CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

FACULTY OF ENVIRONMENTAL SCIENCES (FES)

Department of Water Resources and Environmental Modeling

Pumping Test - Evaluation of Rehabilitation

(MASTER THESIS)

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Prague, 2021

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Environmental Sciences

DIPLOMA THESIS ASSIGNMENT

Bhupin Karki

Landscape Engineering
Environmental Modelling

Thesis title

Pumping tests – evaluation of rehabilitation

Objectives of thesis

I am going to calculate some of the basic hydraulic parameters using the hydrodynamics test. Mainly, we are evaluating the transmissivity, additional resistance and drawdown caused by additional resistance of the pumping well. In the end, we will discuss all the calculated results and impact on well rehabilitation before and after well regeneration.

Methodology

During the evaluation process, the first hydraulic parameter Transmissivity will be calculated by using one of the famous hydrodynamics tests is called Cooper-Jacob (1946) semi-logarithmic method. For the second parameter additional resistance (skin factor) calculation, we are going to use two different methods Cooper-Jacob and the Straight-line method(Alternative). Also, we will be evaluated the drawdown caused by additional resistance using both skin factor. After all, We will compare the results from both methods accordingly.

Keywords: Aquifer, Storativity, Transmissivity, Pumping well, Skin factor, Well rehabilitation

The proposed extent of the thesis

cca 40-60 str.

Keywords

Aquifer, Skin factor, Well rehabilitation

Recommended information sources

Bear, J. Hydraulics of Groundwater. 1979. McGraw-Hill.

Expected date of thesis defence

2020/21 SS – FES

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Declaration

Hereby, I would like to declare that I wrote the thesis with the title “Pumping test: Evaluation of Rehabilitation” independently under the guidance of my supervisor Prof. Ing. Pavel Pech CSc. All the sources of information have been specially acknowledged by reference to the authors.

Prague

25.03.2021 Bhupin Karki

Acknowledgements

I am grateful to my respcted thesis supervisor prof. Ing., Pavel Pech, CSc. for the professional guidance, willingness to consult and the materials and measurement data provided for the calculation and guided me throughout this project. Professor. Pech shows me the way how to translate research thought to the writing.

My sincere thanks to the study departments, staff, and friends of environmental sciences faculty at the Czech University of Life Sciences Prague.

I would also like to thank my friends and family who were always there for me in every ups and down. I am really thankful to the Doc. Maan Rokaya, Xaiyasith Iamsisanith, Araful Islam Himu and Giris Kandel who helped me in different phase on this thesis.

Prague

25.03.2021 Bhupin Karki

Abstract:

The hydrodynamic test is the method used to evaluate different hydraulic parameters. At the same time, well rehabilitation is the wells maintenance method that not only helps to lengthen life span but also increase the production efficiency of the wells. We evaluated hydraulic parameters transmissivity using the Cooper-Jacob time drawdown method, and skin factor and drawdown caused by skin factor using two different methods(Cooper-Jacob and Alternative) on all four pumping wells. At the same time, we analysed both skin factor evaluation technique and how successful is our rehabilitation process after well regeneration at RD-2 and MO-1 pumping wells. The pumping tests were conducted in three different locations of the Czech Republic and recorded Drawdown vs Time data accordingly.

Furthermore, In both wells(RD-2 and MO-1) has a bigger value of drawdown caused by skin factor before regeneration than after regeneration. So, it clearly shows that well rehabilitation is significantly helpful for better performance and prolongs life span of the pumping well.

Keywords: Aquifer, Storativity, Transmissivity, Pumping well, Skin factor, Well rehabilitation

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1. Introduction

Water is one of the most valuable and essential natural resources. As most precious components of the hydraulic system on the Earth, global freshwater(groundwater and surface water) has a huge impact on many different aspects of Earth and human daily life. Surface water directly interacts with the Earth's atmosphere and subsurface water continuously redistributes geothermal energy and it tries to dissolved different minerals in the Earth's crust at a temporal and spatial scales (Gorelick & Ge, 2015).

Firstly, let us know about global distribution of the water and groundwater flows, according to the water survey around 97.33 % water is stored in the ocean and it is too salty for direct human consumption. Then the second largest water storage are ice caps and glaciers with 2.12% which account for nearly 79% of the total global freshwater. More interestingly, Groundwater in the upper 800 m of the subsurface holds 0.31% of the water on the Earth and only till the few hundred meters of the Earth's looks economically feasible. Lakes and streams holding around 0.158% of total water of the Earth's and it is easiest as well as main water resources for human beings, Around 0.083% of the total water contribute by the atmospheric water (Ge & Gorelick, 2015).

Groundwater flows like surface water in a river except it moves much slower in pace. The flow direction of groundwater has a significant impact on the water quality of the well. we should have ideas about where the groundwater is coming from(Sometimes latrine might be near to the well). Generally, we have to carry out a detailed survey to get an exact idea about groundwater flow direction. In the case of the hilly region, the slope of the landscape shows the direction of flow. In the case of a less hilly area, the flow indicator can be the streams or rivers. Rivers always directed to the lowest-lying land. However, it only counts for the natural river, not on the artificial channels (Van Der Wal, 2010).

In fact, one percent of total freshwater(mainly surface water) is easily accessible for humans and other species, irrigation, industry, and energy generation. It is impossible to fulfill the total consumption of water globally by surface water. As a result, every country extracting groundwater to solve the present shortage of water. Nowadays around half of the world population are fulfilled domestic demand and 38 percent of global irrigation is supplied through groundwater (Rodell, et al., 2018).

2.Objectives of the Thesis

The main goal of this research is the evaluation of different hydraulic parameters using the hydrodynamic test for 4 different wells in 3 different location. The evaluation process will be divided into two different phases. The first phase belongs to wells(KV-2 and KV-9) and the second phase is wells(RD-2 and MO-1). These are the main goals of this study,

1. Evaluation of Transmissivity.
2. Calculation of skin factor with using two methods.
3. Evaluation of additional drawdown caused by both skin factor.
4. To see the effectiveness of well rehabilitation in well RD-2 and MO-1
5. Comparison of skin factor evaluation between Cooper-Jacob and Alternative (first straight line) methods.

3. Literature overview

3.1 Origin of Ground Water

Groundwater can be originated in these three ways.

3.1.1Juvenile water(Magmatic water)

Juvenile water is a new type of groundwater source that is appeared in materials deep within the Earth and not previously appeared at the Earth's surface (United States Geological Survey, 2015). In other words, It's origin in molten rocks which are fundamentally found in great depths. In a different point of view, it is less important in groundwater supply. Juvenile water is also called magmatic water because water-rich volatile fluids derived from Magma and It is coming to the atmosphere during a volcanic explosion.

3.1.2 Connate water

It is the types of groundwater which are trapped on the pore space of rock(sedimentary rock). It has been derived from the ocean, rivers and lakes but more importantly, depending on the locality in which sedimentary rock was formed. Connate water has little importance in a quantity of groundwater being obtained from this type of groundwater source. However, it has a significant effect on water quality in various rocks (Hazel, 1975).

3.1.3 Meteoric water

The water which is obtained from the atmosphere and precipitation(could be rainwater, snow and sometimes hail). It is the most significant source to get the groundwater on earth (Hazel, 1975). Rainwater is largely derived from the ocean(also from rivers and lakes) by an evaporation process.

3.2 Distributaion of global water and Movement of groundwater

Nearly 70 percent area of Earth is occupied by water(saltwater and freshwater) but only 2.5%(35 million km^3) of global water contribute by freshwater. In freshwater, approximately two-thirds of global freshwater 68.7 %((24 million km^3) is trapped in a form of snow and glaciers which we cannot use, rest is in surface water(lakes and rivers), groundwater and others (Gleick, 1993).

Gravity is one of the main dominant factors in the groundwater movement, in general, but very valuable conclusions the groundwater movement can be derived by the observation of land surface topography (Heath , 1987).It is also controlled by the hydraulic head because it represents the main two components, the first one is potential energy carried by its elevation above a reference datum(i.e. sea level) and energy produced by pressure. Consequently, water moves the high hydraulic head to low. The velocity of groundwater will be greater if the value of the hydraulic gradient is high. The motion of groundwater in the porous media is categorized into two main parts,

a. Darcian groundwater motion (Darcy law)
b. Non-Darcian groundwater motion.

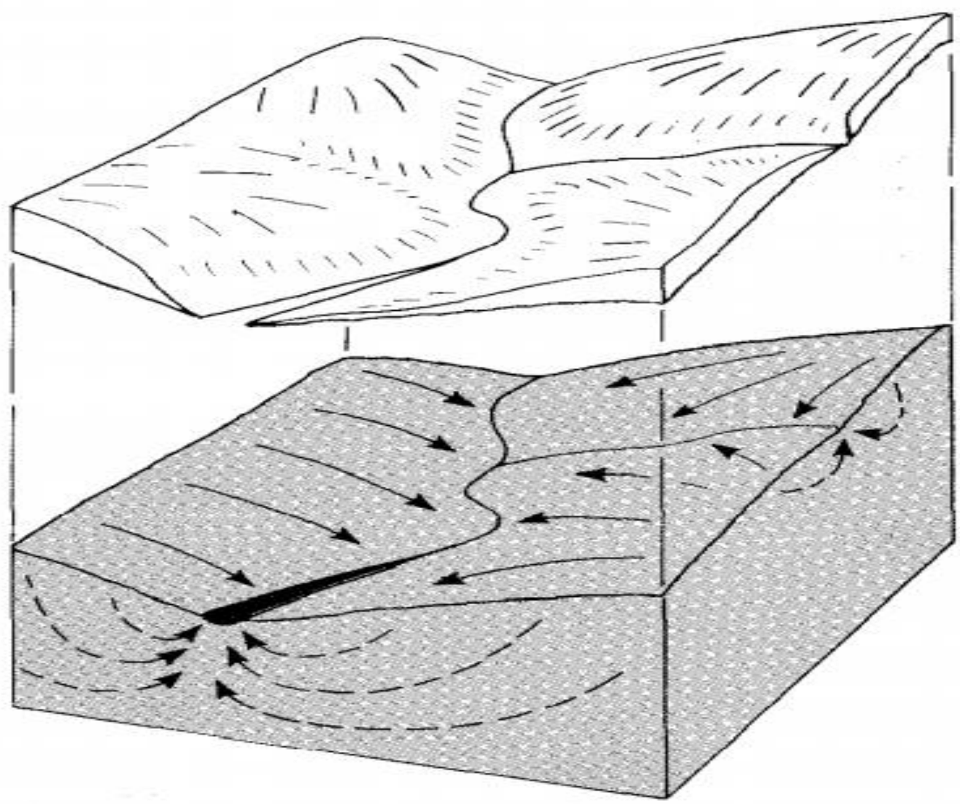

Figure 1. Groundwater movement and topography (Heath , 1987, p. 20)

3.3 Hydrological cycle

This is a continuous process to exchange water between the lithosphere, atmosphere, and biosphere (Narasimhan & T.N, 2009). Usually, the atmospheric water vapor condenses after some time interval it will precipitate as rain, snow, and others. After precipitation, a small amount of water will grab by vegetation and the rest amount of water reaching the ground. One fraction of surface water starts to flow towards oceans and another fraction of precipitation, because of the low permeability of earth only a small amount will infiltrate to the saturated zone (bellow water table).

As a result, water discharge as streamflow, lakes, pond, and wetland. This surface water and discharging groundwater will start to evaporate by solar radiation and transpiration by plants(consumed water) for photosynthesis. Altogether this process referred to evapotranspiration (Narasimhan & T.N, 2009). This is the process of returned water back to the atmosphere is complete the hydrological cycle.

The amount of evaporating water from oceans is usually balanced by the amount being precipitation and surface runoff. As a result, it is a closed system that follows the mass balance equation. There are five main elements to complete the water cycle these are evaporation, transpiration, condensation, precipitation and surface runoff.

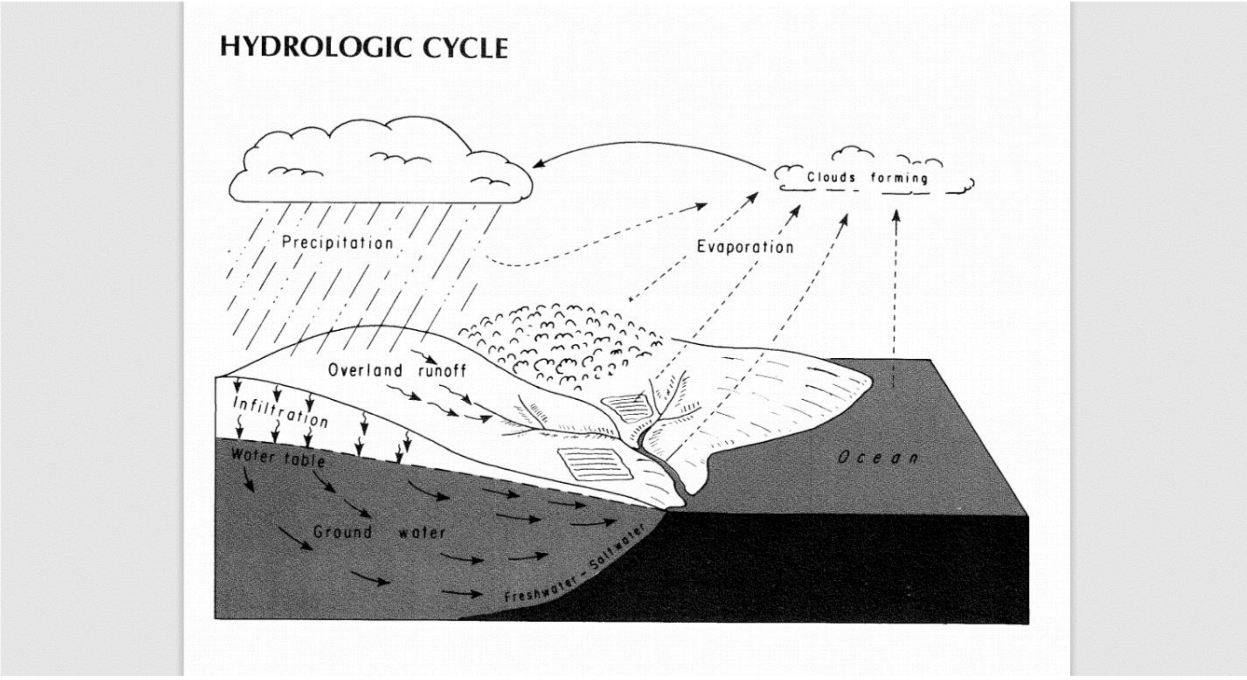

Figure 2. Hydrological cycle (Heath , 1987).

3.4 Water table

It is the boundary line between the unsaturated and saturated zone. The water table varies with humid region, arid and semiarid region. In the humid region, it can be at or near to the surface, streams and lakes of Earth's.However, in semiarid and arid regions it can be hundreds of meters below the surface (Ge & Gorelick, 2015).

It is the topmost part of the saturation zone on the earth where water pressure and air pressure(atmospheric pressure) is equal (Holzer 2010). The saturation zone indicates the pore space is completely covered with water. After enough precipitation water starts to infiltrate through pores space until the saturation zone.

Groundwater is stored on the upper part of the earth's crust on the aquifer and it is the largest unfrozen storage of global freshwater, its moves through aquifer and discharge rate will be in the range of <1 m per year to 30 cm per day (Glazer & Likens, 2012). According to Glazer and Likens, Discharge occurs when the head of the aquifer is higher than the elevation of the water surface and around 20% of the whole aquifer recharge is contributed by the precipitation.

3.5 Hydraulic head

Hydraulic head is the main driven factor of groundwater flow and it determines the mechanical energy per unit weight of the fluid on the groundwater system (Ge & Gorelick, 2015). We can express the hydraulic head using very famous equation is called Bernoulli equation,

Hydraulic head (H) ,

H = hp + hz

where,

hp = $\frac{p}{\rho g}$ - Pressure head (m)

hz = Elevation head (m)

The pressure head represents the energy due to fluid pressure and the elevation head represents energy(gravitational potential energy) due to elevation(height). In this equation, kinetic energy is negligible because of very low groundwater velocity.

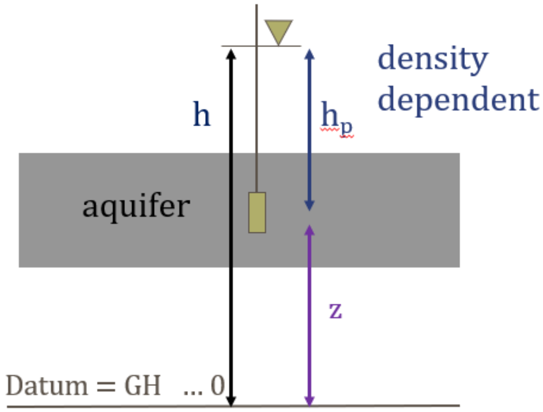

Figure 3. Hydraulic Head(source: Source:From lectures of Groundwater Hydraulics by prof. Pavel Pech).

