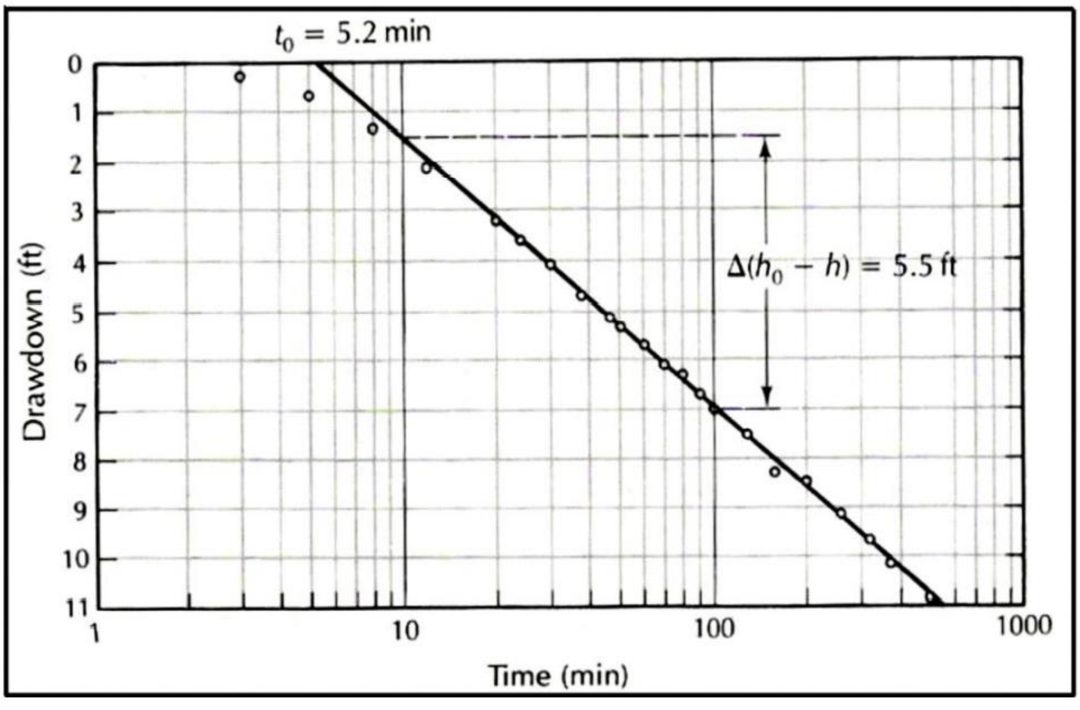


Figure 20: Jacob method of solution of pumping-test data for a fully confined aquifer. Drawdown is plotted as a function of time on semi-logarithmic paper.

The slope of this semi-log graph (Figure 20) will give head difference over logarithmic time. The equation 4.19 is line equation and the slope of build-up semi log graph is expressed in the square brackets:

$$s = \frac{2.3Q}{4\pi T}[\log t + \log(\frac{2.25T}{Sr^2})] \quad (4.22)$$

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

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

$$s_1 = \frac{Q}{4\pi T}\ln\frac{2.25T}{r_1^2 S}t_1 = \frac{Q}{4\pi T}\ln t_1 + \frac{Q}{4\pi T}\ln\frac{2.25T}{r_1^2 S} \quad (4.23a)$$

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

$$s_2 = \frac{Q}{4\pi T}\ln\frac{2.25T}{r_2^2 S}t_2 = \frac{Q}{4\pi T}\ln t_2 + \frac{Q}{4\pi T}\ln\frac{2.25T}{r_2^2 S} \quad (4.23b)$$

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

$$\Delta s = s_1 - s_2 = \frac{Q}{4\pi T}\ln\frac{t_1}{t_2} \quad (4.24)$$

$$\Delta s = s_1 - s_2 = \frac{2.3Q}{4\pi T}\log\frac{t_1}{t_2} \quad (4.25)$$

Note: Jacob method is valid for $u \leq 0.05$ or 0.01, t is large, r is small. It follows that a plot of s against log t should be a straight line (see Figure 20). Extending this line to where it crosses that t axis (i.e., where s is zero and $t = t_o$) gives

$$S = \frac{2.25T}{r^2}t_o \quad (4.26)$$

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

$$\Delta S = \frac{2.3Q}{4\pi T} = \frac{0.183Q}{T} \quad \Rightarrow T = \frac{0.183Q}{\Delta S} \quad (4.27)$$

At first T is calculated (Equation 4.27) then s can be calculated from the equation (4.26) by using T and t_0

4.1.7 ADDITIONAL RESISTANCES (SKIN EFFECT)

Reduction of the water level in the "real" well (ie in the case where we consider the existence of additional resistances on the pumped well and its immediate surroundings) depends on the resistance of the porous environment saturated with water, viscosity and additional losses in the well, its walls and near around the well.

Additional resistance refers to the sum of the phenomena that result in deviations of the measured values of water drawdown in a “real” well compared to the theoretical drawdown obtained under the assumption of an “ideal” model of water flow to a complete well (Kahuda & Pech, 2020). In this case, the additional resistance and the actual borehole volume will not be reflected in the course of the inflow test (i.e., the reduction in this volume is not affected). The drawdown in the water level (or increase) measured at the pumping well (or recharge well) is greater than the calculated drawdown (or increase) in the borehole, which would cause a hydraulic intervention through a hydraulically perfect well without this additional resistance.

Additional resistance in the well and its surroundings increases in the following ways (Houben, 2007)**:**

(a) By the clogging of pores (s_1) with, e.g., a fine material, which reduces the flow rate of the porous environment or disrupts the original internal structure of the porous environment in the vicinity of the wellbore during digging and equipping (it decreases the porous environment's permeability) in rotary drilling, the result of which is so-called sludge bark; in the case of impact drilling, the porous environment in the vicinity of the well is compacted, thereby reducing throughput.

(b) Through a reduction in the wellbore wall cross-section (s_2) for the water inflow where the borehole wall is formed by a filter, perforated casing, etc., by trapping rock particles or backfill in filter openings, including chemical incrustation and the blockage of filter openings by microorganisms and bacteria (Ralph & Stevenson, 1995) **&** (Patel & Singh, 2016).

(c) Via the friction (s_3) of water on the borehole walls and its internal friction (this group also includes the additional resistance arising from the turbulent flow regime of the water inside the borehole and the turbulent flow in the aquifer, especially in the vicinity of the pumping well.

(d) Where appropriate, other types of additional resistance occur (s_n).

The drawdown because of additional resistance is expressed (Figure 21 seen below) as:

$$s_{skin} = s_1 + s_2 + s_3 \dots\dots\dots + s_n,\ then\ s_{skin} = \sum_{i=1}^{n} s_i \qquad (4.28\ )$$

where S_{skin} is the total additional drawdown in the well ("the skin drawdown") caused by the additional resistance in the well and its immediate vicinity (called skin zone). The separation of the individual additional types of resistance involved in the skin effect is very difficult; therefore, the total dimensionless additional resistance coefficient, W (in the petroleum literature, referred to as the skin factor), is commonly used to express the total additional resistance. The total drawdown of the water level measured in the borehole during the pumping test can be expressed (when neglecting the additional resistance resulting from the turbulent flow regime) by the relation:

$$s_w = s_{te} + s_{skin} \qquad (\ 4.29)$$

where s_w is the total drawdown in the pumping well [m]; s_{te} is the theoretical drawdown of the water level in an "ideal" well (zero additional resistances) [m]; and S_{skin} is the additional drawdown of water in the wellbore due to additional resistance [m].

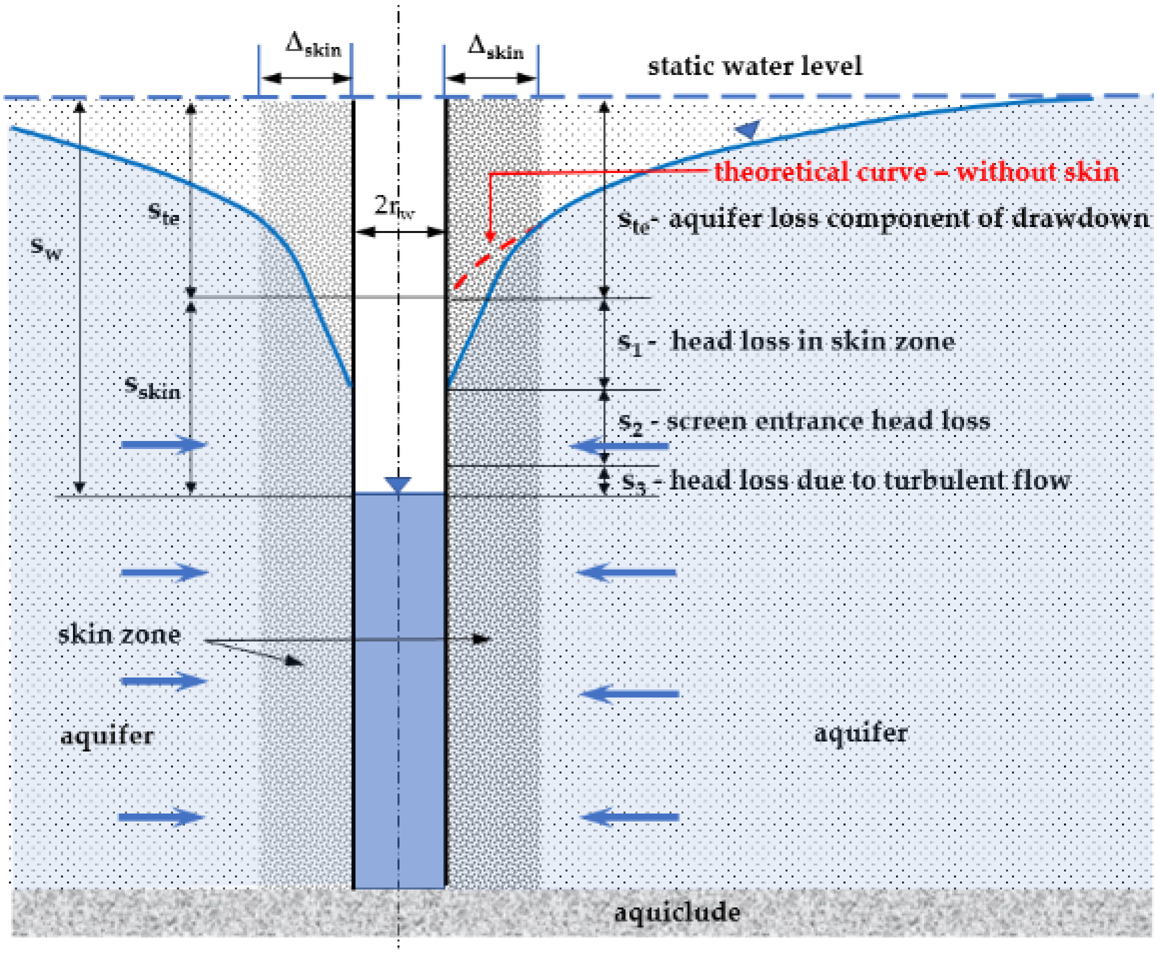


Figure 21: Various head losses in a pumped Real well.

Neglecting the portion of the drawdown that follows from the turbulent flow regime, s_3 (its share in the total additional drawdown is negligible), the magnitude of the additional drawdown caused by additional resistance is dependent on the pumping rate, Q, with the linear relationship (van Everdingen, 1953).

$$s_{skin} = \frac{Q}{2\pi T} W \qquad (4.30)$$

where W is the dimensionless coefficient of additional resistance (skin factor) [–]; and s_{skin} is the drawdown caused by additional resistance [m]. The effect of additional resistance will be included in the total drawdown on the "real" "real" well when the flow is at a tight level.

