Norges miljø- og biovitenskapelige universitet

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Estimation of water access and contaminant risks at the Nyenga foundation in Uganda

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Preface

This is the master thesis of Endre Aaen in hydrology. The thesis is the end product of 5 years of bachelor and masters in environment and naturel resources at NMBU

First of all, a special thanks to Nils-Otto Kitterød and Ellen Jessica Kayendeke for supervising and helping me with gathering information and work in field. Especially thanks to Ellen Jessica coming out helping. It made the fieldwork and work with information gathering a lot easier.

A big thanks to engineers without borders (IUG) for connecting me with the Nyenga foundation and covering travel expenses. Thanks to Nyenga foundation for hosting and making it possible for me to travel to Uganda to do my fieldwork.

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NYENGA

Abstract

Nyenga foundation is a voluntary foundation located on the outskirts of Nyenga village in Uganda. The foundation is running a medicine center, a primary school and are working with engaging the local community in the making of jobs and stimulating local economy.

The area around Nyenga foundation consists of wetlands and rainforest. The main land use is for agriculture use with production of banana, cassava, sweet potatoes, and rice. The water supply of Nyenga foundation is, as big parts of Uganda, based on groundwater from shallow wells and enhanced natural springs. Groundwater is often seen as one of the safest sources of clean fresh water but a lack of education in hygiene and understanding of water dynamics and hydraulics makes shallow water supplies in risk of local pollution.

This thesis use analysis of pumping tests to estimate the yield in the well of Nyenga foundation and doing a risk analysis of the water in the local well. The risk analysis was based on bacteriologic transport, with a hygienization time of 60 days. The pumping test analytic methods used were Theis method, Jacobs method and Boulton-Streltsova curve fitting method. The pumping tests used for analysis was done 29th October to 9th November 2020. This was in a period of unusual heavy precipitation leading up to the time of pumping tests. The results from the tests are therefore seen as the maximum water yield from the well.

The pumping tests had a drawdown of about 5cm. The drawdowns were quite consistent over 4 pumping tests with different durations due to problems with pump failures. Because of a lack of geological data in form of aquifer depth and lack of observation wells, combined with a small drawdown, we had to make some extra assumptions for the analysis. After comparing the results from the pumping tests and field conditions, a storativity (S) of 0.02-0.04 and a hydraulic conductivity (K) of $2*10^{-5}$m/s were estimated. This gave an estimated water yield from the well at Nyenga foundation of 1350-1550 l/h When using this data combined with elevation data and climatic data, risk distances and flow patterns were calculated. The area with high risk of contaminants were set to 10m after adjusting the theoretical area of 2m to account for uncertainties. A max area of influence was estimated to 208 m.

The thesis concludes that the largest contaminant risk comes from local contamination in form of bacteria from feces. This is especially a risk in the area closest to the well. Measures are therefore to stop holding livestock in the area closest to the well.

Contents

Introduction

Hydrology is important for climate, economy, food production and human health (Alex et al., 2019). An understanding of water movement and distribution is important for sustainable management of water resources between sectors as drinking water, industry, farming and power production. On a world basis less than 1% of all water is available freshwater. The majority of this is found as groundwater (Botkin and Keller, 2014). Many of the world's biggest water systems stretch across borders and countries with different water use requirements. Therefore, there is need for international collaboration to not overuse and to distribute to a degree that these resources does not lead to conflicts.

Understanding of water systems are crucial to be able to manage water resources in a sustainable way. In the case of groundwater, properties of storage and transmissivity are used to predict flow patterns and residence time. If ground water usage is higher than recharge over time, the ground water table lowers, which can cause wells to run dry or reduce ground pressure which over time can make the ground unstable and damage infrastructure and buildings. Ground water can also be polluted by lowering the groundwater table, or by diffuse or point pollution by chemicals or bacteria. Monitoring and risk assessment are for these reasons important to be able to make good management decisions.

The Lake Victoria basin is a part of the Nile river basin, which also contain the White Nile river basin and the Blue Nile river basin, with connecting water sheds. The Nile river basin starts in Uganda and flows north into South Sudan, Sudan, where it connects with the Blue Nile coming down from Ethiopia and continues flowing into Egypt before reaching the Mediterranean. This Area includes The African great lakes which includes vast areas of wetland from the Uganda and into South Sudan. (Mugisha, 2007).

Wetlands areas have important ecological and hydrological systems, especially for biodiversity and buffering of water to stop erosion and nutrient transportation (Alex. el.al. 2017). Since 1900, about 50% of the world's wetlands have been removed in favor of farmland and constructions. (Schuyt, 2007) In Uganda 11-15% of the total land area is covered in wetlands. From 1994 to 2008, the wetland areas have declined by 30% (Government of Uganda, 2001). The removal of wetlands has often been done for short period profit (Schuyt, 2005), with big complications for local ecology and society in the long run. Consequences from removal of wetland is often increased erosion from increased water velocity when the water is going through fast flowing diches or channels. This removal of the wetland buffering system also gives faster response in floods and droughts. (Acreman et.al., 2013) Due to these risks it is important to have good knowledge of management and understanding of ecology and hydrology.

The water supply in Uganda mainly comes from groundwater (British geological survey, 2020). Water supply in rural areas are mainly shared community wells. Just a few wells are drilled wells, while most community wells are shallow dug wells. Groundwater is seen as one of the safest water supplies, but lack of education and risk analysis can put wells in danger for contamination. This especially regard shallow wells with short water transport from surface to well. These types of wells are in higher risk of local pollution because of the low residence time and transport lengths.

One of the most used and reliable way to get information about an aquifer is by doing a pumping test. A pump test is a method for estimating water flow and water yield for a given time frame. With a pumping test, it is possible to estimate some properties for the aquifer. Pumping tests are often used as proof for estimates of water availability and to determine maximum yield from a well (British Columbia, 2020). A Pumping test is done by extracting water from a well and monitoring the lowering funnel of the groundwater table in the well and a well in close proximity if possible. By plotting the lowering funnel against time and distance between wells, is it possible to make a calculation of transmissivity and storage capacity from the drawdown area and known discharge. The transmissivity is the average flowrate of water with a known gradient. The storage capacity is the water amount released with lowering in pressure. In open aquifers the storage capacity is the same as effective porosity minus, water held back from capillary forces (Kitterød, 2007).

Thesis Goal

The goal of this thesis is to use groundwater analytics to estimate local water supply safety at the well at Nyenga foundation. The thesis is also containing an estimate of water yield from the well and a suggestion for improvement for water safety. Estimates and analysis are based on pumping tests, climate and topography data.

This thesis is structured with description of study area before presenting theory and procedures for analysis. The results of analysis are then discussed and used to make recommendations for drinking water safety and measures.

Study Area

Nyenga is in the southern part of Uganda. The town is a few km north of the shores of Lake Victoria and 10km west of Jinja (Figure 1). The area is dominated by wetland in the depressions and tropical forest in the surrounding areas. Big parts of the rainforest and wetlands are covered in farmland, with vegetable production as banana, cassava (Manihot esculenta), sweet potato (Ipomoea batatas) and other root vegetables in the forest areas, and rice and sugar canes in the wetland.

Figure 1: Area map of northern part of Lake Victoria. The foundation area is marked with the red pointer. Map is taken from Google Maps.

Nyenga foundation is a voluntary foundation located at the outskirts of Nyenga village. The foundation is registered in Bergen, Norway but operates mainly at Nyenga. The foundation is running an orphanage, health station and a primary school in outskirts of Nyenga. The children's home consists of four buildings. One house for boys and one for the girls, a storage facility and a common. The school consists of 6 buildings placed by the local water supply well. In addition, there are homes for teachers, a grand hall, bioreactor, fishponds, animal housings, and a visitor's house on the property (Figure 2). The foundation is working with educating and helping the local communities through schooling, micro loans and assistance to locals to establish their own workplace. The goal of the foundation is to stimulate local economy and make education more available based on local resources. Through education, the foundation give advice for sustainable development, and help make understanding in meeting different cultures. (Nyenga.no, 2020)

Local Water Supply and Consumption

The water supply in communities around Nyenga foundation is mostly composed of springs and a few wells. The local water supply consists of 1 shallow dug well, 2 drilled wells, and 6 natural springs. (Figure 2 and Figure 4) The wells have hand pumps, while the springs are open continuously running. The springs are constructed by digging out a circle that was filled with coarse stones to increase the permeability. A pipe is then placed in the stones leading the water into a constructed water tap. The springs are gravity driven wells were the pipe is located below the water table. The constructed springs are located were the wetland meets an incline in the terrain. The springs are located on old natural springs and are rectified to increase yield and water safety. Drilled wells are less frequent because of high investment cost and a lack of local maintenance. As an example, one of the drilled wells in the local area of Nyenga broke down after 5 years use and have been out of order the last 6 months. The water level in the wells and springs are quite consistent with a little dip in the dry periods but they are never dry according to local people we talked to.

Field Description

Fieldwork with pumping test and land survey were carried out from 29th October to 9th November 2019. The weather condition leading up to the pumping tests were dominated by more rain the than normal The well at Nyenga foundation is located about 100 meter upstream from the wetland with an elevation difference to the wetland of 10m (Figure 2 and

Figure 3). The gradient of the ground has a slight increase towards a hill in the south. The buildings at the foundation property are mainly parallel to the wetland and train tracks which is running a few hundred meters to the south.

Figure 2: Area map of Nyenga foundation. 1: school buildings, 2 drinking well, 3 visitors house, 4 teachers house, 5 health center, 6 children's home, 7 livestock housing, 8 fishponds, 9 naturel spring, 10 new cowshed and bio reactor, 11 new main hall.

The well at Nyenga foundation is hand dug, with a depth of 3.5 m from the top of the well casing. The well has installed concrete cylinders into the well to stabilize the sides. This makes the horizontal inflow smaller and makes the well mainly have inflow from the bottom of the well. There is probably some high porosity filling around the casing which makes the horizontal water flow follow the casing down and into the well from the bottom.