Bernoulli Equation for ideal fluid,

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

Where,

H= Total head or Energy head (m)

z = elevation head (m)

p = Pressure of the fluid $(\frac{N}{m^2}$ or Pascal)

ρ = Density of the fluid $(\frac{Kg}{m^3})$

v = Velocity of the fluid $(\frac{m}{s})$

g = Acceleration due to gravity $(\frac{m}{s^2})$

3.6 Darcy's Law

In the process of flow through porous media is highly interested in all type of scientists, politicians, economists and engineers who recognized the importance of Groundwater flow. As a result, In 1856 Darcy discovered one-dimensional empiricism and it was the beginning to know the flow in porous media (Whitaker, 1986).

Henry Darcy (1856) described an equation that defines the flow of different fluid into the anisotropic porous media of the soil and it is derived from the Navier-Stokes equation using the formal averaging method (Neuman, 1977).

In general, Darcy’s law is valid for laminar flow of fluid, Newtonian fluid which has small Reynold’s number(Re<10) in the porous aquifer and one-dimensional flow in homogenous porous media.

Assumptions for Darcy's law experiment,

- Soil should be saturated.
- Flow should be laminar (homogenous isotropic in porous media), continuous and steady.
- The total cross-sectional area of soil mass is to be considered.
- Testing time temperature should be 27-degree centigrade.

$$Q = -KA\frac{dh}{dl} \quad (2)$$

Where, Q = Flow rate of fluid ($\frac{m^3}{s}$)

A = Cross-sectional area where the fluid is pass-through (m^2)

K = Hydraulic conductivity of the soil ($\frac{m}{s}$)

h = Piezometric head (m)

l = Distance between two observation (m)

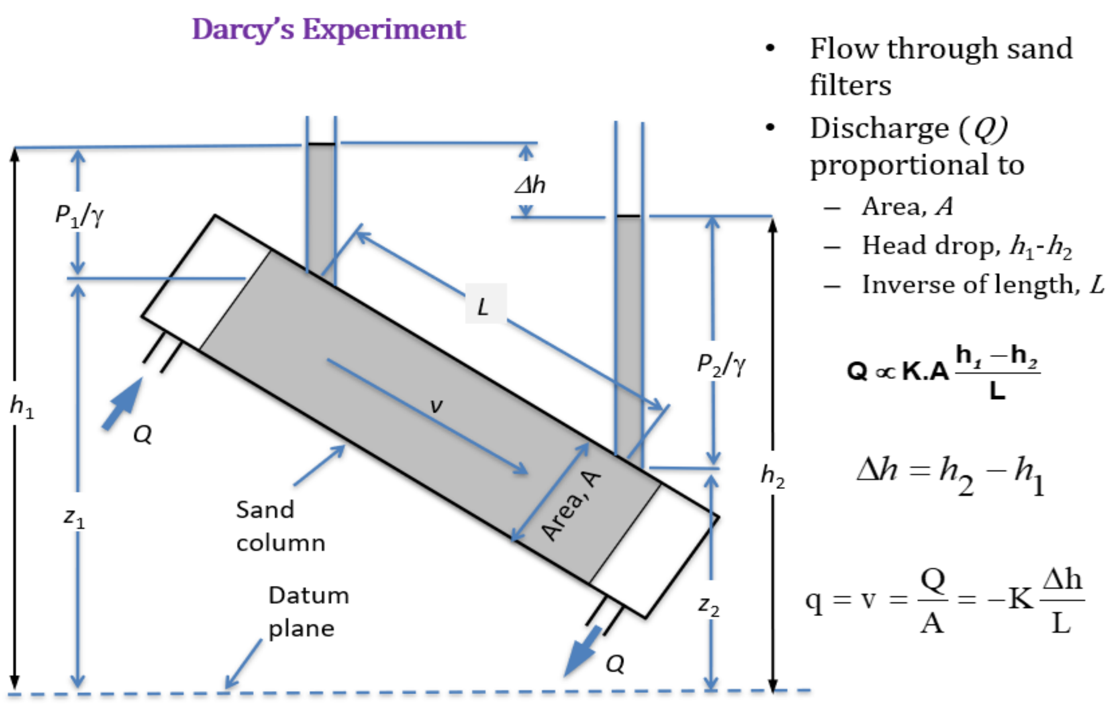

Figure 4. Darcy’s Experiment (Source:From lectures of Groundwater Hydraulics by prof. Pavel Pech).

3.6.1 Condition for Darcy's law validity:

It is a difficult task to predict the exact range of the validity of Darcy's law. However, the best way to determine the range of its validity is to conduct the experiment and figure out the actual relationship between the velocity and hydraulic gradient. for example, the flow through the soil must be laminar and that is true for Reynold number less than one. Sometimes it might be found that variation of Darcy's law occurs, even in the laminar regime when the inertial forces become effective. It has been also found in some cases that Renold's number increases during an increase in the value of characteristics length(D) (Alabi, 2011).

Re_f(0 - 1) = Darcian equation is valid.

Re_f(1 - 10) = Darcian equation is also valid.

If α = $\frac{1}{K}$

or, v = -KJ (3)

so, Hydraulic gradient (J) = αv

In the case of, Re_f(10 - 100) = It is Non- Darcian flow because of that Darcian equation is not valid.

So, we can use previous equation in following form,

$$J = \alpha v + b.v^{m} \quad (4)$$

Where, m = 1.6 - 2.0

In the case of, Re_f > 100) = It is turbulent flow because of that Darcian equation is not valid, to calculate the hydraulic gradient we have to use following equation,

$$J = b.v^{2} \quad (5)$$

3.6.2 Darcy's law in Three dimension:

One dimensional Darcy's law could be derived in three dimensions such as head potential will be expanded to be a function of the three space coordinates, x,y, z, velocity (v) is the vector with components and potential head depends on the position. This equation follow the law of conservation of mass. Consequently, The total amount of fluid entering to the three faces of the cube is equal to amount of fliud leaving from the opposite faces of the cube plus storage changes on it.

so, three dimensional expanded form of Darcy's law, Darcian velocities (v) = -K $\frac{\Delta h}{\Delta l}$ can be written as:

$$v_x = -K_x \frac{\partial h}{\partial x}, \quad v_y = -K_y \frac{\partial h}{\partial y}, \quad v_z = -K_z \frac{\partial h}{\partial z}$$

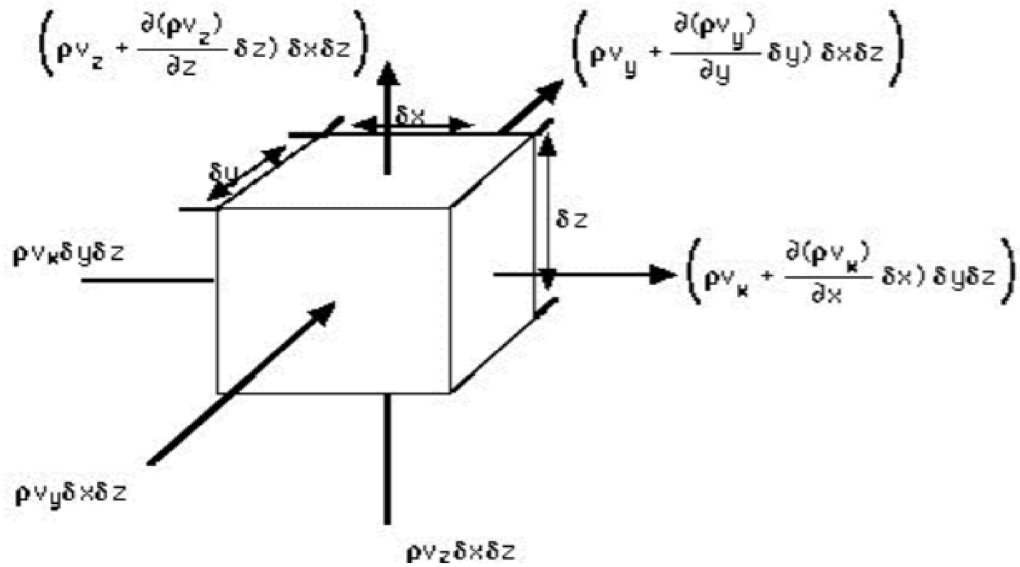

Figure 5. Three dimensional figure of Darcy's laW (Islam, 2020)

Final equation will be,

$$[\frac{\partial(\rho v_x)}{\delta x} + \frac{\partial(\rho v_y)}{\delta y} + \frac{\partial(\rho v_z)}{\delta z}] = - \frac{\partial(M)}{\partial t} \quad (6)$$

where, inflow components are, $\rho v_x \delta_y \delta_z$, $\rho v_y \delta_x \delta_z$ and $\rho v_z \delta_x \delta_y$.

ρ = density of water($\frac{Kg}{m^3}$)

v_x, v_y and $v_z$are the velocities to the x, y and z-direction.

(M) = mass in the elementary cube(Kg)

V= volume of cube($\partial x \partial y \partial z$)($m^3$)

In the case of density of fliuid (ρ)= constant, equation will be:

$$v_s = -K_x \frac{\partial h}{\partial s} \quad (7)$$

3.7 physical properties of the reservoir(aquifer)

3.7.1 Porosity

Porosity is the portion of the rock and soil particles which are not occupied by solid mineral can be cover by groundwater. These spaces are voids, interstices, pores or pore space. Originally, interstices were created by geological processes when the geological formation happened to the Earth and it is found in sedimentary and igneous rock. secondary interstices developed way after the rock was formed (Todd & Mays, 2004).

Soil porosity is an inversely proportional relationship with the size of particles as a result clay has more porosity than sand. It is usually measured in percentage and the range of total porosity of consolidated materials is clay (40-70) % (35-50)%, sand (25-50)%, and gravel (25-40)%.

Porosity is expressed either in decimal fraction or in percentage values. For the porosity calculation we can use this mathematical eqation (Heath , 1987),

$$\text{Porosity } (\emptyset) = \frac{V_t - V_s}{V_t}$$

$$= \frac{V_v}{V_t} \qquad (8)$$

Where,

Ø = Value of porosity in decimal form(-)

V_t = Total volume of soil or rock sample (m^3)

V_s= Volume of the solids in the sample (m^3)

V_v= Volume of openings or voids (m^3)

The value of porosity expressed in decimal value but if we multiply calculated value from the equation by 100, it will be changed into the percentage.

3.7.2 Types of porosity

Total porosity($\emptyset_t$), Effective porosity($\emptyset_e$), and Active porosity($\emptyset_a$)

3.7.2.1 Total porosity($\emptyset_t$)

Total porosity(n) is the total geometric space in the rock occupied by soil pores and does not matter with different size, shape and the degree of interaction between it. It is the total sum of open(n_o) and closed(n_c) porosity. In open porosity, all the pores should be connected to each other and also with the outer space and the closed porosity consists of isolated(closed) and not available interconnected pores (Osipov, et al., 2015).

So, total porosity($\emptyset_t$) = open Porosity($\emptyset_o$) + closed porosity($\emptyset_c$)

$$= \frac{Total\ pore\ volume(V_t)}{bulk\ volume(V)} \quad (9)$$

3.7.2.2 Effective porosity($\emptyset_e$)

Effective porosity($\emptyset_e$) is the part of the rock pore space in which water and gases can transfer one place to another under certain pressure. Effective porosity might change during deformation and fluid are squeezed out due to compression of rock particles (Osipov, et al., 2015). However, the value of effective porosity decreases with pressure and sometimes increases with the head gradient. Therefore, it cannot be assumed as a constant for rock pore space. In very pure sandstone, the values of effective porosity and total porosity will be equal. Effective porosity is the important parameters that are using to solve flow problems of groundwater.

It can be calculated by following equation,

$$\text{Effective porosity}(\emptyset_e) = \frac{V_{pe}}{V_t} \quad (10)$$

Where,

V_{pe}= Total sum of pores volume when the water actually moves where groundwater flows (m^3)

V_t= Total volume of soil (m^3)

Aquifer Matrix	Dry Bulk Density (g/cm^3)	Total Porosity	Effective Porosity
Clay	1.00-2.40	0.34-0.60	0.01-0.2
Peat	--	--	0.3-0.5
Glacial Sediments	1.15-2.10	--	0.05-0.2
Sandy Clay	--	--	0.03-0.2
Silt	--	0.34-0.61	0.01-0.3
Loess	0.75-1.60	--	0.15-0.35
Fine Sand	1.37-1.81	0.26-0.53	0.1-0.3
Medium Sand	1.37-1.81	--	0.15-0.3
Coarse Sand	1.37-1.81	0.31-0.46	0.2-0.35
Gravely Sand	1.37-1.81	--	0.2-0.35
Fine Gravel	1.36-2.19	0.25-0.38	0.2-0.35
Medium Gravel	1.36-2.19	--	0.15-0.25
Coarse Gravel	1.36-2.19	0.24-0.36	0.1-0.25
Sandstone	1.60-2.68	0.05-0.30	0.1-0.4
Siltstone	--	0.21-0.41	0.01-0.35
Shale	1.54-3.17	0.0-0.10	--
Limestone	1.74-2.79	0.0-50.0	0.01-0.24
Granite	2.24-2.46	--	--
Basalt	2.00-2.70	0.03-0.35	--
Volcanic Tuff	--	--	0.02-0.35

Table 1. values of effective porosity and total porosity of different aquifer materials (Borden, 2006).

3.7.2.3 Active porosity($\O_a$)

According to Osipov, it is the volume of pores through which water easily can move under a certain head gradient. In the pore space of fine-grained rocks is occupied by physically bound water and it is tightly by the minerals. The coefficient of active porosity of saturated rocks is the ratio of the volume of pores filled with free water to the total volume of solid minerals particles. It can be calculated using following equation,

$$\text{Active porosity}(\O_{active}) = \frac{V_{pa}}{V_t} \qquad (11)$$

Where,

V_{pa}= Volume of pores when water is moves only because of gravitational force (m^3)

V_t= Total volume of soil (m^3)

3.7.3 Permeability

Permeability is the property of soil that allows transferring water and air from one place to another. The value of permeability mainly determined by the size of materials that means bigger particle size refers to high permeability, smaller particles have low permeability and the ratio of void on the particles also affect on it because more void ratio will create the big area that means permeability also will be greater in the critical condition. A s a result, gravel has greater permeability and clay has lesser.

Mathematical expression for permeability(K_p) is,

$$K_p = \mathrm{C}d^2 \qquad (12)$$

Where,

K_p= Permeability (m^2)

C = Dimensionless constant(-)

d = Characteristics diameters of a pore (m)

3.7.4 Hydraulic conductivity

Hydraulic conductivity is the physical properties of materials that allow transmitting fluid through pore spaces under a unit hydraulic gradient. In a way, it is a Darcian coefficient which captures the velocity of a stream under laminar flow condition to a hydraulic gradient.

The magnitude of the hydraulic conductivity (K) mainly depends on the characteristics of the aquifers and properties of flowing liquid (Pech, 2010). Mathematical equation of hydraulic conductivity is,

$$K= k_p \frac{\rho g}{\mu} \qquad (13)$$

Where,

k_p= Permeability of the porous media(m^2)

g= Acceleration due to gravity($\frac{m}{s^2}$)

ρ= Density of the fluids ($\frac{Kg}{m^3}$)

μ= Dynamic viscosity of water(Pa. s),

K= Hydraulic conductivity($\frac{m}{s}$)

3.7.5 Storativity

It is the volume of discharged water from an aquifer per unit area and per unit change in hydraulic head. For the confined aquifer, storage coefficient ranges from(~10^{-4} - 10^{-12}) and it comes due to the effect of rock and fluid compressibilities. In the case of the unconfined aquifer, there is a small effect of rock and fluid compressibilities will be neglected, so the value of storativity is equal to the specific yield (Rackley, 2017). Mathematically, storage coefficient can be written as:

$$S = \frac{dV_w}{dh} * \frac{1}{A} \qquad (15)$$

$$= s_s b + s_y \qquad (16)$$

Where,

V_w = Volume of water (m^3)

A= Area of aquifer (m^2)

S_y= specific yield (-)

S_s= specific storage (m^{-1})

b= thickness of aquifer(m)

Specific storage calculation of confined and unconfines aquifers in different aspect:

(i). compression of the aquifer due to increase in effective stress

$$S_s = \rho g(\alpha - n\beta_w) \qquad (17)$$

Where,

α = compressibility coefficient of an aquifer ($\frac{m^2}{N}$)

β_w= compressibility coefficient of an aquifer ($\frac{m^2}{N}$)

N or Ø = porosity of aquifers (-)

ρ = density of water($\frac{Kg}{m^3}$)

g = acceleration due to gravity($\frac{m}{s^2}$)

(ii). Storativity of confined aquifer with thickness 'b' :

$$S= S_s b \qquad (18)$$

(iv). Storativity of the unconfined aquifer:

$$S= S_y + S_s h \qquad (19)$$

3.7.6 Transmissivity

It calculates the rate of fluid flow in the presence of a unit hydraulic gradient through a unit thickness of the aquifer. In another way, it is a product of the thickness of aquifer and the average value of hydraulic conductivity in the porous media.

$$T = K.b \qquad (20)$$

Where,

T = Transmissivity($\frac{m^2}{s}$)

K = Hydraulic conductivity($\frac{m}{s}$)

b = Saturated thickness of Aquifer(m)

3.8 Vertical distributation of groundwater (Subsurface water)

3.8.1 Subsurface Water

Subsurface water will occur in between the earth surface and water table(under the water table we will get groundwater). In other words, subsurface water also called suspended water.