(a) For the steady flow (van Everdingen, 1953),

$$s_w = \frac{Q}{2\pi T} (\ln \frac{R}{r_w} + W) \qquad (4.31)$$

where R is the radius of well influence [m]; r_w is the wellbore radius [m]; and W is the coefficient of additional resistance (skin factor) [–].

(b) The unsteady flow regime (using the Cooper–Jacob semi-logarithmic method because this part no longer shows the influence of wellbore storage) can be express as:

$$s_w = \frac{Q}{4\pi T} (\ln 2.246 t_D + 2W) \qquad (4.32)$$

After converting the natural logarithm to a normal logarithm, we obtain the following equation:

$$s_w = \frac{2.303Q}{4\pi T}(\log(2.246t_D) + 2W) \qquad (4.33)$$

If the Cooper–Jacob semilogarithmic straight line is reached in the semilogarithmic graph of the pumping test, we can use Equation (4.33) to evaluate the coefficient of additional resistance. After expressing W and adjusting, we obtain:

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}(\log t + \log\frac{T}{{r_w}^2 S} + 0.8071) \qquad (4.34)$$

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

For steady flow $$s_w = \frac{Q}{2\pi T}(\ln\frac{R}{r_w} + W) \qquad (4.35)$$

For unsteady flow (Cooper Jacob analysis):

$$s_w = \frac{Q}{4\pi T}(ln\frac{2.25Tt}{r_w^2 s} + 2W) \qquad (4.36)$$

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

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

$$Additional\ Drawdown\ Difference = S_{skin\ before} - S_{skin\ after}$$
(4.37)

5. MATERIALS AND METHODS

This part talks about materials and methods use for the evaluation of the additional resistance (skin factor).

In the method for evaluating the coefficient of additional resistance (skin factor) from the early part of a pumping test, dimensionless parameters were used. Dimensionless parameters simplify the solution of hydrodynamic tests on wells by including parameters such as hydraulic conductivity, transmissivity, aquifer storage coefficient, time, well radius, etc. into the dimensionless parameters.

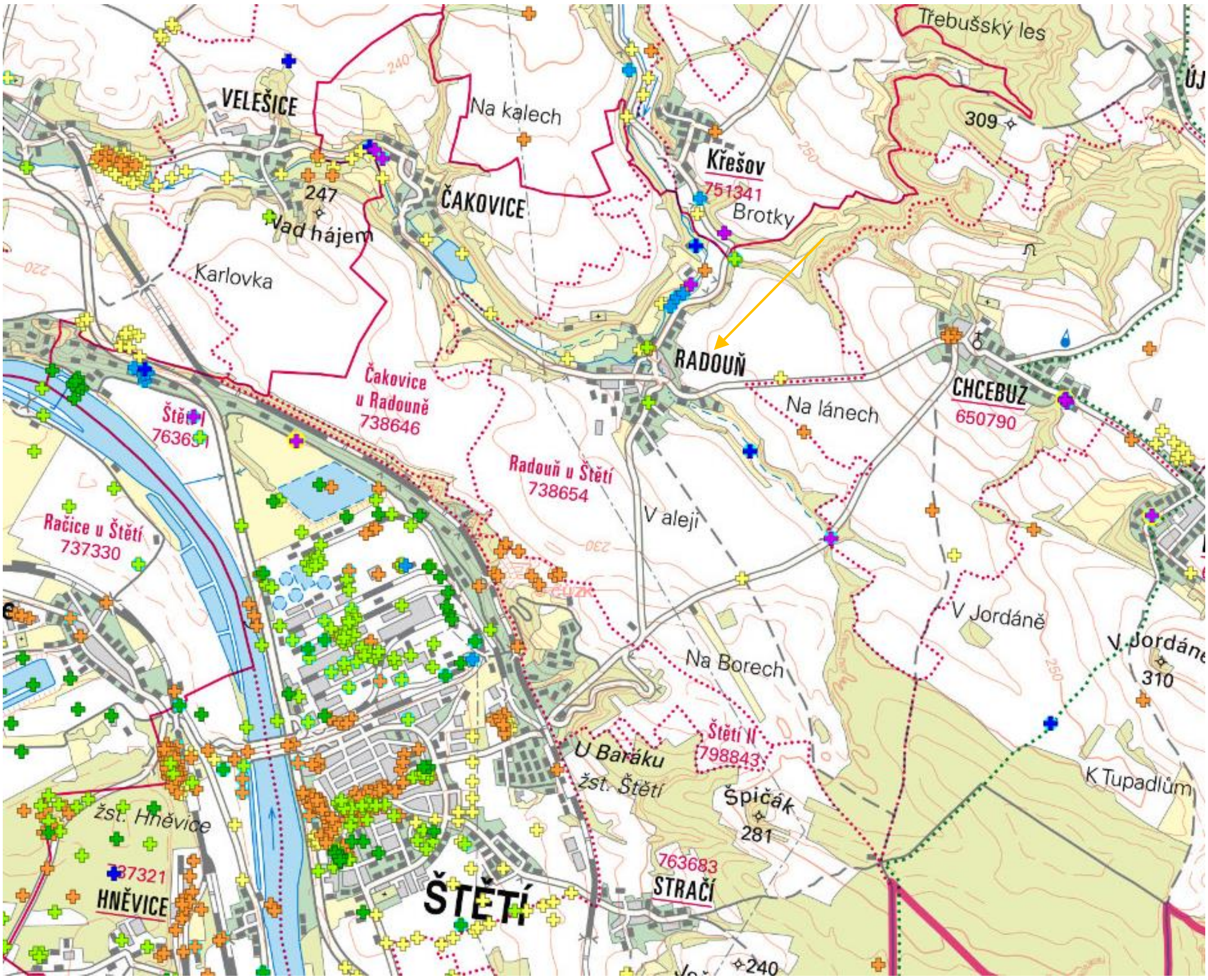
In the pumping well, each well is pumped out to observe the giving drawdown of hydraulic head at the pumping and perceive if any factor creates resistance to flow, a head-loss forms depression and creates hydraulic gradient to the occurred flow. This depression is known as cone of depression. The drawdown of a hydraulic head is used to describe the hydraulic characteristics of an aquifer including the storage coefficient or the storativity (S), hydraulic conductivity (K) and the transmissivity (T).

The storativity is the volume of water released at unit decline in a hydraulic head per unit area of a surface of the aquifer, the hydraulic conductivity is the rate of flow under unit hydraulic gradient and the transmissivity is the rate of flow at unit hydraulic gradient through unit width of cross-section of the aquifer. The pumping test depends on flow (steady state or unsteady state flow) of water and types of aquifers from which water is pumped.

5.1 AREA OF INTEREST

5.1.1 LOCATION OF THE WELL RD2

The map below shows the location of the well RD-2 in the Czech Republic



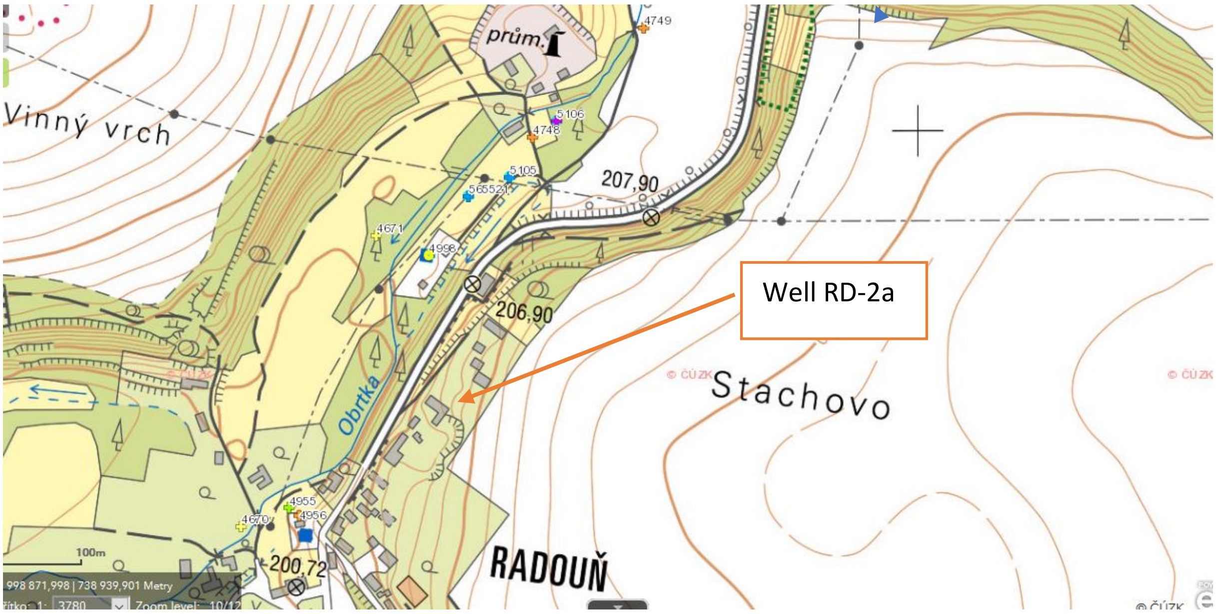


Figure 22: shows the drilling exploration map for well RD-2 in Czech Republic

Atributy	Odkazy
ID GDO	4998
Původní název	RD-2a
Druh objektu	vrt svislý
Hloubka	50
Souřadnice X	999125
Souřadnice Y	738487,5
Nadmořská výška	199
Zaměření vrtu	zaměřený
Zastižený kvartér	5
První hornina pod kvartérem	pískovec
Stratigrafie	Křída
Účel objektu	hydrogeologický
Rok	1975
Geologie	ano
Hmotná dokumentace	ne
Inklinometrie	ne
Hydrogeologie	ano
Karotáž	ne
list ZM 50	02-44
list ZM 25	02-441
list ZM 10	02-44-12

Figure 23: Show well RD-2 location.

5.1.2 Description of the location of Well_RD-2:

Well RD-2 is in the central part of northern Bohemia (Czech Republic) in the locality of the Radouň gas station, operated by a major regional water company. The location with 3 pumping wells represents one of several backbone waters sources in the regional drinking water supply, which provide the main urban and industrial water supply area between Mělník and Ústí nad Labem. Typical operating pumped quantities are very high - up to 55 m^3 / h. The RD-2 borehole is 50 m deep with plywood casing.

5.1.3 Geology and lithology:

The pumping station is in the lower part of the Czech Cretaceous basin in relatively shallow sandstone rocks of Letoman age. The groundwater level is severely limited (even in the presence of artesian wells) with an overlapping impermeable body consisting of Turonian saliva and marlite. The groundwater stream is strongly bound to cracks in the subsoil, which form a typical filtration environment with double porosity.

5.1.4 Well regeneration.

Due to doubts about the resistance of the plywood shell (or the durability of the specific resin to acids), rehabilitation techniques were limited to the mechanical pumping of sediments with limited cleaning using nylon brushes.