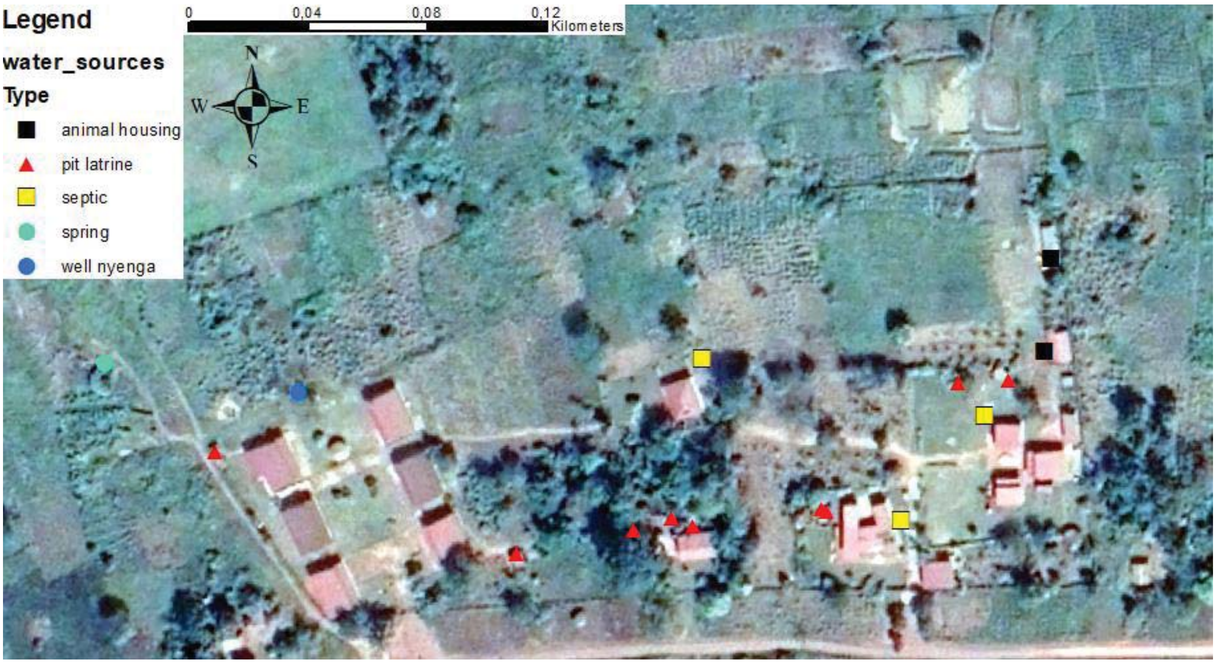

Figure 3: Map of water sources and locations of potential pollution locations.

In 2017 Engineers Without Boarders Norway were at Nyenga and estimated a water consumption of 2700 l/day (Kahlström, 2017). However, this was before the plans for installing a bioreactor and increasing the cow count. When talking to the employees at Nyenga foundation in 2019 they estimated a water consumption of 3000 l/day. In the same survey they measured a yield of approximately 800 l/h from the spring closest to Nyenga foundation and estimated the same yield from the shallow well. The water supply in Nyenga foundation is based on the shallow well, the closest spring and rainfall collection. The well is a big diameter well with a storage capacity of about 1,5 m³. In addition, there are some storage tanks for rainwater harvesting with a total storage capacity of about 8000 l.

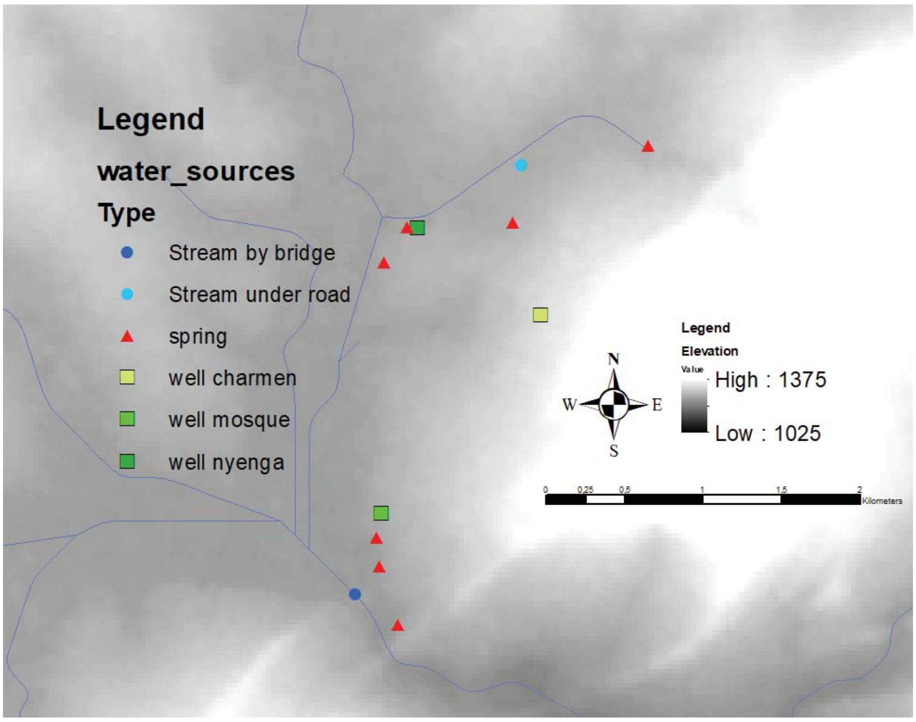

Figure 4: Map of Nyenga local area. streams, wells and springs measured in field are plotted on the elevation map used in the drainage area mapping.

Data, Theory and Method

Climate Data

The east African rainforest have two rain seasons a year. These rain seasons are controlled by the Inter-Tropical Convergence Zone, and comes in the boreal spring and autumn, with most heavy concentrations in March-May and October-November (Nicholson, 2017). The spring rainy season gives 50-80% of total annual precipitation in Ethiopia (Nicholson, 2017), with assuming similar numbers in areas of northern Uganda.

On average the spring rainy season have a 14-day variation, and the autumn rainy season a 10-day variation, for start and end. This makes the rainy season highly variable between years with rainfall variations of 55% for the spring rainy season, and 41% for the autumn rainy season (Nicholson, 2017). Recent trends in climatic changes is an increase of droughts lasting for several rain seasons. (Nicholson, 2017), and a shortening of the spring rainy season for the last decades. This decrease has been 14-65 mm/year per decade. As opposed to the decrease of the spring rainy season the autumn rainy season has increased in duration and intensity, thus giving an increase of total yearly precipitation. (Nicholson, 2017; Cook and Vizy, 2013).

Local weather is controlled by the mesoscale weather systems over Lake Victoria. These systems cause more precipitation at the shores of Lake Victoria then further inland. The rain comes in the night and early morning by the shores and in the afternoon farther inland (Nicholson. 2016).

Rainfall measurements are important in all water models to estimate water coming into the system. The weather data used in this thesis is extracted from https://www.ecmwf.int/. This is simulated weather data with a temporal resolution of one hour for the last 40 years (Figure 5) The data will be used to compare with field measurements to estimate groundwater velocity and the effect area of the well with some simplified equations for groundwater flow. This will then be used to evaluate a risk area for contamination of the well. Data of yearly precipitation, precipitation distribution and temperature variation for the last 40 years can be seen in Figure 5, Figure 6 and Figure 7.

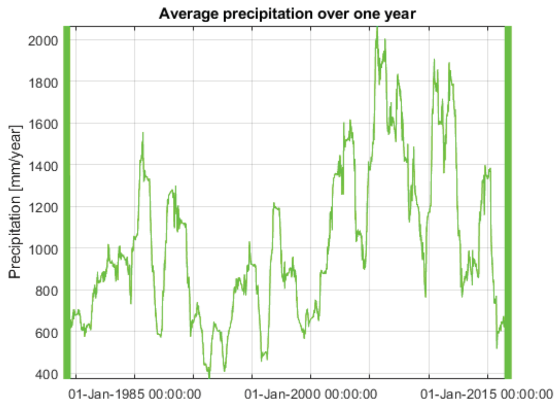

Figure 5: average precipitation over a year, calculated by sliding average.

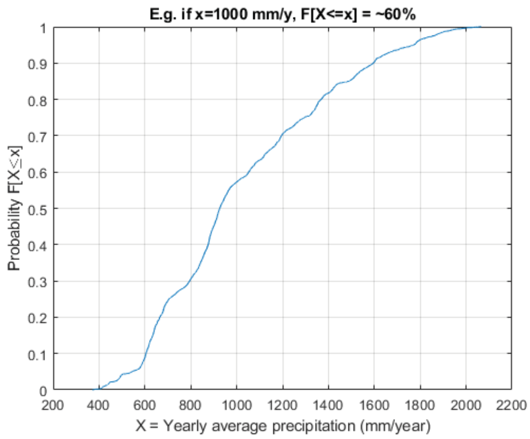

Figure 6: Distribution of yearly precipitation last 40 years.

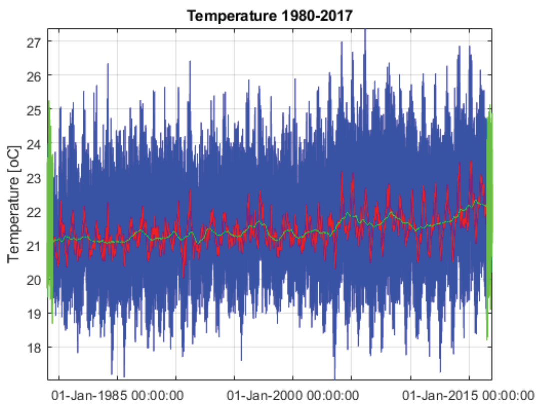

Figure 7: Temperature for the last 40 years. Blue: raw data average per 6 hours, red: sliding monthly average, green: sliding yearly average.

