CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

FACULTY OF ENVIRONMENTAL SCIENCES

Evaluation of Skin Factor

Master Thesis

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Thesis Title:

Evaluation of Skin Factor

Declaration

Hereby, I declare that I have elaborated this thesis independently under the guidance of prof. Ing. Pavel Pech, CSc. and that I mentioned all the literary sources from which I used.

In Prague, 25.03.2020 Xaiyasith Iamsisanith

Acknowledgment

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In Prague, 25.03.2020 Xaiyasith Iamsisanith

Abstract

The aim of the thesis is to determine, whether there is any change in drawdown caused by additional resistance after well rehabilitation. Moreover, we focused on the evaluation of the skin factor and evaluation of resistances in the well RD2 which is located in Central-North Bohemia (Czech Republic) within the Radouň pumping site. The evaluation was conducted in 2015, with gathered data before and after well regeneration.
In this paper, we show the calculation for values of pumping test which includes; transmissivity and storativity. Furthermore, we use these values to determine the differences in water level reduction at the pumping well and observation well. Then, we calculate for additional resistance.

Furthermore, this thesis paper demonstrated the different methods for calculation the evaluation of pumping well before and after; then, discuss the two methods.

For this calculation, we used Jacob's method for pumping test which is the simplification of Theis method to find the parameters of an aquifer such as the storativity and the transmissivity. It is clear that well cleaning is a very useful process to consider to increase duration of well and improve performance.

Keywords: skin factor, well rehabilitation, pumping test, well

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1. Introduction

This work deals with evaluation of skin factor on the wells, which is located in Central-North Bohemia (Czech Republic) within the Radouň pumping site, operated by a major regional waterworks company. The site with its 3 pumping wells represents one of several support water sources in the regional, including drinking water. The supply supporting is via a major water feeder urban and industrial area between Mělník and Ústí nad Labem.

The wells RD2, which is pumping and RD1, which is observation well, in this evaluation we will be able to evaluate the perpendicularity on and around the well. So, comparison for the additional resistances, will be done in order to find out if there was an improvement or deterioration before and after well rehabilitation. In order to calculate these additional resistances, we will use the measured pumping test data, which was measured by a project carried out by the Faculty of the Environmental Sciences, the Czech University of Life Sciences, Prague. Hence, to begin with the evaluation of colmatation, we must first know the basic properties of groundwater hydraulics and know how to use this knowledge to evaluate them.

After, we will discuss what can be caused by the perpendicularity and what would be the suitable solution. In the end, we will calculate the amount of additional resistance before and after cleaning well to the measured values of pumping tests. With these results, we will be able to determine which method is significant and suitable for the evaluation. The methods that were applied to the evaluation included, two methods for evaluation skin factor; the first method, we first determine wellbore storage (C_D), by selecting point B on the "unit" slope line from graph plotted of time (tB) in axis X, and the drawdown at time that time. Then, a drawdown used value for dimensionless time (time of the intersection of the first straight line with the timeline axis). We will have $s^* = f(C_D . t^*)$ After that, we can evaluate the additional drawdown caused by skin factor from the calculated value of dimensionless drawdown (Kahuda & Pech, 2020). And the second is Cooper-Jacob's method. At the end, we compared calculated skin factor from these two methods.

2. Objective of this thesis

The main goal of this diploma thesis is the evaluation of hydrodynamic tests on the well, and its quality using appropriate methods for the change of the additional resistances on and around the well. This method is defined to account for additional pressure drop due to damage or stimulation around the wellbore.

Also, the approach compared the different wells which applied different evaluation methods, and its effects. It also provides design the appropriate methodology for improving performance and efficiency in terms of safety, quality and costs in the future.

3. Literature review

In this section we will review some information on groundwater hydraulics and its application to the hydrodynamic test and overviews of hydrological system which will help us to understand more about the importance of groundwater and develop the suitable approaches for groundwater management. In section will also introduce basic information for well test; especially, the evaluation of skin factor. Also, the section will demonstrate the evaluates of the unsteady groundwater flow to a real well (with wellbore storage and the skin effect) that fully penetrates the confined aquifer. Well resistance (skin effect) and the finite volume of wells (wellbore storage) are two important factors that influence the pump data of the measured boreholes (Kahuda & Pech, 2020). Thus, In the paper, we will focus on the most commonly used method for well testing which is derived from Theis solution. The method is based on a semi-logarithmic representation of the pumping at the well vs. the logarithm of pumping time. The method was introduced by Cooper and Jacob to drawdown tests. (Kahuda & Pech, 2020)

3.1 Basics of hydraulic head and groundwater

Hydraulic head is a very important concept when we study groundwater hydraulics. Hydraulic head can be defined so; hydraulic head is a measurement of water pressure, energy of a body of water above a specified datum, to put it other way; it is a kind of potential energy stores within a body of water, and it is measured in unit of length. The equation that used to defined hydraulic head is shown below: (1)

Bernoulli Equation for ideal fluid is

$$H = z + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{const.} \qquad (1)$$

H is the total head or energy head (m)
z is elevation head (m)
p is pressure $(Pa\ or\ N/m^2)$
ρ is density of the fluid (kg/m^3)
v is velocity (m/s)
g is the acceleration due to gravity (m/s^2)

3.2 Groundwater and hydrological cycle

Water is one of the essential compounds that support all forms of plant and animal life. Due to its hydrogen bond, it contains unique chemical properties. Polarity Due to its quality, groundwater is the most important source of drinking water and is protected against contamination. It is the second source of water on earth. Groundwater is the most important raw material that is extracted from the earth. (Margat, 2013)

There are number of important applications compared to surface water. Groundwater occurs below the surface of the earth, which fills the rooms with cracks or rocks. Groundwater is the main source of drinking water when there is no surface water. The operation of groundwater is cheaper compared to surface water. These benefits reduce the availability of groundwater. (Margat, 2013)

The soil contains 97% of groundwater in aquifers. Many countries use large quantities of groundwater for domestic, agricultural and industrial use. Worldwide, 60% of groundwater was used for agriculture and was still used for domestic and industrial proposals. In many countries, half of the groundwater is extracted for domestic water supply. (Tadiboyina, 2016)

The water cycle is a result of water transformations that occur in the circulation of the atmosphere on the surface and in the underground regions of the earth and then again from the surface to the atmosphere. (Donev, 2017)
As surface water sediments and precipitation, such as melting snow, replenish groundwater, it drains slowly towards the drainage point. When rainfall falls on the land surface, part of the water flows into lakes and rivers. Part of the water from the melting snow and rain seeps into the ground and reaches the saturation zone (Donev, 2017).

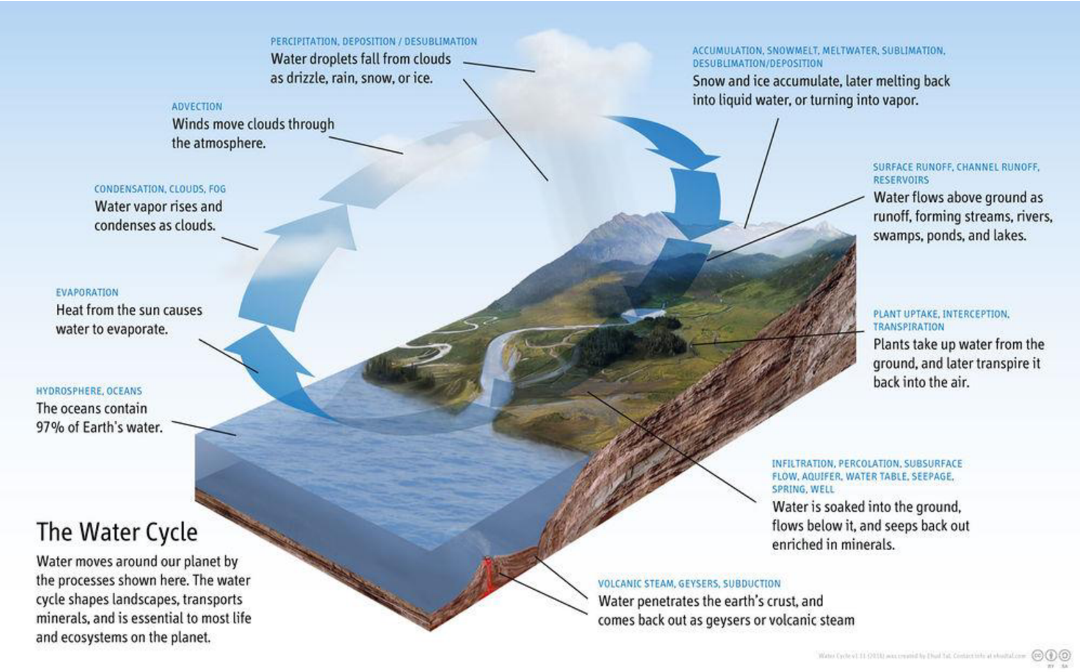
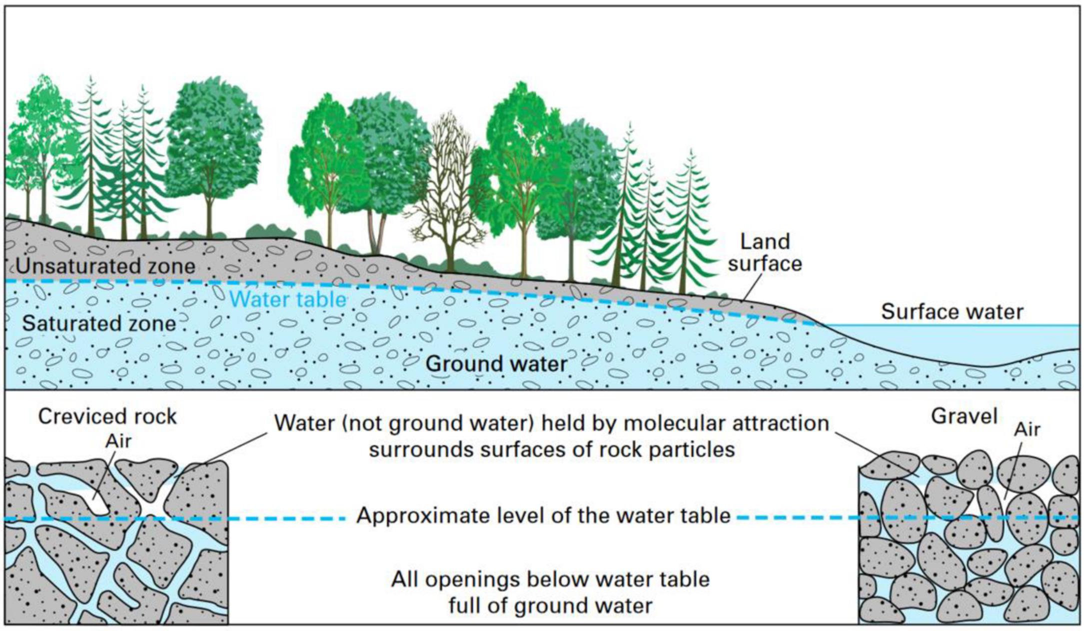


Figure 1: The water cycle depicting how groundwater is replenished (Tal, 2016)

Part of the water quickly evaporates from the water that fell on the earth, some flow into the streams or lakes as land currents, and some penetrate the underground soil. Part of the water that enters the ground is transported back to the atmosphere by plants, another part remains in the percolation zone, and the other reaches the saturated zone (aquifer) with groundwater replenishment, and the remaining water flows along the underground path. Return to the Earth's surface and ocean (Figure 1.). We can see that the water moving in the water cycle does not gain or lose, that is, it is conserved (input-output = change in water storage). Therefore, the water cycle follows the principle of continuity. (Jha, 2014)

3.3 Groundwater and aquifers

Groundwater is one of our most important and valuable resource. As we know that most of the empty space in the soil or rock under the ground, are filled with water. We call the zone that filled of water, aquifer. The amount and movement of the water depend on the characteristics of the porosity and permeability characteristics of the rock or soil, shows in the figure 2.



How ground water occurs in rocks.

Figure 2: How Groundwater Occurs (USGS, n.d.)

An aquifer is a layer of saturated rock through which water can easily move (depending on the type of rock or soil). When stones are severely cracked, they form good aquifers; however, if the rocks have very low porosity, they form poor aquifers. That is why a well has been drilled in the ground to penetrate the aquifer. Usually this water should be pumped to the surface. If water is pumped out of the well faster than filling, the water level drops and the well can dry. When water is pumped out of the well, the water level usually drops into a vacuum cone in the well. Groundwater usually flows along the slope of the water surface to the well. *(Donev, 2017).*

3.4 Vertical distribution of groundwater

Water is partially absorbed into the soil and flows through gravity, is called groundwater which can be divided into two main areas: the unsaturated zone, also called vadose zone or aeration zone, and water that flows into the saturated zone.

- **Unsaturated zone**
  This zone is also known as aeration zone. It is the area that only exists underground. This is the area between the land surface and the water surface. It's called Vadose Zone. It is partly filled with water and partly with air. The water in this area is called vadose water. Any water that occurs in the unsaturated zone is called Vadose water. Likewise, the pressure head in the filtration area has less atmospheric pressure. Water is retained by a combination of adhesion and capillary action; also, called capillary groundwater (Balasubramanian, 2017).

- **Capillary zone**

  This water moves upward from the water surface by capillary action. The capillary water moves slowly in all directions. No water can be pumped from this area for private or commercial water supply because capillary forces hold it with too much force. But the roots of trees and plants can benefit from this water. Due to seasonal changes, the headband moves up and down with the groundwater level. (Tadiboyina, 2016)

- **Water table**

  The top of the saturation zone is called the groundwater table. At the groundwater table, the water in the pores of the aquifers is under atmospheric pressure. The hydraulic pressure at each level within an aquifer of the aquifer corresponds to the depth from the point of the aquifer and is called the hydraulic head. When a well is dug into an aquifer, the static water level in the well is at the same level as the water level. The groundwater table, sometimes called the free or groundwater table, is not a stationary surface. This groundwater level moves up and down for various reasons. It can increase if more water is added to the saturated zone through vertical filtration and decrease during periods of drought while stored water flows to sources, streams, wells and other groundwater drainage points.

- **Saturated zone**

  The zone located below the water table is the zone of saturation. It is also called as phreatic zone. The zone of saturation is also referred to as an aquifer. The saturated zone is defined as the level beneath the water table which all pore spaces are filled with water. (Balasubramanian, 2017)

  In case of heavy rain or infiltration, the saturation can also be a transition state (time-varying) in the soil profile or infiltration zone. This saturation can range from days or weeks to months.

3.5 Characteristics of Aquifer

From a geological point of view, aquifers are called saturated rocks or layers, from which a large amount of water flows into wells and spring (osmotic). These classifications are two functions of water table location within the subsurface, its structure and hydraulic conductivity, identify Aquifers and Unconfined Aquifers and then characterized these aquifers. The characteristics of aquifers depend on the physical properties of the underlying rock (e.g. porosity, permeability, seismic velocity). (Salako, 2018)

- **Confined Aquifer**

  Confined aquifer is an aquifer below the surface of the earth that is saturated with water. Confined Aquifers are aquifers that are found to be covered by a confining rock layer or rock bodies. Layers of impermeable material are both above and below the aquifer, causing it to be under pressure, so when the aquifer penetrates the well, water rises above it.

- **Artesian aquifer**
  An artesian aquifer is a portion of a confined aquifer in which the piezometric surface is not only above the ceiling of the aquifer, but also above ground surface. Once we have a well drilled into this aquifer, it is called an artesian well. The well is called a flowing artesian well if water reaches the ground surface under the natural pressure of the aquifer as in the figure 3.