5.2.1 Location Map of Well KV2 and KV9

The map below shows the location of the well KV2 and KV9 in the Czech Republic

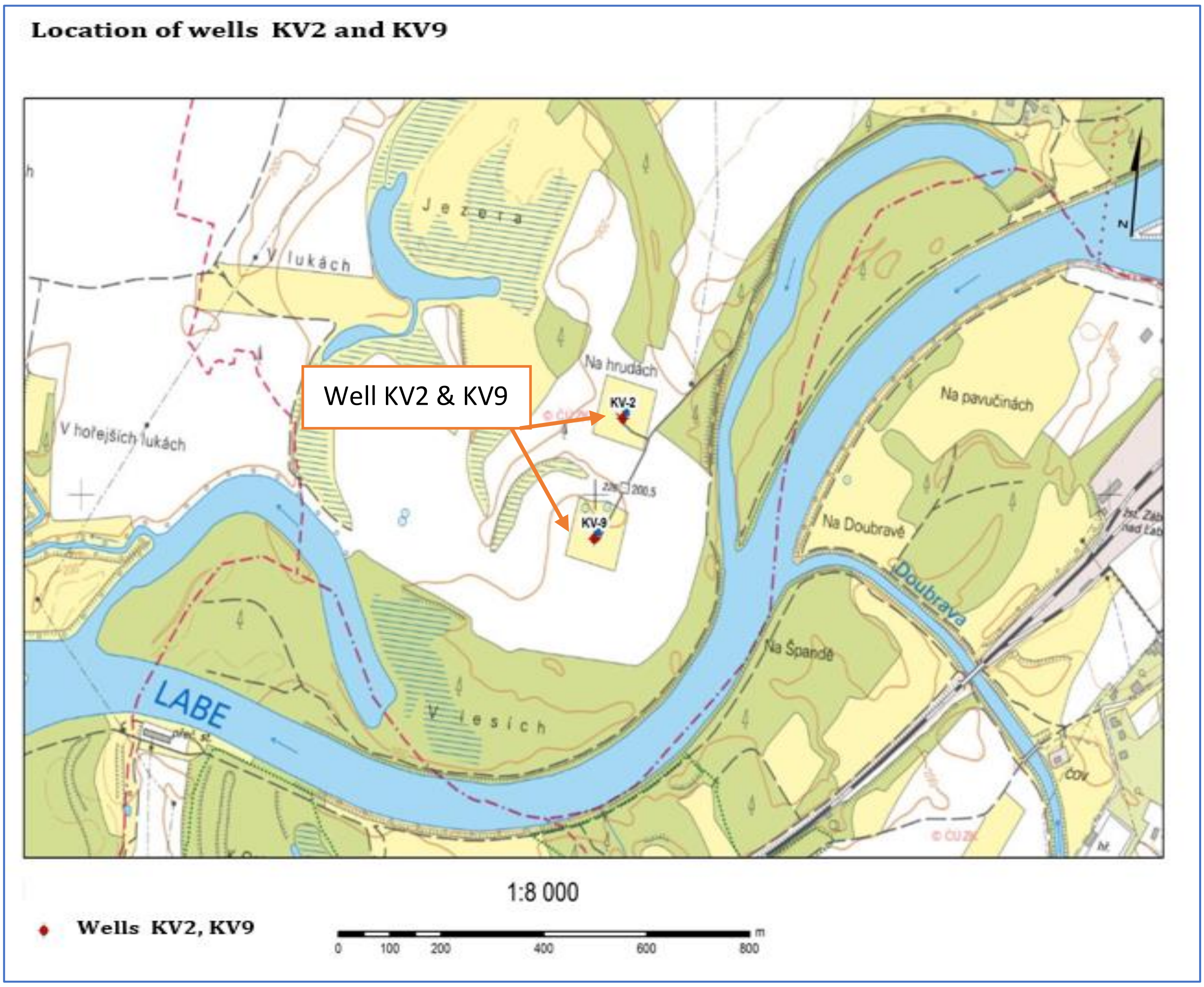


Figure 24: shows the map of well KV2 & KV9.

5.2.2 GEOMORPHOLOGICAL, HYDROGRAPHIC AND CLIMATE CONDITIONS of Well **KV2 and KV9**

The Žehušice basin forms the northwestern part of the Čáslav basin, specifically the lower tectonic depression near the Doubrava, Klejnárka and adjacent Elbe sections, which is characterized by a flat-to-flat hilly relief of Middle Pleistocene and Early Pleistocene terraces, wide floodplains.

The area of the locality of interest is drained in the S, V, slightly in the Z direction (the area is in the convex of the river) to the river Elbe. The hydrological sequence number is 1-04-01-0010-0-00.

From a climatic point of view (Quitt 1971), the locality of interest belongs to the moderately warm climatic area T-2, which is characterized as warm with a long and dry summer. The transition period is very short with warm to slightly warm spring and autumn. Winter is short, slightly warm, and dry to very dry, with a very short duration of snow cover. The average annual temperature is in the range of 8 - 9 ° C. The average annual rainfall is around 600 mm. The snow cover lasts 40 - 50 days a year.

5.2.3 GEOLOGICAL CONDITIONS

From the regional geological point of view, the locality of interest belongs to the Bohemian Massif. The subsoil of the investigated locality is formed by Turonian and sandy siltstones largely covered by Quaternary river and Eolithic sediments.

Quaternary sediments in the locality of interest are mainly represented by gravel sands, then by medium-grained sands with an admixture of clay particles, which occur mainly at the surface. According to archival geological profiles, the thickness of Quaternary sediments in the locality ranges from 14 to 15 m.

5.2.4 LOCATION OF INVESTIGATED WELLS

Boreholes KV2 and KV9 are in the convex bend of the river Elbe (see figure 24). Each of the boreholes is located inside its own fence with an area of approximately 100 m2 and an embankment with a handling shaft and a concrete booth with an established electric current is created above it. In addition, there is another well in each fence, which was used during the pumping test as an observation object (groundwater levels were measured in it). The observation object to the KV2 well is 7 m away, the observation object to the KV9 well is 46.7 m away.

5.2.5 PROFILES AND DESCRIPTION OF WELLS KV2 and KV9

Based on archival data, profiles of the examined wells were created (Figures No. 24). Both boreholes are drilled with a diameter of 1620 mm (up to 5 m deep), followed by a drilling diameter of 1350 mm, which continues to the bottom of the borehole. The backfill for both wells is double - the outer backfill has a fraction of 2-4 mm; the inner backfill has a fraction of 8-16 mm. Boreholes are areas of full equipment equipped with steel with an outer diameter. 426 mm. The perforated equipment area is equipped with an older version of UGI filters with an outer diameter of 360 mm. In addition, the KV-9 well was converted to a lower diameter in the past. However, information on this disguise was not available in the archive data. From the field survey it is evident that the KV-9 well was converted to steel equipment with an outer diameter. 225 mm.

5.3.1 WELL HV5 ULTRASONIC REGENETATION

5.3.2 **Location Map of well HV5**

The locality is in the cadastral area of Všetaty (district of Mělník, Central Bohemian Region). In 2021, the operator of the collection area begins work on the development of a well for reuse of water supply.

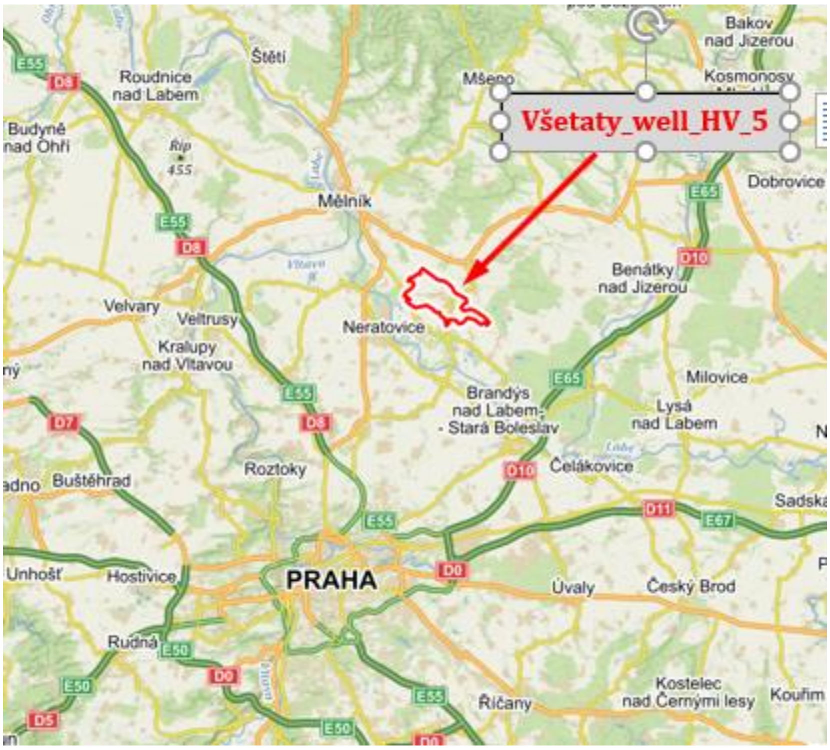


Figure 25: Map showing location of well HV5.

6. EVALUATION OF THE COLLECTED DATA (RESULTS)

In order to complement the assessment of pumping tests carried out as part of the project, the data from vrious wells that have been regenerated by using the traditional and ultrasonic methods were collected and evaluated. On the other hand, the interest on effectiveness and success can be derived from the basic well data on the ultrasound method.

The results were recorded at a constant Discharge (Q) in m^3/s and time (t) in seconds for pumping test before and after regeneration of the water wells. The additional resistace of the various water wells before and after regeneration were evaluated by suing the Slope and the Jacob methods. The results obtained from the two evaluation methods were also compared.