3.8.2 Zone of Aeration

Surface water always moves downward due to gravity of the earth. However, some of the water will stay on the grains and between the water table and surface of the earth because of surface tension.

Which is called suspended water, it is found in Zone of Aeration.

The zone of aeration is extended from the surface of the earth to the water table which contains soil moisture water, intermediate zone and capillary zone(just above the aquifer).

In the soil moisture layer, water is evaporated from the soil as well as it will be used by plants.

In the intermediate zone, the water is held by molecular attraction as well as small or zero movement occurs when recharging of groundwater occurs.

In the capillary zone, It's thickness always depends on the characteristics of the materials which is overlying on the water bed. As a result, The thickness of the capillary zone might vary from a few centimetres to a few meters. The finer materials will be bigger in thickness. This all zone will be recognised by drillers as a sign of proximity of the water. We have better explanation in figure (2) bellow:

3.8.3 Zone of Saturation

It is the zone where all the pores are completely filled with water. In the saturated zone, the top part is called a water table which always fluctuates with groundwater recharge. For the most part of the saturated zone where groundwater is continuous. However, groundwater availability depends on the characteristics and formation of rock. for instance, clay could be saturated but not release the water to a well(or bore) but coarse materials(gravels) would have enormous in yield.

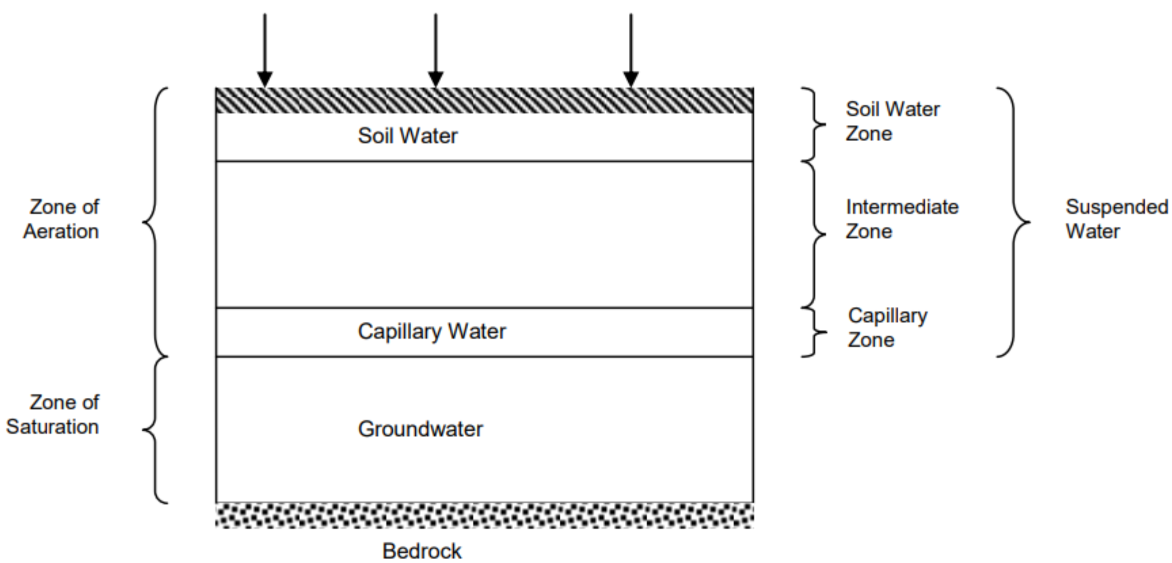

Figure 6. Sub-surface water (Hazel, 1975).

3.9 Types of geological formation of groundwater on the earth (Distributation of saturated zone)

3.9.1 Aquifer(sand and gravel)

An aquifer is a saturated zone beneath of water table which is formed with porous rock or sediments. Groundwater always enters as precipitation seeps until reaching the groundwater aquifer. Generally, aquifers are huge storehouse of water (National Geography, 2015). Aquifer can be formed by different types of sediments and rocks, generally gravel,sandstone,coglomerates and fractured limestone. Consequently, it's categorized according to the types of materials(rock, sediments) which they are composed.

3.9.2 Confined (Pressure or Artisian) aquifer and Unconfined (Non-pressure or water table) aquifer

Confined aquifer have a confining layer on the top of it and that could be impermeable rock or clay. These layers are not allow to transmit water from one aquifer to others. Unconfined aquifer are lie just bellow the permeable layer of the soil and confining layer would be on the bottom. In the context of water pressure, the Confined aquifer has more water pressure than the unconfined aquifer (Ge & Gorelick, 2015).

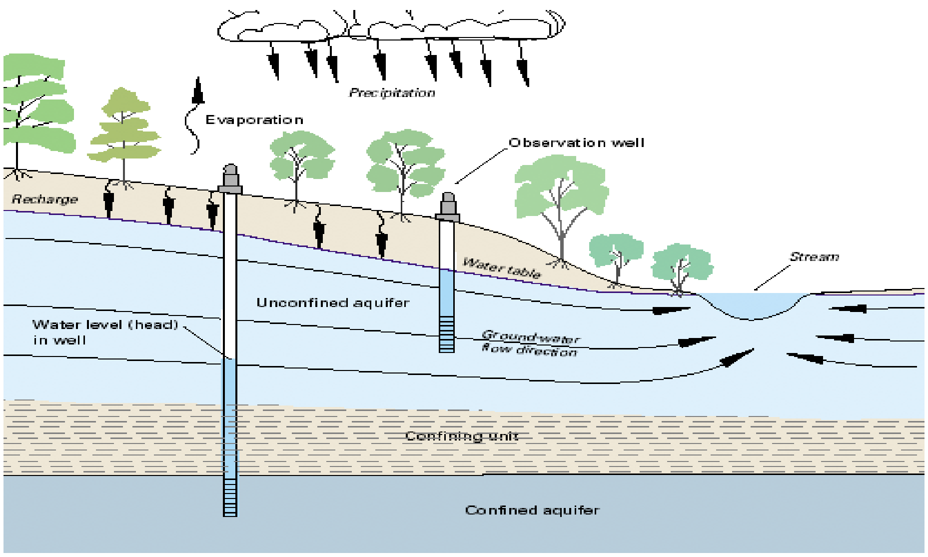

Figure 7. Groundwater aquifers (Utah State University, 2015).

3.9.3 Aquitard (sandy clay)

An aquitard is a body of the earth which tries to restrict the flow of water from one aquifer to another. Most common examples of aquitard are tightly packed clay(sandy clay), cemented sandstones, igneous and metamorphic rooks lacking fractures. It is also known as a combination of aquifer and aquifuge.

In some conditions, it behaves like aquifer and sometimes aquifuge.

3.9.4 Aquiclude (clay)

The materials which have a porosity but impermeable in nature, that means it can easily store the water but does not transmit it. This is happening because of the high value of porosity. Clay is a good example of the aquiclude (The Constructor, 2014).

3.9.5 Aquifuge (granite, basalt etc)

It is the impermeable geological formation that neither porous nor permeable, that means it can not store and permit water. Compact rock(Granite, basalt etc.) is a good example of aquifuge (The Constructor, 2014).

3.10 Formation and function of an Aquifer

3.10.1 Formation of aquifer

Mainly, There are two types of formation which can easily store and transmit water.

3.10.1.1 Porous rock

Types of rock which contains empty space, which can easily hold water like a sponge with their tiny pores. For example, unconsolidated sands and gravels, consolidated sandstones.

3.10.1.2 Fractured rock

It is the geological formation where rock are divided into two or more pieces which creating space on it, and these spaces are storing groundwater. The fracture that sometimes forms a crevice or fissure in the rock. It includes crevices and joints in hard rock, solution channel in limestone, shrinkage cracks in basalt type of volcanic rocks.

3.11 Function of Aquifer

3.11.1 Storage of water

Aquifer stores an enormous amount of water as a reservoir. Its characteristics describing the ability to store water in the pores and also shows how much water it can release under the gravity drainage is its specific yield. These properties are showing elastic storage is the storativity and is related to their elastic properties of water as well as aquifers material (Hazel, 1975).

3.11.2 Transmission of water

Another important function of an aquifer is it transmits groundwater from one place to another. Aquifers must have two fundamental features, it should be permeable and porous in nature. Permeable features going to work to transmit water easily (Hazel, 1975).

The main driving forces to transmit water from one point to another are pressure between these points and gravity force of Earth's. Thus, water flows from high points to low points due to gravity force.

3.11.3 Mixing

This function of an aquifer will work to mix different qualities of water. Low quality of water could be injected from one point of an aquifer, after that, it will be mixed with the local groundwater and this mixture of water going to extract as useable water at another location.

3.12 Different types of hydrodynamic test

2.12.1 Aquifer Test

it is a geologic and hydrologic investigation method which tries to capture location and amounts of groundwater for withdrawals, position and thickness of aquifers and confining beds, transmissivity and storage coefficient of aquifers, hydraulic characteristics of confining beds, position and nature of aquifers boundaries, and quantity of pollutants inside the aquifer. so it is the test to determine groundwater yields, movements and situation of pollutants inside of groundwater system. However, to perform the successful aquifer test, we should necessarily follow some of the steps,

1. we should have ideas about the pre-pumping water level and regional trend.
2. There should be a carefully controlled constant rate.
3. During both drawdown and recovery periods, we should have accurate water level measurement in each and every precise time.

3.12.2 Pumping test

In a common word, pumping test is the very often method to calculate storativity and transmissivity of a geological formation and extracted water from well is assume as an influence by hydraulic head on the formation (Novakowski, 1989).

The pumping test is always depending on the flow of the type (steady and unsteady) and types of an aquifer(confined and unconfined). When we start to pump water from an aquifer, the soil around well starts to generate (resistance and head loss) that creates a hydraulic head to occur flow towards a well. The drawdown will show all hydraulic characteristics including storativity (S), hydraulic conductivity (K) and the transmissivity (T).

3.12.3 Pressure buildup test

The buildup test is the method that will mitigate the latter problems . A drawdown test has to start before the flow condition. For a long flow period, it is necessary to be shut-in. Moreover, It is pretty hard to maintain a constant rate of producing well. The main drawback of the buildup method is well should be closed and that will not generate income. So, shut-in time should be as short as possible to minimize economic loss. However, the shorter shut-in period would provide less information (Jelmert, 2013).

1. Well production should be at a constant(stabilized) rate. at the time (t_p) , close the well.

2. measure the last flowing pressure (P_{wf}), at a time(t_p), and then shutin pressure (P_{ws}).

3. Interpret observed data by using the matched model.

Where, t_p and Δt are showing production time and shutin time respectively.

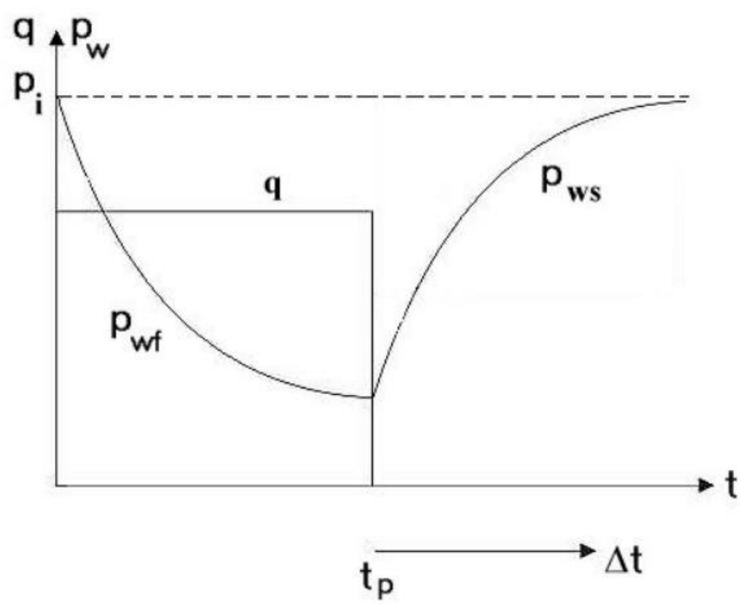

Figure 8. Schematic diagram of an ideal buildup test (Jelmert, 2013).

3.12.4 Drawdown test

Drawdown test is the process that measuring pressure response in the well where discharge (q) will be constant (Kahuda & Pech, 2020).

It is pretty helpful to determine the reservoir boundaries and skin in a particular location. It will be applicable either it should be new wells or the well that have been closed for a long period of time. This test depends on a mathematical model and observed pressure behaviour will be matched with a feasible model. After all, targeted variables(s) predicted by previous matched models. If the assumed model has enormous estimates, then the model is incorrect. To do the test, there is some more assumption, these are constant production rate, homogenous as well as an infinite reservoir, and initially static equilibrium (Jelmert, 2013).

According to the Jelmert, he recommended a three-step procedure for drawdown test.

1. Increase the production rate from 0 to q at t=0, but the rate should be constant.

2. Try to measure the pressure response in the well(P_{wf}), where (wf) indicates well-flowing pressure.

3. Make the interpretation, after matching its resultant behaviour to the model.

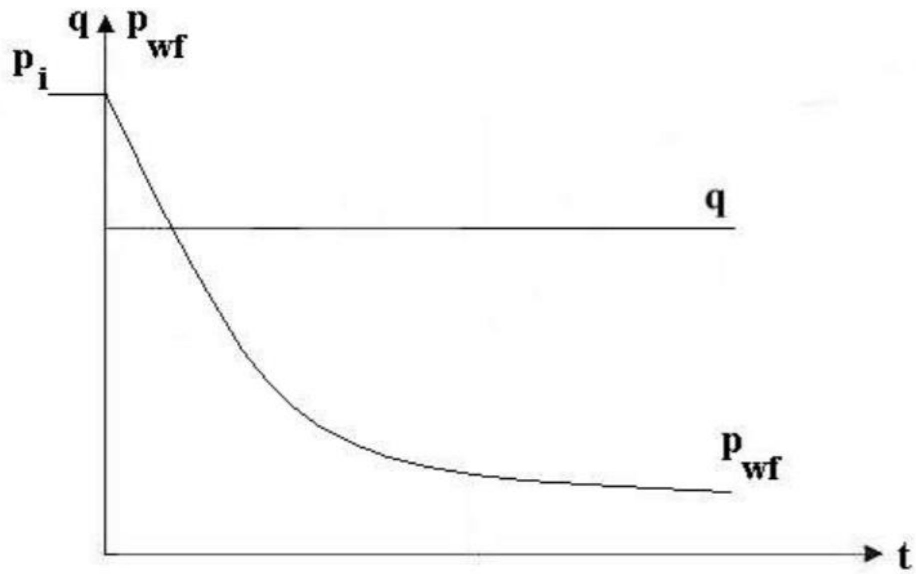

Figure 9. Schematic production rate, well flowing pressure as a function of time (Jelmert, 2013).

3.13 Water wells

Groundwater usually occurs in the saturated zone of soil and rock just below the water table of the earth's surface. If the water storage(aquifers) is good enough permeable then peoples start to drill the surface of the earth to extract the groundwater. So, the pumping well is generating a water flow field in the groundwater system and for the measurement of drawdown, observation well is used (Chen & Lan, 2009). So far pumping well is the best way to extract groundwater. It has to be drilled much deeper than the water table. Generally, the water table fluctuates at a different time (season, years). After a certain amount of water being pumped meanwhile the water level will drop temporarily.

3.14 Wellbore storage

It is the capacity of the well that can absorb or supply any part of the mass flow rate change out of a well (Miller, 1980).

In the maximum case, well test analysis is the idea of the pressure response of the reservoir to a given change in the rate(for the drawdown test, the value start from zero to a constant value and from constant value to zero for buildup test). However, the well produces a constant rate of the flow at the wellhead, then flow will be temporary at the wellbore. As a result, the flow rate from the reservoir into wellbore would not be constant. There are two main causes for the wellbore storage effect, first is due to fluid expansion and second reason by changing the liquid level (Horne, 1995).