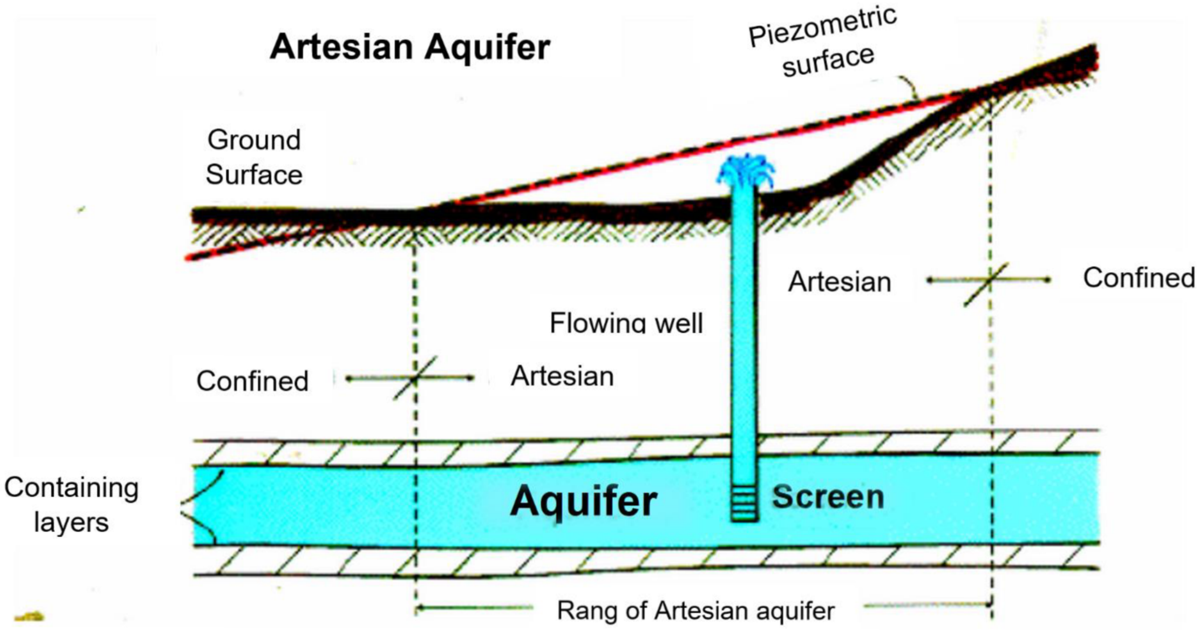


Figure 3: Geological strata giving rise to an artesian well

- **Unconfined Aquifer**
  This layer is generally found located near the land surface. This aquifer is upper water table which is under atmospheric pressure; therefore, it can rise and fall. Due to the Earth's surface than confined aquifers are, and as such are impacted by drought conditions sooner than confined aquifers. Also, it is more vulnerable to contamination from surface pollution as compared to that in confined aquifers.

3.6 Porosity

The porosity is the area voids in rocks or soil and other materials. The porosity (∅) of the aquifer is the percentage of holes occupied by water or air in the total volume of the rock, including solids and cavities These cavities have different shapes and dimensions that has different characteristics which defines the parameters that were used to replicate the ability of groundwater properties. The porosity of the aquifer is calculated as the ratio of the total pore volume to the total pore volume at the time when porosity is determined. (2)

$$\emptyset = \frac{V_v}{V_t} * 100\% \qquad (2)$$

V_v is the volume of voids (m^3)
V_t is the total volume (m^3) (ATHY, 1930)

Porosity (based on 0: 1) is usually less than 0.01 for solid granite and greater than 0.5 for peat and clay.
Porosity is an important consideration when we want to determine the potential volume of water or hydrocarbons that a rock or sediment layer can hold. Sediment porosity is a complex function of many factors, including but not limited to: burial speed, burial depth, properties of primary fluids, properties of overlying sediments (which may prevent escaping of fluids). (Athy, 1930) gives a frequently used relationship between porosity and depth which shows in the equation 3.

$$\emptyset(z) = \emptyset_0 e^{-kz} \quad (3)$$

where $\emptyset_0$ is the surface porosity (m^2), k is the compaction coefficient (m^{-1}) and z is the depth (m). (ATHY, 1930)

- **Active Porosity**
  The active porosity is an important parameter of the pore space, depending on soil structure and state. The maximal value of the active porosity of water saturated soils characterizes the volume of pores occupied by free and osmotic water. (V. I. Osipov, 2013). Active porosity is calculated by the following equation (4).

$$\emptyset_{active} = \frac{V_{pa}}{V_t} \quad (4)$$

  V_{pa} is the volume of pores from which water flows only due to gravitational influence (m^3).

- **Effective porosity**
  Effective porosity is the volume of rock porosity that contributes to the permeability of the reservoir. It is often studied to reflect the porosity of available sediment or rock. The calculation is shown as the following equation (5).

$$\emptyset_e = \frac{V_{pe}}{V_t} \quad (5)$$

  V_{pe} is the total sum of the pores where the water actually moves when groundwater flows (m^3).

Table 1:Representative values of total porosity, effective porosity (Domenico, 1979)

	Total Porosity (Dimensionless)	**Effective Porosity (Dimensionless)**
Unconsolidated Material		
Gravel	0.25 – 0.44	0.13 – 0.44
Coarse sand	0.31 – 0.46	0.18 – 0.43
Medium sand		0.16 – 0.46
Fine sand	0.25 – 0.53	0.01 – 0.46
Silt, loess	0.35 – 0.50	0.01 – 0.18
Clay	0.40 – 0.70	0.01 – 0.18
Sedimentary and Crystalline Rocks		
Karst and reef limestone	0.05 – 0.50	

Limestone, dolomite	0.00 – 0.20	0.01 – 0.24
Sandstone	0.05 – 0.30	0.10 – 0.30
Siltstone		0.21 – 0.41
Basalt	0.05 – 0.50	
Fractured crystalline rock	0.00 – 0.10	
Weathered granite	0.34 – 0.57	
Unfractured crystalline rock	0.00 – 0.05	

From table 1. We can see that the largest porosity is clay, which has 40 - 70 percent. The lowest porosity is found in fine sand, which has a porosity of about 25 - 53 percent; and, gravel that has a porosity of about 25 - 44 percent.

3.7 Permeability, hydraulic conductivity, transmissivity

Permeability, hydraulic conductivity and transmissivity are parameters that reflect the ability of the environment for recharging groundwater. In this section, will review at each of these parameters and how they are calculated.

3.7.1 Permeability

Permeability is the ability of a porous medium to pass water through a hydraulic gradient. Hydraulic gradients represent a decrease in the height of energy per unit length of groundwater flow. The permeability of each environment (soil) is different, it depends only on the physical properties of the porous medium, grain size, grain shape and arrangement, pore interconnection etc., as shown in the figure 4.

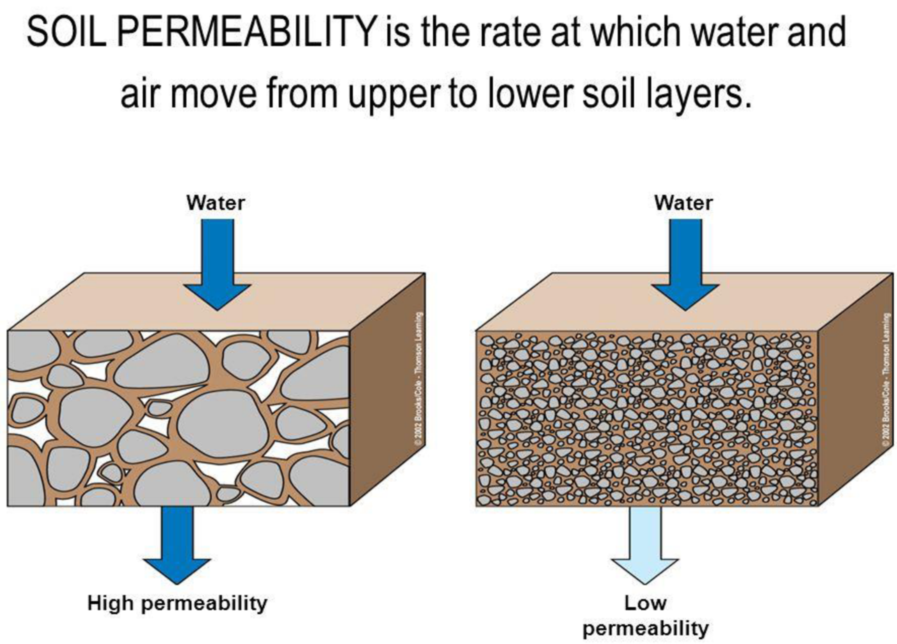


Figure 4: Soil Permeability (AG.& ENVIRONMENTAL SCIENCES ACADEMY, n.d.)

The larger the pores, the better the permeability, but this rule does not always apply. For example, the worst permeable soil is clay. This is because the pores are very small. Otherwise, for example, with thick gravel, it has very good permeability. Pore size is mainly affected by the particle size of the material. Laboratory permeability is determined. These tests include, for example, pumping tests where the amount of water pumped every second is measured and the well level is observed as a function of time. Porosity is a fundamental parameter in hydrogeology. The empirical method of Beyer and Schweiger (1969) allows the calculation of both permeability. The permeability is the function which depends on the shape and the size of a pore space of the porous media. The permeability can be expressed as the equation below:

$$k_p = Cd^2 \qquad (6)$$

Where k_p is the permeability (m^2), C is the dimensionless constant and d is the characteristic diameter of a pore with the dimension of length (m).

3.7.2 Hydraulic conductivity

hydraulic conductivity is one of many geotechnical parameters, it is simple in concept. However, it has some very complex aspects in practice, especially to obtain realistic measurements or estimates of properties.

Mathematically speaking, hydraulic conductivity is Darcy's law coefficient that relates the velocity of a stream under laminar flow conditions to a hydraulic gradient.

If we define the hydraulic conductivity to be related to the hydraulic permeability, we have:

$$K = k_p \frac{\rho g}{\mu} \qquad (7)$$

K is hydraulic conductivity (m/s)
ρ is density of fluid (kg/m^3)
g is gravity acceleration (m/s^2)
μ is dynamic viscosity of water $(Pa.s)$
k_p is the permeability of the porous medium, the units are (m^2)

3.7.3 Transmissivity

Permeability is the rate at which kinematically viscous water moves through a unit width of an aquifer under a unit pressure gradient. Used in place of the term "transmission coefficient". This is because the liquids it contains, while mobile, are generally considered a permeable aquifer property. Therefore, it is called the property of the aquifer, but also the property of the trapped liquid. (LOHMAN, 1975). Transmissivity is the property of permeate liquid in an aquifer. If we have a homogeneous environment, transmissivity is defined as the product of the hydraulic conductivity and the height of the aquifer.
Transmissivity can be calculated using the following formula: (8)

$$T = K.b \qquad (8)$$

T is transmissivity (m^2/s)
K is hydraulic conductivity $m/s)$
b is aquifer thickness (m)

3.7.4 Storage Coefficient (Storativity)

Storativity had been defined by (Theis, 1935) as volume of water that releases or stores a water-bearing layer per unit area of the water-bearing layer per change in area. Note from the definition that the storage coefficient is dimensionless. The storage coefficient of unlimited aquifers is practically the same as the specific yield, since most of the water is released by gravity drainage and only a very small part comes from the compression of the aquifers and the expansion of the water.

Calculation of storativity is shown below: (9)

$$S = \frac{dV_w}{dh} * \frac{1}{A} = S_s b + S_y \qquad (9)$$

V_w is volume of water (m^3)
A is the area (m^2)
S_s is the specific storage(m^{-1})
S_y is the specific yield (-)
b - the thickness of aquifer (m)
Furthermore, storativity can be calculated in different approaches, depend on aquifer type.

- The specific storage for a confined aquifer can be expressed as below:
  While we have compaction of the aquifer caused by increasing effective stress

$$S_s = \alpha\rho g + \beta_w\, n\, \rho\, g \qquad (10)$$

Then, we can rewrite:

$$S_s = \rho g(\alpha + n\beta_w) \qquad (11)$$

Where α – coefficient of compressibility of aquifer (m^2/N)
β_w - coefficient of compressibility of aquifer (m^2/N)
$n\ or\ \emptyset$ – porosity (m^2),
ρ – density of water (kg/m^3)
g – gravity acceleration (m/s^2)

And then storativity for confined aquifer with thickness, b:

$$S = S_s b \qquad (12)$$

- The specific storage for an unconfined aquifer can be expressed as below:

$$S = S_y + hS_s \qquad (13)$$

3.8 Darcy's Law (Basic Equation)

This law explains the water flow through an aquifer. Darcy's law (conservation of momentum) was determined experimentally by Darcy, it can be derived from the Navier-Stokes equations. Likewise, Analogous to Fourier's law, Ohm's law, or Fick's law. We normally use Darcy's law (conservation of momentum) and the continuity equation (conservation of mass), to derive the groundwater flow equation. (Pech, Environmental Hydraulics, 2017)
Equation that Darcy expressed in equation as below:

$$Q = -KA * \frac{dh}{dl} \qquad (14)$$

Q is discharge (m^3/s)
K is the hydraulic conductivity (m/s)
A is the area (m^2)
h is the piezometric head (m)
l is the distance between two observing points (m)

- **Darcy's Velocity**
  Darcy velocity $(v_D = Q/A)$ is a fictitious velocity due to it cover the flow occurs across the entire cross-section of the sediment sample. The flow actually takes place only through interconnected pore channels (voids). So, we must use the void area not total area. (Pech, Environmental Hydraulics, 2017)

$$v_D = \frac{Q}{A_v} \qquad (15)$$

where A_v is area of voids in a cross-section (m^2)

Hence, Effective porosity, $\emptyset_{eff}$ for actual groundwater velocity (seepage velocity) - v_A, we have: equation (16)

$$v_{actual} = -K\nabla h/\emptyset_{eff} \qquad (16)$$

Then,

$$v_D\ (Q) = V_{actual} * \emptyset_{eff} \qquad (17)$$

Where $-K\nabla h = q =$ specific discharge or Darcy's flux

- **Darcy's law in three dimensions**
  Darcy's law is generally valid for laminar flow and small Reynolds number Newtonian fluids in porous aquifers. Flow in homogeneous porous media is one-dimensional. (Neuman, 1977)
  During the past few decades, several theoretical analyzes of fluid flow through porous media have been reported in the literature. Some of these analyzes treat the flow as a stochastic process, while others rely on various simplified models to represent the shape of the porous media. (Neuman, 1977)

However, in the practically work, there is also the extension of Darcy's law in three dimensions by (Bear & Cheng, 2010) that is written with parameters shown in Figure 5 as follow:

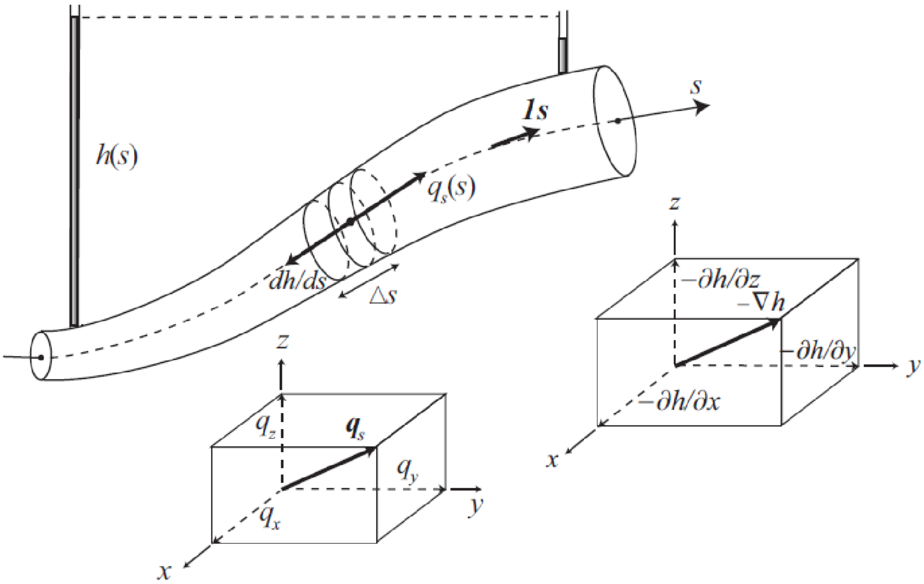


Figure 5:Three-dimensional tube of flow. (Bear & Cheng, 2010)

From the figure above, we can have the equation as follow:

$$q = -K(x, y, z)(\frac{\partial h}{\partial x} + \frac{\partial h}{\partial y} + \frac{\partial h}{\partial z}) \quad (16)$$

Where q is specific discharge and $\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \frac{\partial h}{\partial z}$ or (∇h) are three dimensional components of the hydraulic gradient vector. The porous medium is called an anisotropic medium If the permeability of an aquifer at a point is independent of direction. The equation (17) expresses Darcy's law for anisotropic media.

$$q_x = K_x \cdot \frac{\partial h}{\partial x}, \qquad q_y = K_y \cdot \frac{\partial h}{\partial y}$$

$$and\ q_z = K_z \cdot \frac{\partial h}{\partial z} \quad (17)$$

- **Validity of Darcy's Law**
  The Darcy's validity explained by using Reynold number as the following:

Once, $Re_f(0-1)$ – Darcy equation is valid

$Re_f(1-10)$ – Darcy equation is also valid

If $a = 1/K$

$v = -KJ \longrightarrow J = av$

$Re_f(10-100)$ – Non-Darcian flow (Darcy equation is not valid), we can use the equation in form:

$$J = av + b.v^m \qquad (18)$$

where $m = 1.6 - 2.0$

$Re_f > 100$ – Turbulent flow (Darcy equation is not valid) then for hydraulic gradient we must use:

$$J = b\,v^2 \qquad (19)$$

3.9 Non Darcian Groundwater Motion

Darcy's law expresses the linear relationship between specific flow (q) and hydraulic gradient (J) but this situation only occurs at low Reynolds number ($Re < 1$) as show in the equations (18 and 19). Though, in some cases, the liner relation between specific storage (q) and hydraulic gradient (J) is not linear as shown in Figure (6). So turbulent microscopic flow is definitely non-Darcy.

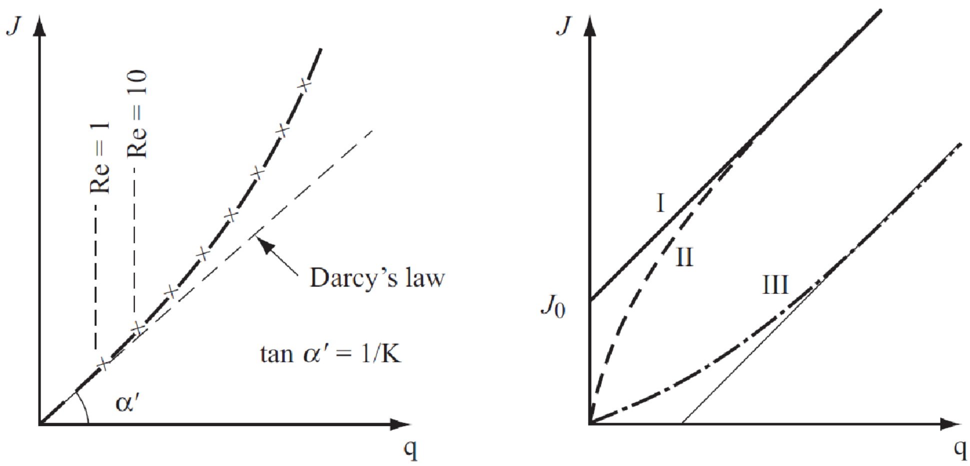


Figure 6: Relationship between hydraulic gradient (J) and specific discharge (q) (Bear & Cheng, 2010)

Darcy's law is an approximation that describes the flow of a fluid in a porous medium and is effective over a limited range of low speeds. Therefore, Reynolds number is

used to identify if the flow is laminar, turbulent or transient flow of fluid. Flow of groundwater, mostly has a Reynolds number less than 1. Nevertheless, 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. (Firdaouss, Guermond, & Quere, 1997).
It is proposed to solve the non-Darcian flow in two phases by combining the volume of the depressive cone and the concepts of variation of well pumping. The straightforward view is that if the flow coming from the elastic storage of the aquifer can be isolated from the leakage contribution, the aquifer can be considered confined aquifer with only a flexible contribution from the reservoir to the well.
Thus, 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, 2009)

3.10 Continuity equations

The continuity comparison reflects the fact that mass is retained in any non-nuclear continuum mechanical analysis. The approach compares by adding the rates of mass inflow and outflow control volumes and comparing the net inflow with the rate of mass change contained in it. This is demonstrated in the figure below. (Bob McGinty, 2012)

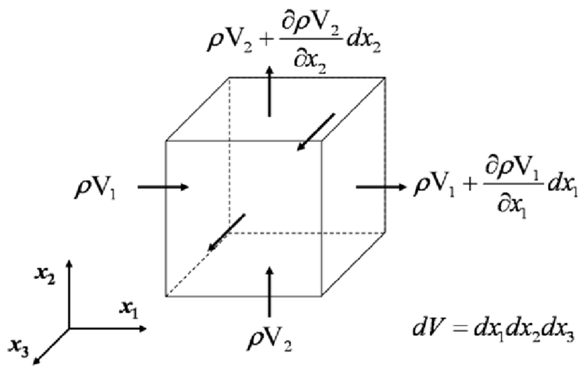


Figure 7: the continuity equation.

Once we assume that Mass for inflow mass outflow rate = 0

We have, flow in … $dy.dz$

$$(\rho v_x)dydz$$

flow out … $dy.dz$

So, $$\left((\rho v_x) + \frac{\partial(\rho v_x)}{\partial x}dx\right)dz\,dy$$

Flow in = Flow out (Continuity equation)

$$-\left(\frac{\partial(\rho v_x)}{\partial x}\right)dx\,dz\,dy$$

$$(\rho v_x)dy\,dz - \left((\rho v_x) + \frac{\partial(\rho v_x)}{\partial x}dx\right)dz\,dy = 0 \quad \Longrightarrow$$

(20)

For the confined aquifer, the flow and the flow are stead state, the continuity equation expressed as the following equation. (Pech, Environmental Hydraulics, 2017)
Balance of mass for x, y, z:

$$-\left(\frac{\partial(\rho v_x)}{\partial x}\right)dx\,dy\,dz - \left(\frac{\partial(\rho v_y)}{\partial y}\right)dx\,dy\,dz - \left(\frac{\partial(\rho v_z)}{\partial z}\right)dx\,dy\,dz = 0 \ldots\ldots./$$

$$\Downarrow$$

$$-\left(\frac{\partial(\rho v_x)}{\partial x}\right) - \left(\frac{\partial(\rho v_y)}{\partial y}\right) - \left(\frac{\partial(\rho v_z)}{\partial z}\right) = 0 \qquad (21)$$

While, incompressible liquid ρ = constant

Then, continuity equation for steady flow expressed as:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \qquad (22)$$

4. Well test

The main objective of well testing when drilling a well is to test and evaluate the target formation. Well tests are typically used to evaluate aquifer parameters and formation damage before and after workovers. Moreover, conducting a well test is one of the normal method of investigating the reservoir. Well test is basically a period during which the production of the well is measured, either at the well head with portable well test equipment, or in a production facility. (Spivey & Lee, 2013).
The main purpose of a well test is to determine aquifer parameters, storativity,S and transmissivity,T and the productivity of a new well. Well testing involves a variety of measurements and different types of downhole equipment to gather information about well properties.

There are two methods that are in common usage for calculating aquifer coefficients from time-drawdown data. Both approaches are graphical. The first involves curve matching on a log-log plot (the Theis type-curve method), and the second involves interpretations with a semilog plot (the Cooper-Jacob method).

4.1 Unsteady-state flow

4.1.1 Theis's method

The idea for unsteady-state flow, was first introduced by (Theis, 1935). He came up with formula that introduces the time factor and the storativity.

Similarly, Theis stated that the influence of the discharge extends outward with time when a well penetrating an extensive confined aquifer is pumped at a constant rate. The rate of decline of head, multiplied by the storage coefficient and summed over the area of influence, equals to discharge. (Kruseman, 2000)

The equation that (Theis, 1935) derived for the transient flow of groundwater to a well, was originally for fully penetrating well in a confined aquifer. However, the equation may also be used for unconfined aquifer if the drawdown is considerably smaller than the saturated thickness.

Basic equation – for the radial symmetric flow of groundwater under unsteady regime is (Theis, 1935)

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial \mathrm{s}}{\partial \mathrm{r}} = \frac{\mathrm{S}}{T}\frac{\partial \mathrm{s}}{\partial \mathrm{t}} \qquad (23)$$

where
s – drawdown (m)
r – radial distance (m)
S – storativity (-)
T – transmissivity (m^2/s)
t – time (s)

The assumptions for solving this equation

it is a flow in confined aquifer to a complete well:

- gravitational forces are negligible
- constant density and viscosity of water
- aquifer has infinite areal extent
- pumping well fully penetrate full thickness of the aquifer
- flow to pumping well is horizontal
- flow is unsteady
- (diameter of a pumping well is very small (negligible) so that storage in the well can be neglected)
- the well is pumped with constant rate Q
- aquifer is horizontal and bounded on bottom and on the top by impermeable layers (confined aquifer)
- aquifer flow to the pumped well is radial and laminar, so Darcy's law is applied
- the confined aquifer is homogeneous and isotropic
- the height of the aquifer where the flows to the well is constant and has a size b; transmissivity, T and storativity (aquifer storage), S are constant over time and space
- the water supply from the aquifer to the well changes during the pumping test from Qaq = 0 to final inflow Qaq = Q = const.

- before pumping begins i.e. for t = 0 the hydraulic head is in all points of the aquatic environment constant and equals H - this also applies to the water level at a well

A standard type curve was developed by Theis which relates the theoretical response of an aquifer to pumping. The Theis solution of equation (23) is

$$s = \frac{Q}{4\pi T} W(u) \qquad (24)$$

Where s – drawdown (m)
Q - pumping rate (m^3/s)
$W(u)$ – Theis well function (-)
T – transmissivity (m^2/s)
u – argument of Theis function

The type curve is obtained by plotting $W(u)$ (the well function of u) vs. $1/u$ where:

$$W(u) = -0.5722 - ln \ u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \cdots \qquad (25)$$

and argument of Theis function is:

$$u = \frac{r^2 S}{4Tt} \qquad (26)$$

where: r is distance from the pumping well to the observation well (m),
t is time (s)
According to Theis, the drawdown of an aquifer (m) at a given distance, r from the pumping well at time, t is related to $W(u)$:

$$s = \frac{Q}{4\pi T} W(u) \qquad (27)$$

Using equations (25), (26) and (27) with time-drawdown data from an aquifer test, S and T for the aquifer can be calculated. Nevertheless, an analytical solution for the equations is involved and a graphical solution is commonly used instead.

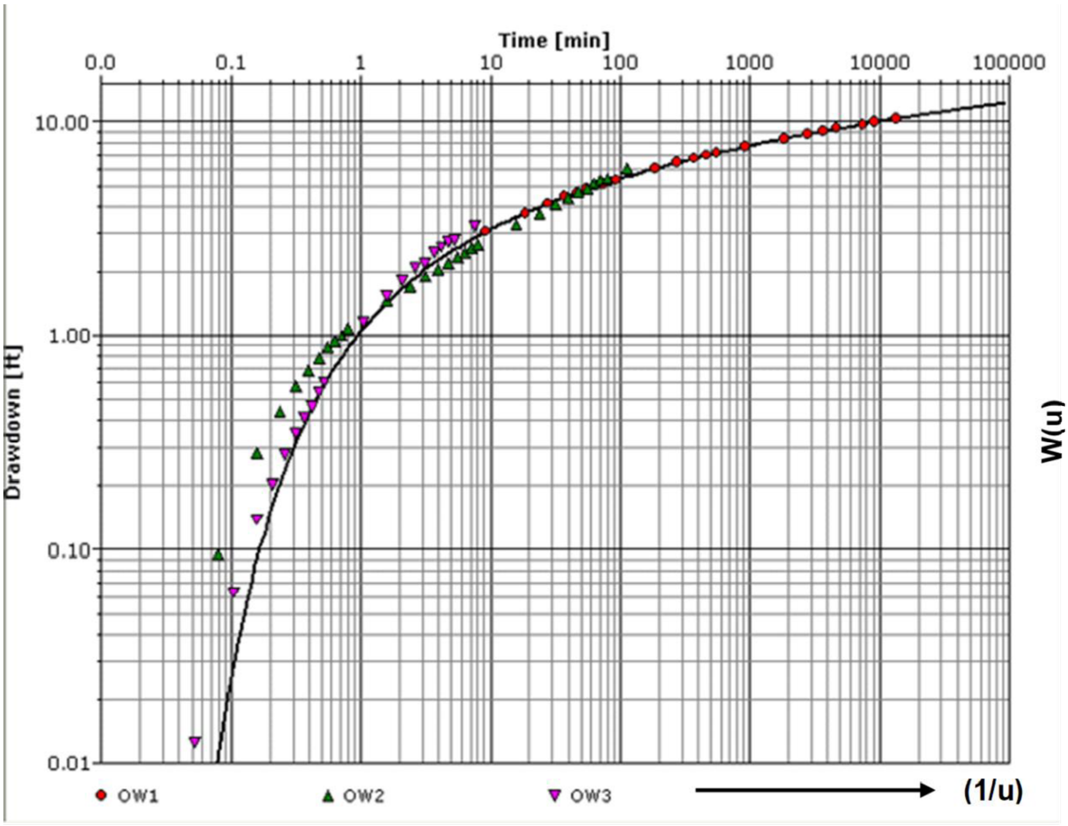


Figure 8: An example of the Theis graph (Waterloo Hydrogeologic, 2018)

4.1.2 Cooper-Jacob's Method

The Cooper-Jacob method (Cooper and Jacob 1946) is a late approximation derived based on Theis-type curve method. To estimate the well function $W(u)$, this method involves truncation of the infinite Taylor series need to be used. Not all initial time measurement data is considered valid for this method of analysis because of this truncation. For $1/u$ we can use the two terms of equation (25) with the difference 0.25 %. The resulting equation is:

$$s = (\frac{2.3Q}{4\pi T})\ log_{10}(\frac{2.25Tt}{Sr^2}) \qquad (28)$$

This solution is appropriate for the conditions shown in the following figure (9).