6.1.1 EVALUATION OF WELL_RD2 PUMPING TEST BEFORE REGENERATION

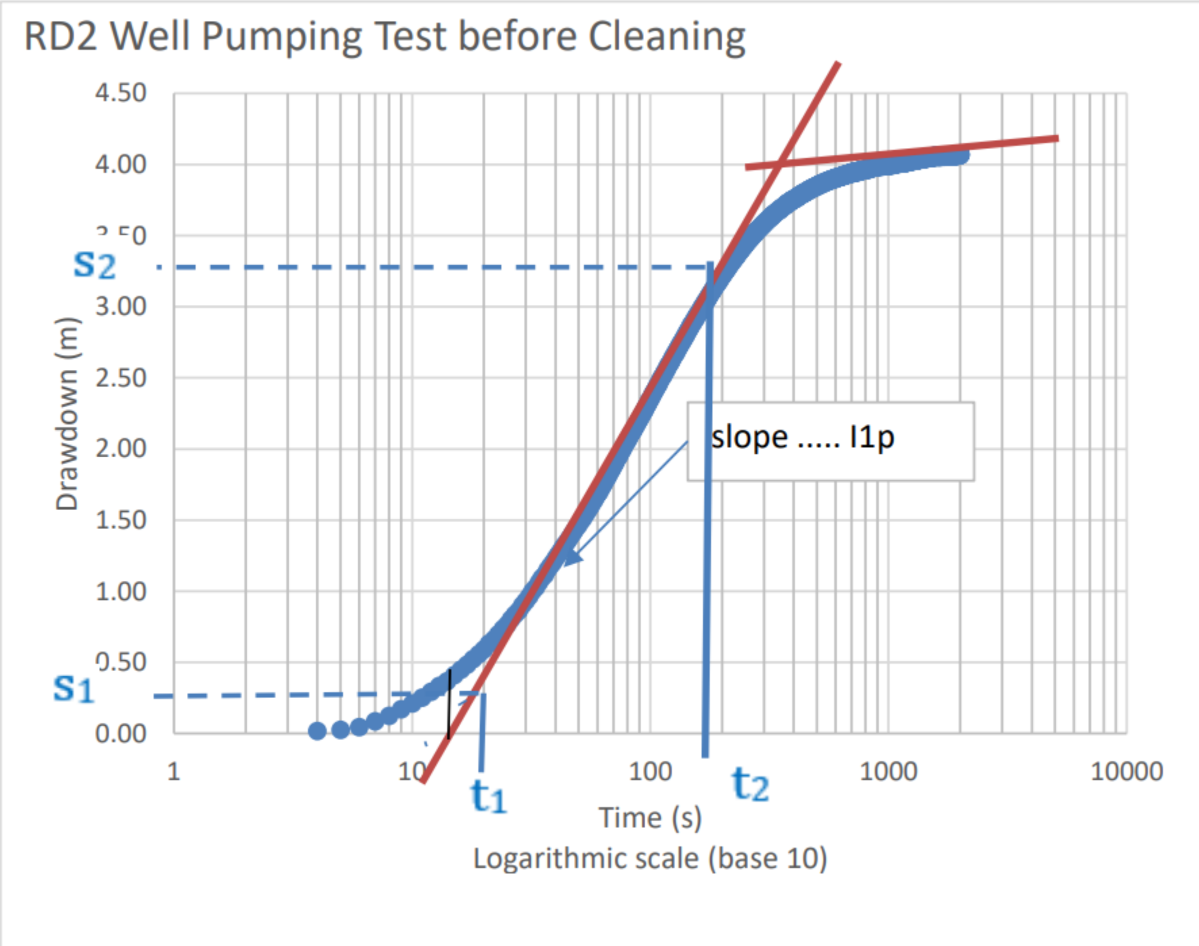


Figure 26: RD2 well graph for Pumping Test before Regeneration

1) Evaluation of Coefficient (C)

Discharge (Q) = 14.8 l/s = $\frac{14.8}{1000} = 0.0148\ m^3/s$

Transmisivity(T) = 0.00741 m^2/s

Radius of well (r_w)= 0.1500m

Storativity (S) = 0.04932 m^{-1}

$$C = Q\frac{t_i}{s_i} = 0.0148 * \left(\frac{10}{0.21}\right) = 0.70476\text{m}^2$$

$$C_D = \frac{C}{2\pi r_w{}^2 S} = \frac{0.70476}{2*\pi*0.15^2*0.04932} = 101.0776$$

$$slope(I_{1P}) = \frac{s_2 - s_1}{\log t_2 - \log t_1} = \frac{3.20-0.21}{\log(196)-\log(10)} = 2.3138$$ (see fig. 6.1 R2 well graph before regeneration)

2) Evaluation of skin factor, W for slope I_{1p}

Table 2 below shows the values obtained from the Well_RD2 pumping test before regeneration

Discharge, $Q(m^3/s)$	0.0148
Transmisivity, $T(m^2/s)$	0.00741
Storativity, S(-)	0.04932
Radius of well, $r_w(m)$	0.15
C_D[-]	101.0776

$$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right)$$

$$W = \frac{1}{0.86}\left(\frac{2*\pi*0.00741*2.3138}{0.0148} - 1.027 * \log(101.0776) - 1.0237\right) = 4.879$$

3) Evaluation of skin factor, W from Jacob method:

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\frac{2.246\, T\, t}{r_w^2 S}$$

For t = 1000s ….. s_W = 4m

$$W = \frac{2*\pi*0.00741*4}{0.0148} - \frac{1}{2} * \ln\left(\frac{2.246*0.00741*1000}{0.15^2*0.04932}\right) = 7.776$$

6.1.2 **EVALUATION OF WELL_RD2 PUMPING TEST AFTER REGENERATION**

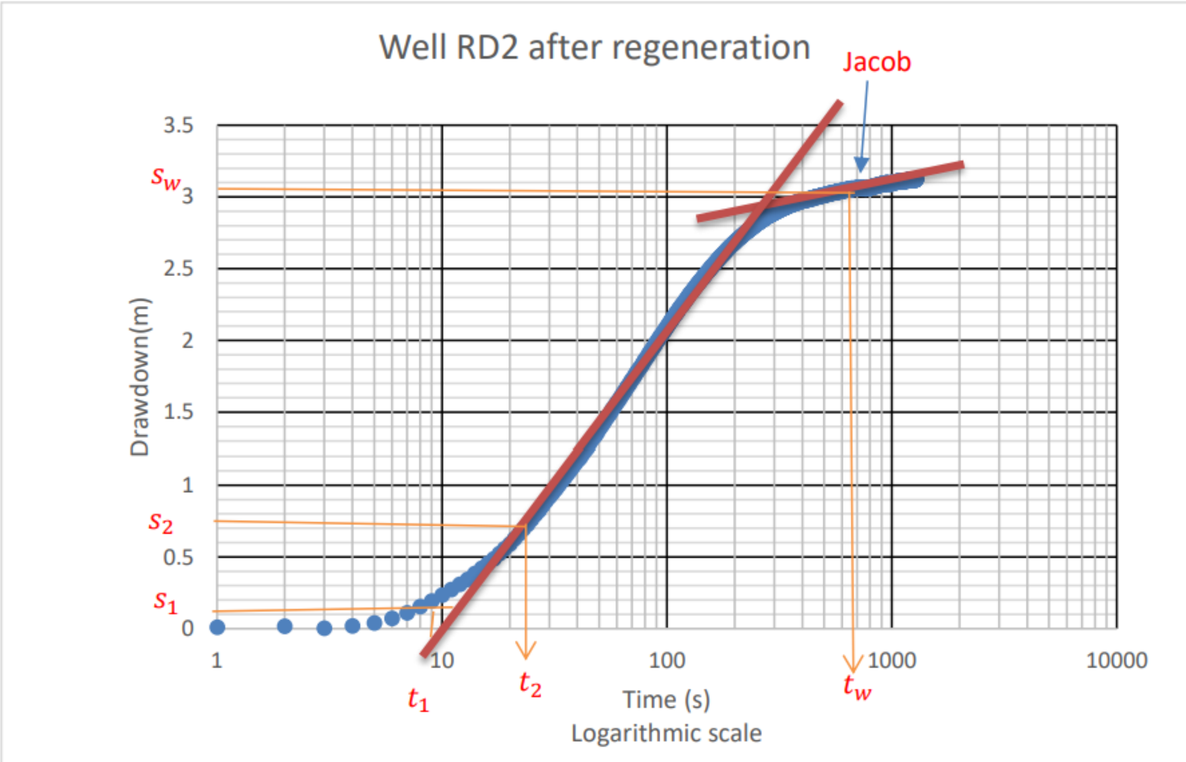


Figure 27: Well_RD2 pumping test graph After Regeneration.

1) **Evaluation of Coefficient (C)**

Discharge (Q) = 14.8 l/s = $\frac{14.8}{1000} = 0.0148\, m^3 s^{-1}$

Transmisivity(T) = $0.00741 m^2 s^{-1}$

Radius of well (r_w)= 0.1500m

Storativity (S) = 0.04932 m^{-1}

s_j = 0.074m, t_j= 6s

$C = Q\frac{t_i}{s_i} = 0.0148 * \left(\frac{6}{0.074}\right) = 1.269\text{m}^2$

$C_D = \frac{C}{2\pi r_w{}^2 S} = \frac{1.269}{2*\pi*0.15^2*0.00018} = 49851.707$

$slope(I_{1P}) = \frac{s_2 - s_1}{\log t_2 - \log t_1} = \frac{2.67-0.07}{\log(196)-\log(10)} = 2.6$

$\Delta s = s_2 - s_1 = 0.45 - 0.07 = 0.38m$

$T = 0.183\ \frac{Q}{\Delta s} = 0.183\ \frac{0.0148}{0.38} = 0.007127\ m^2 s^{-1}$

2) Evaluation of skin factor, W from slope I_{1p}

Table 3: below shows the values obtained from the Well_RD2 pumping test after regeneration

Discharge, Q(m^3/s)	0.0148
Transmisivity, T(m^2/s)	0.007127
Storativity, S(-)	0.00018
Radius of well, r_w(m)	0.15
C_D[-]	49851.707

$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027\log C_D - 1.0237\right)$

$W = \frac{1}{0.86}\left(\frac{2*\pi*0.007127*2.6}{0.0148} - 1.027*\log(49851.707) - 1.0237\right) = 2.348$

3) Evaluation of skin factor, W from Jacob method:

$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\left(\frac{2.246\ T\ t}{r_w^2 S}\right)$

For t = 700s ….. s_w = 3.06m

$W = \frac{2*\pi*0.007127*3.06}{0.0148} - \frac{1}{2}*\ln\left(\frac{2.246*0.007127*700}{0.15^2*0.00018}\right) = 1.84$

6.2.1 EVALUATION OF WELL_MO1 PUMPING TEST BEFORE REGENERATION.

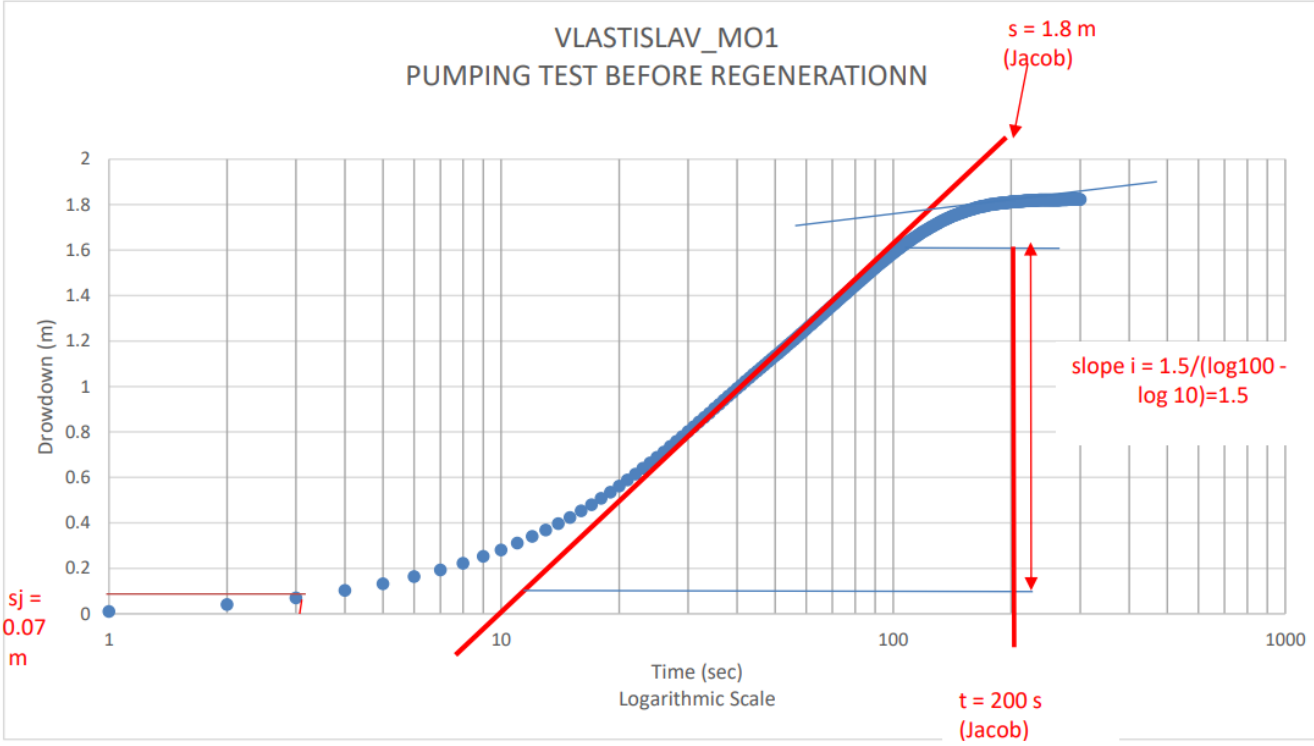


Figure 28: Well MO1Graph for Pumping Test Before Regeneration

1) **Evaluation of C**

$$C = Q\frac{t_j}{s_j} = 0{,}0025.(3/0.07) = 0.10714$$

$$C_D = \frac{C}{2\pi r_w^2 S} = \frac{0.10714}{6.28.0.1625^2 0.01025} = 63$$

slope I_{1p} = 1.5/(log100 - log 10)=1.5 (see fig 18 MO1 graph before regeneration)