Geology

The Nyenga area is dominated by pyrite and laterite (Geological survey of Finland, 2014). Laterite is a weathered, iron oxide rich, rock type. The rock type is formed under moist conditions with access to good drainage and iron rich mother rock (Britannica, 2020). This makes it common in tropical areas like central Africa. The rock type has clay like properties with high variations in permeability (Bonsor, 2013). This comes from the way water pass though laterite, in cracks. This make the water yield in wells differ within a small area depending on the crack formation in the rocks. The wetlands of Nyenga have in addition a WRB histosol topsoil. (WRB. 2014)

An aquifer is a saturated permeable geological unit with sufficient water yield, that makes economic sense to extract (Kruseman and de ridder, 1991). The most common types of aquifer is sand and gravel deposits and fractured rock. Water storage in groundwater are defined by aquifers, which is a water transmitting layer and aquitard or aquicludes, which is impermeable layers with low to no permeability (Kruseman and de ridder, 1991). Aquifer are classified as confined, leaky or unconfined depending on the stratification of these layer types. Analysis of groundwater is also often based on that the aquifers are homogeneous and isotropic. This is simplified compared to the real conditions but make it easier to analyze. (Kruseman and de ridder, 1991). Simplification is especially useful when working with fractured aquifers due to the big variations over short areas. Unconfined aquifers are often defined by topography with high elevation and larger hydrological features as rivers and lakes. This must be taken into consideration with setting the boundary conditions of an aquifer.

The aquifer at Nyenga is set in laterite which is seen as a fractured aquifer. The aquifer is also probably unconfined with water table following the topography when merging with the wetland, seen at the natural springs. Lack of geological data makes the geological composition and stratification unknown. This means we need to set some extra assumptions of the aquifer, increasing the uncertainty of the analysis of the aquifer.

Theory

Darcy's Law

Darcy's law describes the relation between flow rate and flow path through a porous medium.

In equation 1 and 2, q is velocity (length/time), K is hydrological conductivity (length over time) and dh/dl is the gradient of the hydraulic head. When including a cross area of flow over time we get the specific discharge Q (length^3/time). (Kruseman and de Ridder, 1991)

Eq. 1 $$q = \mathrm{K} * (\mathrm{dh/dl})$$

Eq. 2 $$\mathrm{Q} = \mathrm{K} * \mathrm{A} * (\mathrm{dh/dl})$$

Head Value Estimate

To have an estimate of the groundwater gradient for use in water velocity calculations we use a basic ground water equation for calculating the head value (Figure 8). The function used is using infiltration rate and hydrologic conductivity with known water levels to adjust a head value estimate. This basic model does not take topography into consideration and are not suitable for areas with big gradient shifts.

The analytic method for estimating groundwater head in unconfined aquifer is based on Dupuit-Forchheimer (Hendriks, 2010; Kitterød, 2020).

The analysis is assuming the mass balance is steady state with boundary conditions x=L and $h=h_o$ (Hight). Out from Darcy law we can assume $Q = -K * h * \frac{dh}{dx}$ because A is the same as h when working in two dimensions. The Q is also length^2/time because of the same reason. When including infiltration N(m/s) we assume all water infiltrates over area x (m) which gives us:

$$N_x = q * h$$

since $\mathrm{q} = -\mathrm{K} * \frac{dh}{dx}$ we get:

$$N_x = -K * h * \frac{dh}{dx}$$

We use the kernel rule of derivation to get:

$$N_x = -K * \frac{1}{2} * \frac{dh^2}{dx}$$

Reformulating for integrating:

$$dh^2 = \frac{-2}{K} * N_x$$

integrating gives:

$$h^2 = \frac{-N}{K} * x^2 + C$$

Solving equation for C we get:

$$C = h^2 + N * \frac{x^2}{K}$$

Inserting for C and changing x=L and h=h_0 we get:

Eq.3 $$h^2 = \frac{N}{K(L^2 - x^2)} + h_0^2$$

Eq.3 is adjusted by changing the value for k and N to make the h values fit the measured levels in the two wells. After finding a value for k and N, the height value is used to calculate the gradient.

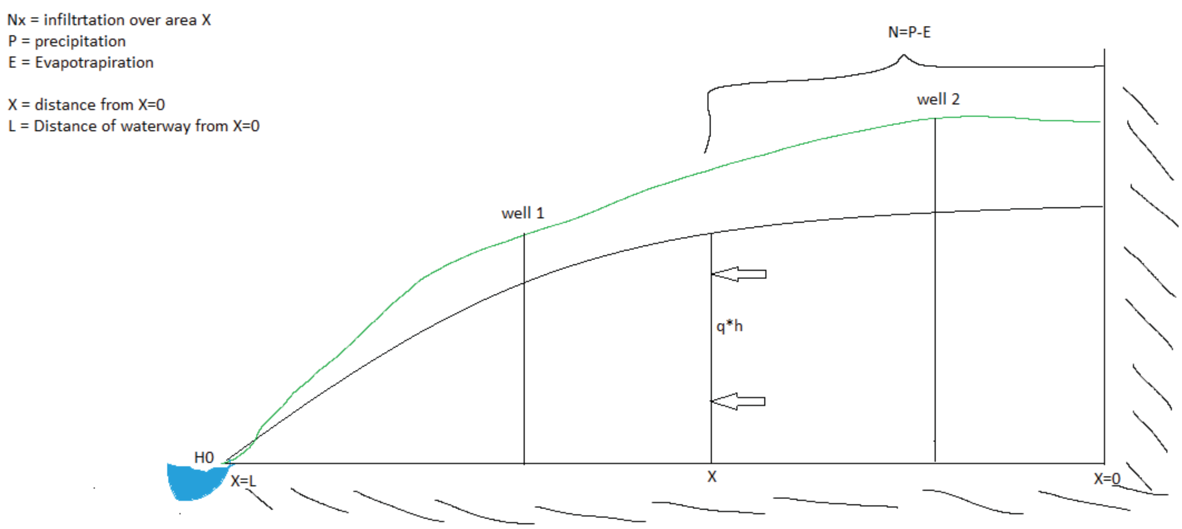

Figure 8: Head value is calculated using eq. 3 with input from this figure. N total infiltration where P is precipitation and E is evapotranspiration. X is distance from head elevation top. L distance from head elevation top to lowest head elevation. q flowrate distance/time. h aquifer depth. h_0 is elevation by lowest head value. The two wells are used to adjust the head value.

Pore Water Velocity

Ground water velocity is based on the groundwater gradient, effective porosity, and horizontal hydrologic conductivity. To be able to do a calculation of water velocity we are assuming all water transport in the aquifer is horizontal. This assumption comes because of lack of geological data of soil composition and stratification. We are also assuming the ground is homogeneous, isotropic and have a uniform thickness.

By using Darcy's law, we can calculate the pore water velocity (q) by knowing the gradient and the hydrologic conductivity. By including the gradient estimated using the head from eq.3 into eq.1 and K from analysis from pumping test, we can make an estimate of q over a distance depending on the resolution of head value.

To estimate the distance of flow over the 60-day hygienization time for bacterial growth we have to take the change in pore water velocity into consideration. Since the pore water velocity is changing by the gradient, we need to define the distances where the velocity is valid depending on the gradient changes. A higher resolution with calculations for small distances will give a more precise estimate if the head values are accurate.

When dealing with water velocity in groundwater you have to take into consideration the viscosity changes with temperature. For the case of Nyenga the variations in annual average temperature is about 3 degree Celsius (Figure 7). With an annual temperature of 21 degree Celsius the viscosity change is negligible.

Analytical Procedures

Pump Test Analysis

To analyze the results, we use Theis-, Jacobs- and Boulton-Streltsova methods (BS). Due to the lack of observation wells, we use different methods to have a more robust estimate of transmissivity (T) and storativity (S). This also means we must set some extra assumptions for analysis. Assumptions under is given for methods if other is not given.

Theory given for Theis, Jacobs and BS are based on “Analysis and evaluation of pumping test data” by Kruseman and de Ridder (1991).

Assumptions for Theis- and Jacobs method:

- The aquifer is confined.
- The aquifer has a seemingly infinite areal extent.
- The aquifer is homogeneous, isotropic and of uniform thickness over the area of influence by the test.
- The groundwater level in observation points is horizontal over the area of influence at the start of the test.
- Pump discharge is constant.
- The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow.
- The flow to the well is in unsteady state. The drawdown difference with time are not negligible, nor is the hydrologic gradient constant with time.

Due to the lack of an observation well, and the use of big radius well, are we also assuming

- Piezometer distance is well radius and the measured drawdown at piezometer is equal to well drawdown

Theis Method

Theis method is one of the most common analyzing methods for well measurements. Theis method is based on the connection between storativity and discharge. When pumping time increases the influenced area will increase. ''the rate of decline of head, multiplied by the storativity and summed over the area of influence, equals the discharge" (Kruseman and de Ridder, 1991).

Theis equation:

Eq. 4 $$s = \frac{Q}{4\pi T} * W(u)$$

Where s is drawdown (distance) measured in a piezometer at distance r from the well. Q is discharge (volume/time), T is transmissivity (distance^2/time) and $u = \frac{r^2 * S}{4Kt}$. t is time from pumping start, S is dimensionless storativity and r is distance from well to piezometer well. W(u) is Theis well function which is an exponential integral of u,$\int_u^\infty e^{-y} dy/y$. This is developed into $\mathrm{W(u)} = -0.5772 - \ln(\mathrm{u}) + \mathrm{u} - \frac{\mathrm{u}^2}{2.2!} + \frac{\mathrm{u}^3}{3.3!} - \frac{\mathrm{u}^4}{4.4!} + \cdots$ This well function is used in the curve fitting as the reference of normal drawdown ratio (drawdown per time). The difference in storativity and transmissivity will shift the placement of the plotted drawdown compared to the reference curve.

By using the equation for $u = \frac{r2S}{4Kt}$ it is possible to find a value for storativity (S) if the discharge, time and drawdown is known.

Eq. 5 $$T = \frac{Q * W(u)}{4\pi s}$$

As $\frac{Q}{4\pi T}$ and $\frac{4T}{S}$ are constants because of the method assumptions, the relations between log s and $\frac{r^2}{t}$ will be similar to the relations between log W(u) and log (u).