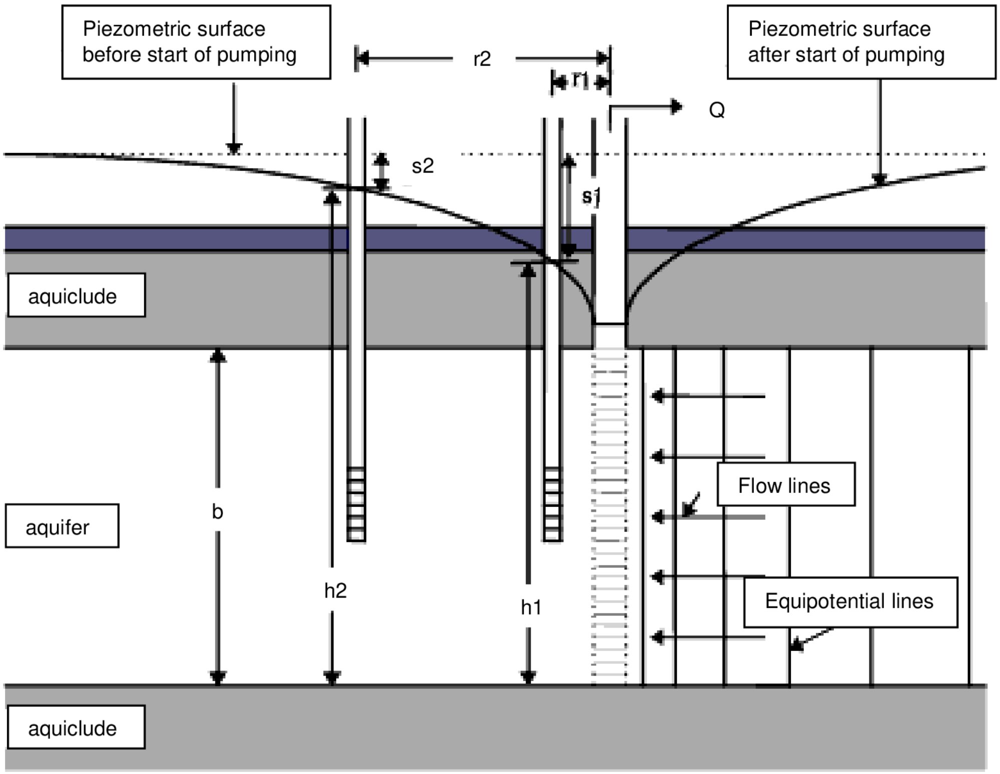


Figure 9: Appropriation solution for the conditions (Waterloo Hydrogeologic, 2018)

The Cooper-Jacob solution assumes the following:

- The aquifer is confined and has an "apparent" infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is pumped at a constant rate
- The well is fully penetrating
- Water removed from storage is discharged instantaneously with decline in head
- The well diameter is small, so well storage is negligible
- The values of u are small (rule of thumb $u < 0.01$) (Waterloo Hydrogeologic, 2018)

Cooper-Jacob: Time-Drawdown Method

From the equation 28 when the limiting condition is met, plots as a straight line on semi-logarithmic paper. Thus, after sufficient time has elapsed, straight-line plots of drawdown versus time can ensue. In pumping tests with multiple observation wells, the closer wells will meet the conditions before the more distant ones. Time is plotted along the logarithmic X axis and drawdown is plotted along the linear Y axis. (Waterloo Hydrogeologic, 2018)

The slope of the straight-line at an observation well (see figure. 10) intercepts the time-axis, where $s = 0$. Consequently, the interception point has the coordinates $s = 0 \, and \, t = t_0$ (Batu, 1998)

Transmissivity and storativity are calculated as follows:

$$T = \frac{2.3Q}{4\pi\Delta s} \qquad (29)$$

where Δs is the difference drawdowns $s_2 - s_1$, for times t_2 and t_1, which is lying on the straight-line in semilog graph s vs. $log\ t$

$$S = \frac{2.25Tt_0}{r^2} \qquad (30)$$

t_0 – time for $s = 0\ (s)$

An example of a Cooper-Jacob Time-Drawdown analysis graph has been included below:

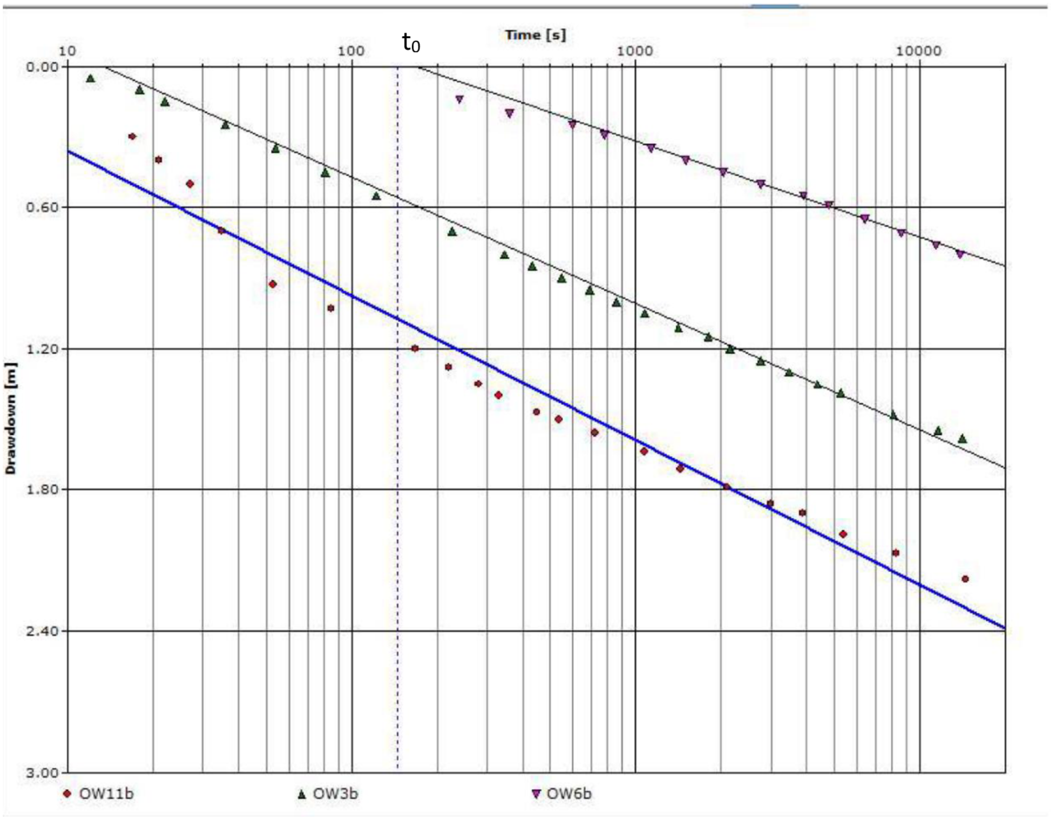


Figure 10: example of a Cooper-Jacob Time-Distance-Drawdown analysis graph. (Waterloo Hydrogeologic, 2018)

For the Cooper-Jacob Time-Distance-Drawdown Solution Method The data requirements are:

- Drawdown vs. time data at three or more observation wells
- Distance from the pumping well to the observation wells
- Pumping rate (constant)

5. Additional Resistance

Additional resistances arise on the actual well. Due to the additional resistances, there is a difference in the measured values between the actual well and the theoretical assumption for an ideal well. Additional resistances may already occur during the construction of the well, such as sludge bark. This creates a thin, less permeable layer.

Estimating these resistors is very difficult and can include many errors. All of these total resistances can be evaluated by comparing actual tests to ideal well conditions, and well conditions can provide overall additional resistance.
Moreover, other causes of additional resistance on the well are various hydromechanical, chemical, biological and other phenomena that may occur on the well and its surroundings during the exploitation of the well. (Pech, 2010)

Therefore, in order to calculate the total drawdown caused by additional resistance at our sampling well, equation (31) is used. (Pech, 2010)

$$s_W = s_K + s_F + s_P + s_I + s_T + s_T + s_{TP} + s_O \qquad (31)$$

Where s_w is the reduction due to additional resistances and on the right side of the equation there are partial reductions that are divided by reduction due to borehole perpendicularity (s_K), reduction of borehole wall active section (s_F), incomplete penetration (s_P), blockage (s_I) (s_T), turbulent flow mode (s_{TP}) and other types of additional resistors (s_O).
Since the additional resistances are poorly expressed, a total dimensionless coefficient W is used to calculate the reduction of water level overall as the equation (33) below:

$$s_v = s_{te} + s_w \qquad (32)$$

Where s_v is the total level reduction (m), s_{te} is the theoretical level reduction (m) and s_w is the level reduction due to additional resistances (m).

According to (Van Everdingen,1953), if we neglect the additional resistances due to friction and the turbulent flow regime, then we can use the linear relation (33) to calculate the additional reduction of water in the well due to the additional resistances.

$$s_w = \frac{Q}{2\pi T} W \qquad (33)$$

where W is dimensionless coefficient of additional resistances (skin factor) and Q is the pumping rate.
Relationships for calculation of total water level reduction in steady-state flow (33) and non-steady-state flow, where we calculate the total reduction by substituting into Theis equation (27) and then for dimensionless time $\frac{1}{u} > 100$ (36). (Pech, 2010)

- for steady flow

$$s_v = \frac{Q}{2\pi T}\left(ln\frac{R}{r_v} + W\right) \qquad (34)$$

- for unsteady flow

$$s_v = \frac{Q}{4\pi T}(W(u) + 2W) \qquad (35)$$

- for Cooper-Jacob analysis

$$s_v = \frac{Q}{4\pi T}\left(ln\frac{2{,}246Tt}{r_v^2 S} + 2W\right) \qquad (36)$$

If we want to find the difference between times t_1 and t_2 then,

$$s_2 - s_1 = \Delta S = \frac{Q}{4\pi T}(ln\frac{2{,}246T}{r_v^2 S} + \ln t_2 + 2W - \ln\frac{2{,}246T}{r_v^2 S} - \ln t_2 - 2W) \qquad (37)$$

After adjustment, we can have equation (38) for evaluation transmissivity, T

$$\Delta s = \frac{Q}{4\pi T}\left(ln\frac{t_2}{t_1}\right) \qquad (38)$$

5.1 Chemical Resistance

We know that chemicals existing in the water are usually in freshen form unless a treatment method focusses the contaminant. In many types of plastic pipe are used for service encountered in treatment of contaminated groundwater and leachate, as well as well construction.

Any damage to pipes by dilute chemicals will be gradual and may result in pipe swelling and loss of strength over time. So, it is important to see suitability of a material for various chemical concentrations and temperatures. When increased temperatures, some chemicals become more aggressive and attack some materials. Also, the plastics may soften and lose strength at elevated temperatures which reduces the safe pressure rating. So, it is very important to consider material selection due to the interaction of temperature and concentration. (The U.S. Environmental Protection Agency, (EPA), 1994)

Hence, there must be a proper way to select materials for construction, as table (3).

Table 2: Guideline for selecting proper materials of construction.
(The U.S. Environmental Protection Agency, (EPA), 1994)

		Suitable Material of Construction				
Application	Carbon Steel	Stainless Steel	Fiberglass	Plastics	Elastomers	Coatings
Skids	x					x
Panels	x	x	x			
Pressure vessels	x	x	x			x
Small tanks		x	x	x		
Large tanks	x					x
Gaskets					x	
Hoses				x	x	
Acid service		x	x	x	x	
Base service	x		x	x	x	
Solvents	x	x			x	
Structures	x		x			x
Covers			x			
Biogas storage	x			x	x	
Pumps	x	x	x	x	x	
Mixers		x				x

Besides, selecting materials of construction and coatings compatibility for Ground-Water/Leachate as shown in the table of example below:

Table 3: Materials of Construction and Coatings Compatibility for Ground-Water/Leachate Treatment Systems. (The U.S. Environmental Protection Agency, (EPA), 1994)

	Materials of Construction								Elastomers							Coatings	
Contaminant	**Carbon Steel**	**SS**	**PVC**	**HDPE**	**PP**	**PVDF**	**PTFE**	**Fiber-glass**	**Rubber**	**Neoprene**	**Buna-N**	**Hypalon**	**EPT/EPDM**	**Viton**	**Teflon**	**Phe-nolic Expoxy**	**Poly-mide Polyester**
Arsenic	NR	C	C	E	200	275	450	E	NR	E	C	NR	NR	NR	E	C	NDF
Benzene	E	E	NR	C	NR	150	450	NR	NR	NR	C	NR	NR	E	E	C	C
Acadmium	NDF	NDF	G	NDF	NDF	NDF	NDF	E	NR	E	NR	E	NR	NR	E	NDF	NDF
Chloroform	NR	E	NR	C	NR	125	450	NR	NR	NR	NR	NR	NR	E	E	NR	NR
Chromium and compounds	NR	C	C	E	125	175	450	C	C	C	C	C	C	E	E	NDF	NDF
Copper andcompounds	NR	E	E	E	175	225	450	E	E	E	E	E	E	E	E	E	NDF
1,1 - Dichloroethane (1,1-DCA)	NDF	NDF	NDF	C	175	125	450	NR	NR	NR	NR	NR	NR	E	E	NDF	NR
1,1-Dichloroethylene (1,1-DCE)	NDF	C	NR	NR	125	225	450	NR	NR	NR	NR	NR	NR	E	E	NDF	NDF
1,2-trans-Dichlorethylene (1,2-trans-DCE)	NDF	C	NDF	NR	124	225	450	NDF	NR	NR	NR	NR	NR	E	E	NDF	NDF
Ethylbenzene	C	E	NR	C	NR	125	450	NR	NR	NR	NR	NR	NR	E	E	NDF	NDF
Lead	C	C	C	E	NDF	NDF	NDF	NDF	C	C	G	C	C	E	E	NDF	NDF
Methylen chloride	NR	E	NR	C	NR	125	450	NR	NR	NR	NR	NR	C	G	E	NR	NR
Polychlorinated biphenyls (PCBs)	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NR	NR	NR	NR	NR	E	E	NDF	NDF
Perchloroethylene (PCE)	C	E	NDF	C	NR	275	450	G	NR	NR	NR	NR	NR	E	E	E	C
Phenol	NR	E	NR	SS	150	125	450	NR	E	G	NR	G	NR	G	E	C	NR
Toluene	E	E	NR	C	NR	175	450	C	NR	NR	C	NR	NR	E	E	G	C
1,1,1-Trichloroethane (1,1,2-TCE)	NDF	NDF	NDF	C	NR	150	450	C	NR	NR	NR	NR	NR	E	E	C	NR
1,1,2-Trichloroethylene (1,1,2-TCE)	C	E	NR	C	NR	275	450	NDF	NR	NR	NR	NR	NR	E	E	NR	NR
Xylenes	E	E	NR	C	NR	200	450	NDF	NR	NR	C	NR	NR	E	E	E	E
Zinc and compounds	NR	C	E	E	175	200	450	NDF	G	C	C	C	E	E	E	C	C

Key

C	Conditional; consult supplier	NDPE	High density polythylene	PVC	Polyvinyl chloride
E	Excellent, all concentrations	NDF	No data found	PVDF	Polyvinyl idene fluoride (Kynar)
EPT/EPDM	Ethylene-polyplene Diene-terpolymer	NR	not recommended	SS	Stainless steel
G	Good, low concentrations preferred	PP	Polypropylene	200, etc.	Suitable to temperature show, F
		PTFE	Polytetrafluoroethlene (Teflon)		

The information in the table 3, lists the coatings that can be applied to steel or concrete, which significantly improves the corrosion resistance of these materials. Usually, surface preparation is required. Also, Sandblasting and chemical etching with acid are common applied. Some coatings may be applied on the steel rust, but their service life will not long-lasting. Application instructions are included with each product. The designer should contact the coating supplier for recommendations on suitable products.