Table 4: below shows the values obtained from the Well_MO1 pumping test before regeneration

Discharge, Q(m^3/s)	0.00247
Transmisivity, T(m^2/s)	0.00772
Storativity, S(-)	0.01025
Radius of well, r_w(m)	0.1625
C_D[-]	63

2) **Evaluation of skin factor, W for slope I_{1p}**

$$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right)$$

$$W = \frac{1}{0.86}\left(\frac{6.28*0.00772*1.5}{0.0042} - 1.027 * \log(63) - 1.0237\right) = 30.9$$

3) **Evaluation skin factor, W from Jacob method:**

$$W = \frac{2\pi T s_W}{Q} - \frac{1}{2}\ln\frac{2.246\, T\, t}{r_w^2 S}$$

For t = 200s ….. s_w = 1.8 m

$$W = \frac{6.28 * 0.00772 * 1.8}{0.00247} - \frac{1}{2}\ln(\frac{2.246\ 0.00772 * 200}{0.1625^2 * 0.0105}) = 30.6$$

6.2.2 WELL _MO1 PUMPING TEST AFTER REGENERATION

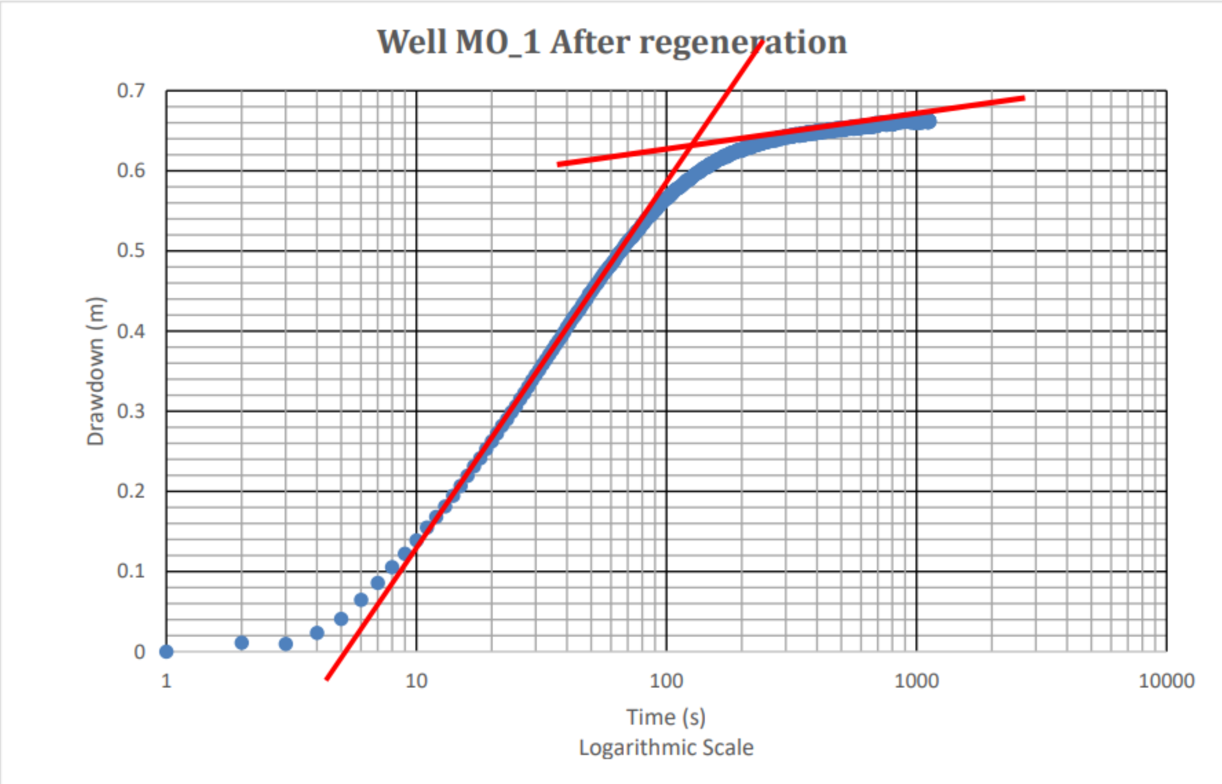


Figure: 29 Well_MO1 Pumping test graph After Regeneration.

1) **Evaluation of C**

t_j = 4 s, s_j = 0.02 m, Q = 0.00247 m^3s^{-1}

$$C = Q\frac{t_j}{s_j} = 0.00247 * \frac{4}{0.02} = 0.494\ m^2$$

$$C_D = \frac{C}{2\pi r_w^2 S} = \frac{0.494}{6.28.0.1625^2 0.01025} = 290.489$$

$$\text{slope } I_{1p} = \frac{0.56-0.02}{\log 100 - \log 10} = 0.54$$

$$\Delta s = s_2 - s_1 = 0.106 - 0.02 = 0.04\ m$$

$$T = 0.183\ \frac{Q}{\Delta s} = 0.183\ \frac{0.00247}{0.04} = 0.0113\ m^2 s^{-1}$$

2) **Evaluation of skin factor, W for slope I_{1p}**

Table 5: below shows the values obtained from the Well_MO1 pumping test after regeneration

Discharge, Q(m^3/s)	0.00247
Transmisivity, T(m^2/s)	0.0113
Storativity, S(-)	0.01025

Radius of well, r_w(m)	0.1625
C_D[-]	290.489

$$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right)$$

$$W = \frac{1}{0.86}\left(\frac{6.283*0.0113*0.04}{0.00247} - 1.027 * \log(290.489) - 1.0237\right) = 13.917$$

3) Evaluation skin factor, W from Jacob method:

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\frac{2.246\, T\, t}{r_w^2 S}$$

For t = 500s ….. s_w = 0.65m

$$W = \frac{6.283* 0.0113*0.65}{0.00247} - \frac{1}{2}\ln\left(\frac{2.246\ 0.0113*500}{0.1625^2*0.0105}\right) = 13.306$$

6.3 EVALUATION OF WELL_K2 PUMING TEST BEFORE REGENERATION

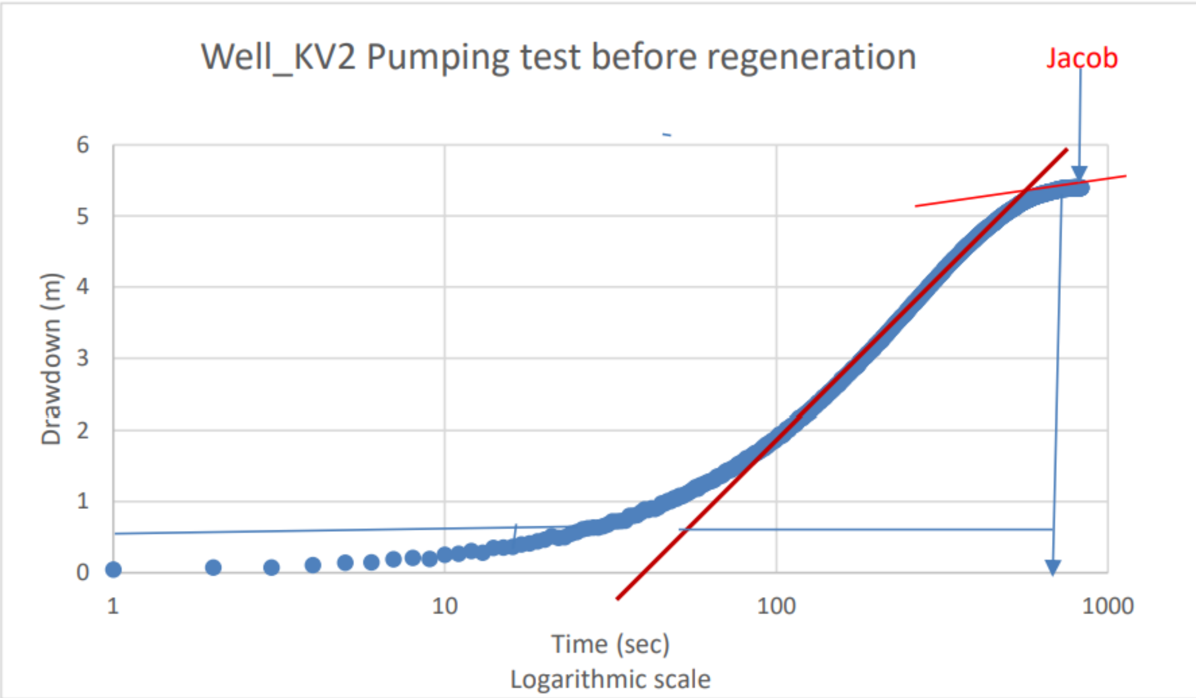


Figure 30: Graph of Well_K2 pumping test before regeneration

1) Evaluation of Well-bore storage (C)

From figure 30

t_j = 3s s_j = 0.07m

$C = Q\frac{t_j}{s_j}$ = 0,0022($\frac{3}{0.07}$) = 0.094 m^2

$$C_D = \frac{C}{2\pi {r_w}^2 S} = \frac{0.094}{2*\pi*0.17^2*0.076} = 6.815$$

Transmissivity (T) evaluation

$\Delta s = s_2 - s_1 = 0.408 – 0.041 = 0.4$

$$T = 0.183 \frac{Q}{\Delta s} = 0.183 \frac{0.0022}{0.4} = 0.001007 \, m^2 s^{-1}$$

Discharge = 2.2 l/s = 2.2/1000 = 0.0022m^3s^{-1}

Table 6: Well_K2 parameters values for pumping test before regeneration

Discharge, Q(m^3s^{-1})	0.0022
Transmisivity, T(m^2s^{-1})	0.001007
Storativity, S(-)	0.076
Radius of well, r_w(m)	0.17
C_D[-]	6.815

$$slope(I_{1P}) = \frac{s_2 - s_1}{\log t_2 - \log t_1} = \frac{5.0527 - 0.2477}{\log(100) - \log(10)} = 5$$ (see fig. 6.3 Well_KV2 graph before regeneration)

2) **Evaluation of skin factor (W) from slope I_{1p}:**

$$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right)$$

$$W = \frac{1}{0.86}\left(\frac{2*\pi*0.001007*5}{0.0022} - 1.027 * \log(6.815) - 1.0237\right) = 14.527$$

3) **Evaluation of skin factor (W) from Jacob method:**

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\frac{2.246\, T\, t}{r_w^2 S}$$

For t = 660s ….. s_w = 5.3373m

$$W = \frac{2*\pi*0.001007*5.3373}{0.0022} - \frac{1}{2} * \ln\left(\frac{2.246*0.001007*660}{0.17^2*0.076}\right) = 12.08$$