Wellbore storage coefficient (C) will be calculate using following equation:

$$C = \frac{V}{\Delta p} \tag{21}$$

C= Wellbore storage (m^2)

V = Volume produced (m^3)

Δp = Pressure drop (Pa)

3.15 Well Productivity

It indicates the production rate per unit drawdown. Its values will differ in different well but it should be as high as possible. Generally, a reservoir can be produced by several wells but sometimes small reservoir might be produced by a single well. However, each well has a specific area for drainage. The wells productivity is always measuring by productivity index(PI) which tries to capture the rate of flow in per unit pressure drawdown. The PI index also helps to measure the quality of the well at a particular situation (Jelmert, 2013).

Mathematically,

$$PI = q/\Delta p \tag{22}$$

Where, q = discharge of well (m^3s^{-1})

Δp = small pressure (Pa)

3.16 Well Cleaning and rehabilitation

Water wells should need to maintain periodically for its better efficiencies. Well efficiencies only will be at the better condition after rigorously cleaning the well screen, gravel pack and natural formation. So, well rehabilitation is the art of the well maintenance process. In the beginning, well efficiency will be close to 100 percent but after some production time, it will start to decrease eventually. In many cases, normal mechanical well cleaning and acidization technique demonstrate as an effective well protection method. The effectiveness of frequent cleaning will prevent from casing deteriorate problem. Hence, well rehabilitation and cleaning technique are the finest technique to increase well efficiency (National Water Services, 2016).

None of the well preventive maintenance or rehabilitation treatment will efficiently solve every well problems. However, a qualified well driller can be a better option to solve well problems in a specific geographical location. Even driller also be able to recommend appropriate treatment options and the well owner is selecting the best method of treatment. we have to figure out the main causes of the problem to identify the proper treatment. The main causes of well problems are physical, chemical and biological plugging. Rehabilitation will be initiated when the performance of the well declined by about 25 per cent, it always should be performed by a licensed well driller or well rehabilitation specialist (Government of Canada, 2020).

The main purpose of performing a well treatment are:

- To obtain effective deposit removal
- custom-tailor treatment to find the specific problem, aquifer type and to know well construction details.
- to make good penetration into surrounding formation
- for good agitation of chemicals.

Factors that should be considered while well treatment:

- The pump must be removed and the well should be off-line for 2/3 days to complete the treatment process.
- Specialized equipment and expert personal will be needed to complete the rehabilitation process.
- Both chemical and mechanical methods will be used for effective cleaning.
- The type of deposit, as well as the physical condition of the well, must be considered

3.17 Additional resistance (Skin effect)

Skin effect is a head loss in the damaged zone near a water well and it is the results of several factors including physical, chemical, and biological phenomena acting on the well. Normally these phenomena capture the invasion of mud during the drilling time, fine materials migration, imperfect perforations and many more (Kahuda & Pech, 2020). The skin effect is denoted by dimensionless notation S_f and used to characterize all the additional resistance that exist on the well and its surroundings. The additional resistance (skin effect) and wellbore storage (finite volume of a wellbore) are the main components that have more impact on data measurement at the pumping well.

Additional resistance would increase in the well and it's surrounding by several factors like clogging of pores(s_1), due to reduction in the wellbore wall cross-section (s_2) and it is due to the borehole formed by a filter, perforated casting etc.), additional resistance due to the friction(s_3) of the water with borehole wall and it's internal friction(it also includes additional resistance due to turbulent flow regime of the water inside borehole as well as turbulent flow on the aquifers) and many more (Kahuda & Pech, 2020).

So, drawdown due to the additional resistance will be expressed in the following way,

$$s_{skin} = s_1 + s_2 + s_3 + \ldots\ldots\ldots\ldots\ldots + s_n \qquad (23)$$

$$= \sum_{i=1}^{n} s_i$$

Where, s_{skin} is the total skin drawdown and it is caused by the additional resistance at skin zone.

The total water level will be measure at borehole during pumping test is expressed by the following equation;

$$s_w = s_{te} + s_{skin} \qquad (24)$$

Where,

s_w= Total drawdown in the pumping well (m).

s_{te}= Theoretical drawdown (ideal)of the water level in zero additional resistance(m).

s_{skin}= Additional drawdown of water in the wellbore due to skin effect(additional resistance)(m).

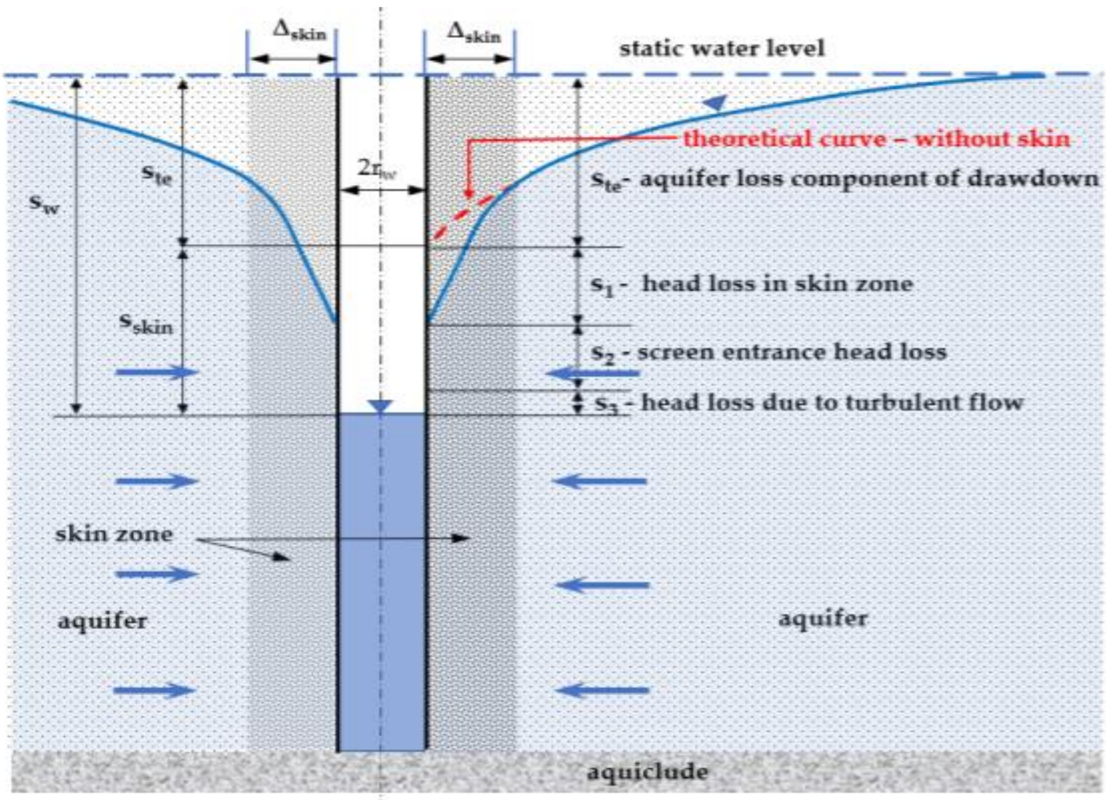

Figure 10. Real well with various head losses in a well (Kahuda & Pech, 2020).

We are going to neglect the portion of the drawdown due to turbulent flow regime, s_3 (negligible contribution for total additional drawdown), the magnitude of the total additional drawdown caused by additional resistance on the pumping rate(Q) with a linear relationship,

$$s_{skin} = \frac{Q}{2\pi T} S_F \text{ or W} \quad (25)$$

Where,

$W\,(S_F)$= coefficient of additional resistance (skin factor)(-).

s_{skin}= drawdown caused by additional resistance(m).

The effect of additional resistance on the total drawdown on the real well when the flow is at tight level;

a. For the steady flow

$$s_w = \frac{Q}{2\pi T}\left(ln\,\frac{R}{r_w} + W\right) \quad (26)$$

Where,

R= Radious of well influence(m).

r_w= Radious of wellbore(m)

S_F= coefficient of additional resistance(skin factor) (-).

b. For unsteady flow(Using the Cooper-Jacob semilogarithmic method because it doesn't show a wellbore storage effect anymore in the unsteady flow regime)

$$s_w = \frac{Q}{4\pi T} (ln\ 2.246 t_D + 2W) \qquad (27)$$

After converting to the normal logarithm, then equation will be:

$$s_w = \frac{2.303\ Q}{4\pi T} (log(2.246 t_D) + 2W) \qquad (28)$$

The Cooper- Jacob semilogarithmic straight line after reached in the semilogarithmic graph of the pumping test. Then, we can use the equation(28) to evaluate the coefficient of additional resistance in this form:

$$W = \frac{2\pi T_w}{Q} - \frac{1}{2}(\log t + \log\frac{T}{S r_w^2} + 0.8091) \qquad (29)$$

3.18 Theis(1935) solution

In 1935, Charles Theis invented the equation that can describe cone of depression all around a pumping well under non-steady state condition. It is also known as the theis nonequlibirium method and tool for estimating the transmissivity and storativity of nonleaky aquifers (Jong, 2020).

Firstly, Theim invented the equation to solve the steady-state flow to the well in 1906 for confined aquifer. Unfortunately, there is a problem in steady-state where you have to pump pretty long time before you get a stable cone of depression, at least till you reach quasi-steady state and this situation is not always practical. In 1935, Charles V Theis developed the equation that can describe the cone of depression around the well under non-steady state condition (Geosearch International, 2020).

The basic equation of Theis (1935) for unsteady radial flow,

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{T}\frac{\partial s}{\partial t} \qquad (30)$$

Where,

s= drawdown(m)

r= radial distance(m)

S= storativity(-)

T= transmissivity($\frac{m^2}{s}$)

t= time(s)

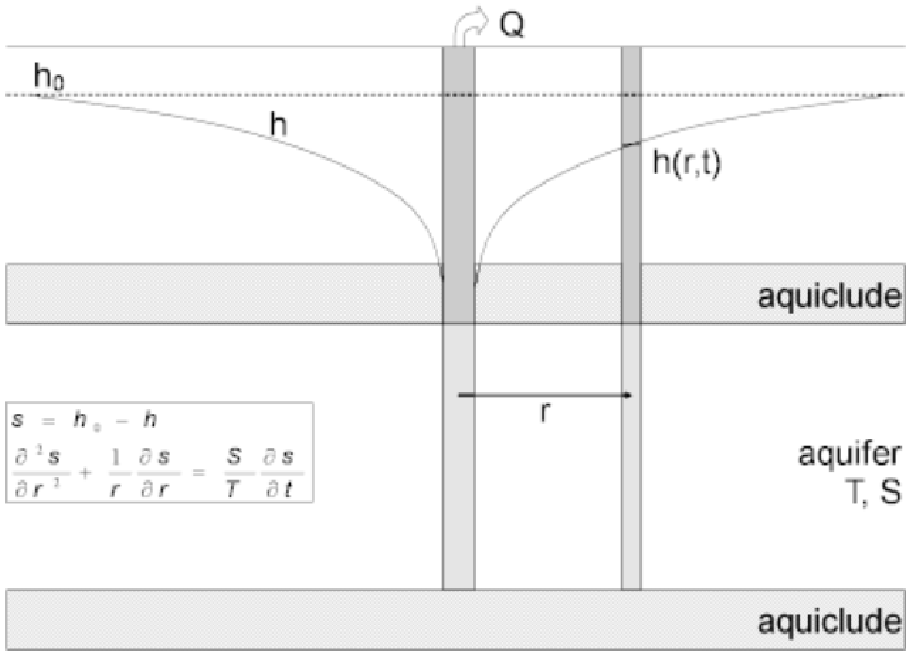

Figure 11. Theis method for unsteady radial flow (Aqtesolv, 2015).

Assumptions for Theis equations for completion of well in a confined aquifer;

- Negligible gravitational forces.
- The confined aquifers should be homogenous and isotropic.
- Viscosity and density of the water must be constant.
- Aquifer should have infinite areal extent.
- Pumping well should penetrate the full thickness of the Aquifer.
- Unsteady flow.
- flow to the pumping well must be horizontal.
- It should have a small diameter of well(to neglect storage of the well).
- well should have a constant pumping rate(Q).
- Horizontal aquifer and should bounded by top and bottom by impermeable layers(confined aquifers).
- Aquifer flow to the pumping well is laminar and radial(because of that Darcy's law is applied)
- The height of the aquifers where a flows to the well is constant and where size (b), Transmissivity(T)and storativity(S) are constants over time and space.

- The water supply from the aquifers to the well changes while the pumping test Q_{aq}= 0 to final inflow Q_{aq}= Q = constant.
- Before the pumping occurs(when t=0), the hydraulic head of the aquatic environment is constant in all points and it is equal to H, it also applies to the water level at a well

Theis also developed a standard type of curve to show the response of an aquifer to pumping. This equation is the solution of basic equation(upper equation);

$$s = \frac{Q}{4\pi T} W(u) \qquad (31)$$

Where, W(u) is well function.

$$W(u) = -0.5722 - \ln(u) + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \cdots \qquad (32)$$

u – argument of Theis well function $u = \frac{Sr^2}{4Tt}$

s = drawdown at distance (r) at time (t) after the start of pumping(m)

Q = well discharge ($\frac{m^3}{s}$)

r= Distance from centre of pumping well (m)

S= Aquifer storativity(-)

t= time since the start of the pumping(s)

3.19 Cooper-Jacob (1946) semi-logarithmic method to evaluate hydraulics parameters (storativity and transmissivity)

The **C**ooper and Jacob(1946) modified nonequilibrium method(solution) is a lately derived approximation method from the Theis type curve method. This modification includes matching a straight line to drawdown data plotting as a function of the logarithm time since pumping of well begin. So, It is a modified form of the Theis(1935) solution for a transient flow, well with constant discharge from the homogenous and isotropic nonleaky confined aquifer with the infinite extent and uniform thickness.In a recent time, well test interpretation has led to the development of the complementary graphical procedure is called derivative analysis which can improve the reliability of the Cooper and Jacob method more clearly (Aqteslov, 2015).

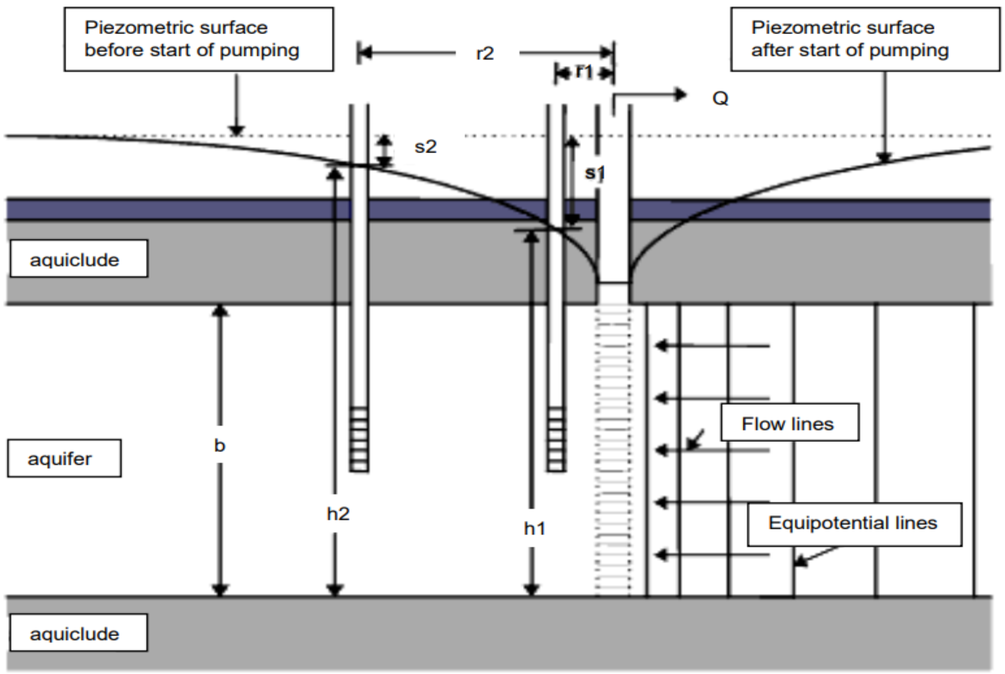

Figure 12. Solution for appropriate condition (Waterloohydrogeologic, 2018)

Basic assumptions;

- Aquifer with infinite areal extent.
- Aquifer should be homogenous, isotropic and uniform in thickness.
- Control well should be fully penetrating.
- Water flow to the control well should be horizontal.
- Aquifer should be nonleaky confined aquifer.
- The flow should be unsteady.
- The water should be released instantaneously from the storage with decline hydraulic head.
- It should have a small diameter of well(to neglect storage of the well).
- Values of u should be small(i.e., r is small and t is large)

The well function $W(u)$,

$$W(u) = -0.5722 - \ln(u) + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \cdots \qquad (33)$$

Due to the small values of ‘u’(i.e. large values of t and small values of r), Cooper and Jacob found that the Theis well function will be approximated only using the first two terms, Then well function $W(u)$ will be;

$$W(u) = = -0.5722 - \ln(u) \tag{34}$$

The critical value of u should be in reasonably small for the accurate approximation of the Theis well function. There is two different recommendation for the critical value of 'u'. According to (Driscoll 1986), it should be ($u \leq 0.05$) and by the (Kruseman and de Ridder 1994), it should be ($u \leq 0.01$).