Eq. 6 $$\log s = \log\left(\frac{Q}{4\pi T}\right) + \log\left(W(u)\right)$$

Eq. 7 $$\log\left(\frac{r^2}{t}\right) = \log\left(\frac{4T}{S}\right) + \log(u)$$

Theis is then based on the curve fitting method between log s, log ($\frac{r^2}{t}$) and log W(u), log u. This results in two curves which looks similar but with a vertical and horizontal offset by the constants $\frac{q}{4\pi T}$ and $\frac{4T}{S}$. Instead of using (normal curve fitting) log s, log ($\frac{t^2}{t}$) and log W(u), log u there are more convenient to use W(u), $\frac{1}{u}$ and s, $\frac{t}{r^2}$.

Procedure for Theis curve fitting method

- Plot Theis well function on a loglog paper against W(u) and $\frac{1}{u}$
- Plot observed data on loglog paper against s and $\frac{r^2}{t}$. make sure the two loglog papers have the same scales
- Superimpose the curve data to get the best fit. Make sure to keep the axes parallel
- Select an arbitrary point on the two overlapping sheets.
- Read the coordinates for W(u), $\frac{1}{u}$, s, and $\frac{r^2}{t}$.

  Tip: the point doesn't have to be on the curve. It is easier when using a point along two of the 10^0=1 axis.

- Solve equations for T and S by using the values from the selected point.

  Note: S must be between 0-1.

Jacobs Method

Jacobs method have the same assumptions as for Theis equation. Jacobs method is a steady state approximation of Theis equation. From $\frac{r^2 S}{4Tt}$, "u" will decrease when "t" increases and "r" decreases. This makes it possible to neglect the drawdown in the near area of the well after long time pumping because t=∞. This gives us:

Eq. 8 $$s = \frac{2.30 * Q}{4\pi T} * \log\left(\frac{2.25 * T * t}{r^2 * S}\right)$$

s is drawdown, Q is discharge, T is transmissivity, t is time and r is distance from pumping well to measuring well.

Because Q, S and T are constant, a plot of s versus t near the well will become linear for observations near the well.

Assumptions

same as for Theis in addition to:

- The values of u are small (u<0.01) r is small and t is sufficiently large.

Procedure for Jacob's method

- Plot s versus t on a semi log paper (t in logarithmic scale)
- Draw a line through the points
- Extend the line to it crosses the s=0 and read t0
- Determine the slope of the line and delta s for log cycle of t.
- Substitute values for Q and delta s and calculate T. Use the T and t_0 to find S. ($S = \frac{2.25Tt}{r^2}$)

$$T = \frac{230Q}{(4\pi * delta(s))}$$

Boulton-Streltsova's (BS) Curve-Fitting Method

BS is used for unconfined large diameter wells and have the following assumptions:

- The aquifer is unconfined.
- The aquifer has a seemingly infinite areal extent.
- The aquifer is homogeneous, anisotropic and of uniform thickness over the area of influence by the test.
- The groundwater level in observation points is horizontal over the area of influence at the start of the test.
- Pump discharge is constant.

- The well does not penetrate the entire thickness of the aquifer.
- The well is not small; hence storage in the well cannot be neglected.

Added conditions:

- The flow to the well is in an unsteady state
- Sy/Sa>10

Sy=specific yield of the aquifer and is equal to S for unconfined aquifers.
Sa=storativity of compressible aquifer, assumed to be 10^{-3}

The BS is based on two-part curve fitting. First curve fitting is with type A curves. Then fitting of late time pumping is against type B curves. The type B is fitted for use on small radius wells, but long-time pumping will over time make it possible no neglect the well storage.

Eq. 9 $$S = \frac{Q}{(4\pi\, T(b1/D))}$$

Eq. 10 $$uB = \frac{r^2 S}{(4Tt)}$$

Procedure for BS method

- Plot the Type A and type B curves on loglog paper plotting W(u) versus $\frac{1}{u}$
- Plot the data on loglog paper at the same scale as for the type curves. The data is plotted with s versus t.
- Match the data with the type A curve and note the values for W(u), $\frac{1}{u}$, s and t for an arbitrary point on the sheet.
- Match the late time data with the Type B curves and note the values for W(u), 1/u, s and t for an arbitrary point on the sheet.
- The two calculations should give approximately the same result for T.

Methods

Pumping Tests

The well at Nyenga foundation in installed with a hand pump. This made it difficult in periods to control flowrate due to locals removing the lock placed on the pump and pumped during the pumping tests. For pumping we used three electric 12 V pumps of the type Eijkelkamp submersible pump "gigant" and booster. As power supply, we were connected to the main power at Nyenga foundation. This power is supplied by solar power and are stored in 170Ah batteries. This made the power supply stable during the pumping tests. To supply the pumps, we were using three adapters. The adapters were old computer adapters demodulated to fit the socket of the pumps. The adapters had the following specifications: 12 V 2 A, 12 V 3 A and 19 V 3,4 A. To estimate the output of the pumps we measured the time of filling a 10 l bucket.

For logging the water table, we used a Von Essen Diver and a Von Essen baro to compensate for the flux in air pressure. The baro was lowered into the well about 50 cm below the pump casing. The diver was lowered to a depth 30 cm above the well bottom. The logging frequencies we used were: 10 sec, 30 sec and 2 min for the different pumping tests. A base line of the water table was established by logging the diver and baro for 3 days between the pumping tests, logging every 5 min. This information was used to establish how the ground water table fluctuates in steady state.

Spring and river measurements

Measurements of the local springs and streams were done as input to water balance of the catchment of the wetland. Taking measurements in the wetland was not possible because of heavy vegetation and swampy march. Measurements were therefore done in easy access locations where the wetland streams were flowing through culverts under the roads.

Around Nyenga foundation's local area there are 7 springs. To estimate the yields at these springs we used the same method as for measuring discharge in the pumping test. This data is found in appendix 6.

At the rivers, we used the areal-velocity method to estimate discharge. Areal distance method was used instead of salt dilution method because of a lack of a conductivity meter.

At location "Stream under road" in Figure 4, there was a river crossing a road where the water was flowing through two culverts under the road. The bottom of the culverts were filled with sediments. This made the geometry to a 45 degrees cube simplifying the area calculations. To measure velocity, we measured the time for floating sticks and bottles to cross through the culvert under the road. The measurements were repeated to get a lower uncertainty.

At “bridge” (Figure 4), the river was much bigger. This made measuring the river cross-section harder. To estimate the depth of the river, we used a measuring tape taped to a tree we lowered from the bridge over the river and measured the depth to the bottom of the river and the water table in the river. The river divided into two flow paths under the bridge. We therefore carried out measurements for each path and added them to get the total water flow. The depth of the river was measured every 50cm across the river to make an estimate of the areal of the river calculated by interpolating between the points and integrating these values. For finding the river velocity, we used the same approach as at the location where the water was running in culverts under the road, where we dropped sticks into the river and measured the time for the sticks to cross under the bridge. 40 measurements were taken and mean calculated to get an average time.

Water sampling

For water sampling we collected water from the well, the closest spring and from a stream going through the local wetland. The water samples were collected into sampling bottles brought from NMBU prewashed three times before collecting the sample. The samples were collected with the pumping equipment at the well the day before departure for home. The samples were then set in a refrigerator until testing at the lab back at NMBU. We also collected bacteriological samples in water bottles from the spring and well to be analyzed at Makerere University.

To conserve the samples, we added some HNO3 to prohibit high content of Fe and Mn felling out. This treatment was done to one sample from the well and from the spring and wetland sample. We also collected a non-treated sample from the well. This because treatment can dissolve Cu and Cr from the bottles and into the sample. The treatment also means we cannot measure N and C in the treated samples.

Water Sample Analysis

For lab analysis, we did physical tests for pH, alkalinity, turbidity, and conductivity. Nutrient analysis was done for P, N and different anions and cations with ion chromatography (IC). The samples were also analyzed for some of the most common metals regards to health with inductively coupled plasma mass spectrometry (ICP). Both IC and ICP were done by personal at NMBU water lab.

Conductivity

Conductivity was measured using a conductivity meter

pH and Alkalinity

pH gives a measurement if the water is acidic, basic or natural. For drinking water, the pH should be between 6.5 and 9.5 following the Norwegian heath authorities (Folkehelseinstituttet 2018). To measure pH and alkalinity we used 100 ml sample. We measured pH at start and the amount acid added to reach pH 4,5. The amount acid added can be used to calculate the buffer capacity of the water in form of $CaCO_3$.

Turbidity

Turbidity is measure of how transparent water is. A high number means the water is more polluted. By filtering the water sample, the suspended material is removed and only diluted materiel remains. Water samples were filtered with 0,45 micrometer filter and measured with a photometer at FNU860+-60nm.

Phosphorus

Phosphorus was measured in total and dissolved phosphorus (particles <0,45 µm). Analysis were done according to EN-NS 1189. Oxidation chemical were added to oxidase all P to orthophosphate. The samples were then autoclaved and added ascorbic acid and molybdat to form antimony phosphate. Antimony phosphate have a blue color with is measured with a photometer. The color is then compared to standards with a known concentration of P, in this test 0.2 mg/l.

Nitrogen

For Nitrogen we measured both total N, and dissolved N ($NH4^{+}$) filtered with pore size 0.45 µm. The nitrogen was oxidized with peroxydisulfate to form $HN4^{+}$ following NS 4743. Total N were measured by IC.

Results

Background Monitoring

Background monitoring of the water level was done for three day between pumping test 2 and 3. This was done to have some data to compare with for log duration pumping tests (Figure 9).