6.4. EVALUATION OF WELL_K9 PUMPING TEST BEFORE REGENERATION

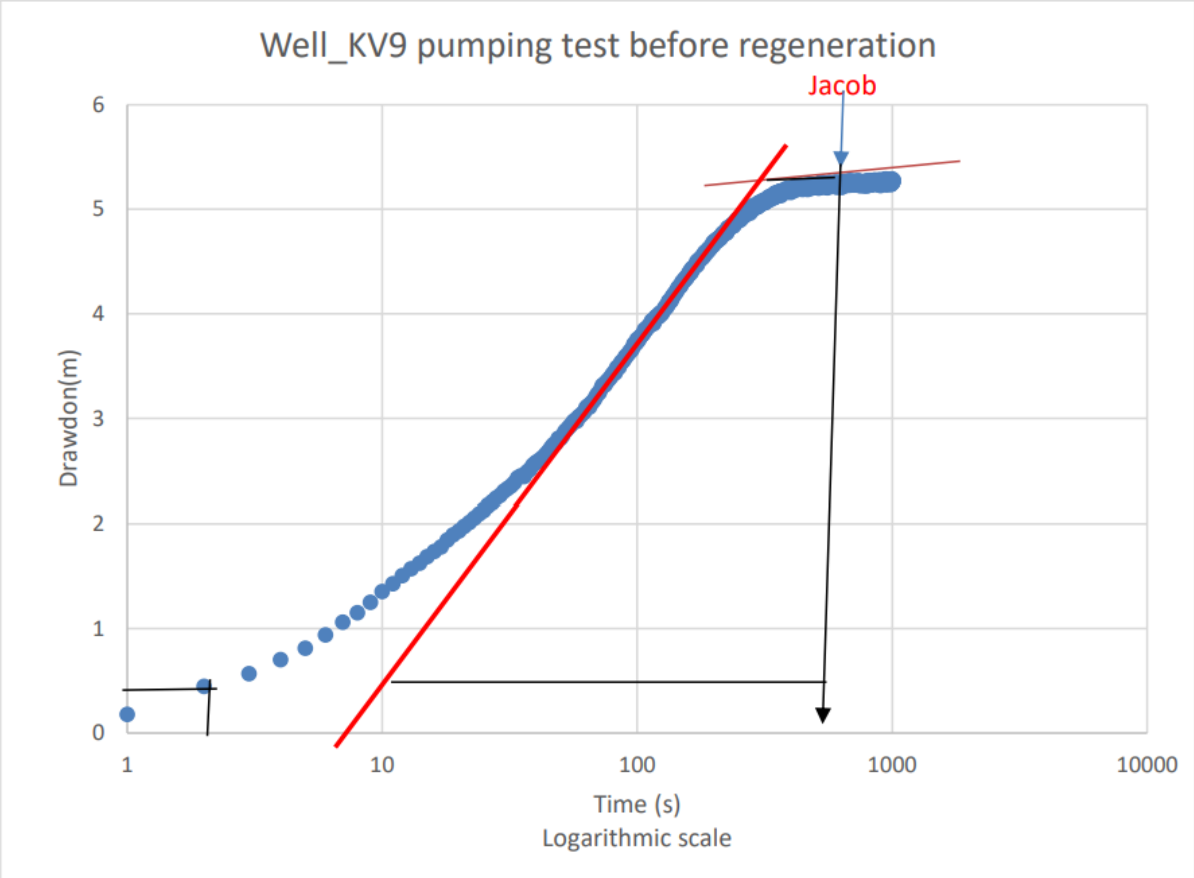


Figure 31: Graph of Well_K9 pumping test before regeneration.

1) **Evaluation of Well-bore storage (C)**

Discharge(Q) = 4.2 l/s = 4.2/ 1000 = 0.0042 m^3s^{-1}

From figure 6.4

t_j = 2 s_j = 0.45

$C = Q\frac{t_j}{s_j} = 0.0042(\frac{2}{0.45}) = 0.018$

$C_D = \frac{C}{2\pi r_w{}^2 S} = \frac{0.018}{2*\pi*0.1125^2*0.076} = 3.06$

Transmissivity (T) evaluation

$\Delta s = s_2 - s_1 = 0.6 - 0.4 = 0.2m$

$T = 0.183\ \frac{Q}{\Delta s} = 0.183\ \frac{0.0042}{0.2} = 0.003843\ m^2s^{-1}$

Table 7: Well_KV9 parameters values for pumping test before regeneration

Discharge, Q(m^3/s)	0.0042
Transmisivity, T(m^2s^{-1})	0.00384
Storativity, S(-)	0.076
Radius of well, r_w(m)	0.1125
C_D[-]	3.06

$$slope(I_{1P}) = \frac{s_2 - s_1}{\log t_2 - \log t_1} = \frac{3.67-0.45}{\log(96)-\log(10)} = 3.3$$ (see fig. 6.4 Well_KV9 graph before regeneration)

2) Evaluation of skin factor (W) from slope I_{1p}

$$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right)$$

$$W = \frac{1}{0.86}\left(\frac{2*\pi*0.003843*3.3}{0.0042} - 1.027 * \log(3.642) - 1.0237\right) = 20.27$$

3) Evaluation of skin factor (W) from Jacob method:

$$W = \frac{2\pi T s_W}{Q} - \frac{1}{2}\ln\frac{2.246\,T\,t}{r_w^2 S}$$

For t = 800s ….. s_W = 5.1m

$$W = \frac{2*\pi*0.003843*5.1}{0.0042} - \frac{1}{2} * \ln\left(\frac{2.246*0.003843*800}{0.1125^2*0.076}\right) = 24.97$$

6.5.1 EVALUATION OF WELL_HV5 PUMPING TEST BEFORE REGENERATION USING ULTRA SOUND

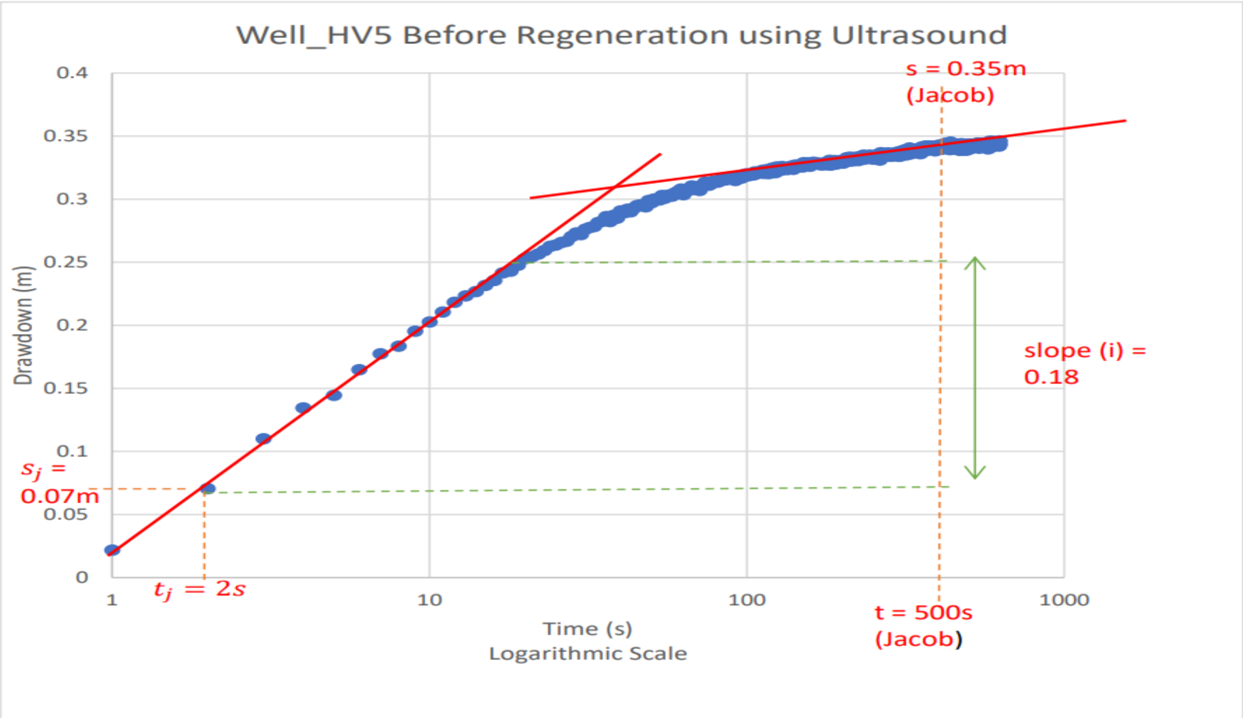


Figure 32: Regeneration of Well_HV5 using ultrasound (Before)

1) **Evaluation of Coefficient (C)**

t_j = 2 s, s_j = 0.05 m, Q = 0.008247 m^3s^{-1}

Inverse Value of the slope when emptying the borehole ($1/I_p$) = 29.5

$$C = Q * \frac{1}{Ip} = 0.00648 * 29.5 = 0.19116\ m^2$$

$$C_D = \frac{C}{2\pi r_w^2 S} = \frac{0.19116}{6.283.0.1885^2 0.001} = 856.263$$

slope $I_{1p} = \frac{0.25-0.07}{\log 20 - \log 2} = 0.18$

2) **Evaluation of skin factor, W for slope I_{1p}**

Table 8: below shows the values obtained from the Well_HV5 Before Ultrasound Regeneration

Discharge, Q(m^3/s)	0.00648
Transmisivity, T(m^2/s)	0.052177
Storativity, S(-)	0.001
Radius of well, r_w(m)	0.1885
C_D[-]	856.263

$$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right)$$

$$W = \frac{1}{0.86}\left(\frac{6.283*0.052177*0.18}{0.00648} - 1.027 * \log(856.263) - 1.0237\right) = 5.896$$

3) Evaluation of skin factor, W from Jacob method:

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\frac{2.246\, T\, t}{r_w^2 S}$$

$$\Delta s = s_2 - s_1 = 0.11 - 0.07 = 0.04\, m$$

$$T = 0.183\, \frac{Q}{\Delta s} = 0.183\, \frac{0.00648}{0.04} = 0.029646\, m^2 s^{-1}$$

For t = 500s ….. s_w = 0.35m

$$W = \frac{6.283*0.029646*0.35}{0.00648} - \frac{1}{2}\ln\left(\frac{2.246\ 0.029646*500}{0.1885^2*0.001}\right) = 4.318$$