5.2 Hydromechanical Resistance

Hydromechanical resistance contains conditions such as stiffness, scratch resistance, abrasion resistance, slip resistance, bearing resistance, flexibility and formability.

These mentioned activities, may happen during or after the construction. For example, while digging and especially equipping of sampling boreholes

The mechanical resistance of a component or work piece refers to its behavior under the influence of mechanical forces. These include elasticity, viscosity, hardness and brittleness as well as stiffness under high stresses; for instance, pressure or traction.

So, the optimal solution it is mainly important to be aware of the mechanical stresses employed on the component. This adhesion may not be reduced via mechanical stresses such as vibration, deformation, elongation, pressure or impact If effective corrosion protection is to be achieved.
Materials used for construction or parts of pump, especially subsurface should be considered carefully. This is also related to choosing suitable materials of construction in the table: 2.

5.3 Biological Resistance

Biological processes are sensible to organic and in organic toxicity. The result is inhibition of biological activity. Heavy metals retard cellular metabolism by disrupting protein functions in enzyme systems (Nyer, 1992). However, acclimation of biological sludges to metals can increase the toxic threshold of the microbial population which will enhance biological treatment performance.

Some organic compounds can also exhibit toxicity. Phenol, for example, can be toxic at high concentrations but is biodegradable at low concentrations (W. Eckenfelder, 1999). (Brusseau, 1993) reported biodegradation occurring at alcohol concentrations of less than 1 percent and concentrations greater than 10 percent causing toxicity to microorganisms.
On the other hand, protein and cellular integrity can be attacked or destroyed if there are high concentrations of oxidizing agents such as chlorine, ozone, and hydrogen peroxide, which results in decreased biological activity.

6. Method and materials

This part focus on materials and methods use for the evaluation of the skin factor. We have pumping well and observation well. Then, each well is pumped out to observe the giving drawdown of hydraulic head at the pumping and observation wells. And, perceive if there is any factor 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 describe 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.

6.1 Research plan

In order to achieve the primary objectives of this research, the actual test data were well gathered. This field test data had to be prepared for test well analysis; especially, for drawdown observation in both pumping well and observation well. For this test, a large number of observations were collected in February 2015. In addition, the well test data reflected significant variations that needed to be smoothed out before analysis. Data collection from pumping well and observation well included date and time, head, draw-down and discharge. For more details for data collection, please see the table (4) below.

Table 4: Formats for taking data from pumping well.

Sr. No.	Date/ Time	Time, t [min]	H logger [m]	H logger [m from O.B]	Drawdown (s) [m] - pumping well	H manually [m from O.B.]	Discharge (Q) RD2[l/s]

This format, applied to both pumping well and observation well which were used to to evaluate the storativity and the transmissivity.

7. Area of interest

RD-2 (Radouň)

7.1 Location:

The RD-2 well is located in Central-North Bohemia (Czech Republic) within the Radouň pumping site, operated by a major regional waterworks company. The site with its 3 pumping wells represents one of several backbone water sources in the regional drinking water supply supporting via a major water feeder urban and industrial area

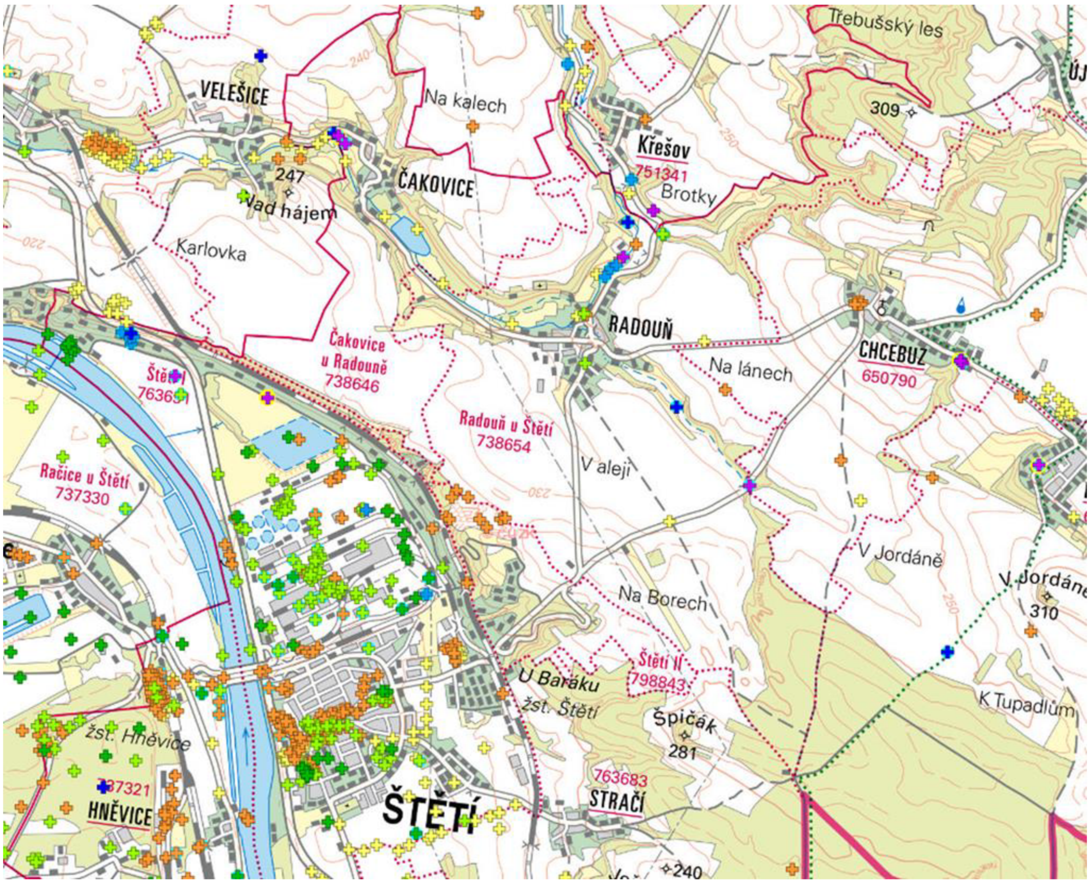


Figure 11: Drilling exploration Map in Czech Republic (Czech Geological Survey, 2020)

between Mělník and Ústí nad Labem. Typical operational pumping rates are very high – up to 55 m^3/h. The well RD-2 is of 50 depths with plywood casing.

7.2 Geology and lithology:

The pumping site is located within the lower part of the Bohemian Cretaceous Basin in relatively shallow sandstone rocks of Cenomanic age. The groundwater table is strongly confined (even with occurrence of artesian wells) with an overlaying aquitard consisting of Turonian marls and marlites. The groundwater flow is strongly bound to fractures in the bedrock forming a typical dual-porosity filtration environment.

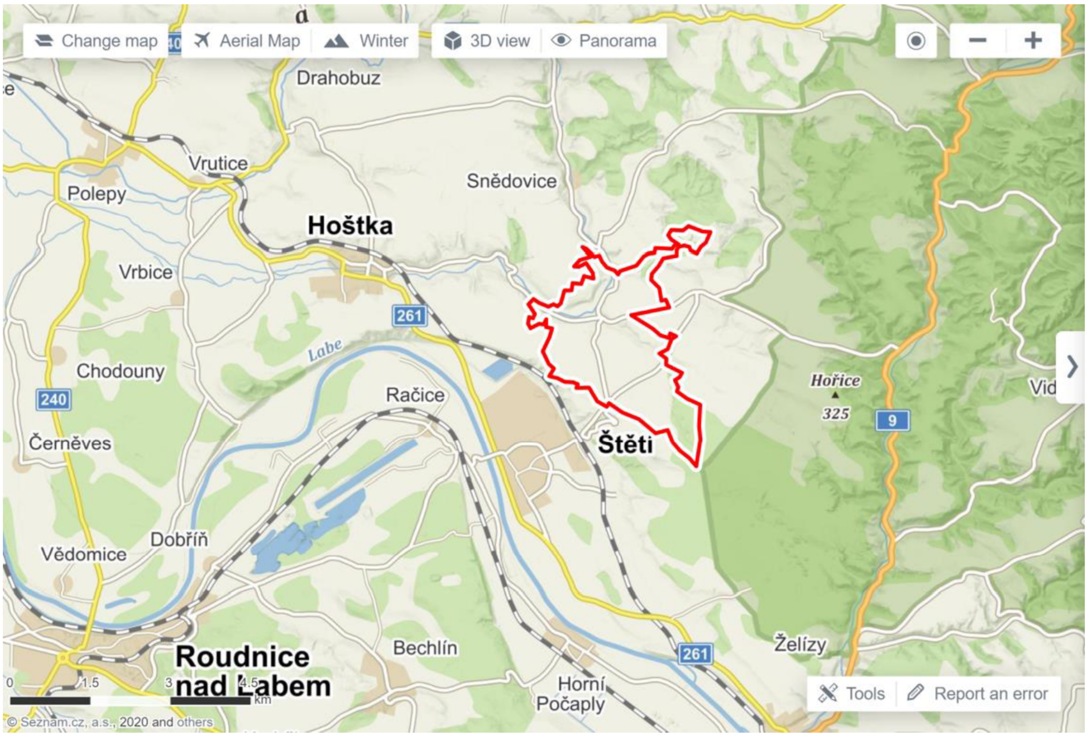


Figure 12: Radoun Area in the Czech Republic Map (Mapy.cz, 2020)

7.3 Well rehabilitation:

The rehabilitation works were performed during spring 2015. Due to doubts about the resistance of the plywood casing (resp. durability of the specific resin towards acids) the rehabilitation techniques were limited to mechanical air-lift sediment pumping with a limited assistance of nylon brushes.

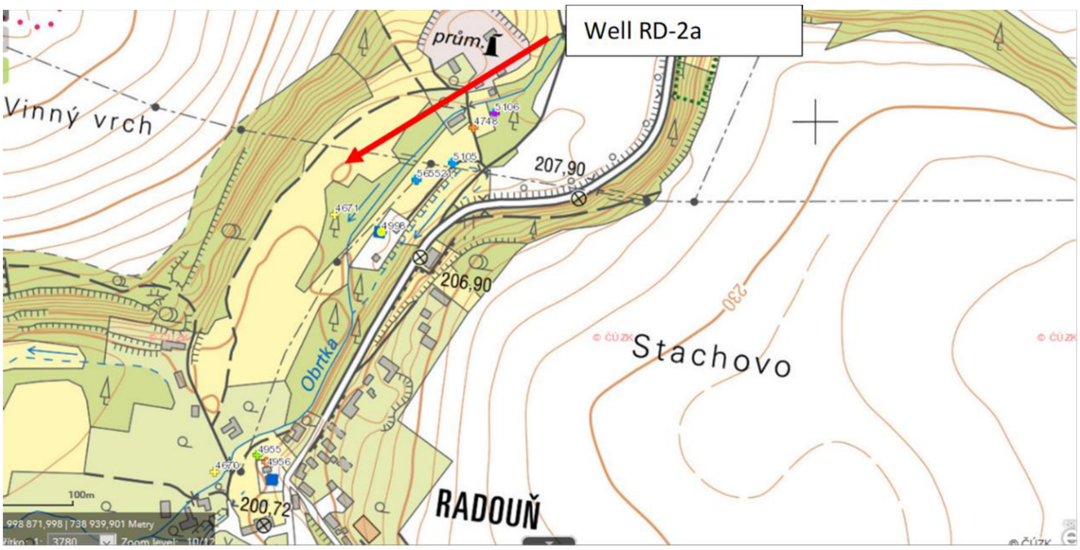


Figure 13: Map shows Radoun well site (Czech Geological Survey, 2020)

8. Evaluation of Additional Resistance

The additional resistances can be evaluated to compare resulted values of the pumping well in actual condition with observation well in the same area and the same condition. The total drawdown can be evaluated from adjusting the equation (36).

$$s_v = \frac{Q}{4\pi T}(ln\frac{2.25Tt}{r_v^2 S} + 2W)$$

Then, for the difference of resistance at time t_1 and t_2 from equation (36) the following applies:

$$s_2 - s_1 = \Delta s = \frac{Q}{4\pi T}(ln\frac{2,246T}{r_v^2 S} + \ln t_2 + 2W - \ln(\frac{2,246T}{r_v^2 S} - \ln t_2 - 2W) \quad (37)$$

After adjustment, we can have equation (38)

$$\Delta s = \frac{Q}{4\pi T}\left(ln\frac{t_2}{t_1}\right) \quad (38)$$

The additional drawdown caused by the skin factor is expressed from the equation (33).

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

After that the additional drawdown differences between before and after cleaning can be evaluated according to equation (39):

$$s_{skin\ldots before} - s_{skin\ldots afer} \quad (39)$$

9. Results

Drawdown was recorded at a constant discharge rate (Q) and time (t) in before and after cleaning pumping tests.

9.1 The Pumping Test Before Well Cleaning (I)

9.1.1 Pumping Well (RD2)

a. Application in Excel

First, the calculation of the difference in time from the beginning of the pumping test to the end of the pumping test, and then we logged the difference in second. For both boreholes, we calculated the difference in water level reduction for the individual times since the beginning of the measurement (Table 5).

Table 5: Table of measured values of the pumping test in February 2015

RD2	Date + Time	t[min]	logt[min]	time [sec]	Hlogger/ column[m]	Hlogger[m from O.B.]	drawdown s[m]	$H_{manually}$ [m from O.B.]	QRD2 [l/s]
	2/21/15 12:03 PM	-		0	11.3772	0.6250	0.0000	0.6250	0.0
	2/21/15 12:03 PM	0.02	-1.7782	1	10.7459	1.2563	0.6313		14.8
	2/21/15 12:03 PM	0.03	-1.4771	2	11.4044	0.5978	-0.0272		14.8
	2/21/15 12:03 PM	0.05	-1.301	3	11.3959	0.6063	-0.0187		14.8
	2/21/15 12:03 PM	0.07	-1.1761	4	11.3605	0.6417	0.0167		14.8
	2/21/15 12:03 PM	0.08	-1.0792	5	11.3505	0.6517	0.0267		14.8
	2/21/15 12:03 PM	0.10	-1	6	11.3314	0.6708	0.0458		14.8
	2/21/15 12:03 PM	0.12	-0.9331	7	11.2906	0.7116	0.0866		14.8
	2/21/15 12:03 PM	0.13	-0.8751	8	11.2539	0.7483	0.1233		14.8
	2/21/15 12:03 PM	0.15	-0.8239	9	11.2080	0.7942	0.1692		14.8
	2/21/15 12:03 PM	0.17	-0.7782	10	11.1665	0.8357	0.2107		14.8
	2/21/15 2:07 PM	124.70	2.09587	7482	7.1994	4.8028	4.1778		14.8
	2/21/15 2:08 PM	124.72	2.09592	7483	7.1983	4.8039	4.1789		14.8

The table (5) is only part of all the evaluation from the beginning of pumping to the end of pumping. However, the additional information, also showed the evaluation after pumping (recovery time of drawdown) immediately from the ending of pumping time as show in the table 6 below.