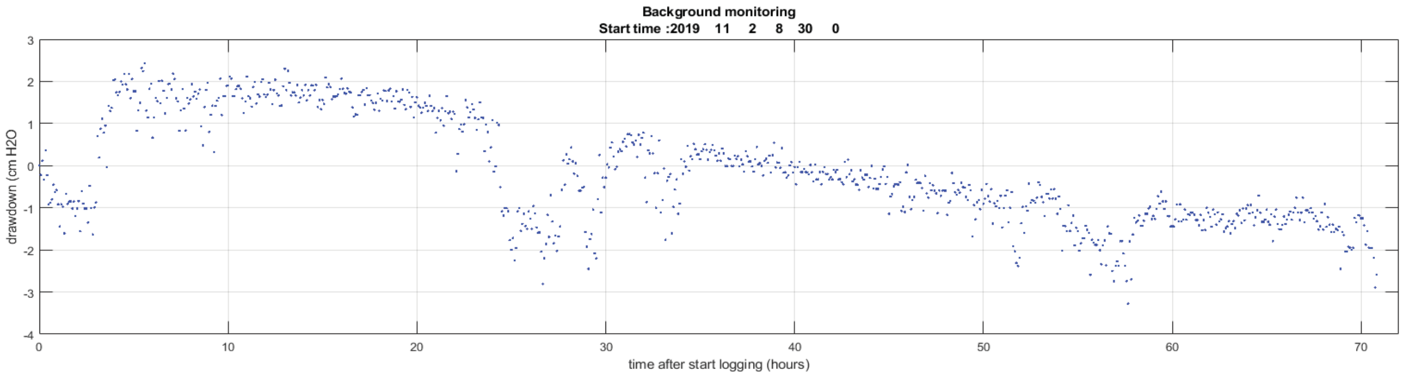

Figure 9: Background readings of the water level in the Nyenga foundation well between pumping test 2 and 3.

Pumping test

Drawdown was logged with the diver and adjusted for barometric pressure with the baro. The diver and baro were logging at intervals of 10 sec for pumping test 1 (Figure 10), 5 min for pumping test 2 (Figure 11) and 2 min for pumping test 3 (Figure 12) and 4 (Figure 13). Figure 15 illustrates pumping test 4.2, which are results from pumping test 4 adjusted with manual measurements. The points in 4.2 are every 5000 sec. This interval was chosen because, writing all values of pumping test 4 to 4.2 would have to be done manually because of the manual adjustment, which would have taken too much time. The chosen interval shows the tendency in pumping test 4.

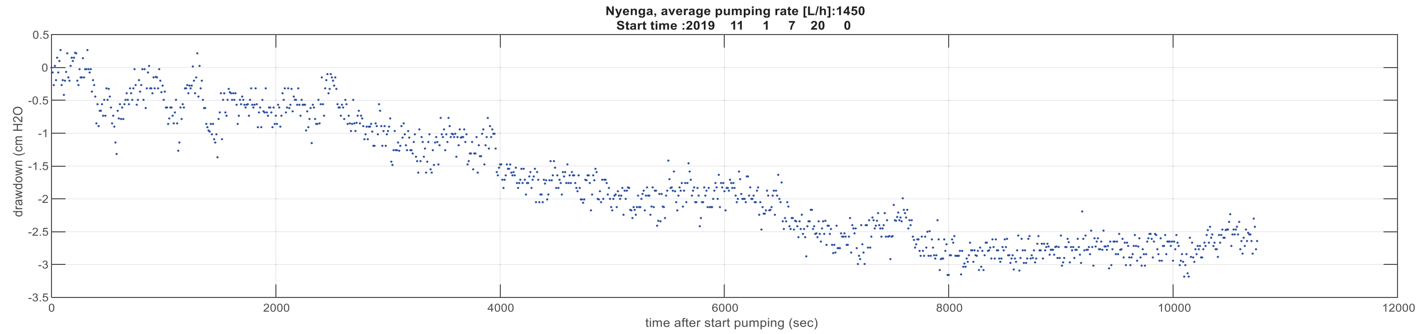

Figure 10: Results of pumping test 1. The water level is declining for 3 hours before rising again from 3-6 hours.

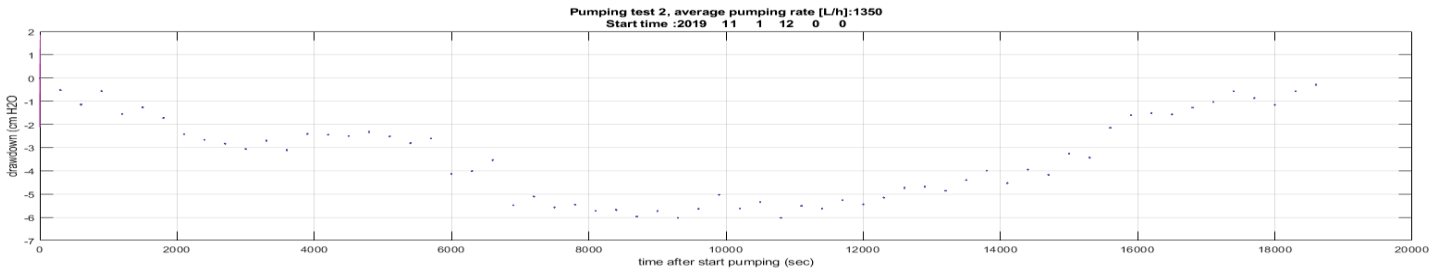

Figure 11: Results from pumping test 2. the water levels were declining for the first 3 hours before rising again until 6 hours when the test ended

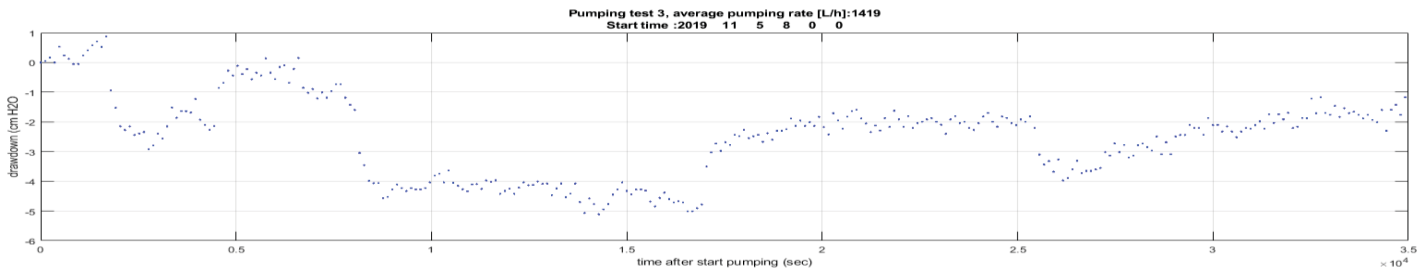

Figure 12: Results from pumping test 3. the water level was sinking and rising in the start before levelling for a while. Midway through the pumping test there was some time with a parallel increase in water level before lowering rapidly and slowly rising until test end.

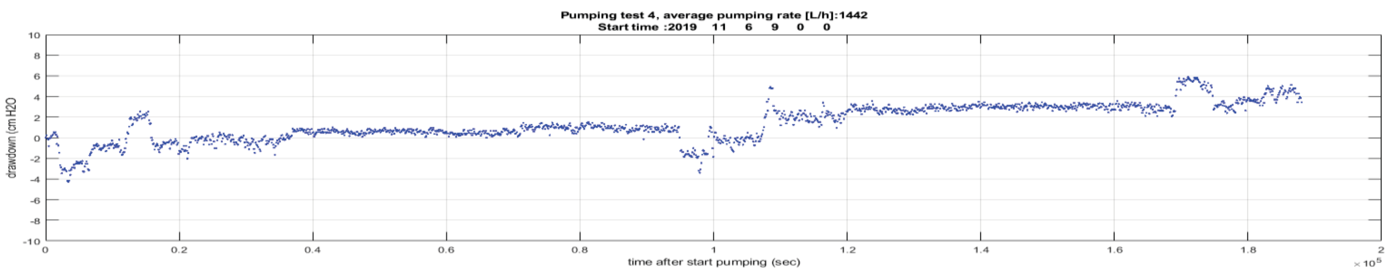

Figure 13: Results of pumping test 4. The water level is variating some in the start before steadily increasing though the pumping test until test stop. There are some higher variation in water level in the start mid and end for shorter time periods.

Manual measurements of the water level in the well of pumping test 4 show a drawdown of 2,5 cm after 9 hours of pumping and 3 cm after 19 hours. When adjusting the results from pumping test 4 to these measurements we get a drawdown shown in Figure 14. Figure 15 is then the same plot simplified with measurements extracted for every 5000 sec.

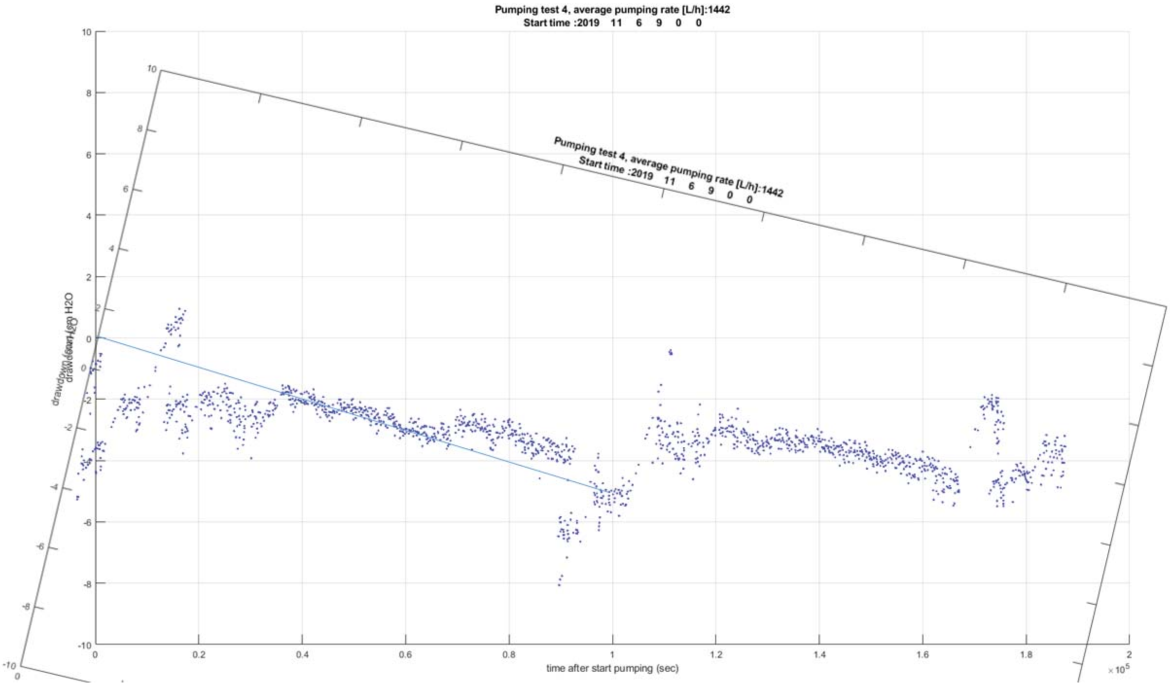

Figure 14: Simplified results from pumping test 4. This result is referred as to 4.2 in the thesis. It holds the same characteristics as pumping test 4 after adjusting for manual measurements.