Let's combine the Theis equation and new value of well function $W(u)$, then we will get Cooper and Jacob equation of approximate calculation for drawdown for nonleaky confined aquifer,

$$s = \frac{Q}{4\pi T}\left[-0.5722 - \ln\left(\frac{Sr^2}{4Tt}\right)\right] \tag{35}$$

Cooper-Jacob equation after converting to decimal logarithms,

$$s = \frac{2.303Q}{4\pi T}\left[\log\left(\frac{2.25Tt}{Sr^2}\right)\right] \tag{36}$$

3.19.1 Cooper-Jacob time-drawdown method (waterloohydrogeologic, 2018).

Transmissivity and storativity will be calculated as follows:

$$\text{Transmissivity(T)} = \frac{2.303Q}{4\pi\Delta s} \tag{37}$$

$$\text{Storativity(S)} = \frac{2.25Tt_0}{r^2} \tag{38}$$

Where, t_0= time (at s=0) for observation well and Δs= difference in drawdown(s_2- s_1) at t_2 and t_1.

following data will be needed for Cooper-Jacob time-drawdown methods

- Drawdown vs time data of an observation well.
- The distance needed between pumping well and observation well.
- The pumping rate(constant) of the well will be needed.

The well with multiple observation well, the closest observational well meets the condition before than distance ones. Time will be plotted along the logarithmic X-axis and drawdown will be plotted along the Y-axis.

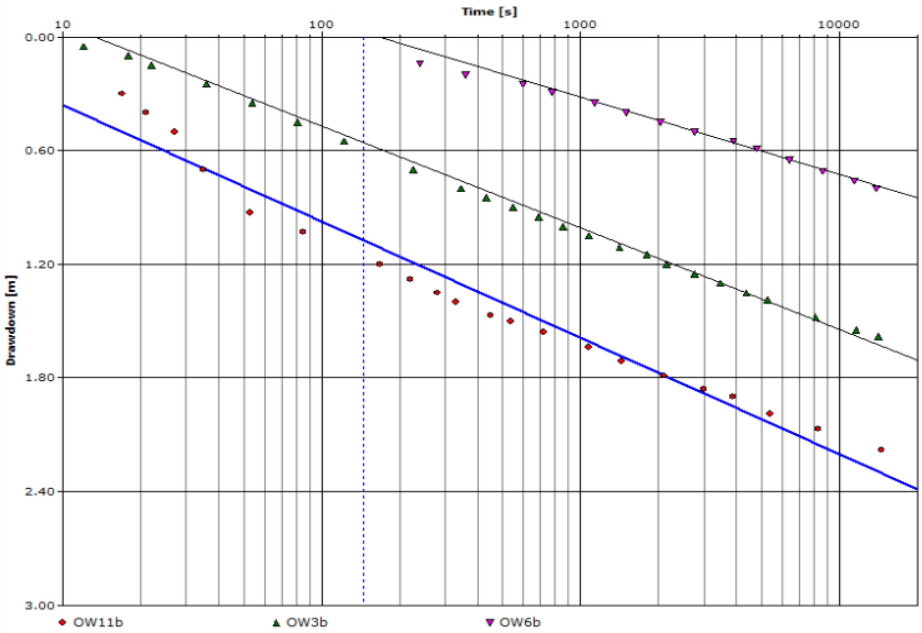

Figure 13. Cooper- Jacob time drawdawn analysis graph (waterloohydrogeologic, 2018).

3.19.2 Cooper-Jacob distance-drawdown method(II)

Transmissivity(T) $= \frac{2.303Q}{2\pi\Delta s}$ (39)

Storativity(S)= $\frac{2.25Tt_0}{(r_0)^2}$ (40)

Where, r_0 is the distance observation well from pumping well defined by the intercept at s_0(zero drawdown).

following data will be needed for Cooper-Jacob distance-drawdown method.

- Drawdown vs time data of an three or more observation well.
- The distance needed between pumping well and observation well.
- The pumping rate(constant) of the well will be needed.

It applies when we are getting simultaneous drawdown data from three or more than three observation well. The observation well distance will plot along the x-axis and drawdown in the y-axis.

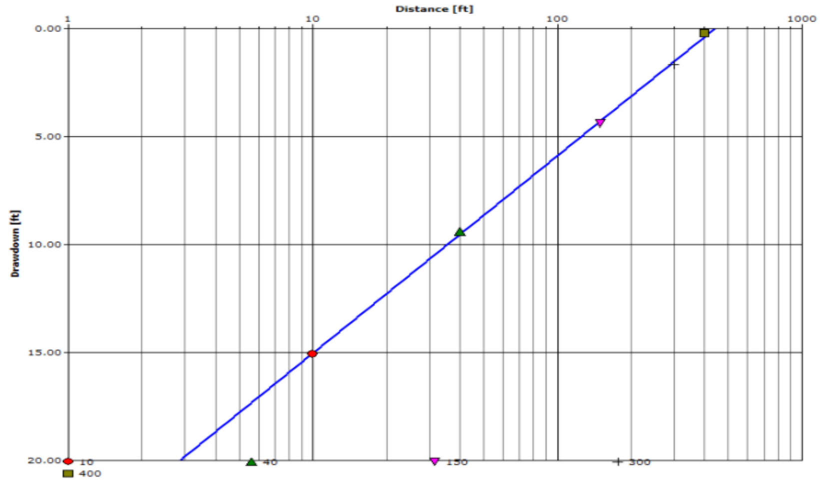

Figure 14. Cooper- Jacob distance drawdown analysis graph (waterloohydrogeologic, 2018).

3.19.3 Cooper-Jacob time- distance drawdown method(III).

Transmissivity(T) $= \frac{2.303Q}{4\pi\Delta s}$ (41)

Storativity(S)= $\frac{2.25Tt_0}{(r_0)^2}$ (42)

It applies when we are getting simultaneous drawdown data from three or more than three observation wells (similar with Distance-Drawdown method).Where, drawdown will plot along the Y-axis and ($\frac{t}{r^2}$) along the X-axis.

following data will be needed for Cooper-Jacob Distance-Drawdown method.

- Drawdown vs time data of an three or more observation well.
- The distance needed between pumping well and observation well.
- The pumping rate(constant) of the well will be needed.

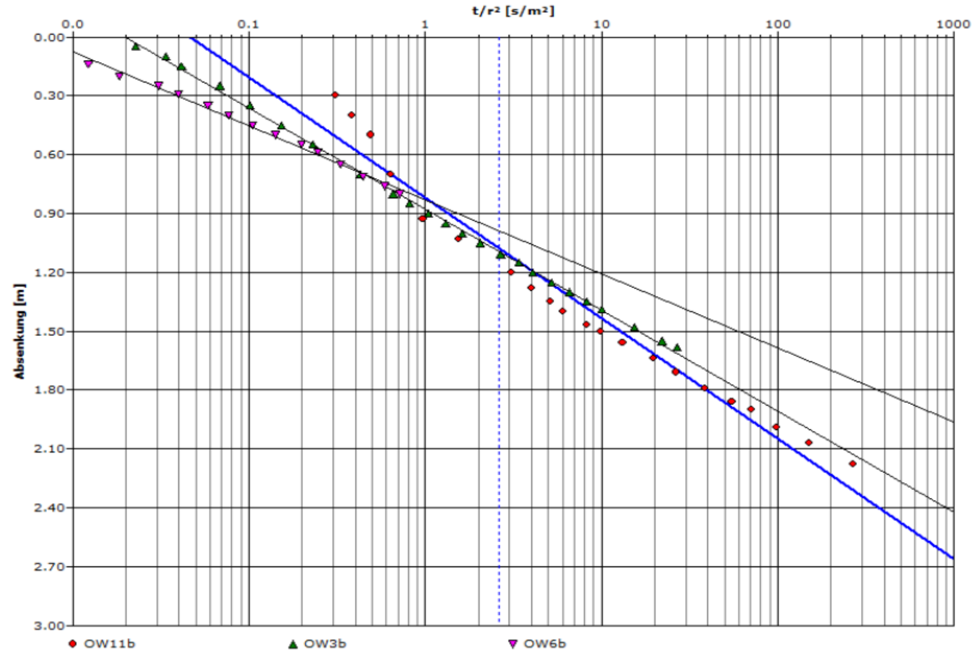

Figure 15. Cooper- Jacob Time-Distance-Drawdawn analysis graph (waterloohydrogeologic, 2018).

3.20 Agarawal methods for additional resistance(skin factor)

It is the method that tries to show the importance of wellbore storage with a skin effect for the short time transient flow. Initially, The skin effect defined by Van Everdingen and Hurst and also explain its causes due to the infinitesimally thin damaged region around the wellbore region. The modern well analysis is appropriate to the short time data and it is really hard to interpret in a meaningful way due to the effect of different skin effect(perforations, partial penetration, several types of fractures and non-Darcy flow etc). the short time data are the pressure information from the straight-line portion of the well test. So, Agrawal presented not only a fundamental idea about wellbore storage with skin effect for short time transient flow on the wells but also gives a good interpretation of short time well test (Agarwal, et al., 1970).

So, Dimensionless wellbore storage is:

$$C_D = \frac{C}{2\pi r_w^2 S} \qquad (43)$$

Where C= unit factor of well-storage (m^2)

S= Storativity (-)

If we use Theis solution for real well we must write according to van Everdingen,

$$s_w = \frac{Q}{2\pi T}(W(u) + 2W \qquad (44)$$

Where, W = skin factor (-)

For Cooper-Jacob method – real well – we use equation in the form (with skin factor)::

$$s_W = \frac{Q}{2\pi T}\left(ln\frac{2.246\,T\,t}{r_w^2 S} + 2W\right) \quad (45)$$

We express coefficient of additional resistances (skin factor)

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\frac{2.246\,T\,t}{r_w^2 S} \quad (46)$$

For the method slope of the first straight line "I_{1P}" in (PECH a kol., 2018) was derived the following equation:

$$I_{1PD} = 0{,}86\,W + 1{,}0127\,(\log C_D) + 1{,}0237 \quad (47)$$

Where

I_{1PD} – slope of the first straight line (graph s_w vs. log t)

C_D – dimensionless wellbore storage (-)

And for skin factor, W can be written

$$W = \frac{1}{0{,}86}\left(\frac{2\pi\,T\,I_{1P}}{Q} - 1{,}027\log C_D - 1{,}0237\right) \quad (48)$$

4. Research Methodology

4.1 Research area

4.1.1 Well KV2 and KV9

Profiles and Description

Both (KV2 and KV9) boreholes are drilled with a diameter of 1620mm(up to 5m deep), and it is followed by a drilling diameter of 1350mm till the bottom of the borehole. Then, backfill for both well is double, outer backfill has a fraction of 2-4 mm and inner has a fraction of 8-16 mm. The perforated equipment area is equipped with an older version of UGI filters which has an outer diameter of 360 mm. and boreholes area of full equipment equipped with steel and it has an outer diameter of 426 mm.

Also, The KV9 well was converted to a lower diameter some years ago but information on this disguise is not available in the archive.It seems from the field survey, the KV9 well was converted to steel equipment with an outer diameter of 225mm.

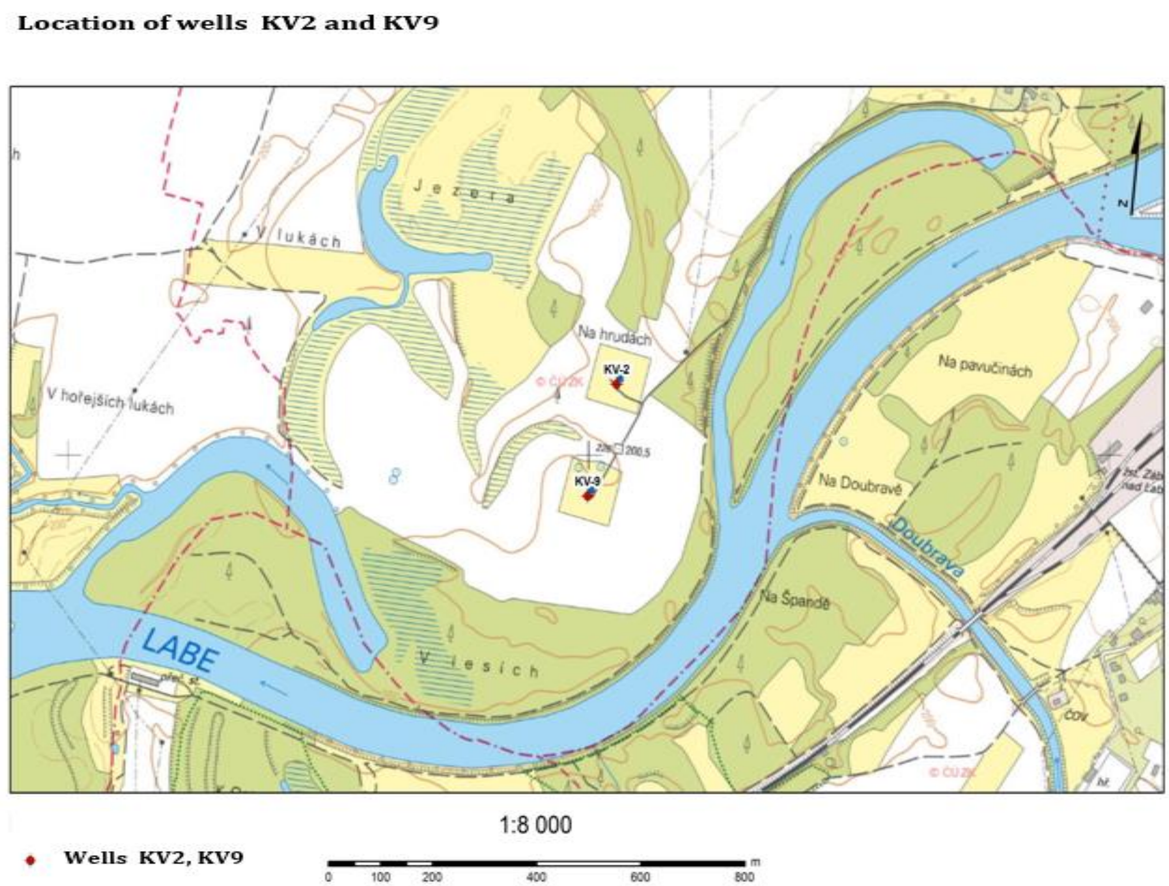

Figure 16. Geological map of KV-2 and KV-9 wells

4.1.1.1 Geomorphological, Hydrographic and Climate description:

The Žehušice basin is in the northwestern part of the Caslav basin. The lower tectonic depression near to the Doubrava, Klejnarka and Elbe sections. It is described by the flat to flat hilly relief of middle Pleistocene and early Pleistocene landscape, and large scale floodplains. The area of interest is drained in the S, V, slightly in the Z direction to the Elbe river. Its hydrological sequence number is 1-04-01-0010-0-00.

According to (Quitt 1971), the Climate condition of this locality is a moderately warm climate area (T-2) and It refers to the warm with a long and dry summer. The transition time is quite short with warm to slightly warm Spring and Autumn. During winter, it is short with slightly warm and dry to extremely dry with a short duration of snow cover. So, the average temperature of this locality varies from 8 -9 degree centigrade, the annual average rainfall is approximately 600 mm, and the average snow cover is 40 to 50 days per year.

4.1.1.2 Geological description

KV2 and KV9 wells located in Bohemian Massif, the subsoil of the locality is formed by Turonian as well as sandy siltstones and it is largely covered by the Quaternary river and Eolithic sediments. The Quaternary sediments mainly represented by gravel sands, medium-grained sands with an admixture of clay particles, and it is mainly available at the surface. By the archival geological profiles, the Quaternary sediments at that location vary from 14 to 15m in thickness.

4.1.2 Well Radoun(RD-2)

Well RD-2 is located in central part of northern Bohemia of the Czech Republic. It is operated by a major regional water company at Radoun gas station. There are three pumping wells and these are strong backbones of the urban and industrial water supply for the area between Mělník and Ústí nad Labem. Typical operating pumped quantities are very high(up to 55 m^3/ hour and RD-2 boreholes is 50m deep with plywood casing.