Table 6: Table of measured values of the pumping test in February 2015 (After ending pumping)

	2/21/15 2:08 PM	0.03	-1.4771	2	7.2541	4.7481	4.1231		0.0
	2/21/15 2:08 PM	0.05	-1.301	3	7.3089	4.6933	4.0683		0.0
	2/21/15 2:08 PM	0.07	-1.1761	4	7.3622	4.6400	4.0150		0.0
	2/21/15 2:08 PM	0.08	-1.0792	5	7.4166	4.5856	3.9606		0.0
	2/21/15 2:28 PM	20.88	1.3198	1253	11.2251	0.7771	0.1521		0.0
	2/21/15 2:28 PM	20.90	1.32015	1254	11.2291	0.7731	0.1481		0.0

b. Calculation of Transmissivity (T)

To calculate the transmissivity, the pumping test graph (Figure: 14) need to be plotted which the relation of the reduced water level (drawdown) on time. The x-axis shows the time in minutes and the y-axis the increase of the drawdown at the borehole. Also, the calculation of slope the equation (40) is applied by cutting the slope times with a line.

$$i = (s_2 - s_1)/(\log t_2 - \log t_1) \quad (40)$$

Where s_2 is the value of drawdown corresponding to time t_2 and the beginning point of calculation is s_1. The discharge rate was around 14.8 l/s or 0.0148 m^3/s

From the table 5, we can plot the graph below:

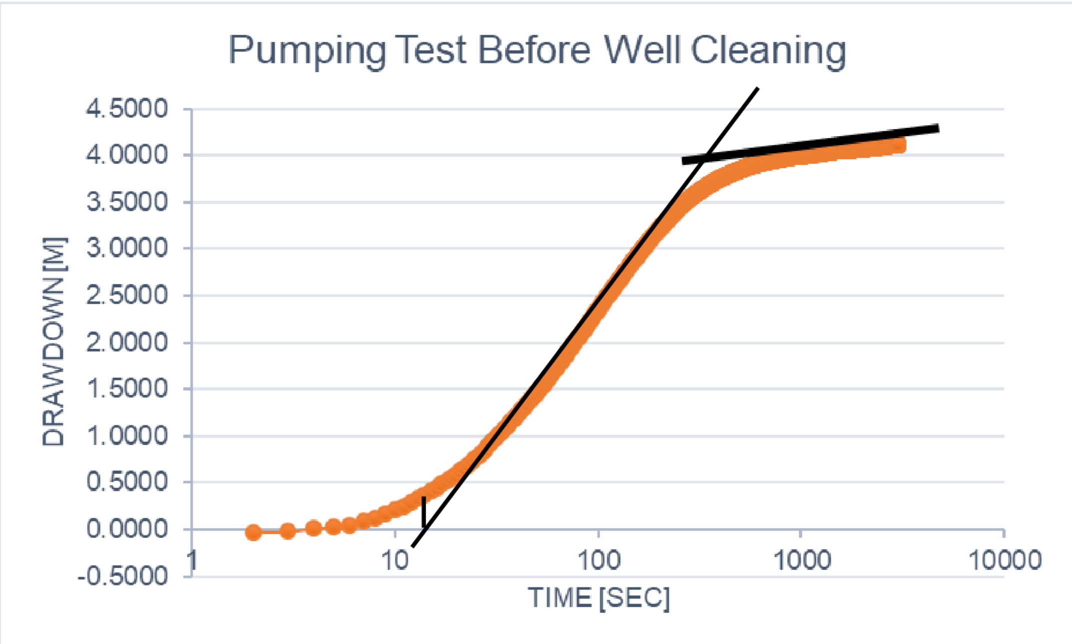


Figure 14: The graph of the drawdown vs time plotted on logarithmic scale.

$s^* = 0.35$ m

From the graph figure14, we can calculate the transmissivity (T), by using the equation (41) we can rewrite equation (41) as express below.

$$T = 0.183 \frac{Q}{i} \quad (41)$$

From the plotted graph figure 14, I used the point where time (t_1) at 500th second which had value of drawdown (s_1) equal to 3.8473 m and time (t_2) at 2000th second which had value of drawdown (s_2) equal to 4.0682 m.

So, from the equation 40, we have:

$$i = \frac{4.0682 - 3.8473}{\log(2000) - \log(500)}$$

$$i = 0.3669$$

From this, we can calculate Transmissivity value as:

$$T = 0.183 \frac{0.0148}{0.3669}$$

Then,

T =	**0.0074 m^2.s^{-1}**

c. Calculation for Storage Coefficient

The calculation for pumping well for storativity, values of drawdown on well RD2 that corresponded to logarithmic times. Again, we have plotted a line through the graph, which goes through the values, where the difference is approximately the same and that goes through the x-axis, where we get the desired time t_0. This time, however, is logarithmic and is in minutes, so we unlogged it and converted it to seconds.

$$S = 2.246 \frac{Tt_0}{r^2} \tag{42}$$

$$S = 2{,}246 \frac{0.007082 \ * 60}{40^2}$$

S =	**0.00062**

d. Wellbore storage calculation and coefficient of additional drawdown

According to (Ramey, 1970), the beginning of the pump test, a straight line with a "unit slope" can be seen on the pumping test (from several seconds to approximately several minutes, depending on the well diameter and pumping rate).

Table 7: time (s) vs. drawdown (m). Several seconds selected from the beginning of pumping

Time [s]	Drawdown [m]
4	0.0167
5	0.0267
6	0.0458
7	0.0866
8	0.1233
9	0.1692
10	0.2107

From the drawdown table 7, we can plot the graph, as figure below:

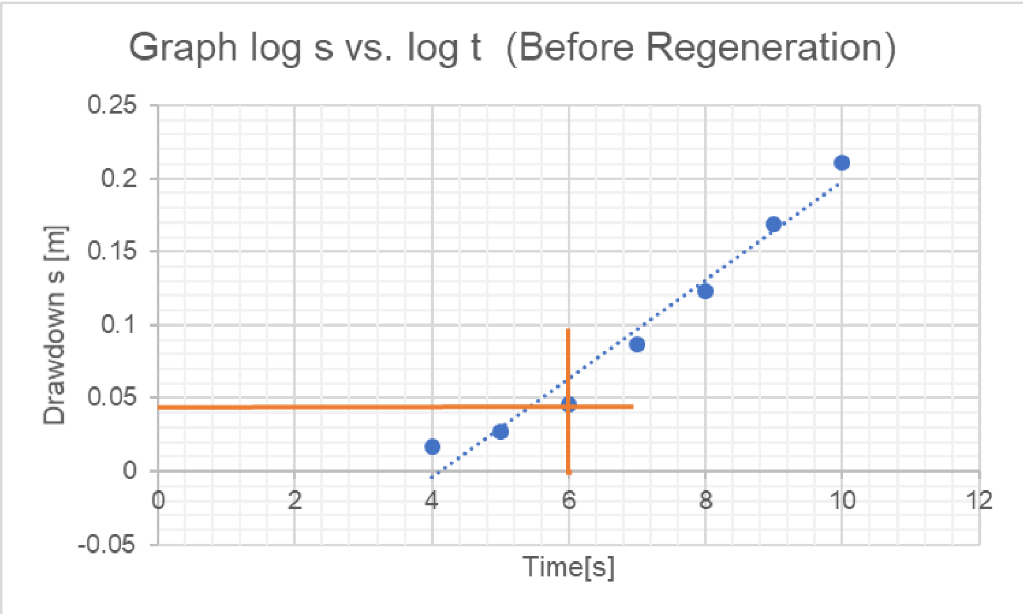


Figure 15: Graph log s vs. log t at the beginning of the pumping test when the water is pumped only from the wellbore's own volume

According to (Ramey, 1970)The "straight line" with the "unit slope" lasts until all the water is pumped from the well's volume. The "straight line" with the "unit slope" lasts until all the water is pumped from the well's volume.

From figure 15, we can determine the unit factor of the wellbore storage, C, from the following equation (43).

$$C = Q \frac{t_B}{s_B} \qquad (43)$$

Then, we have value from the figure. 15

$$C = 0.0148\ \frac{6}{0.0458} = 1.94$$

The wellbore unit storage factor (C), can be used to calculate the coefficient of additional resistance. Once, S_F is the coefficient of additional resistance (skin factor); $W = S_F$

So, equation 44 can be applied. (Kahuda & Pech, 2020)

$$W = \frac{1}{0,166}\left(\frac{2\pi T s^*}{Q} - 0,1908\ log\frac{C}{2\pi\ r_W^2 S} - 0,2681\right)$$

(44)

$$W = \frac{1}{0,166}\left(\frac{2\pi * 0.0074 * 0.35}{0.0148} - 0,1908\ log\frac{1.94}{2\pi\ 0.15^2 * 0.00062} - 0,2681\right)$$

W =	5.78

e. Calculation for additional drawdown caused by Additional Resistances

Once we have the average value of coefficient of additional resistances, we can apply the average value to calculate drawdown caused by the skin factor. with the following equation (33).

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

$$s_{skin} = \frac{0,0148}{2\pi * 0.0074}\ 5.78$$

Sw =	1.8450 m

f. Calculation for Specific Discharge (q)

At the end of our calculations we find the value of specific discharge.

$$q = \frac{Q}{s_v}$$

(45)

$$q = \frac{0,0148}{4.3}$$

$$q = \mathbf{0.0034\ m^2/s}$$

9.1.2 Observation Well (RD1)

a. Application in Excel

In the observation well, the measurement took parts on February 2015 from 12:03 PM to 2:28 PM; so, the evaluation measured the drawdown, every 20 second from beginning of pumping 0th second to 8,680th second as demonstrated in the table below:

Table 8: Drawdown Measurement for Observation Well, February 2015

RD1 Obs	Date + Time	OBS t[min]	time [sec]	Hlogger/ column[m]	Hlogger[m from O.B.]	OBS s[m]	$H_{manually}$ [m from O.B.]
	2/21/15 12:03 PM	-	-	9.14	0.77	-	**0.77**
	2/21/15 12:03 PM	0.33	20	9.12	0.79	0.02	
	2/21/15 12:04 PM	0.67	40	9.08	0.83	0.06	
	2/21/15 12:04 PM	1.00	60	9.05	0.86	0.09	
	2/21/15 12:04 PM	1.33	80	9.01	0.90	0.13	
	2/21/15 12:05 PM	1.67	100	8.98	0.93	0.16	
			-				
	2/21/15 2:27 PM	144.33	8,660	8.97	0.94	0.17	
	2/21/15 2:28 PM	144.67	8,680	8.97	0.94	0.17	

b. Calculation of Transmissivity (T)

Same as the pumping well, to calculate the transmissivity of observation well, the drawdown had to be plotted according to the example data showed in the table 8. (Figure: 16) need to be plotted which the relation of the reduced water level (drawdown[m]) on time [second].

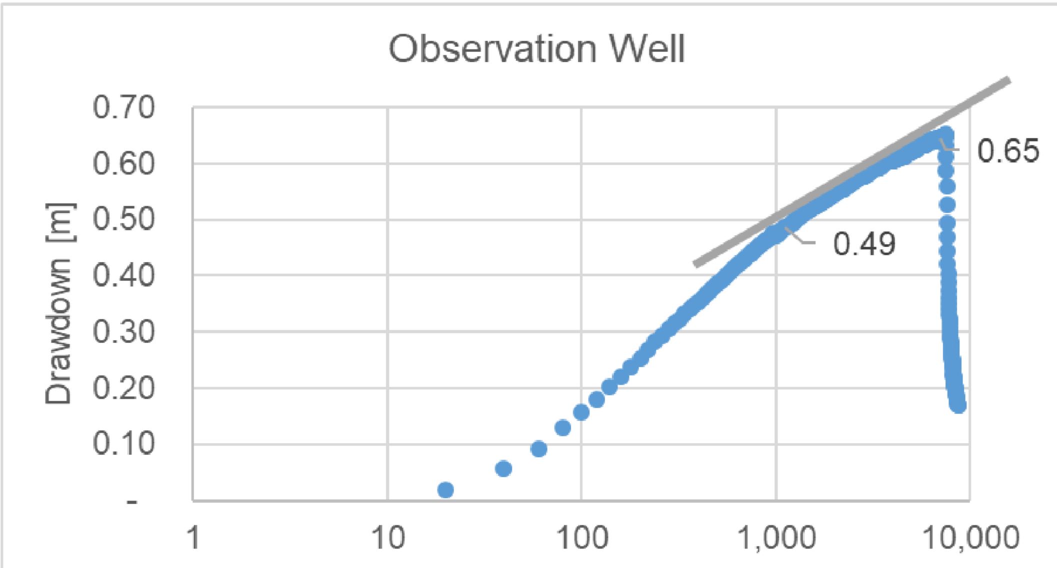


Figure 16: The graph of the drawdown vs time plotted on logarithmic scale (Observation well)

Where s_2 is the value of drawdown corresponding to time t_2 and the beginning point of calculation is s_1. And The discharge rate was around 14.8 l/s or 0.0148 m^3/s as well.

When assumed that all the parameters of the pumping well and observation well are the same, the calculation for transmissivity can be as the following:

From equation 33. We can calculate hydraulic gradient (i)

Since the plotted graph figure 16, I used the point where time (t_1) at 900th second which had value of drawdown (s_1) equal to 0.4650 m and time (t_2) at 5100th second which had value of drawdown (s_2) equal to 0.6241 m.

Then,

$$i = \frac{0.6241 - 0.4650}{\log(5100) - \log(900)}$$

$$i = 0.2112$$

Thus,

$$T = 0{,}183 \frac{0{,}0148}{0.2112}$$

T =	**0.01282 m^2.s^{-1}**

c. Calculation for Storage coefficient (S)

To calculate this, equation (42) was applied with the calculated transmissivity and substituted into the following equation and calculate the storativity.

$$S = 2.246 \frac{T t_0}{r^2}$$

$$S = 2{,}246 \frac{0.01282409 * 57}{40^2}$$

Then,

S =	**0.001031**

9.2 The Pumping Test After Well Cleaning

To evaluate the pumping test after regeneration we also use the same methods and parameters as for evaluation before regeneration.

9.2.1 Pumping Well

a. Application in Excel

To evaluate the pumping well after regeneration, the measurement data took more time to evaluate the drawdown, it took 4 days of testing. However, in this following example calculation, we only showed for the first two hours from the whole evaluation.

Table 9: Table of measured values of the pumping test in May 2015

RD2 After	Date + Time	t[min]	logt[min]	time [sec]	Hlogger/ column[m]	Hlogger[m from O.B.]	drawdown s[m]	$H_{manually}$ [m from O.B.]	QRD2 [l/s]
	5/6/15 2:19 PM	-		0	9.0912	1.2600	0.0000	1.2600	0.0
	5/6/15 2:19 PM	0.02	-1.7782	1	9.2105	1.1407	0.0100		14.2
	5/6/15 2:19 PM	0.03	-1.4771	2	9.0727	1.2785	0.0185		14.2
	5/6/15 2:19 PM	0.05	-1.301	3	9.0875	1.2637	0.0037		14.2
	5/6/15 5:06 PM	166.65	2.22181	9999	5.8647	4.4865	3.2265		14.2
	5/6/15 5:06 PM	166.67	2.22185	10000	5.8637	4.4875	3.2275		14.2

b. Calculation of Transmissivity (T) and Storativity (S)

To calculate the transmissivity, the pumping test graph (Figure: 17) needs to be plotted again as the following figure.