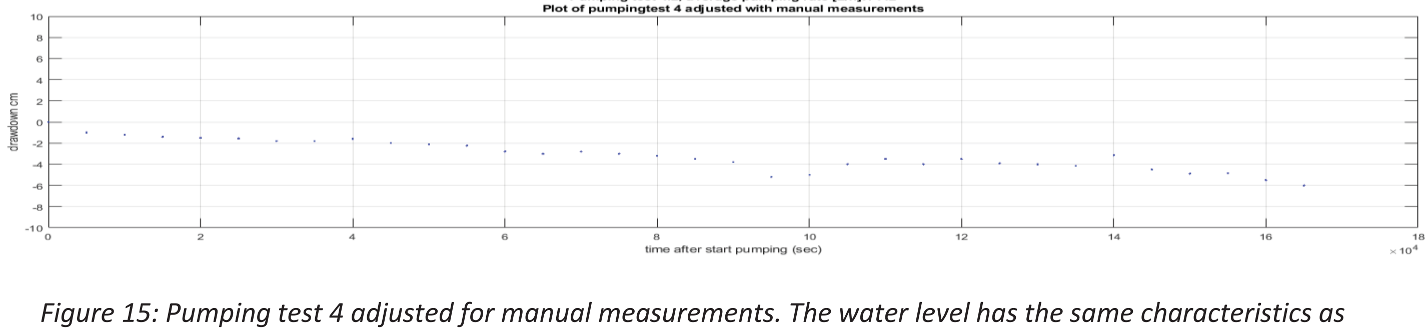

Figure 15: Pumping test 4 adjusted for manual measurements. The water level has the same characteristics as the original pumping test 4 in figure 13, a total decline in water level.

Analysis

Figure 16, 17, 18 and 19 are showing the curve fittings of Theis, Jacobs and BS method. Results shown in the figures are from pumping test 2 for Theis and Jacob's and from pumping test 4 for BS-method. These tests were chosen because they were the easiest to understand when describing the results. Results from other pumping test analysis is showed in appendix 1 to 3.

Theis Method

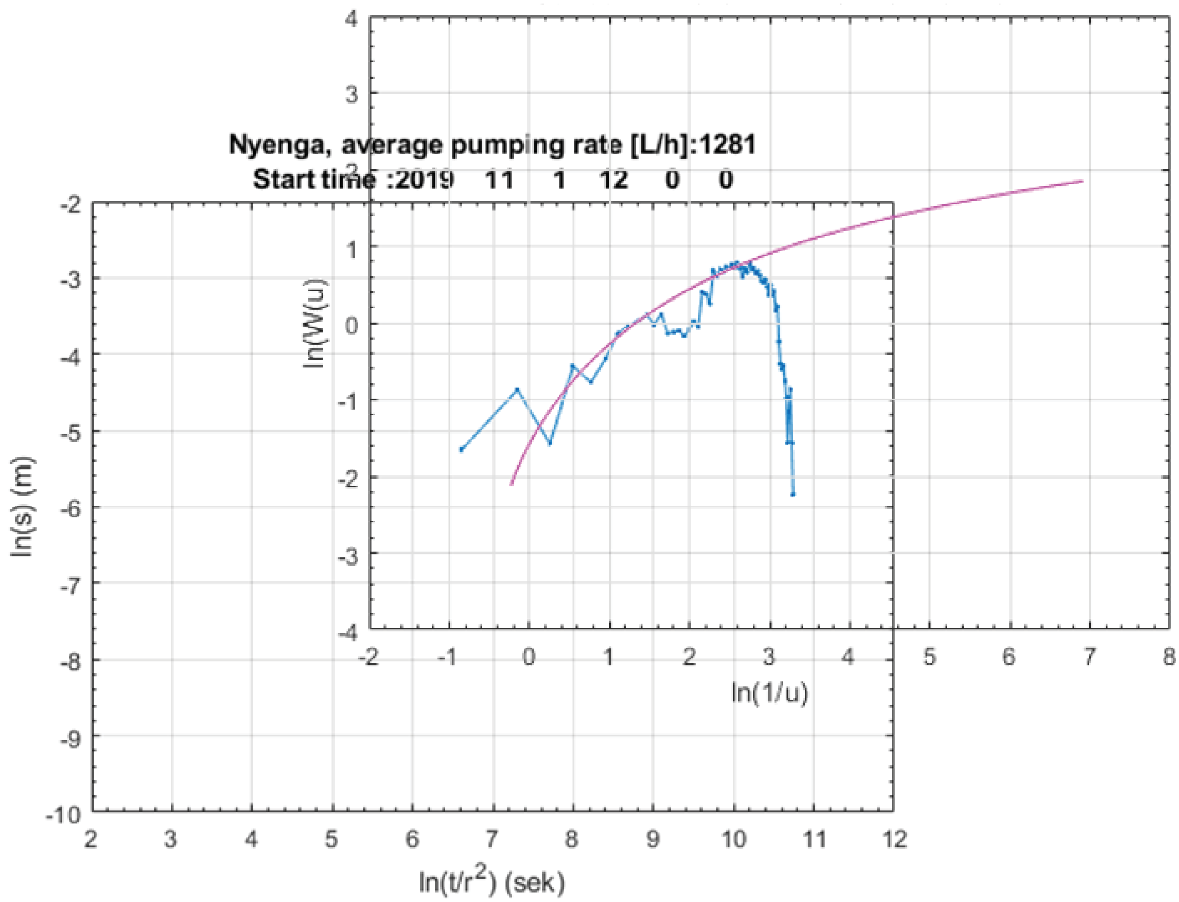

Figure 16: Theis fitting curve in pink in laid on top of the drawdown were the two curves fits best. The curves are plotted in logarithmic scale with 1/u against W(u) for the fitting curve and s against t/r^2 for the drawdown. The result from the curve fitting can be seen in table 1.

When reading values for an arbitrary point in figures for Theis curve fitting method (Figure 16 and Appendix 1) we get the values in table 1. These values are then put into equations 4 and 5 to give values for T and S. All values for S were >1 with means none of them can be used.

Table 1: Values from points in Theis curve fitting figures. Pump test 4.2 is the reworked curve after adjusting for manual measurements. T is the value for transmissivity calculated with eq.5.

Pump test nr.	ln W(u)	ln 1/u	ln s	ln t/r^2	T
Pump test 1	0	0	-3,8	8,45	0,0014
Pump test 2	0	0	-3,6	7,4	0,0012
Pump test 3	0	0	-4,2	6,6	0,0021
Pump test 4	0	0	-4,4	6,05	0,0026
Pump test 4.2	0	0	-3,4	10,6	0,00096

Jacobs Method

Results from Jacob's method is in figure 17. The result is from pump test 2 while pump test 1, 3 and 4 is in appendix 2.

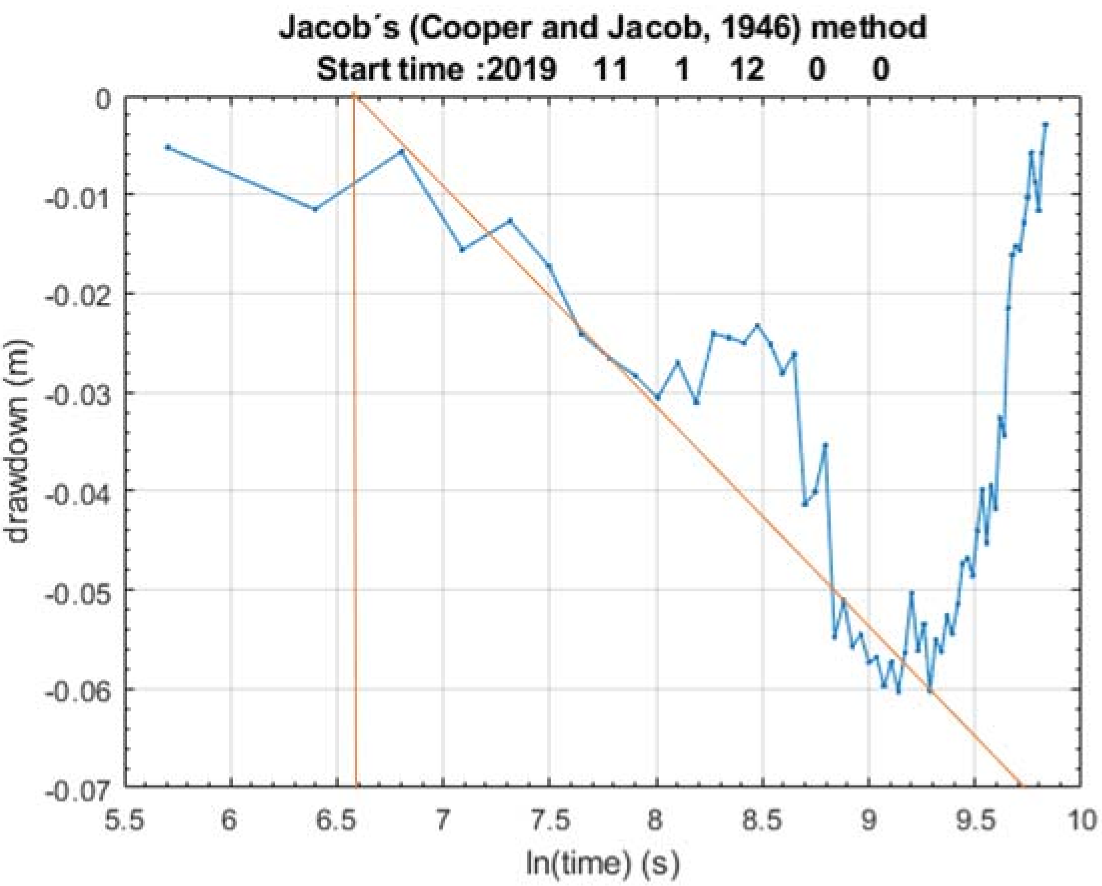

Figure 17: Jacobs method for pumping test 2. The vales for s extracted from the method is shown in table 2.