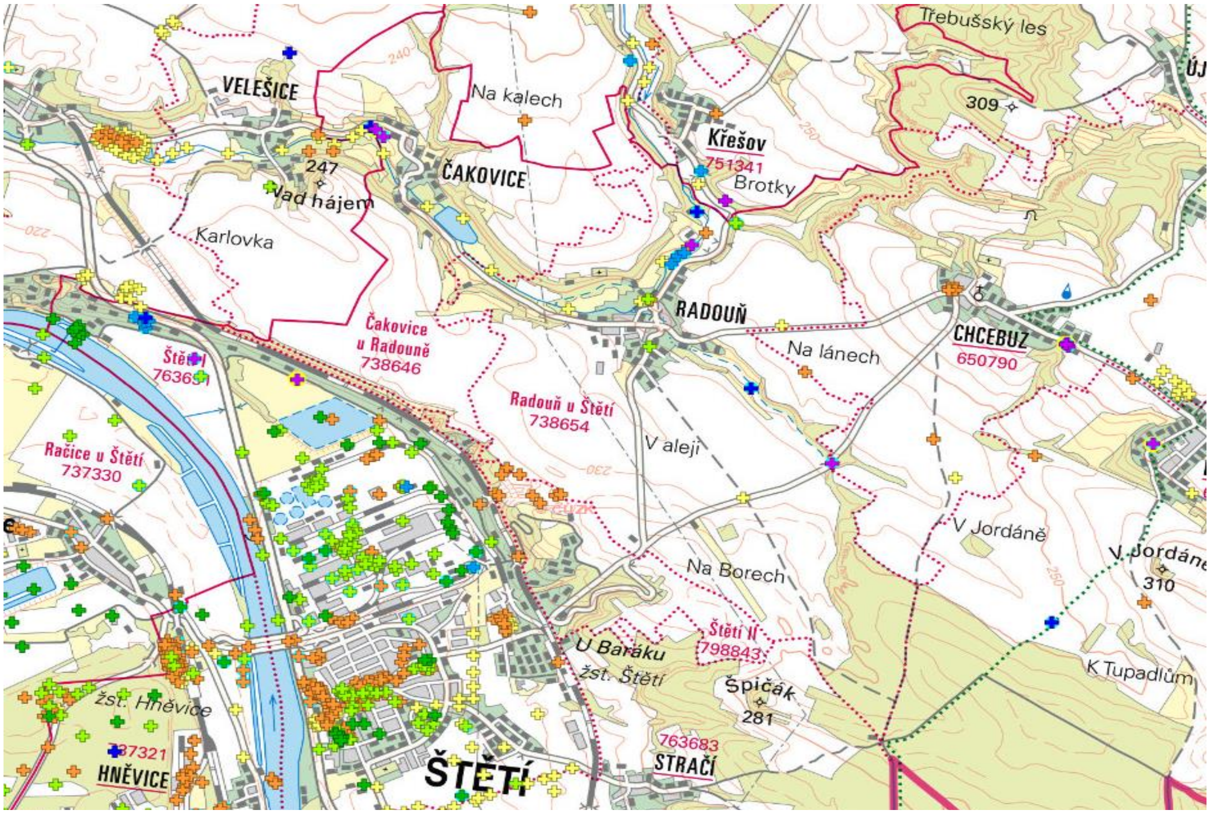

Figure 17. Geographical map of Radoun pumping site((mapy.geology.cz, n.d.).

4.1.2.1 Geology and lithology:

The location of pumping well situated in the lower part of the Czech Cretaceous basin with shallow sandstone rocks of the Letoman age. The groundwater level is limited to overlapping impermeable body including Turonian saliva and marlite. So, the groundwater stream is strongly bounded by clacks in the sub-soil, which form a typical filtration with double porosity.

4.1.3 Vlastislav (MO-1)

The Vlastislav site has a total of 5 different pumping wells and it is operated by (SČVK). The hydrodynamics tests were performed before and after regeneration, they took place in two phases from 18 to 19 August 2014 and 31 October to 11 November 2014. For the measurement of water level, automatic water probes with 1 second of the time interval used for the 1 to 2 hour during the beginning of pumping well. The other measurements are extended proportionally according to the changing dynamics. In the context of all records, the corrections were made for the influence of air pressure at the groundwater table. The automatic measurements were supplemented by the use of manual measurements to check and calibrate all the data readings. Readings on the pumped yield were read from mechanical calibrated water meters. In the end, the communication between surface streams and groundwater in the pumping area was evaluated by using water meter laths.

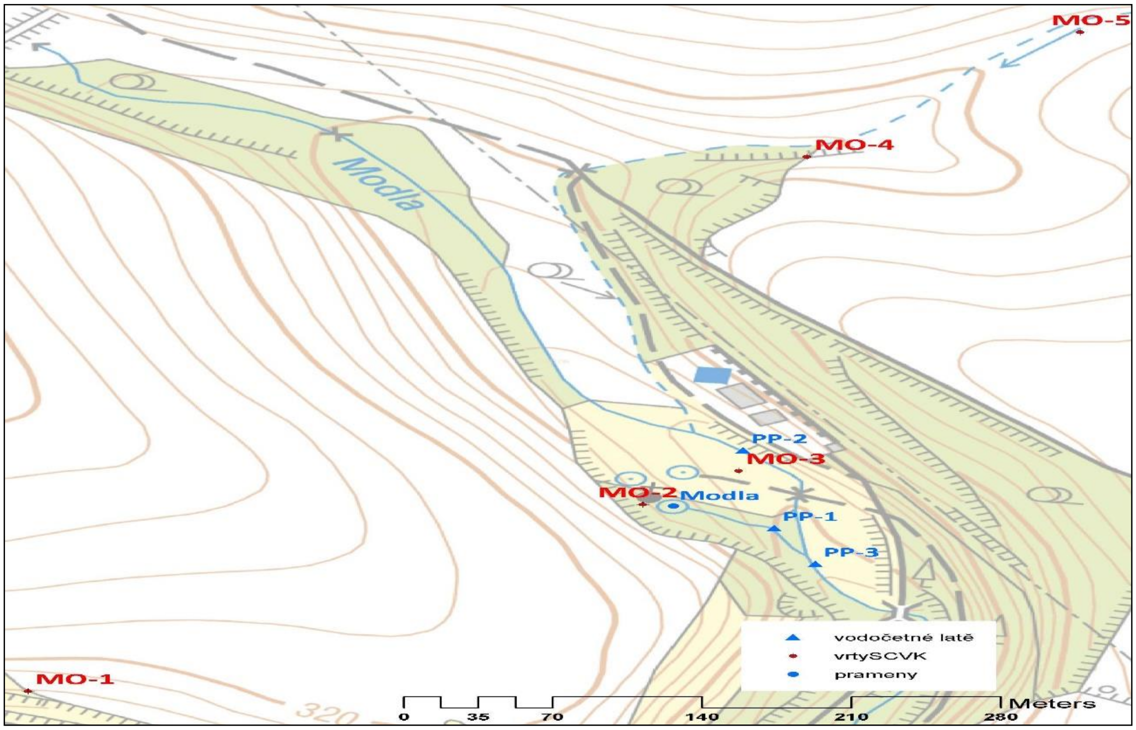

Figure 18. Representation of Vlastislav (MO-1) well site.

4.2 Format of data collection

The research data has been collected using the same procedure for all wells. we recorded a large volume of time vs drawdown and discharge data. all the drawdown are recorded corresponding time with constant discharge. Here is the format of our data collection,

Sr. No.	Date/Time	Time, t(min)	H logger (m)	Drawdown(s)(m) -pumping well	Discharge(Q) (l/s)

4.3 Research methodology description

I am going to describe our research methodology in more expanded form.

First of all, I would create a time vs drawdown curve in a logarithmic way, where drawdown will be in Y-axis and time in X-axis. we have collected data from 4 different wells(KV2, KV9, RD2 and MO1) in 3 different locations. From KV2 and KV9, I would calculate transmissivity, additional resistance(skin factor), drawdown caused by skin factors.

The skin factors will be calculated using two different methods, first is the Cooper-Jacob methods at the late part of the(time vs drawdown) curve, and the second one is the Alternative(slope) method using the early part of the same curve. In the case of transmissivity, Cooper-Jacob time-drawdown method will be used for all three different locations. After getting all these parameters, we will compare both skin factors and drawdown caused by both skin factor.

Secondly, Only for RD-2 and MO-1, we will calculate skin factor, Transmissivity, and drawdown caused by both skin factor in the same way as KV-2 and KV-9. However, all these parameters will be evaluated before and after well regeneration(cleaning).

In the end, we will compare and discuss all the results.

a. Transmissivity(T)

(i). Cooper-Jacob time-drawdown method

$$\text{Transmissivity(T)} = \frac{2.303Q}{4\pi\Delta s}$$

$$= \frac{0.183\text{Q}}{\Delta s}$$

b. Additional resistance(Skin factor)(W)

(i). Cooper-Jacob Methods

$$W = \frac{2\pi T s_w}{Q} - \frac{1}{2}\ln\frac{2.246\,T\,t}{r_w^2 S} \tag{49}$$

Where,

s_w= Random drawdown in Cooper-Jacob (late part) of the curve(m).

t or t_w = time during drawdown (s_w)(sec).

T= transmissivity(m^2/s).

S= Storativity(-).

r_w= Radious of well(m).

Q= Discharge(m^3/s)

(ii) Alternative (straight line or slope) Method(PECH a kol., 2018).

$$W = \frac{1}{0.86}\left(\frac{2\pi\, T\, I_{1P}}{Q} - 1.027 \log C_D - 1.0237\right) \tag{50}$$

Where,

T= transmissivity(m^2/s).

S= Storativity(-).

r_w= Radious of well(m).

Q= Discharge of well((m^3/s).

C= Wellbore storage

C_D= Dimensionless wellbore storage coefficient.

(I_{1p}) or (i) = Slope of early part of the curve

t_j= Early Timeof the pumping at drawdown s_j.

s_j= Drawdown of beginning phase(before t<10 second).

$$C = Q * \frac{t_j}{s_j} \tag{51}$$

$$C_D = \frac{C}{2\pi r_w^2} \tag{52}$$

$$i = (s_2 - s_1)/(\log t_2 - \log t_1) \tag{53}$$

s_2, s_1= drawdown when time equal to t_2, t_1 respectively at early part of time vs drawdown curve.

(iii). Drawdown (s_w) caused by additional resistance(skin factor)

$$s_w = \frac{Q}{2\pi T} W \tag{54}$$

5. Results:

5.1 KV-2 well

These calculations are based on the recorded observation with a constant discharge rate of 2.2 l/s and observation are recorded in each second of the total observation period(830 seconds).

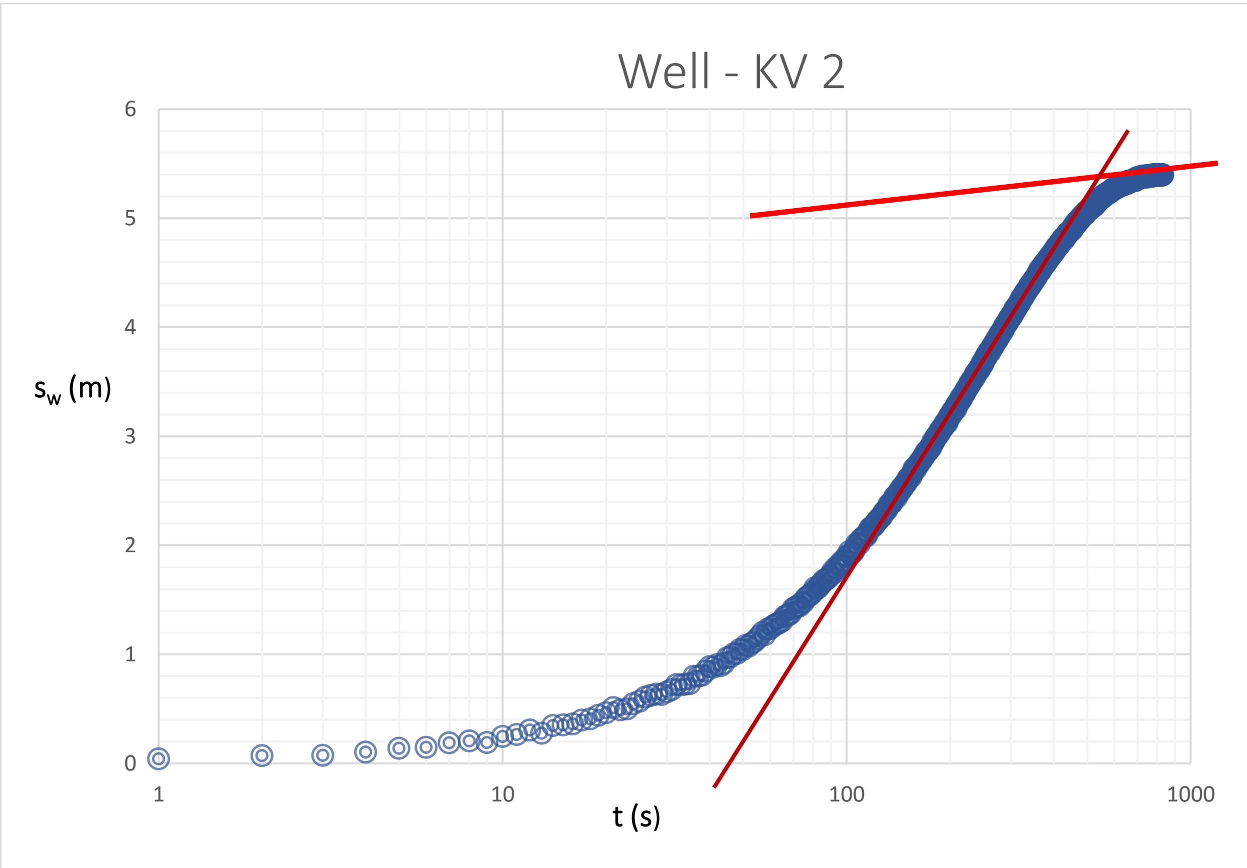

Figure 19. Representation of time vs drawdown plot of the KV-2 pumping well.

(I) Transmissivity evalution

$$\text{Transmissivity(T)} = \frac{2.303Q}{4\pi\Delta s}$$

$$= \frac{0.183Q}{\Delta s}$$

= (0.183* 0.0022)/(0.407)

= 0.000989 m^2/s

Where, Δs= s2 - s1 (s_2 and s_1 are drawdown to corresponding time t_2 and t_1, for upper part of the curve) , Q is discharge in m^3/s.

(II) Skin factor evaluation

(a) Skin factor using Cooper-Jacob methods

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

$$= \frac{(2*3.14*0.000989*5.3)}{(0.0022)} - 0.5*\ln(\frac{(2.246*0.000989*627}{(0.076)*(0.17)^2}$$

= 11.74

Where, s_w=5.3 m and t= 627 s.

(b) Wellbore storage(C) and Dimensionless wellbore storage coefficient (C_D) evaluation.

$$C = Q*\frac{t_j}{s_j}$$

= (0.0022*4)/(0.1039)

$$= \frac{(0.0022*4)}{(0.1039)}$$

= 0.084697 m^2

(where, the values of tj and sj are 5 and 0.8141 respectively and it is taken from beginning of pumping well)

$$C_D = \frac{C}{2\pi r_w^2}$$

$$= \frac{(0.084697)}{(6.28*0.17^2)}$$

= 6.140391

(c) Slope (I_{1p} or i) Evaluation

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

Then, slope(I_{1p}) = $\frac{(5.0527-1.9)}{\log(500)-\log(100)}$

= 4.510494

(d) Skin factor using Alternative (straight line or slope) methods.

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

= $\frac{1}{0.86}(\frac{6.28*0.000989*4.510494}{0.0022}$ - 1.027*log(6.140391) – 1.0237)

= 12.68

(III) Drawdown (s_w) caused by both additional resistance(skin factor)

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

(p). Using Cooper-Jacob methods

(s_w) = $\frac{(0.0022*11.73933)}{(2*3.14*0.000989)}$

= 4.16m

(q). Using Alternative (straight line or slope) methods

(s_w) = $\frac{(0.0022*12.67512)}{(2*3.14*0.000989)}$

= 4.49m

5.2 KV-9 well

All the calculations are based on the recorded observation with a constant discharge rate of 4.16 l/s and observation are recorded in each second of the total observation period(527 seconds).