6.5.2 EVALUATION OF WELL_HV5 PUMPING TEST AFTER REGENERATION USING ULTRA SOUND

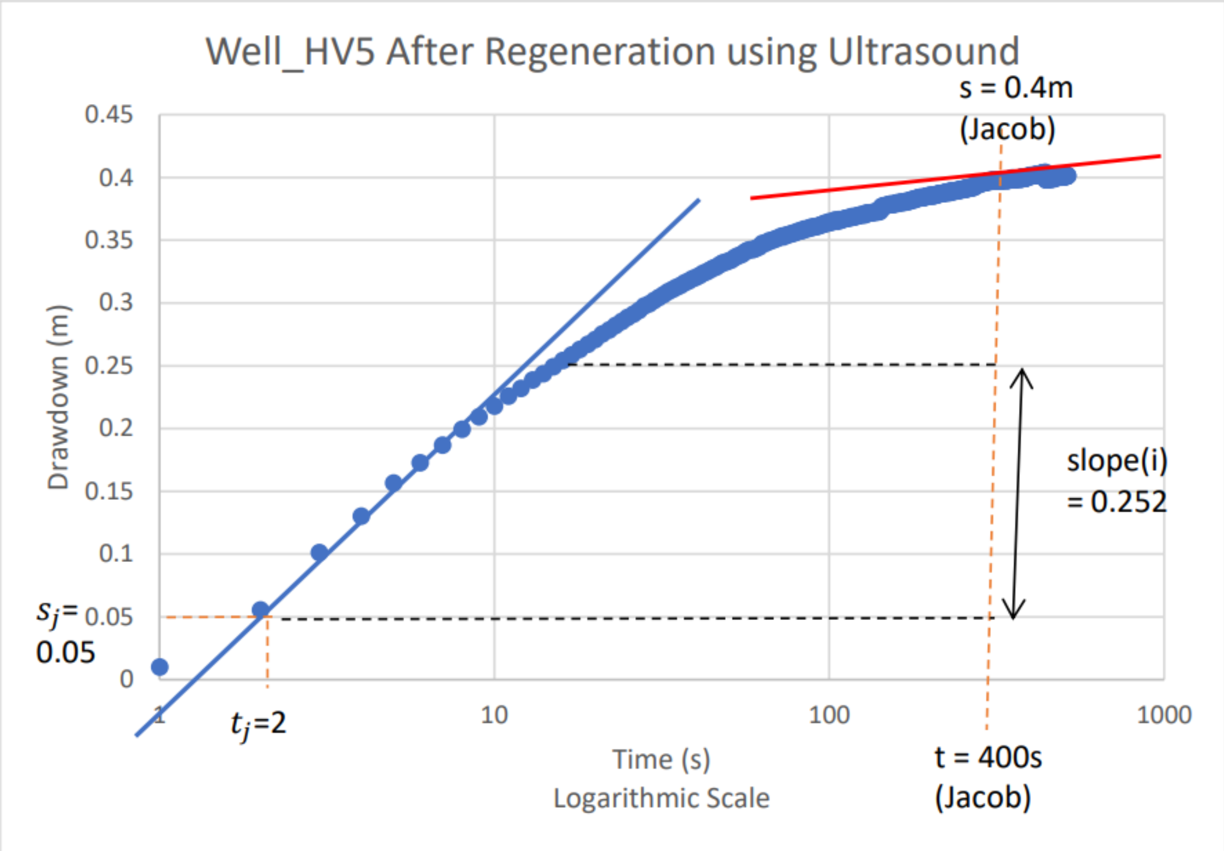


Figure 33: Regeneration of Well HV5 using Ultrasound (After)

2) Evaluation of Coefficient (C)

$t_j = 2$ s, $s_j = 0.05$ m, $Q = 0.008247$ m^3s^{-1}

$1/I_p = 36.26$, I=0.18

$$C = Q * \frac{1}{\text{Ip}} = 0.00824 * 36.26 = 0.298782 \text{ m}^2$$

$$C_D = \frac{C}{2\pi r_w^2 S} = \frac{0.298782}{6.283.0.1885^2 0.001} = 1338.3363$$

$$\text{slope } I_{1p} = \frac{0.25-0.05}{\log 15 - \log 2} = 0.252761$$

2) **Evaluation of skin factor, W for slope I_{1p}**

Table 9: below shows the values obtained from the Well_HV5 After Ultrasound Regeneration

Discharge, Q(m^3/s)	0.00824
Transmisivity, T(m^2/s)	0.052177
Storativity, S(-)	0.001
Radius of well, r_w(m)	0.1885
C_D[-]	1338.3363

$$W = \frac{1}{0.86}\left(\frac{2\pi T I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right)$$

$$W = \frac{1}{0.86}\left(\frac{6.283*0.0113*0.252761}{0.00824} - 1.027*\log(1338.3363) - 1.0237\right) = 3.455$$

3) Evaluation of skin factor, W from Jacob method:

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\frac{2.246\,T\,t}{r_w^2 S}$$

$$\Delta s = s_2 - s_1 = 0.1 - 0.05 = 0.05\,m$$

$$T = 0.183\,\frac{Q}{\Delta s} = 0.183\,\frac{0.00824}{0.05} = 0.0113\,m^2s^{-1}$$

For t = 400s ….. s_w = 0.4 m

$$W = \frac{6.283*0.0301584*0.4}{0.00824} - \frac{1}{2}\ln\left(\frac{2.246\;0.0301584*400}{0.1885^2*0.001}\right) = 3.905$$

7 DISCUSION AND CONCLUSION

7.1 DISCUSSION: FIELD WORK

Figure 34: Ultrasonic regeneration set

Figure 35: Ultrasound probe

7.1.1 Methodology of regeneration works.

The purpose of the work was the experimental correction of wellbore storage of the well - ie removal of sediment from the bottom of wells, coatings on corroded casings and incrustations on the walls of well equipment. The basic premise of mechanical regeneration was to reach the original bottom of the well and remove foreign objects from the bottom. Using a complex of mechanical regeneration, the interior of the borehole, mudguard, and the opening of the maximum number of perforation holes, which are currently clogged with the material, were cleaned using a combination of several technologies. The specificity of the effect of the ultrasonic wave lies in the mechanical cleaning of the wellbore in the space behind its casing.

The tested well HV-5 was drilled in 1977 and is currently held as a backup water collection source of the subject Středočeské vodárny, a.s. within the catchment area of Všetaty. In the period of approx. 1980-2000, the well was intensively used with an operating yield of <10 l / s. It is a collecting drilled well of drilling diameter d=450mm with steel equipment DN377mm with a section of drilled perforation 4.2-11.0 m p.t. The well collects water from a shallow collector of Quaternary age, the groundwater level (HPV) is about 1 m p.t. During the previous operation, the well was never regenerated, hydrodynamic tests were performed only at the time of commissioning of the well in 1977 (when the well was tested for Q = 20.61 l / s).

7. 2 CONCLUSION

Table 10: shows summary of the difference on the evaluation of additional resistance from both the slope and the Jacob method

S/No.	NAME OF WELL	VALUE OF SKIN FACTOR, W BEFORE REGENERATION		VALUE OF SKIN FACTOR, W AFTER REGENERATION		DIFFERENCE BETWEEN BEFORE & AFTER REGENERATION	
		FROM SLOPE (i)	FROM JACOB METHOD	FROM SLOPE (i)	FROM JACOB METHOD	SLOPE	JACOB
1	RD2	4.879	7.776	2.348	1.84	2.531 (52%)	5.936 (76%)
2	KV2	14.527	12.08	-	-	-	-
3	KV9	20.27	24.97	-	-	-	-
4	MO1	30.9	30.6	13.917	13.306	16.983 (55%)	17.294 (57%)
5	HV5	5.896	4.318	3.455	3.905	2.441 (41%)	0.413 (10%)

From the table above, the evaluation of the coefficient of additional resistance (W) of the various Wells from both the slope and Jacob methods produce almost the same results. Well MO1 shows the same results after the evaluation of additional resistance from the Slope and Jacob method for both before and after regeneration. Considering Well RD2 and HV5 values obtained for the coefficient of additional resistance after the regeneration from both the Slope (i) and Jacob method also produced almost the same results. However, the results obtained for the evaluation of the coefficient of additional resistance (W) for the Wells RD2, KV2 , KV9 and HV5 differs a bit before the regeneration from the Slope method and Jacob method (from table %). Therefore, the Ultrasound regeneration method produced very precise cleaning results.

Comparing the results obtained for all the wells, it can be observed from the table above that there is a significant change in the coefficient of additional resistance after the regeneration except wells KV2 and KV9 which has no data for the after regeneration. Hence, the coefficient of additional resistance (W) was smaller after the regeneration. This demonstrates the success of the regeneration.

REFERENCES

Aarts, A., Ooms, G., Bil, K., Petroleum, E. B.-E., & 1998, undefined. (1998). Enhancement of liquid flow through a porous medium by ultrasonic radiation. *Onepetro.Org*. https://www.onepetro.org/conference-paper/SPE-50594-MS

Abramov, V. O., Mullakaev, M. S., Abramova, A. v., Esipov, I. B., & Mason, T. J. (2013). Ultrasonic technology for enhanced oil recovery from failing oil wells and the equipment for its implemention. *Ultrasonics Sonochemistry*, *20*(5). https://doi.org/10.1016/j.ultsonch.2013.03.004

Abramova, A. v., Abramov, V. O., Bayazitov, V. M., & Nikonov, R. v. (2017). A method for water well regeneration based on shock waves and ultrasound. *Ultrasonics Sonochemistry*, *36*. https://doi.org/10.1016/j.ultsonch.2016.12.023

Allen, G. J. ; F. K. A. (1995). *Aqueous cleaning and verification processes for precision cleaning of small parts*. 411–419.

BÄCHLE, A. , M. P. (1992). Mechanical methods of regeneration of wells. *27th Seminar on Water Chemistry, Optimization of Groundwater Extraction via Filter Wells*.

Batu Vetat. (1998). *Aquifer Hydraulics: A Comprehensive Guide to Hydrogeologic Data Analysis* (1st ed., Vol. 79). Wiley Inter-Science.

Bear, J., & Cheng, A. H.-D. (2010). *Modeling Groundwater Flow and Contaminant Transport*. Springer Netherlands. https://doi.org/10.1007/978-1-4020-6682-5

BERLITZ, B. , K. H. (1997). Well regeneration with ultrasound -. *Bbr Water and Pipe Construction*, *48*, 19–23.

Bott W. Wilken R. D. (2002). *Experiences with the regeneration of wells using ultrasound on a semi-technical scale. bbr 11/2002*. *11*, 22–28.

Butler, J. J., & Liu, W. Z. (1991). Pumping tests in non-uniform aquifers — the linear strip case. *Journal of Hydrology*, *128*(1–4). https://doi.org/10.1016/0022-1694(91)90132-2

Champion, B., Bas, F. van der, Facilities, G. N.-S. P. &, & 2004, undefined. (2004). The application of high-power sound waves for wellbore cleaning. *Onepetro.Org*. https://www.onepetro.org/journal-paper/SPE-82197-PA

Chen, C.-S., & Chang, C.-C. (2002). Use of cumulative volume of constant-head injection test to estimate aquifer parameters with skin effects: Field experiment and data analysis. *Water Resources Research*, *38*(5). https://doi.org/10.1029/2001WR000300

Chen, C.-S., & Chang, C.-C. (2006). Theoretical evaluation of non-uniform skin effect on aquifer response under constant rate pumping. *Journal of Hydrology*, *317*(3–4). https://doi.org/10.1016/j.jhydrol.2005.05.017

Davis, S. N. (1988). Sandstones and shales. Hydrogeology. *The Geological Society of North America, Boulder Colorado. 1988. p 323-332. 3 Fig, 4 Tab, 61 Ref.*, 323–332.

Dupuit Jules. (1863). *Etude Th´eoriques et Pratiques Sur le Mouvement Des Eaux Dans Les Canaux D´ecouverts et `a Travers Les Terrains Perm´eables.*

DVGW. (2001). Well regeneration - DVGW data sheet W 130. In *DVGW* (Vol. W130, pp. 28-undefined).

E & F.N. SPON. (1990). Wataer Wells Monitoring, Maintenace, REhabilitation. In P. Howsam (Ed.), *Proceedings of International Groundwater Engineering conference*. Cranfield Institute of Technology, UK.