The values we chose for calculating T and S were t_0=6,6, t_1=9,7 and s=-0.07. When we put these and the corresponding values from pumping test 1-4, into equation 8 we got the results in table 2. Values for S are not included in the table because none of the pumping tests gave S<0.

Table 2: Input from pumping test to eq. 8 for calculating T and S from values for s, T0 and T1. Due to the irregular drawdown of pump test 3 are there two lines 3 and 3,2. Pump test 4,2 is for the reworked pumping curve of pumping test 4. In pump test 4 are the drawdown negative.

Pumping test nr.	S	T0	T1	T
Pumping test 1	-0,035	7,38	9,58	0,0021
Pumping test 2	-0,07	6,6	9,7	0,0013
Pumping test 3	-0,06	6,6	10,18	0,0019
Pumping test 3,2	-0,06	8,4	11,8	0,0018
Pumping test 4	-0,1	10,18	4	0,0018
Pumping test 4,2	-0,1	9,9	12,5	0,0012

Boulton-Streltsova (BS) Method

Figure 18 and 19 shows BS curve fitting test of the reworked results (4,2) of pumping test 4. Values used were taken from curve fittings and used with eq 9 and 10 to calculate T and S are shown in table 3. Calculated T and S is then showed in table 4.

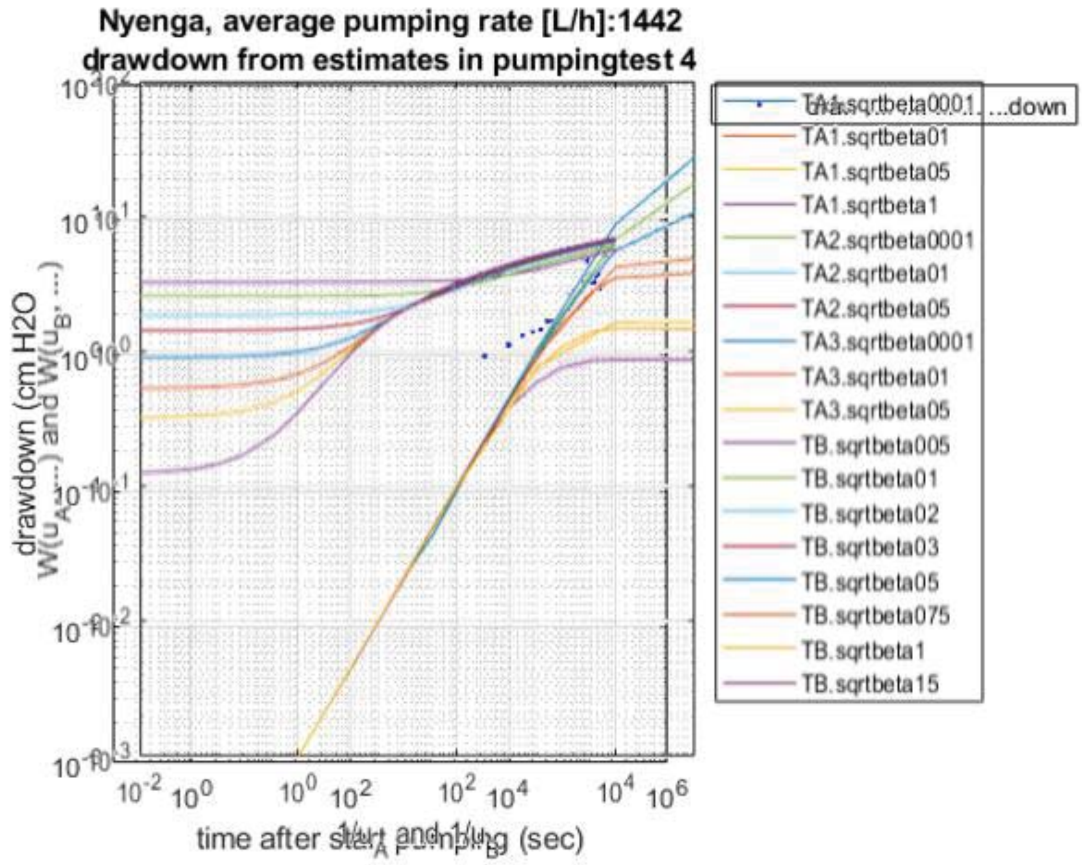

Figure 18: Curve fitting of pumping test 4.2 against alpha curves. Manual plotting show biggest correlation with curve TA2.0001.

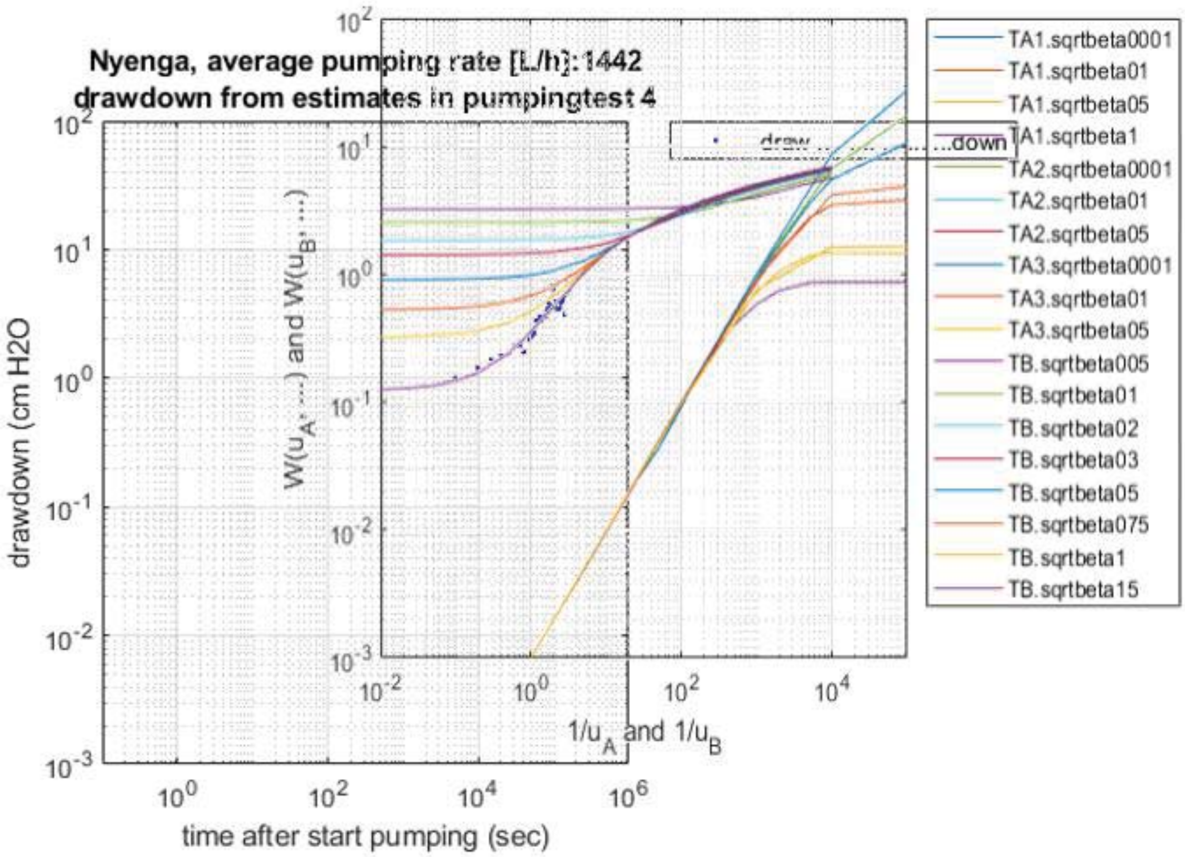

Figure 19: Curve fitting of pumping test 4.2 against beta curves. Manual fitting show a biggest correlation with curve TB.15.

Table 3: The table shows the input for eq. 9 and 10 from BS curve fitting from Figure 18, Figure 19 and in appendix 3.

Pumping test nr.	s (A)	t (A)	1/u (A)	W(u) (A)	s (B)	t (B)	1/u (B)	W(u) (B)
Pump test 1	0,5	3	1	1	0,7	800	1	1
Pump test 2	1	1	0,7	0,6	3	1000	1	1
Pump test 3	1,1	1,1	1	1	1	400	1	0,5
Pump test 4	1	10	5	1	1	4000	1	3
Pump test 4,2	1	11,2	1	1,1	1	500	1	0,16

Results for T and S from BS shows a variance from 1.6e-5 to 9.9e-6 for T and 0,01 to 1 for S. Average T and median T is 2.2798e-5 and 1.6794e-5 (table 4). For Storativity (S) we are not using results from pumping test 4 and 4.2 due to the extreme values compared to the other pumping tests. This give S an average of 0.030 and a median of 0.0265.

Table 4: Results of BS method for T and S.

Pumping test nr.	T A	T B	S
Pump test 1	6,6315e-5	8,2893e-6	0,0265
Pump test 2	1,7905e-5	9,9472e-6	0,0398
Pump test 3	2,8515e-5	1,5683e-5	0,0251
Pump test 4	3,1875e-5	9,5626e-6	1,5300
Pump test 4,2	3,5063e-5	5,1000e-6	0,0102

Catchment

The catchment was estimated by following the water divide ending in the river draining the wetland area. This is almost the same location where discharge measurements were done. We are assuming the discharge in the river correlates to the catchment drainage. We are by this assuming the infiltration is equal to drainage. This also means we are neglecting the water consumption and are including it into evapotranspiration. This is done since there are no big scale water consuming activity in the catchment. The estimation of the catchment was done manually with topological map (figure 20). This elevation model had a resolution of 1 m. There is some uncertainty in the estimate of the catchment due to manual placement. The ground water divide does not need to follow the topography. Rivers and streams in the catchment were automatically regenerated in ArcGIS pro by following the lowest point in valleys. These estimated streams were close to the observed flow path but divided sometimes due to the flatness of the valley floor.