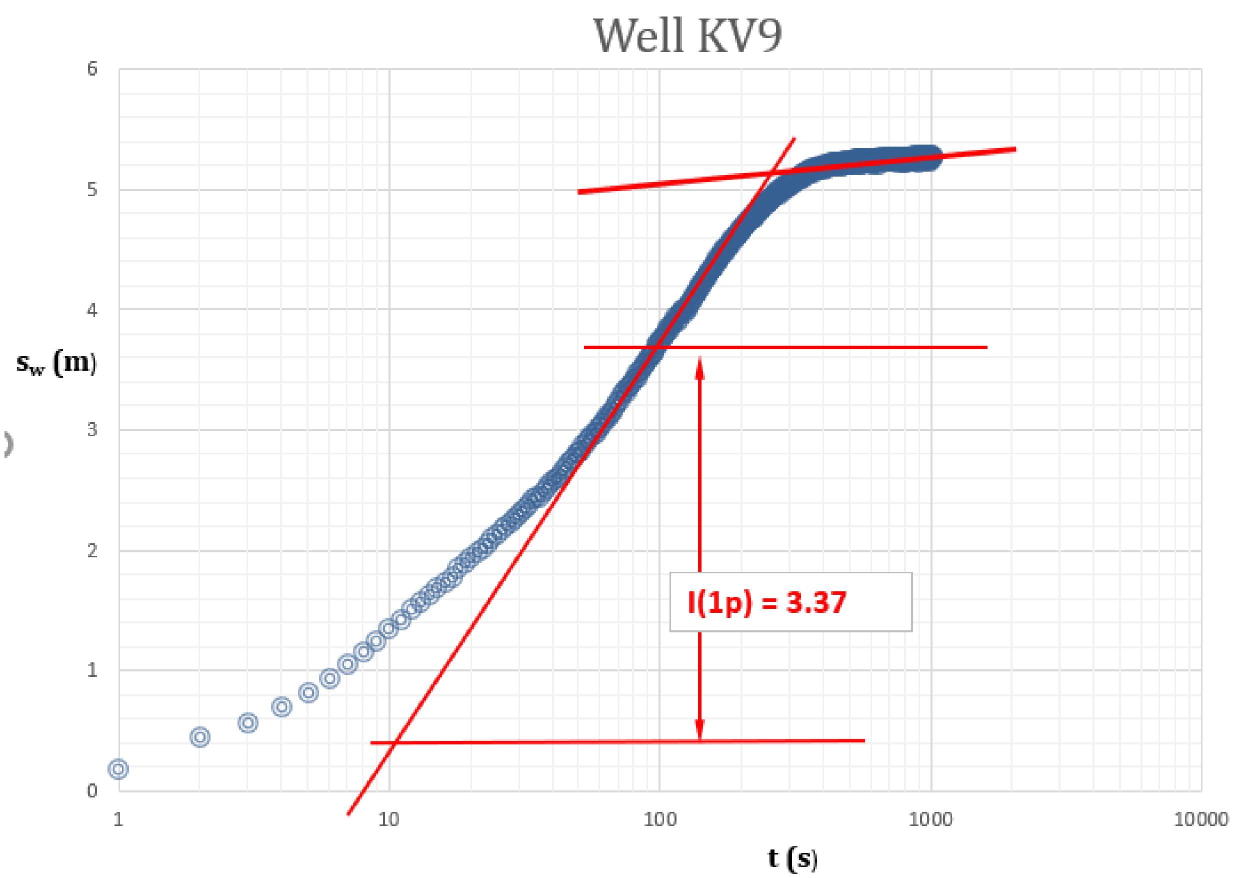

Figure 20. Representation of time vs drawdown plot of the KV-9 pumping well.

(I) Transmissivity evalution

$$\text{Transmissivity(T)} = \frac{2.303Q}{4\pi\Delta s}$$

$= \frac{0.183Q}{\Delta s}$

= (0.183* 0.00416)/(0.1488)

= 0.005116 m^2/s

Where, $\Delta s = s_2 - s_1$ (s_2 and s_1 are drawdown to corresponding time t_2 and t_1, for upper part of the curve) , Q is discharge in m^3/s.

(II) Skin factor evaluation

(a) Skin factor using Cooper-Jacob methods

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

$$= \frac{(2*3.14*0.005116*5.2359)}{(0.00416)} - 0.5*\ln(\frac{(2.246*0.005116*653}{(0.076)*(0.1125)^2}$$

= 35.96

(b) Wellbore storage(c) and Dimensionless wellbore storage coefficient (C_D) evalution.

C= Q*$\frac{t_j}{s_j}$

$= \frac{(0.00416*5)}{(0.8141)}$

= 0.02555 m^2

(where, t_j and s_j are 5 and 0.8141 respectively and it is taken from beginning of pumping well)

$C_D = \frac{C}{2\pi r_w^2}$

$= \frac{(0.2555)}{(6.28*0.1125^2)}$

= 4.229678

(c) Slope (I_{1p} or i) Evaluation

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

Then, slope(I_{1p}) = $\frac{(3.8-0.43)}{\log(100)-\log(10)}$

= 3.37

(d) Skin factor using Alternative (straight line or slope) methods.

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

$= \frac{1}{0.86}(\frac{6.28*0.005116*3.37}{0.00416}$ - 1.027*log(4.23) – 1.0237)

= 28.33

(III) Drawdown (s_w) caused by both additional resistance(skin factor)

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

(p). Using Cooper-Jacob methods

(s_w) = $\frac{(0.00416*35.95788)}{(2*3.14*0.005116)}$

= 4.66m

(q). Using Alternative (straight line or slope) methods

(s_w) = $\frac{(0.00416*28.3286)}{(2*3.14*0.005116)}$

= 3.67m

5.3 RD-2 well(Before Regeneration)

These calculations are based on the recorded observation with a constant discharge rate of 14.8 l/s and observation are recorded in each second of the total observation period(6000 seconds).

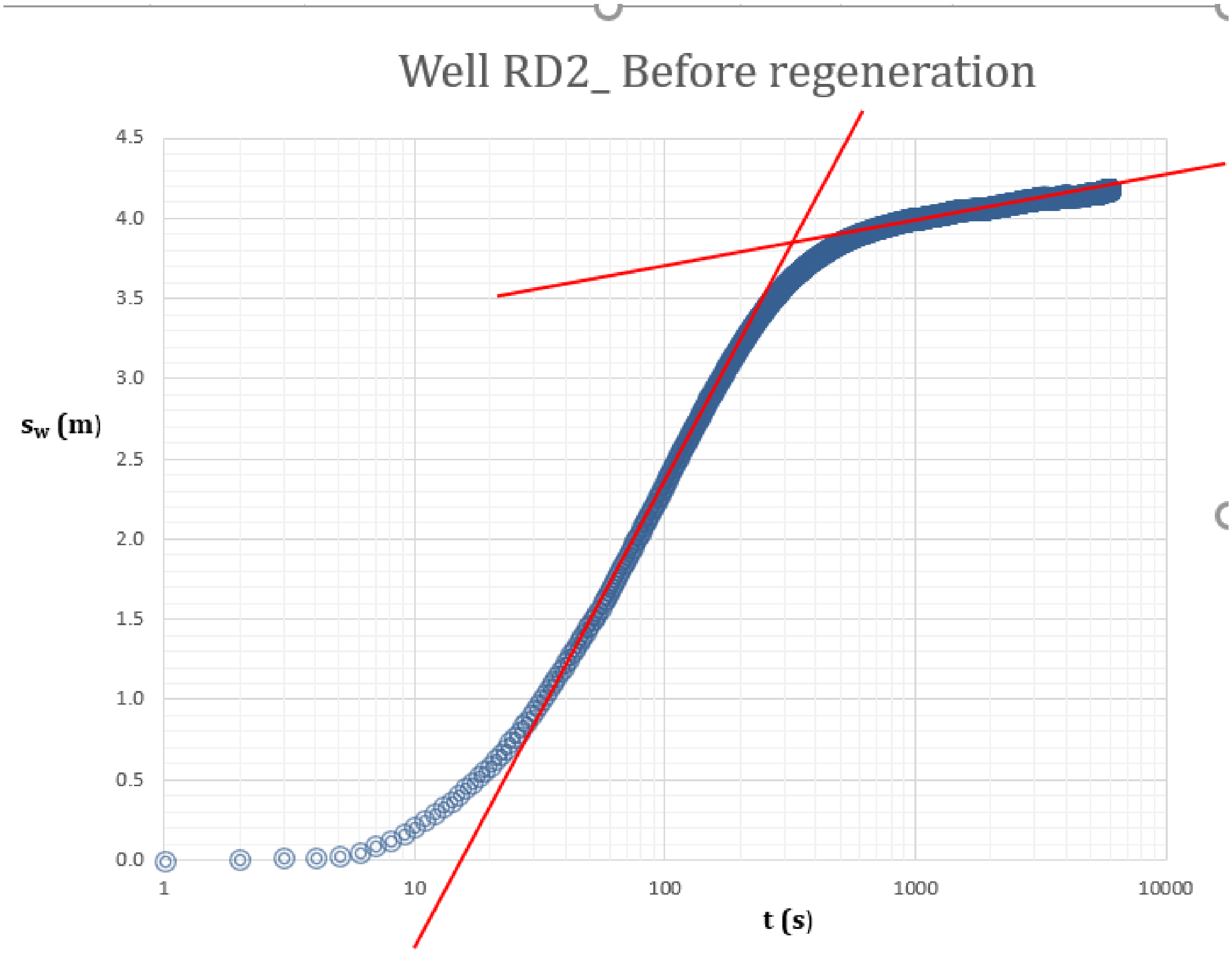

Figure 21. Representation of time vs drawdown plot of the RD-2 pumping well before regeneration

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(I) Transmissivity evalution

Transmissivity(T) $= \frac{2.303Q}{4\pi\Delta s}$

$= \frac{0.183\text{Q}}{\Delta s}$

= (0.183* 0.0148)/(0.07)

$= 0.0387 \ m^2/s$

Where, $\Delta s = s_2 - s_1$ (s_2 and s_1 is drawdown to corresponding time t_2 and t_1, for upper part of the curve) , Q is discharge in m^3/s.

(II) Skin factor evaluation

(a) Skin factor using Cooper-Jacob methods

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

$$= \frac{(2*3.14*0.0387*4.04)}{(0.0148)} - 0.5*\ln(\frac{(2.246*0.0387*1438}{(0.0012)*(0.15)^2}$$

$= 58.65$

Where, $s_w = 4.04$ m and $t = 1438$ s.

(b) Wellbore storage(c) and Dimensionless wellbore storage coefficient (C_D) evalution.

$$C = Q*\frac{t_j}{s_j}$$

$$= \frac{(0.0148*5)}{(0.03)}$$

$= 2.47 \ m^2$

(where, the values of t_j and s_j are 5 and 0.03respectively and it is taken from beginning of pumping well)

$$C_D = \frac{C}{2\pi r_w^2}$$

$$= \frac{(2.47)}{(6.28*0.15^2)}$$

$= 1454.75$

(c) Slope (I_{1p} or i) Evaluation

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

Then, slope(I_{1p}) = $\frac{(3-1)}{\log(165)-\log(32)}$

= 2.81

(d) Skin factor using Alternative (straight line or slope) methods.

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

= $\frac{1}{0.86}$($\frac{6.28*0.0387*2.81}{0.0148}$ - 1.027*log(1454.75) – 1.0237)

= 47.44

(III) Drawdown (s_w) caused by both additional resistance(skin factor)

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

(p). Using Cooper-Jacob methods

(s_w) = $\frac{(0.0148*58.65)}{(2*3.14*0.0387)}$

= 3.57m

(q). Using Alternative (straight line or slope) methods

(s_w) = $\frac{(0.018*48.63)}{(2*3.14*0.0387)}$

= 2.89m

5.4 RD-2 well(After regeneration)

All these evaluations are based on the recorded observation with a constant discharge rate of 14.8 l/s and observation are recorded in each second of the total observation period(1282 seconds).

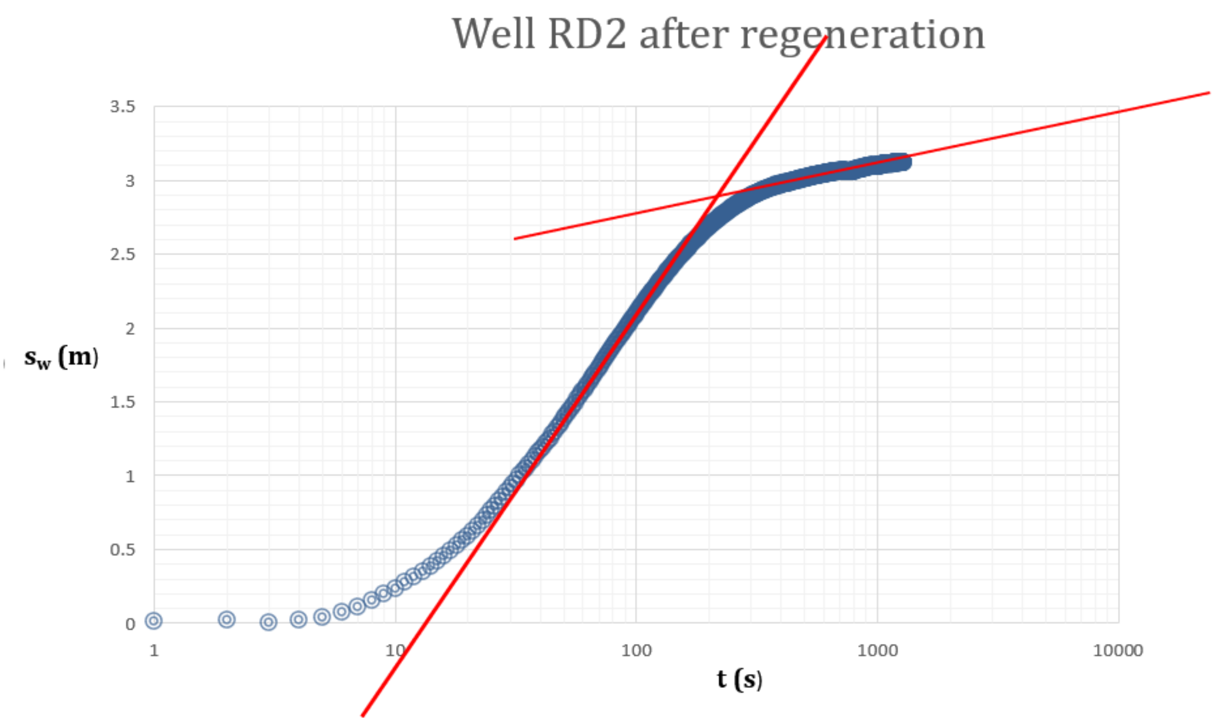

Figure 22. Representation of time vs drawdown plot of the RD-2 pumping well after regeneration.

(I) Transmissivity evalution

Transmissivity(T) $= \frac{2.303Q}{4\pi\Delta s}$

$= \frac{0.183Q}{\Delta s}$

$= 0.0387$ m²/s

Where, $\Delta s = s_2 - s_1$ (s_2 and s_1 is drawdown to corresponding time t_2 and t_1, for upper part of the curve) , Q is discharge in m^3/s.

(II) Skin factor evaluation

(a) Skin factor using Cooper-Jacob methods

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

$$= \frac{(2*3.14*0.0387*3.0243)}{(0.0148)} - 0.5*\ln(\frac{(2.246*0.0387*527}{(0.0012)*(0.15)^2}$$

=51.79m

(b) Wellbore storage(c) and Dimensionless wellbore storage coefficient (C_D) evalution.

$$C = Q*\frac{t_j}{s_j}$$

$$= \frac{(0.0148*5)}{(0.0415)}$$

$= 1.79 \text{ m}^2$

(where, the values of tj and sj are 5 s and 0.0415 m respectively and it is taken from beginning of pumping well)

$$C_D = \frac{C}{2\pi r_w^2}$$

$$= \frac{(1.78744)}{(6.28*0.15^2)}$$

= 70277.57

(c) Slope (I_{1p} or i) Evaluation

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

Then, slope(I_{1p}) = $\frac{(2.145-1.0006)}{\log(105)-\log(33)}$

= 2.28

(d) Skin factor using Alternative (straight line or slope) methods.

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

$= \frac{1}{0.86}(\frac{6.28*0.0387*2.28}{0.0148}$ - 1.027*log(70277.57) – 1.0237)

= 37.47

(III) Drawdown (s_w) caused by both additional resistance(skin factor)

$$\text{Drawdown } (s_w) = \frac{Q}{2\pi T} W$$

(p). Using Cooper-Jacob methods

$(s_w) = \frac{(0.0148*51.79)}{(2*3.14*0.0387)}$

= 3.15m

(q). Using Alternative (straight line or slope) methods

$(s_w) = \frac{(0.0148*37.47)}{(2*3.14*0.0387)}$

= 2.28m

5.5 Vlastislav_MO_1 well(Before Regeneration)

These calculations are based on the recorded observation with a constant discharge rate of 2.47 l/s and observation are recorded in each second of the total observation period(527 seconds).

Figure 23. Representation of time vs drawdown plot of the MO-1 pumping well before regeneration.

(I) Transmissivity evalution

$$\text{Transmissivity(T)} = \frac{2.303Q}{4\pi \Delta s}$$

$$= \frac{0.183Q}{\Delta s}$$

$$= (0.183 * 0.00247)/(0.036)$$

$$= 0.012556 \text{ m}^2/\text{s}$$

Where, $\Delta s = s_2 - s_1$ (s_2 and s_1 is drawdown to corresponding time t_2 and t_1, for upper part of the curve) , Q is discharge in m^3/s.