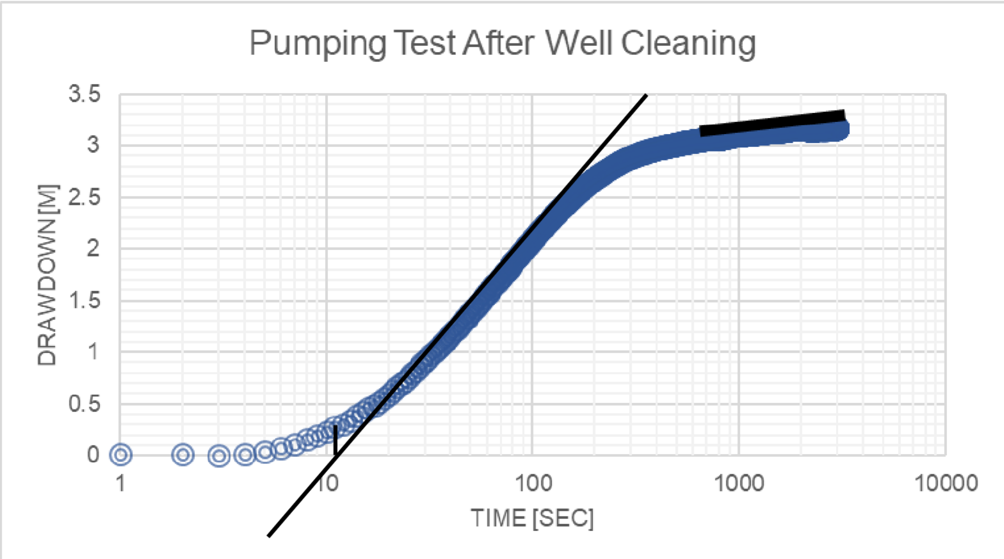


Figure 17: The graph of the drawdown vs time plotted on logarithmic scale (After regeneration)

s^{*} =0.25 m

The same as before cleaning, we know that aquifer properties are the same; so, we applied the same value of transmissivity as in before regeneration.

T =	0.0074 $m^2.s^{-1}$

So, the storage coefficient also had the same value

S =	0.00062

c. Wellbore storage calculation and coefficient of additional drawdown

a straight line with a "unit slope" can be seen on the pumping test. And again, we use the same value of wellbore value(C) as before.

$$W = \frac{1}{0{,}166}\left(\frac{2\pi * 0.0074 * 0.25}{0.0148} - 0{,}1908\, log\frac{1.94}{2\pi\, 0.15^2 * 0.00062} - 0{,}2681\right)$$

W =	3.89

d. Calculation for Additional Resistances

Once we have the average value of coefficient of additional resistances, we can apply the average value to calculate drawdown caused by the skin factor. ($\boldsymbol{S_w}$ **or** $\boldsymbol{S_{skin}}$**)** with the following equation (33).

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

$$s_w = \frac{0{,}0142}{2\pi * 0.007382}\, 3.89$$

Sw =	1.2426 m

e. Calculation for Specific Discharge (q)

At the end of our calculations we find the value of specific discharge.

$$q = \frac{Q}{s_v}$$

(44)

$$q = \frac{0{,}0148}{3.3}$$

$$q = \mathbf{0.0044}\ \mathrm{m^2/s}$$

9.2.2 Observation Well

a. Application in Excel

In the observation well, the measurement took parts on May 2015. this time, the evaluation measured the drawdown every 5 minutes as showed in the table of data in the following.

Table 10:Drawdown Measurement for Observation Well, May 2015

RD1 After	Date + Time	OBS t[min]	time [sec]	Hlogger/ column[m]	Hlogger[m from O.B.]	OBS s[m]	$H_{manually}$ [m from O.B.]
	5/6/15 2:20 PM	-	-	8.84	1.03	-	
	5/6/15 2:25 PM	5	300	8.51	1.36	0.33	
	5/6/15 2:30 PM	10	600	8.43	1.44	0.41	
	5/6/15 2:35 PM	15	900	8.39	1.48	0.45	
	5/6/15 2:40 PM	20	1,200	8.36	1.51	0.48	
	5/7/15 9:25 AM	1,145	68,700	8.23	1.64	0.61	
	5/7/15 9:30 AM	1,150	69,000	8.23	1.64	0.61	

b. Calculation of Transmissivity (*T*) and Storativity (S)

Same as before, to calculate the transmissivity of observation well, the drawdown had to be plotted according to the example data showed in the table 10. (Figure: 18) need to be plotted which the relation of the reduced water level (drawdown[m]) on time [second].

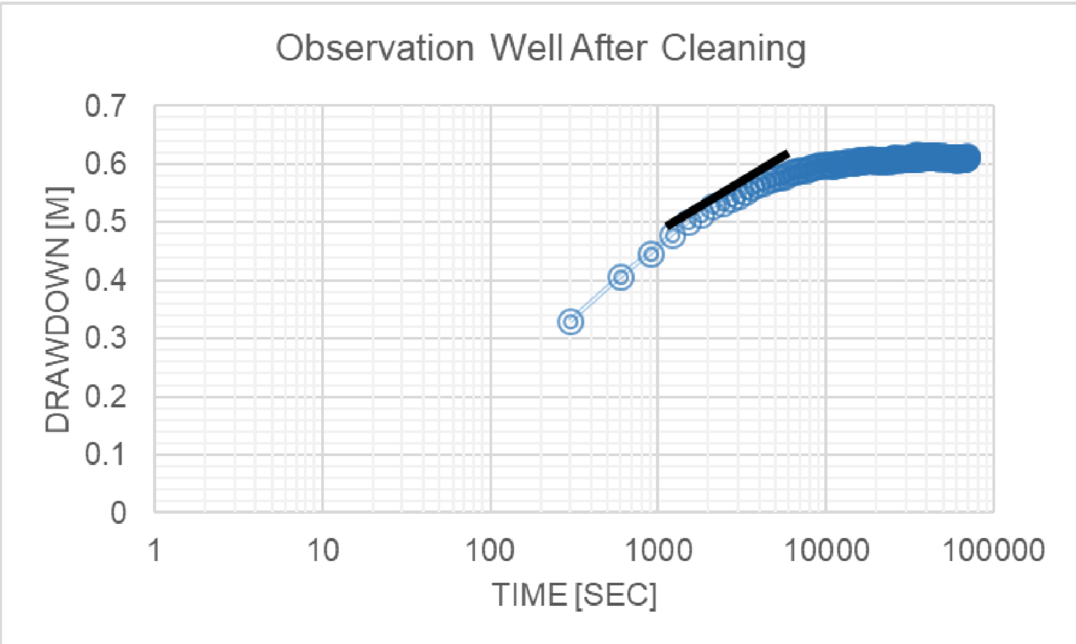


Figure 18: Drawdown plotted corresponding to time in logarithmic scale after well cleaning on May 2015.

The same as before cleaning, we know that aquifer properties are the same; so, we applied the same value of transmissivity as in before regeneration for observation well.

T =	**0.0128 $m^2.s^{-1}$**

Then, the calculated storage coefficient when the drawdown (sw) is zero with equation of straight line from observation well and the result of time t0 is 60 sec by applying the equation 42 is:

S =	**0.00108**

c. The pumping test before and after rehabilitation comparation

The evaluation of the pumping test before and after regeneration, we can see that the solve of the drawdown is decrease, that means the additional the skin factor is less, as show in the figure (). It shows the before and after well rehabilitation the graphs show the plotted drawdown in February and May respectively.

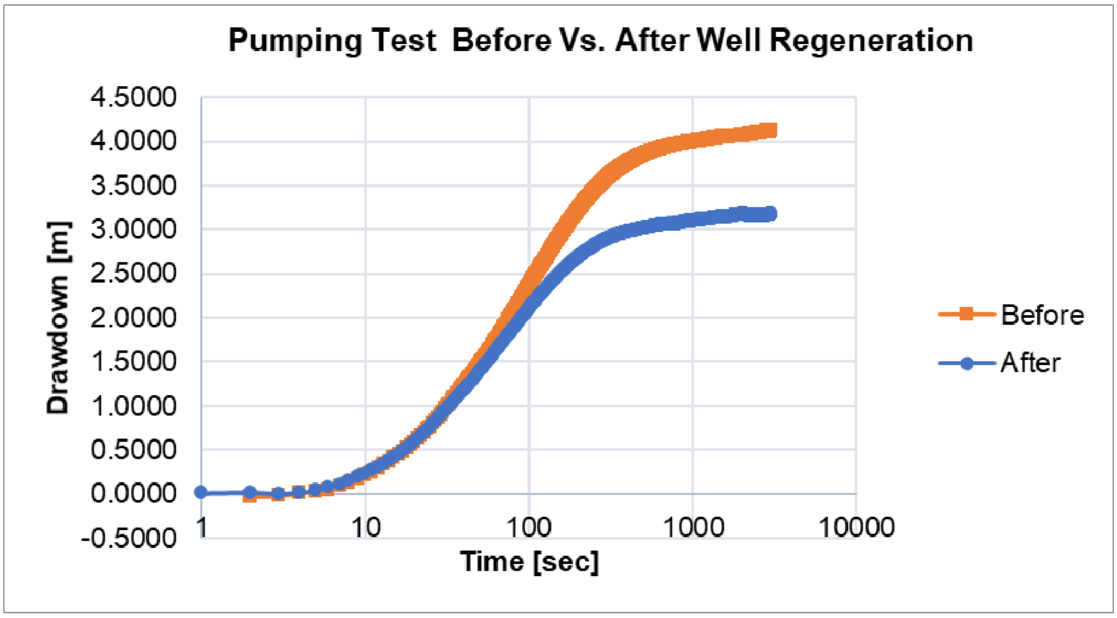


Figure 19: Comparation drawdown in pumping well before and after rehabilitation

The differences between s_{skin} before and s_{skin} after can be seen as the following equation (38).

$$s_{skin...before} - s_{skin...afer}$$

Then,

$$1.8450 - 1.2426 = \mathbf{0.6024\ m}$$

10. Alternative Method for Evaluation of Skin Factor

In this method, the evaluation mainly applied calculation of slope (i), transmissivity (T), storativity (S), additional resistance W, additional drawdown due to skin factor (Sw) and specific yield. All of these above-mentioned calculations, used the same relationships as for evaluation before and after regeneration.

10.1 The Pumping Test before Regeneration

First, to find the hydraulic gradient of slope in the pumping well, we also plotted the graph of drawdown corresponding to time.

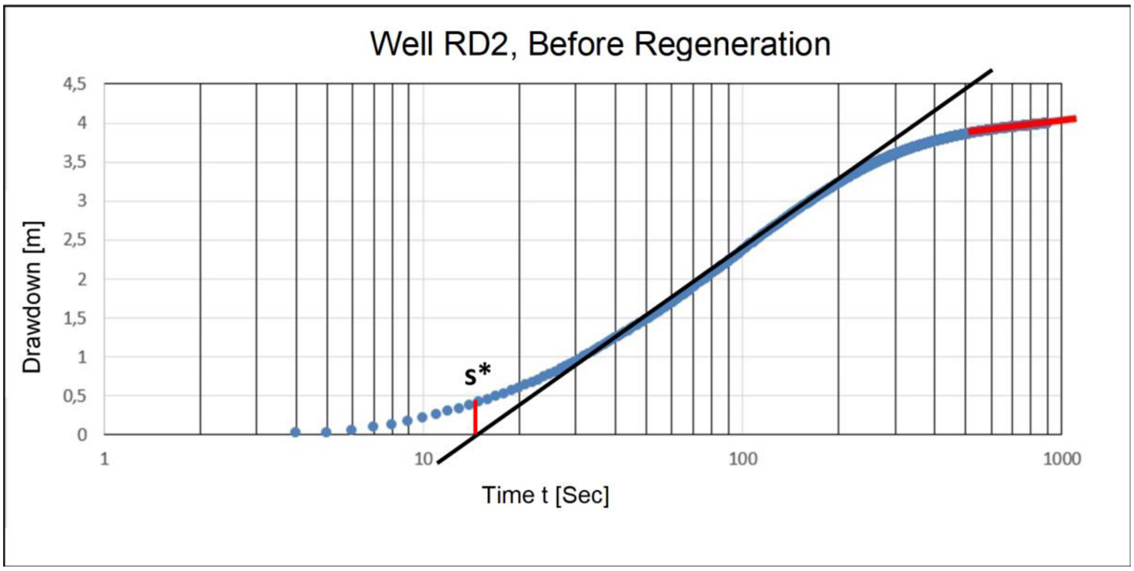


Figure 20: Well RD2, drawdown plot before cleaning

$s^* = 0.4$ m

Once we know that value of Transmissivity and Storativity are not changing during regeneration. Then, results from selected slopes the same points and times, we can apply results from T and S, from the first method. As the following:

Thus, we have:

Transmissivity:

$$T = 0,0074\ m^2/s$$

Storativity:

$$S = 0,00062$$

After calculating the storativity, we then approached to the calculation for coefficient of additional resistances:

$$W = \frac{2\pi T s_v}{Q} - \frac{1}{2}\left(\ln t + \ln\frac{T}{r_v^2 S} + 0{,}8091\right)$$

$$W_1 = \frac{2\pi * 0{,}0074 * 4}{0{,}0148} - \frac{1}{2}\left(\ln 500 + \ln\frac{0{,}0074}{0{,}15^2 * 0.00062} + 0{,}8091\right)$$

$$W_1 = 5.91$$

$$W_2 = \frac{2\pi * 0{,}0074 * 4}{0{,}0148} - \frac{1}{2}\left(\ln 600 + \ln\frac{0{,}0074}{0{,}15^2 * 0.00062} + 0{,}8091\right)$$

$$W_2 = 5.82$$

$$W_3 = \frac{2\pi * 0{,}0074 * 4}{0{,}0148} - \frac{1}{2}\left(\ln 700 + \ln\frac{0{,}0074}{0{,}15^2 * 0.00062} + 0{,}8091\right)$$

$$W_3 = 5.75$$

Then, we have the result value for the coefficient of additional resistances W from the average of the values W1, W2, W3:

$$\boldsymbol{W = 5,82}$$

The average value of the coefficient of additional resistances is further used to calculate in the equation for calculating the additional drawdown caused by additional resistances (s_w).

$$s_w = \frac{Q}{2\pi T} W$$

$$s_w = \frac{0{,}0148}{2\pi * 0{,}004938429} 5{,}82$$

$$\boldsymbol{s_w = 1.85} \textbf{ m}$$

Finally, we find the value of specific discharge by applied the following equation.

$$q = \frac{Q}{s_v}$$

$$q = \frac{0{,}0148}{4}$$

$$q = \boldsymbol{0,0037} \textbf{ m}^2\textbf{/s}$$

10.2 The Pumping Test after Regeneration

As we have mentioned, the evaluation for after regeneration we use the same relationships as for evaluation before regeneration. The slope, storativity and transmissivity values remain the same as before regeneration. Then the graph of drawdown need to be plotted again.