Fair, G. M., & Hatch, L. P. (1933). Fundamental Factors Governing the Streamline Flow of Water Through Sand. *Journal - American Water Works Association*, *25*(11). https://doi.org/10.1002/j.1551-8833.1933.tb18342.x

Fetter C. W. (2001). *Applied hydrogeology., 4th edn.(Prentice Hall: Upper Saddle River, NJ).*

Firdaaouss Mouaouia, Guermond Jean-Luc, & le Quere Patrick. (1997). Nonlinear corrections to Darcy's law at low Reynolds numbers. *Journal of Fluid Mechanics*, 331–350.

Fokker. (2013). NUMERICAL MODELING OF PERIODIC PUMPING TESTS IN WELLS PENETRATING A HETEROGENEOUS AQUIFER. *American Journal of Environmental Sciences*, *9*(1). https://doi.org/10.3844/ajessp.2013.1.13

Gollapudi, U. K., Bang, S. S., & Islam, M. R. (1994, February 7). Ultrasonic Treatment for Removal of Asphaltene Deposits During Petroleum Production. *All Days*. https://doi.org/10.2118/27377-MS

Helm, D. C. (1975). One-dimensional simulation of aquifer system compaction near Pixley, California: 1. Constant parameters. *Water Resources Research*, *11*(3). https://doi.org/10.1029/WR011i003p00465

Hemker, C. J. (1984). Steady groundwater flow in leaky multiple-aquifer systems. *Journal of Hydrology*, *72*(3–4). https://doi.org/10.1016/0022-1694(84)90089-1

Holzer, T. L. (2010). The Water Table. *Ground Water*, *48*(2). https://doi.org/10.1111/j.1745-6584.2009.00640.x

HOUBEN, G. , T. C. (2003). *Regeneration and rehabilitation of boreholes* (pp. 196–250).

Houben, G. ; T. C. (2007). *Water Well Rehabilitation and Reconstruction* (3rd ed.). McGraw Hill Professional: Two Penn Plaza.

Kahuda, D., & Pech, P. (2020). A New Method for the Evaluation of Well Rehabilitation from the Early Portion of a Pumping Test. *Water*, *12*(3). https://doi.org/10.3390/w12030744

Kerms G. (1979). Well aging and well regeneration DVGW: Further education courses water supply technology for engineers and scientists, Course 1: Water extraction-DVGW-Series Water. *Self-Published*, *201*, *563 S*.

Klute, A., & Dirksen, C. (2018). *Hydraulic Conductivity and Diffusivity: Laboratory Methods*. https://doi.org/10.2136/sssabookser5.1.2ed.c28

Kuttruff H. (1988). *Physics and Technology of Ultrasound. - 415 S., 216 Fig., 14 Tab., Stuttgart (Hirzel).*

Kuttruff, H. (2012). *Ultrasonics: Fundamentals and applications*. https://books.google.com/books?hl=en&lr=&id=KqbnCAAAQBAJ&oi=fnd&pg=PA1&dq=KUTTRUFF,+H.+(1988):+Physics+and+Technology+of+Ultrasound.+&ots=MW3sBJxuMI&sig=Ui0IvXs8DV3fFTihXOnhJYSVrsw

Kutzner J. (1983). *Fundamentals of Ultrasound Physics - 111 S., 50 Fig., Stuttgart (Teubner).*

Lattman, L. H. (1958). Technique of mapping geologic fracture traces and lineaments on aerial photographs. *Photogrammetric Engineering*, *24(4)*, 568–576.

Liddle, R. L. , & J. B. S. (1997). Determination of mean hydraulic head and gradient, aquifer efficiency, and lag time in a tidally affected two-aquifer system. *In Proceedings of the 11th National Outdoor Action Conference and Exposition: Aquifer Remediation/Ground Water Monitoring/Geophysical Methods*, 409–421.

Lim, J.-L., & Okada, M. (2005). Regeneration of granular activated carbon using ultrasound. *Ultrasonics Sonochemistry*, *12*(4). https://doi.org/10.1016/j.ultsonch.2004.02.003

Moench, A. F. (1985). Transient Flow to a Large-Diameter Well in an Aquifer With Storative Semiconfining Layers. *Water Resources Research*, *21*(8). https://doi.org/10.1029/WR021i008p01121

Mutreja, K. N. (1986). *Applied Hydrology*. TATA McGraw-Hill Publishing Company Limited.

Neuman, S. P. (1977). Theoretical derivation of Darcy's law. *Acta Mechanica*, *25*(3–4). https://doi.org/10.1007/BF01376989

Nielsen, D. R., Th. Van Genuchten, M., & Biggar, J. W. (1986). Water flow and solute transport processes in the unsaturated zone. *Water Resources Research*, *22*(9S). https://doi.org/10.1029/WR022i09Sp0089S

Nimmo, J. R., Rubin, J., & Hammermeister, D. P. (1987). Unsaturated flow in a centrifugal field: Measurement of hydraulic conductivity and testing of Darcy's Law. *Water Resources Research*, *23*(1). https://doi.org/10.1029/WR023i001p00124

Noltingk, B. E. (1962). *The Effects of Intense Ultrasonics in Liquids*. https://doi.org/10.1007/978-3-642-45976-4_4

Normann-Schmidt S. (1992). *Well regeneration - chemical processes. - 27th seminar on water chemistry, optimization of groundwater extraction using filter wells, series of publications by the Institute for Water Supply, Wastewater Disposal and Spatial Planning at TU Darmstadt. 65*.

Park, Y.-J., Lee, K.-K., & Kim, J.-M. (2000). Effects of Highly Permeable Geological Discontinuities upon Groundwater Productivity and Well Yield. *Mathematical Geology*, *32*(5). https://doi.org/10.1023/A:1007514405501

Pasandi, M., Samani, N., & Barry, D. A. (2008). Effect of wellbore storage and finite thickness skin on flow to a partially penetrating well in a phreatic aquifer. *Advances in Water Resources*, *31*(2). https://doi.org/10.1016/j.advwatres.2007.09.001

Patel, M. C., & Singh, A. (2016, February 24). Near Wellbore Damage and Types of Skin Depending on Mechanism of Damage. *Day 1 Wed, February 24, 2016*. https://doi.org/10.2118/179011-MS

PAUL, K. (1994). Relationships between well construction and the different types of well aging Part 1. In *bbr water and pipe construction* (Vol. 45, pp. 26–37).

Pech, P. (2004). Estimation of a well damage or stimulation. *Sci. Agric. Bohem*, *35*, 131–135.

Pechstein, A., Attinger, S., Krieg, R., & Copty, N. K. (2016). Estimating transmissivity from single-well pumping tests in heterogeneous aquifers. *Water Resources Research*, *52*(1). https://doi.org/10.1002/2015WR017845

Pohlmann R. (1960). *Problems of ultrasonic transmission at interfaces.-Acustica*. *10,* 217–229.

Ralph, D. E., & Stevenson, J. M. (1995). The role of bacteria in well clogging. *Water Research*, *29*(1). https://doi.org/10.1016/0043-1354(94)E0077-J

Renard, P. (2006). Hydraulics of Wells and Well Testing. In *Encyclopedia of Hydrological Sciences* (Vol. 13, pp. 151-undefined). John Wiley & Sons, Ltd. https://doi.org/10.1002/0470848944.hsa154a

Richard, S. K., Chesnaux, R., Rouleau, A., & Coupe, R. H. (2016). Estimating the reliability of aquifer transmissivity values obtained from specific capacity tests: examples from the Saguenay-Lac-Saint-Jean aquifers, Canada. *Hydrological Sciences Journal*, *61*(1). https://doi.org/10.1080/02626667.2014.966720

Sander, P. (2007). Lineaments in groundwater exploration: a review of applications and limitations. *Hydrogeology Journal*, *15*(1). https://doi.org/10.1007/s10040-006-0138-9

ŞEN, Z. (2000). Non-Darcian groundwater flow in leaky aquifers. *Hydrological Sciences Journal*, *45*(4). https://doi.org/10.1080/02626660009492360

Shang, J., Flury, M., & Deng, Y. (2009). Force measurements between particles and the air-water interface: Implications for particle mobilization in unsaturated porous media. *Water Resources Research*, *45*(6). https://doi.org/10.1029/2008WR007384

Smith Stuart. (1982). *Ground Water Hydrology for Water Well Contractors: Vol. chapter 15* (Rau John). National Water Well Association.

Soulsby, D. (2010). Technical review: borehole drilling and rehabilitation under field conditions. *Tech. Geneva, Switzerland, ICRC.*

Theis, C. v. (1935a). The relation between the lowering of the Piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Transactions, American Geophysical Union*, *16*(2). https://doi.org/10.1029/TR016i002p00519

Theis, C. v. (1935b). The relation between the lowering of the Piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Transactions, American Geophysical Union*, *16*(2), 519–524. https://doi.org/10.1029/TR016i002p00519

Thiem A. Neis U. (1999). *Ultrasound in environmental engineering, TUHH Reports on sanitary engineering, 25, Hamburg.*

Thiem G. (1906). *Hydrologische Methoden JM Gebhardt Leipzig*. *56*.

Todd David Keith. (1980). *Groundwater Hydrology* (2nd ed.). John Wiley and Sons, Inc.

Todd David Keith, & Larry W. Mays. (2005). *Groundwater Hydrology* (Zobrist Bill & Welter Jennifer, Eds.; 3rd ed.). John Wiley and Sons, Inc.

van der Bas, F., de Rouffignac, E., Zuiderwijk, P., & van Batenburg, D. (2004, October 10). Near Wellbore Stimulation by Acoustic Waves. *All Days*. https://doi.org/10.2118/88767-MS van Everdingen, A. F. (1953). The Skin Effect and Its Influence on the Productive Capacity of a Well. *Journal of Petroleum Technology*, *5*(06). https://doi.org/10.2118/203-G

Venkitaraman, A., Roberts, P. M., & Sharma, M. M. (1995). Ultrasonic Removal of Near-Wellbore Damage Caused by Fines and Mud Solids. *SPE Drilling & Completion*, *10*(03). https://doi.org/10.2118/27388-PA

Whitaker Stephen. (1986). *Flow in Porous Media I: A Theoretical Derivation of Darcy's Law*. *1*, 3–25.

WIACEK, H. (2003). *Well regeneration by means of ultrasound - validation of laboratory results in practice*.

Wilken, R. D. , & B. W. (2002). Well regeneration by powerful ultrasound. *Ultrasound in Environmental Engineering II, TUHH Reports on Sanitary Engineering*, *35*, 159–172.

Wilken, R., II, W. B.-U. in environmental engineering, TUHH, undefined, & 2002, undefined. (n.d.). Well regeneration by powerful ultrasound. In *osti.gov*. Retrieved December 7, 2020, from https://www.osti.gov/etdeweb/servlets/purl/20339928#page=167

Wilson, C. P. v. (2007). Groundwater Hydrology (2nd edn) by D. K. Todd. Wiley, New York, 1980. 552 pp. ISBN 0 471 08641 X. *Geological Journal*, *17*(4). https://doi.org/10.1002/gj.3350170407

Wolfgang Bott, Hella Wiacek, & Rolf-Dieter Wilken. (2003). *Development of a procedure for well regeneration using an Ultrasound unit*.

Wu, C.-M., Yeh, T.-C. J., Zhu, J., Lee, T. H., Hsu, N.-S., Chen, C.-H., & Sancho, A. F. (2005). Traditional analysis of aquifer tests: Comparing apples to oranges? *Water Resources Research*, *41*(9). https://doi.org/10.1029/2004WR003717