(II) Skin factor evaluation

(a) Skin factor using Jacob- Cooper methods

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

$= \frac{(2*3.14*0.013*1.82)}{(0.00247)} - 0.5*\ln(\frac{(2.246*0.013*241}{(0.01)*(0.16)^2}$

= 53.03

(b) Wellbore storage(c) and Dimensionless wellbore storage coefficient (C_D) evalution.

$C = Q*\frac{t_j}{s_j}$

= (0.0022*4)/(0.1039)

$= \frac{(0.00247*5)}{(0.132)}$

= 0.094 m^2

(where, the values of t_j and s_j are 5 s and 0.132 m respectively and it is taken from beginning of pumping well)

$C_D = \frac{C}{2\pi r_w^2}$

$= \frac{(0.094)}{(6.28*0.1625^2)}$

= 55.04

(c) Slope (I_{1p} or i) Evaluation

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

Then, slope(I_{1p}) = $\frac{(1.56-0.02)}{\log(100)-\log(10)}$

= 1.54

(d) Skin factor using Alternative (straight line or slope) methods.

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

$= \frac{1}{0.86}(\frac{6.28*0.012*1.5}{0.00247}$ - 1.027*log(55.04) – 1.0237)

$= 52.41$

(III) Drawdown (s_w) caused by both additional resistance(skin factor)

$$\text{Drawdown } (s_w) = \frac{Q}{2\pi T} W$$

(p). Using Cooper-Jacob methods

$(S_w) = \frac{(0.00247*53.03)}{(2*3.14*0.01256)}$

$= 1.66$ m

(q). Using Alternative (straight line or slope) methods

$(S_w) = \frac{(0.00247*52.41)}{(2*3.14*0.01256)}$

$= 1.64$m

5.6 Vlastislav_MO_1 well(After Regeneration)

These calculations are based on the recorded observation with a constant discharge rate of 2.47 l/s and observation are recorded in each second of the total observation period(1125 seconds).

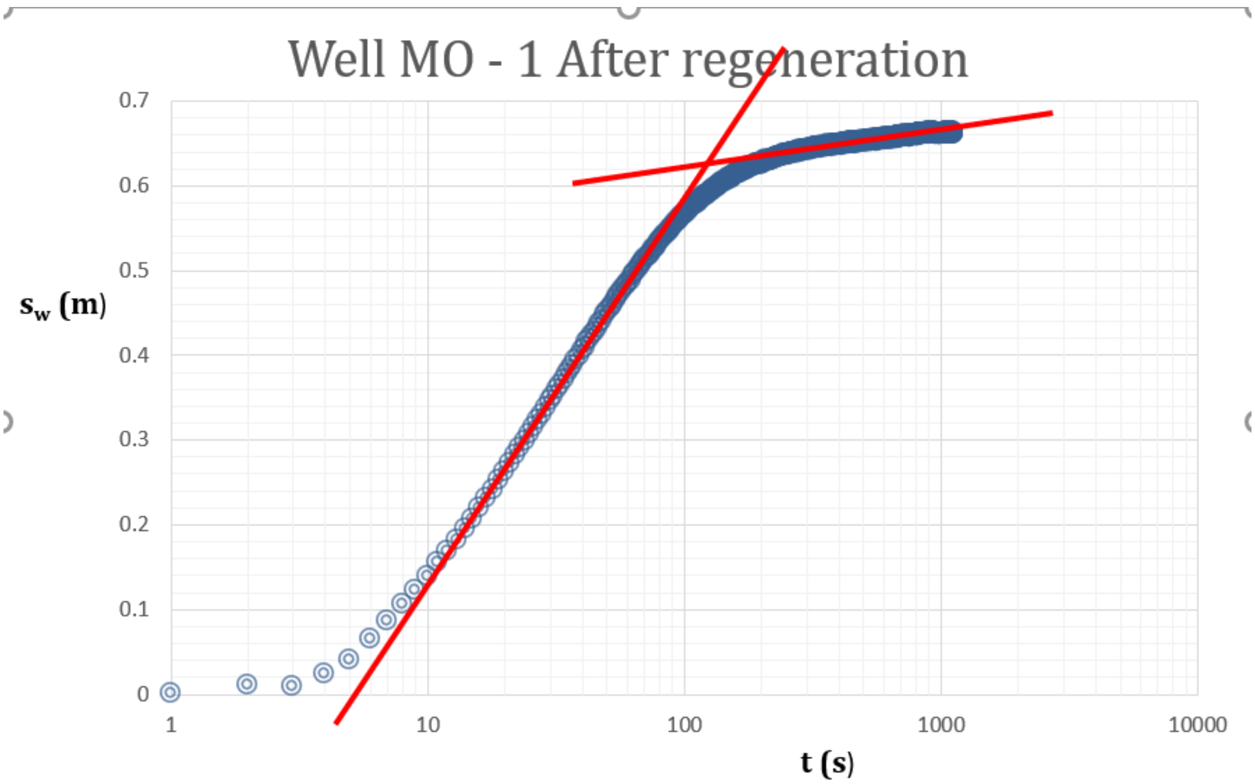

Figure 24. Representation of time vs drawdown plot of the MO-1 pumping well after regeneration.

(I) Transmissivity evalution

Transmissivity(T) $= \frac{2.303Q}{4\pi\Delta s}$

$= \frac{0.183Q}{\Delta s}$

$=$ 0.01256 m^2/s

Where, $\Delta s = s_2 - s_1$ (s_2 and s_1 is drawdown to corresponding time t_2 and t_1, for upper part of the curve) , Q is discharge in m^3/s.

(II) Skin factor evaluation

(a) Skin factor using Cooper- Jacob-methods

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

$$= \frac{(2*3.14*0.01256*0.6451)}{(0.00247)} - 0.5*\ln(\frac{(2.246*0.01256*355}{(0.01025)*(0.16)^2}$$

= 19.91m

(b) Wellbore storage(c) and Dimensionless wellbore storage coefficient (C_D) evalution.

$$C = Q*\frac{t_j}{s_j}$$

$$= \frac{(0.00247*5)}{(0.04)}$$

= 0.31 m^2

(where, the values of t_j and s_j are 5 s and 0.04 m respectively and it is taken from beginning of pumping well)

$$C_D = \frac{C}{2\pi r_w^2}$$

$$= \frac{(0.31)}{(6.28*0.1625^2)}$$

= 179.44

(c) Slope (I_{1p} or i) Evaluation

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

Then, slope(I_{1p}) = $\frac{(0.57-0.12)}{\log(100)-\log(10)}$

= 0.45

(d) Skin factor using Alternative (straight line or slope) methods.

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

$= \frac{1}{0.86}(\frac{6.28*0.01256*0.45}{0.00247}$ - 1.027*log(179.44) – 1.0237)

= 12.8m

(III) Drawdown (s_w) caused by both additional resistance(skin factor)

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

(p). Using Cooper -Jacob methods

$(s_w) = \frac{(0.00247*19.91)}{(2*3.14*0.01256)}$

= 0.62m

(q). Using Alternative (straight line or slope) methods

$(s_w) = \frac{(0.00247*12.8)}{(2*3.14*0.01256)}$

= 0.40 m

5.7 Results and its Comparison

5.7.1 Representation of evaluation transmissivity, skin factor, additional drawdown caused by skin factor, wellbore storage coefficient and slope of the all pumping well.

Name	Methods	Transmissivity (T) (m^2/s)	Skin Factor(W)	Wellbore - storage coefficient(C) (m^2)	Dimensionless Wellbore storage(C_D)	Slope (I_{1P})	Drawdown caused by skin factor(s_w) (m)
KV-2	Method 1	0.000989	11.74				4.16
	Method 2		12.67	0.084	6.14	4.51	4.49
KV-9	Method 1	0.0051	35.96				4.65
	Method 2		28.32				3.67
RD-2 (before)	Method 1	0.0387	58.65	0.025	4.23	3.37	3.57
	Method 2		47.44	2.47	14547.5	2.8	2.89
RD-2 (after)	Method 1		51.79				3.15
	Method 2		37.47	2.27	10541.6	2.27	2.28
MO-1 (before)	Method 1	0.0126	53.03				1.66
	Method 2		52.4	0.09	55.04	1.5	1.64
MO-1 (before)	Method 1		19.91				0.62
	Method 2		12.8	0.305	179.44	0.45	0.40

Table 2. Representation of evaluation transmissivity, skin factor, additional drawdown caused by skin factor, wellbore storage coefficient and slope of the all pumping well.

5.7.2 results comparison between KV-2 and KV-9

Name of the wells	Transmissivity (T) (m^2s^{-1})	Methods	Skin factor (W)	Drawdown caused by skin factor (s_w) (m)	Percentage difference in Skin factor (W)	Percentage difference in drawdown (s_w)
KV-2	0.000989	Method 1	11.74	4.16	7.4%	7.4%
		Method 2	12.68	4.49		
Difference			0.94	0.33		

KV-9	0.005116	Method 1	35.96	4.66	21.2%	21.2%
		Method 2	28.33	3.67		
Difference			7.63	0.99		

Table 3. Results comparison between Cooper-Jacob and Alternative method of skin factor and additional drawdown caused by skin factor of KV-2 and KV-9 pumping well.

5.7.3 Results comparison of well MO-1(Before and after Regeneration)

Name of the wells	Transmissivity (T) (m^2s^{-1})	Methods	Skin factor (W)	Drawdown caused by skin factor (s_w) (m)	Percentage difference in Skin factor (W)	Percentage difference in Skin(W) (Before and after)	Percentage difference in (s_w) (Before and after)
MO-1 (before regeneration)	0.013	Method 1	53.03	1.66	1.16 %	1. Jacob = 62.45 %	1. Jacob = 62.6 %
		Method 2	52.41	1.64			
Difference			0.62	0.02			
MO-1 (after regeneraton)	0.013	Method 1	19.91	0.62	35.61 %	2. Alternative = 75.54 %	2. Alternative = 75.6 %
		Method 2	12.82	0.40			
Difference			7.09	0.22			

Table 4. Results comparison between Jacob and Alternative method of skin factor and additional drawdown caused by skin factor of MO-1 well for before and after regeneration.

5.7.4 Result comparison of well RD-2(Before and After Regeneration)

Name of the wells	Transmissivity (T)	Methods	Skin factor	Drawdown caused by	Percentage difference	Percentage difference in	Percentage difference in

	$(m^2 s^{-1})$		(W)	skin factor (s_w) (m)	in Skin factor (W)	Skin(W) (Before and after)	(s_w) (Before and after)
MO-1(before regeneration)	0.0387	Method 1	58.65	3.57	19.11%	1. Jacob = 11.7 %	1. Jacob = 11.7 %
		Method 2	47.44	2.89			
Difference			11.21	0.68			
MO-1 (after regeneraton)	0.0387	Method 1	51.79	3.15	27.65%	2. Alternative = 21 %	2. Alternative = 21 %
		Method 2	37.47	2.28			
Difference			14.32	0.87			

Table 5. Results comparison between Cooper-Jacob and Alternative method of skin factor and additional drawdown caused by skin factor of RD-2 well for before and after regeneration.

6. Results discussion

All the hydrodynamic tests had been performed in three different locations of the Czech republic with four different wells. However, two wells evaluated before and after regeneration and the rest two are without. The wells cleaning technique plays a significant role not only to lengthen the production time of the well but also protect the pipe fittings and joints inside of the wellbore. During this research, all the observations were recorded at a constant rate of discharge in every second of the observation period.

The values of transmissivity and storativity are the same for before and after cleaning because the pumping well located on the same aquifer. As we know that, due to the absence of the observation wells, the Storage coefficient will be determined from the composition of the porous materials of the aquifers. Therefore, we already have the values of discharge and storage coefficient.

I have been calculated transmissivity using the Cooper-Jacob Time-Drawdown method from the top part of the time vs drawdown curve in all four wells. However, the only difference is we determined skin factor and drawdown caused by skin factor two times in wells RD-2 and MO-1 for before and after regeneration. 1. First method(Cooper-Jacob)

In this part, we calculated transmissivity, coefficient of additional resistance(skin factor), and drawdown caused by skin factor. First of all, we plot drawdown vs time curve in a logarithmic way and then we took from the top part of the curve to calculate all these parameters. We used the Cooper-Jacob per time drawdown method (T= 0.183*Q/Δs) to determined Transmissivity of the aquifer. After getting transmissivity we are choosing some referential values of drawdown (s_w) in top part of the curve with corresponding time(t) for calculation of skin factor(W_{Jacob})= $\frac{2\pi T s_w}{Q} - 0.5 * Ln(\frac{2.246*T*t}{Sr_w^2})$ and Drawdown caused by skin factor using (s_w)= $\frac{Q}{2\pi T} W_{Jacob}$.

2. Alternative method(Straight line I_{1p})

We are using the same transmissivity from Cooper-Jacob methods throughout this calculation as well. After that, we determined the wellbore storage coefficient (C = $\frac{Q*t_j}{s_j}$), where s_j and t_j were taken before 10 seconds from the beginning of the pumping test. As a new step, we calculated the dimensionless wellbore storage coefficient(C_D= $\frac{C}{2\pi S r_w^2}$) and slope (I_{1p}= $\frac{(s2-s1)}{(log t2-\log t1)}$) using early part of the time vs drawdown curve. After all, finally we evaluated coefficient of skin factor ($W_{Alternative}$= $\frac{1}{0.86}$($\frac{2\pi T I_{1p}}{Q}$ – 1.027* log(C_D) – 1.0237) from Alternative method and drawdown caused by that skin factor (s_w= $\frac{Q}{2\pi T} W_{Alternative}$).

These calculations procedures are the same for all four wells but the only difference is that we calculated skin factor and drawdown caused by skin factor twice(before and after) with RD-2 and MO-1 wells.

The evaluated values of Transmissivity from wells KV-2 and well KV-9 are 0.000989 m^2/s and 0.0051 m^2/s respectively. we also evaluated skin factor(W) and drawdown caused by skin factor two times in each wells using the Cooper-Jacob method and Alternative method.

KV-2 Well, the determined skin factors are 11.74 and 12.67 with a 7.3 % difference in each other. The drawdowns caused by skin factors are 4.16m and 4.49m with the same amount of difference as skin factor. So, it seems both methods are effective during the calculation process.

KV-9 Well, The additional resistance from the calculations are 35.96 and 28.32 with a 21% difference. The determined values of additional drawdown caused by skin factors are 4.65m and 3.67 respectively with the same amount of difference as skin factor.

For the rest two wells (RD-2 and MO-1)

The main two reasons for this RD-2 and MO-1 evaluation are to check the how effective Cooper-Jacob method and Alternative in the calculation of skin factor and what will be the difference in the skin factor and drawdown caused by skin factor before and after regeneration process of wells.

The transmissivity was evaluated on the same procedure as KV-2 and KV-9 wells with values 0.0387 m^2/s (RD-2) and 0.01256 m^2/s(MO-1). One important note is that we used the same transmissivity for before and after regeneration because of the wells in the same aquifer.

For RD-2 well,

The skin factor coefficients are 58.65 and 47.44 using both methods before regeneration with a 19 % difference with each other. After regeneration, the skin factor coefficient falls to 51.79 and 37.47 with a 27% difference in each other. So, the skin factor coefficient drops due to the regeneration and which is the positive effect of well cleaning.On the other hand, The drawdowns caused by skin factors before regeneration are 3.57m and 2.89m respectively. After regeneration, the values drop to 3.57 to 3.15m and 2.89 to 2.28m. So, This drawdown caused by skin factor drops due to the rehabilitation process.

In the case of MO wells,

The skin factor coefficients are 53.03 and 52.41 using both methods before regeneration with a 1% difference with each other. After regeneration, the skin factor coefficient is dropping down to 19.91 and 12.82 with a 35 % difference in each other. So, the skin factor coefficient drops down due to the regeneration and which is the positive effect of well cleaning.

In the case of drawdown caused by skin factor, The calculated values before regeneration are 1.66m and 1.64m. After regeneration, the values rapidly drops to 1.62m to 0.66m and 1.64m to 0.40m. So, This drawdown caused by skin factor falls due to the well regeneration.

7. Conclusion

All the hydrodynamic tests were conducted on the four wells in 3 different location with a constant rate of discharge during the pumping test. The hydraulic parameters Transmissivity, skin factor and drawdowns caused by skin factors are measured successfully with good accuracy except for skin factor calculation in MO-1 well after regeneration. Both Cooper-Jacob and Alternative methods are looks capable for evaluation of skin factor.

In the case of wells with before and after regeneration, all the results showed the skin factor and drawdown caused by skin factor after regeneration are smaller than before wells regeneration. If the values of skin formation are going to be lesser then the value of the permeability will be bigger. As a result, the production efficiency and well life span will be an increase. So, it shows the skin effect also will be correlated with the drawdown.

To sum up, Our all evaluation shows that the drawdown caused by additional resistance after regeneration is significantly smaller than before regeneration in all case. Therefore, well rehabilitation is successful in all cases.

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