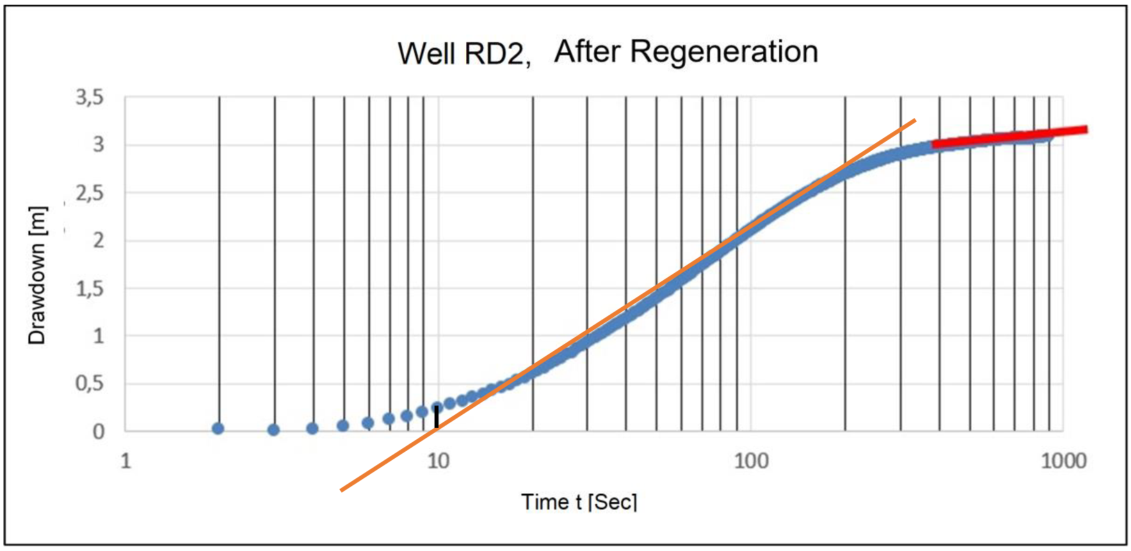


Figure 21: Well RD2, drawdown plot after cleaning

s* = 0.25 m

The maximum drawdown after well cleaning, we can that it is at 3 m. So, this calculation, we use 3 m instead of 4 m like before.

$$i = \ 0,548$$

$$T = 0,0074\, m^2/s$$

$$S = 0,00062$$

$$W = \frac{2\pi T s_v}{Q} - \frac{1}{2}\left(\ln t + \ln \frac{T}{r_v^2 S} + 0{,}8091\right)$$

$$W_1 = \frac{2\pi * 0{,}0074 * 3}{0{,}0148} - \frac{1}{2}\left(\ln 500 + \ln \frac{0{,}0074}{0{,}15^2 * 0.00062} + 0{,}8091\right)$$

$$W_1 = \ 2.77$$

$$W_2 = \frac{2\pi * 0{,}0074 * 3}{0{,}0148} - \frac{1}{2}\left(\ln 600 + \ln \frac{0{,}0074}{0{,}15^2 * 0.00062} + 0{,}8091\right)$$

$$W_2 = \ 2.68$$

$$W_3 = \frac{2\pi * 0{,}0074 * 3}{0{,}0148} - \frac{1}{2}\left(\ln 700 + \ln \frac{0{,}0074}{0{,}15^2 * 0.00062} + 0{,}8091\right)$$

$$W_3 = \ 2.60$$

The average value for coefficient of drawdown from value of W1, W2, and W3 is:

$$\boldsymbol{W = 2.68}$$

The value of W is again proceeded to calculate the additional drawdown due to skin factor.

$$s_w = \frac{Q}{2\pi T} W$$

$$s_w = \frac{0{,}0148}{2\pi * 0.0074} * \ 2.68$$

$$\boldsymbol{s_w = \ 0.85\ m}$$

At the end of our calculations we find the value of specific discharge.

$$q = \frac{Q}{s_v} \tag{43}$$

$$q = \frac{0{,}0148}{3}$$

$$q = 4{,}733333333 * 10^{-3} = \boldsymbol{0{,}0049\ m^2/s}$$

11. Method Value Comparation

in this, we compared the values from both calculated methods. The first method, we calculated transmissivity and storativity, using the slope of hydraulic gradient from the plotted graph. These calculations, applied for both methods.

But then, the calculation for coefficient of additional resistance (W), was done by applied the value calculated from wellbore storage (C), then used to estimate the additional drawdown caused by skin factor according to (Kahuda & Pech, 2020).

For the second method (Jacob method), the coefficient of additional resistance (W), was calculated by using the average values from three W calculated values, then use the average value to calculate additional drawdown due to skin factor.

Table 11: Comparation value from 2 methods

Compare Result values Methods						
		T [m2/s]	S[-]	W	sw [m]	q [m2/s]
Method 1	Before	0.0074	0.00062	5.78	1.84	0.00344
	After			3.89	1.24	0.00430
Differences					0.6	
Method 2	Before	0.0074	0.00062	5.82	1.85	0.00370
	After			2.68	0.85	0.00490
Differences					1	

From the table, we can see that, the values of coefficient additional resistances, the values of additional drawdown due to skin factor, and the specific discharge values, are slightly different. So, we can conclude that after regeneration, the well performance capacity was increased.

12. Conclusion and Discussion

The Radouň well site in the north of Czech Republic, have been operating since 1975. Therefore, under field conditions, well skin may be non-uniformly distributed over the screen section. Thus, the skin factor evaluation need to be conducted to investigate skin effect on aquifer response. When we know that the wellbore flux distribution of the pumping well is inversely related to additional drawdown due to the variation of skin factor, creating three-dimensional flow in the vicinity of the pumping well.

In well site, Radouň, after long time of operation, additional resistance may alter permeability of the porous formation surrounding the well screen, thereby creating a skin region around the well. Yet, skin factor has influence on aquifer drawdown even if wellbore storage is absent in the pumping well (Chang and Chen, 2002; Chen and Chang, 2003). So, it had been regenerated many times during the operation duration. However, the performance of the well and groundwater in the area, need to be maintained frequently. As a result, the rehabilitation in 2015 is one of the processes conducted to improve the well performances.

The well test was carried out before and after rehabilitation process of well in the Radouň well site, used the calculation of the evaluation of skin factor in the pumping well, approached by Cooper Jacob's method which is the simplification of Theis's method; and the method $s^* = f(CD.t^*)$ according to (Kahuda & Pech, 2020).

- The first methods, we applied Jacob's methods for the evaluation. So, calculation included; Transmissivity, Storativity, Coefficient of additional resistance, and Additional Drawdown due to skin factor. In the evaluation, pumping well before regeneration, we used the hydraulic gradient slope (i), from the drawdown graph plotted with selected time (in second), corresponding with point of drawdown at that time, $i = (s_2 - s_1)/(\log t_2 - \log t_1)$. After that, we calculated the transmissivity, $T = 0.183\frac{Q}{i}$; and storativity, $S = 2.246\frac{Tt_0}{r^2}$. As we know that, the transmissivity and storativity of the site need to be the same before and after regeneration, we also used these values in both evaluation methods. Then, coefficient of additional drawdown (W) by applying calculation of wellbore storage (C) which applied: $C = Q\,\frac{t_B}{s_B}$, and then, $W = \frac{1}{0,166}\left(\frac{2\pi T s^*}{Q} - 0,1908\,log\frac{C}{2\pi\, r_W^2 S} - 0,2681\right)$ additional drawdown due to skin factor (s_{skin}), we used $s_{skin} = \frac{Q}{2\pi T}\,W$ and specific discharge (q), using $q = \frac{Q}{s_v}$ results were determined by applying the same equations as the first method which calculated separately before and after rehabilitation. The results from the first method expressed the change in drawdown and additional resistances, as well as the specific discharge as show in the comparation table 11. The coefficient of additional resistance (W) and additional drawdown due to skin effect (s_{skin}) showed significant changes. We can assume that
- The second method, calculation for transmissivity (T), and storativity (S) values from the first method. Then, the values for coefficient of additional resistance (W) was calculated three times, (different point of drawdown vs. time), then use the average W

from the three results for the evaluation of additional drawdown due to skin effect. For calculation of s_{skin}, we applied the same equation the first method.

The results from both methods showed distribution of wellbore specific discharge in the pumping well is inversely related to the variation of skin factor, where aquifer drawdown changes in integrated with skin factor.

The comparison of skin factor determined from these correlations against the skin factors determined from the pumping test data indicated that both methods results value of the well rehabilitation, after was less than before. The two methods expressed obviously the changes of drawdown and additional resistances.

Consequently, the coefficient of additional resistances and additional drawdown caused by skin factor, had noticeable differences. The results indicated that drawdown was correlated with skin effect. After regeneration, we can see that the skin formation was less which mean we have more permeability. The result of the difference of additional drawdown caused resistances before and after pumping was significant.

13. References

AG.& ENVIRONMENTAL SCIENCES ACADEMY. (n.d.). *Water and Soil Management*. Retrieved from woodland high school: http://woodlandhighag.weebly.com/watersoil-manag.html

Athy L. F., 1930: Density, porosity and compactation of sedimentary rocks.

Balasubramanian P. A., (2017, August 8): Vertical distribution of groundwater. https://www.slideshare.net/bala1957/vertical-distribution-of-groundwater

Bear J. & Cheng A., 2010: Modeling Groundwater Flow and Contaminant Transport, 23. Springer, Dordrecht. doi:https://doi.org/10.1007/978-1-4020-6682-5

Bob McGinty P. P., 2012, February, *Continuity Equation*. Retrieved from https://www.continuummechanics.org: https://www.continuummechanics.org/continuityequation.html

Batu V., 1998: Aquifer Hydraulics: *A comprehensive guide to hydrogeologic data analysis*. John Wiley α Sons. New York, NY. 727s.

Van Everdingen A.F., 1953: The skin effect and its influence on the productive capacity of a well. *Journal of Petroleum Technology* 5: 171-176. https://doi.org/10.2118/203-G

Papadopulos I.S., Cooper H.H., 1967: Drawdown in a well of large diameter. Water Resources Research 3: 241 - 244. https://doi.org/10.1029/WR003i001p00241

Bourdet, D., 2002: Well test analysis: The use of advanced interpretation models. Handbook of Petroleum Exploration and Production : 426s. http://dx.doi.org/10.1016/s1567-8032(03)x8026-x

Watlton W.C., 2007: *Aquifer test modeling*, 1st ed.; CRC Press: NY, US. ISBN-13: 978-1-4200-4292-4

Agarwal R.G., Al-Hussainy R., Ramey H.J., 1970: An investigation of wellbore storage and skin effect in unsteady liquid flow: I. Analytical treatment. Society of Petroleum Engineers Journal 10: 279-291. http://dx.doi.org/10.2118/2466-PA

Brusseau M. L., 1993: In *Complex Mixtures and Groundwater Quality* (p. 15). Tucson: Department of Soil and Water Sciences, University of Arizona.

Czech Geological Survey. (2020, March 1). *http://www.geology.cz*. Retrieved from https://mapy.geology.cz/vrtna_prozkoumanost/

Domenico P. A., 1979: Ground-water hydrology and hydraulics. In *Ground-water hydrology and hydraulics.* Water Resources Publication.

Donev J., 2017: *Energy Education*. Retrieved 6 13, 2019, from Groundwater as a part of the hydrologic cycle: http://imnh.isu.edu/digitalatlas/hydr/concepts/gwater/aquifer.htm.

Firdaouss M., Guermond J.-l. & Quere P. L., 1997: Nonlinear corrections to Darcy's law at low Reynolds numbers. In *Journal of Fluid Mechanics* (pp. 343, 331-350).

Jha D. M., 2014, February 7: Ground Water,Wells and Pumps. New Delhi, India. Retrieved from ecoursesonline.

Kahuda D. & Pech P., 2020: A new method for the evaluation of well rehabilitation from the early portion of the pumping test. Water 12 :1-21.

Kruseman G., 2000. Unsteady-state flow . In G. Kruseman, *Analysis and Evaluation of Pumping Test Data* (p. 61). TNO Institute of Applied Geoscience, Delft.

LOHMAN S. W., 1975: Ground-Water Hydraulics. In *Ground-Water Hydraulics.* WASHINGTON: GEOLOGICAL SURVEY PROFESSIONAL PAPER 708.

Mapy.cz. (2020, 3). Retrieved from mapy.cz: https://en.mapy.cz/turisticka?x=14.3817587&y=50.4712510&z=12&source=ward&id=9162

Margat J., 2013: Groundwater around the World, CRC Press/Balkema.

Neuman S. P.,1977: Theoretical derivation of Darcy's law. Acta Mechanica 1: 155-157.

Nyer E. K.,1992: Groundwater Treatment Technology. In *Groundwater Treatment Technology, Second Edition.* New York: Van Nostrand Reinhold Company.

Pech P., 2010 : Additional Resistances In *Speciální případy hydrauliky podzemních vod.* (stránky 42-45). Czech University of Life Sciences in Prague and VÚV TGM. Praha, 103 s.

Pech P. ,2017: Environmental Hydraulics. Prague, Czech Republic. https://home.czu.cz/storage/52485_Env-Hydraulics-all.pdf (27.5.2020)

Ramey H. H., 1970: Short-time well test data interpretation in the presence of skin effect and wellbore storage. Journal of Petroleum Technology 11: 97-104. doi:10.2118/2336-PA

Salako A., 2018: Aquifer, classification and characterization. Rijeka: IntechOpen. doi:10.5772/intechopen.72692

ŞEN Z., 2009: Non-Darcian groundwater flow in leaky aquifers.Hydrological Sciences Journal 45: 598-599. doi: 10.1080/02626660009492360

Spivey J. P. & Lee J., 2013: Well test. In *Applied well test interpretation.* Texas: Richardson, Texas : Society of Petroleum Engineers.

Tadiboyina R., 2016: *Studies and analysis of specific heavy metals in industrial groundwaters in and around Vijayawada Andhra Pradesh India.* Retrieved from https://shodhganga.inflibnet.ac.in: https://shodhganga.inflibnet.ac.in/handle/10603/269514

Tal E., 2016, June 26: *Water Cycle*. Retrieved from wikicommons: https://upload.wikimedia.org/wikipedia/commons/b/b1/Diagram_of_the_Water_Cycle.jpg

The U.S. Environmental Protection Agency, (EPA),1994: Ground-water and Leachate Treatment Systems. In Chemical Resistance Tables (p. 25). Ohio: U.S. Environmental Protection Agency, Office of Research and Development, Center for Environmental Research Information.

USGS. (n.d.). *Aquifers and Groundwater*. Retrieved from usgs: https://www.usgs.gov/special-topic/water-science-school/science/aquifers-and-groundwater?qt-science_center_objects=0#qt-science_center_objects

Osipov F. S., 2013: Active Porosity and Its Effect on the Physical Mechanical. Moscow: Sergeev Institute of Environmental Geoscience, Russian Academy of Sciences.

Eckenfelder W. J., 1999. In Industrial Water Pollution Control, 3rd Edition. New York: McGraw-Hill, Inc.

Waterloo Hydrogeologic, 2018: Pumping Tests: Theory and Analysis Methods. Retrieved February 27, 2020, from www.waterloohydrogeologic.com: https://www.waterloohydrogeologic.com/help/aquifertest/index.html?_cooper-jacob_method_confined_.htm

Cooper H. H., Jacob C. E., 1946: A generalized graphical method for evaluating formation constants and summarizing well-field history. *Transactions, American Geophysical Union* 27: 526-534. https://doi.org/10.1029/TR027i004p00526

Theis C.V., 1935: The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Transaction American Geophysical Union* 16: 519-524. https://doi.org/10.1029/TR016i002p00519

Horne R.N., 1995: Modern well test analysis: a computer aided approach, 4th. ed.; Petroway, Inc.: Ed. Palo Alto, US. pp. 185 ISBN -0-9626992-09

Kresic N., 2007: Hydrogeology and groundwater modeling, 2nd ed.; CRC Press, Taylor and Francis, US. ISBN: 13: 978-0849333484

Yeh H. D., Chang Y. Ch., 2013: Recent advances in modeling of well hydraulics. Advances in Water Resources **2013**, 51, 27-51. https://doi.org/10.1016/j.advwatres.2012.03.006

Adebayo A. R., Bager, B. S., 2019: A simple NMR methodology for evaluating filter cake propertiesand drilling fluid-induced formation damage. Journal of Petroleum Exploration and Production Technology, 9. https://doi.org/10.1007/s13202-019-00786-3

Houben G., Treskatis Ch., 2007: Water Well Rehabilitation and Reconstruction, 3rd. ed.; McGraw Hill Professional. ISBN: 0-07-148651-8