The catchment area was then divided into three catchments were the smallest one is draining under the road where we did measurements. By comparing the average runoff from the two measurement points and the connected area we can get a rough estimate of average drainage per areal. This will then be compared to the simulated runoff in the climate data.

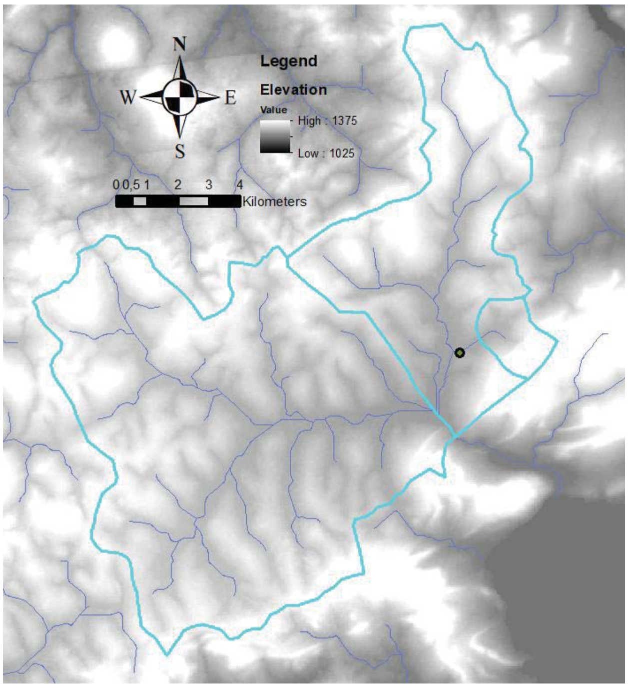

Figure 20: Elevation map and catchment of Nyenga area. Nyenga foundation is located at the green dot east of the center of the map. Blue lines are showing the catchment found by following the highest point draining to the river draining under the bridge in Figure 4.

Water Head, Water Velocity and Risk Distance

The elevation raster was used to manually find the most probable pathway of the ground water. The flow path was estimated by assuming the flow direction was 90 degree on the elevation heights (Figure 21). The flow path was split into 100 splits where each split is 24 meters and assigned an elevation value out from the elevation raster. The head value with eq 4 is then calculated for each split (Figure 22).

Figure 21: Map of groundwater flow path into the well of Nyenga foundation (blue square in left upper corner). The flow path goes though the well of the chairman (blue square in the middle). The chairman well is at split 50 ca.1200m in Figure 22. The flow path is manually drawn and may be different out from geological conditions.

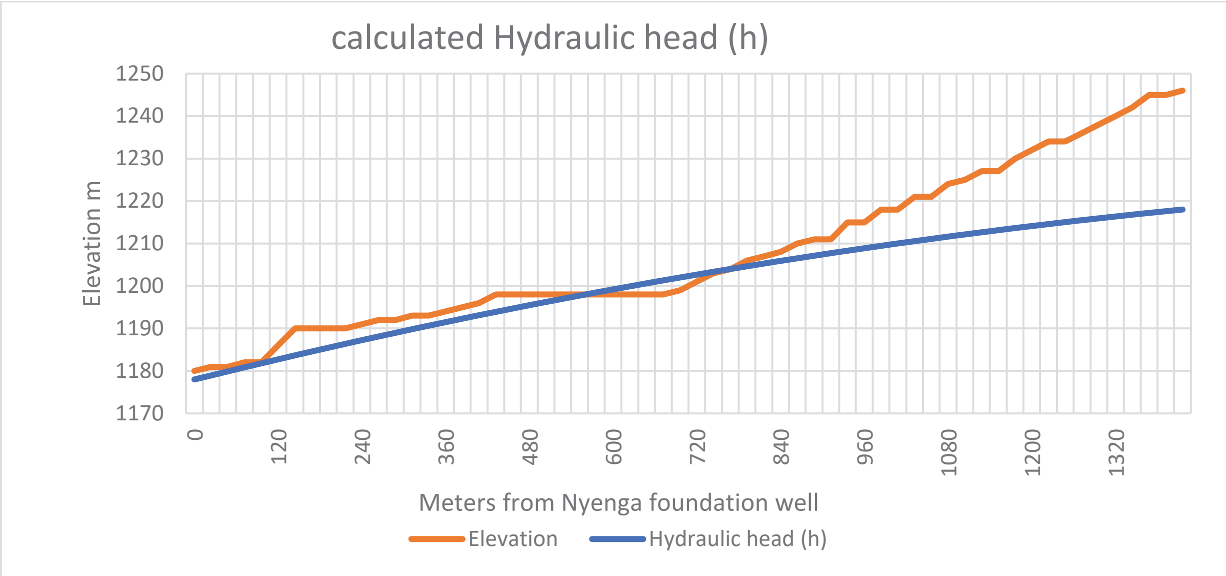

Figure 22: Calculated head values plotted with elevation of the flow path. The head is only a estimate for the first 1200m (50 split). This because we have no reference father into the flow path to adjust the head value.

To estimate a risk area, we have to estimate of the pore water velocity. The pore water velocity can be estimated by using Darcy's law where $K = \frac{T}{h}$. For simplicity, the layer depth of water transport is set equal to 2.5 m, the same as the water depth in the well. This is done because K is estimated with the assumption that the well is fully penetrating the aquifer. Calculations of q, risk distance and used values can be seen in Table 5. The calculations used the gradient between the 24 m long splits calculated in Figure 22.

Table 5: Estimated risk distance using the input from the T to calculate k and q. The value for T is the highest, lowest and the most likely value from Theis, Jacobs and BS combined. The most likely value is taken from a subjective evaluation between field conditions and results from the analysis. q Is the velocity using the gradient in the first split. Distance is calculated using gradients for every 24m found with Figure 8.

Description	T (m2/s)	K (m/s)	q (m/s)	Risk distance (m)
Max q	0.0026	0.00104	-4.21e-5	208m
Most likely q	0.00002	0,000008	-3,24e-7	1.6m
Min q	0.000005	0.000002	-8.10e-8	0.42m

Physical Analysis

Water sample description can be seen in Figure 6. Water sample 2 which was used for the physical analysis (table 7) had a low buffer capacity, neutral to acidic pH and a low turbidity. The buffer capacity is lower than expected while conductivity and Turbidity is low as expected from ground water.

Table 6: Explanation of sample nr. with description of location and sample treatment.

Sample nr	Comment
1	Sample from dug well. Prepared with HNO3
2	Clean sample from well
3	Sample from local spring. Prepared with HNO3
4	Sample from wetland beneath well. Prepared with HNO3
Std	Standard solution (0.2 mol/l) for corrugation measurements
Blank	Distilled water for corrugation measurements

Table 7: Results from physical analysis of water sample 2.

pH	5.67
Conductivity	67.0
Alkalinity	1.354ml 0,02M/100ml
Turbidity	4.2

Phosphorus

Results for photometer measurements of dissolved- and total phosphor are shown in appendix 4. The concentration of dissolved- and total phosphorus were low with 0,5 µg/l for dissolved P for sample 2 and 3.5 µg/l, 1.6 µg/l and 6.3 µg/l for total P for sample 2,3 and 4. Total P for sample 1 had negative absorbance which give a negative P content and for that reason 0.

Nitrogen (ammonia)

Results for photometer readings of NH4 measurements can be seen in appendix 4. The content of NH4 (N) is calculated to 0,028mg/l.

IC

Results of ions is shown in Table 8 Table 8: Results from IC analysis with uncertainty and recommended values from the Norwegian health authorities. The test was done at NMBU water lab.which is the results from IC. Recommendations for ions from the Norwegian health authorities are also given in the same table.

Table 8: Results from IC analysis with uncertainty and recommended values from the Norwegian health authorities. The test was done at NMBU water lab.

Measured	Value in mg/l	Uncertainty (microgram/l)	Recommended values from Norwegian health authorizes (mg/l)
Alkalinity (as CO3)	245	12	0,6 meq/l
Boron	0,0430	0,0058	0,1-0,2
Calcium	95,4	7,3	25
Chlorine	74,0	3,8	200
Color (Hazen unit)	16,0	3,7	20
Dissolved inorganic carbon	57,1	6,3	
Dissolved organic carbon	4,64	0,70	
Fluoride	0,123	0,034	1,5
Hardness (as CaCO3)	342	25	
Magnesium	25,4	2,0	35
Nitrate + Nitrite (as N)	2,87	0,28	50 + 0,05
pH	8,40	0,17	6.5 – 9,5
Potassium	3,51	0,29	25
Silica	0,275	0,033	
Sodium	43,0	4,2	200
Sulfate (as SO4)	76,1	4,0	250
Total Nitrogen	3,21	0,32	

ICP

Table 9 show the results from ICP.

Table 9: Results for metals from ICP, done at NMBU water lab. Full scheme can be seen in appendix 5.

Limits per l	25mg	50µg	0,4mg	0,2mg	2,0mg	10µg	3µg	20µg
Sample nr.	Ca	Cr	Mn	Fe	Cu	As	Cd	Sb
1	3,5	13	0,0080	0,12	7,8	<0,019	0,015	<0,0051
2	3,7	2,7	0,0062	0,19	0,23	<0,019	<0,0078	<0,0051
3	4,1	14	0,035	0,41	2,9	0,035	0,014	0,0062
4	6,0	17	0,18	3,3	2,6	0,29	<0,0078	0,015

Bacteriological analysis

The analysis sent to the University of Makerere for bacteriological analysis came back blank, for both samples, from the well and spring. There was no registered bacteriological growth when the water samples were tried cultivated.

Discussion

Background Monitoring

The background measurements in Figure 9 shows a trend where the groundwater level is slowly declining from the level established in the evening of the first day of monitoring. The level then sinks about 3,5 cm during the next two days. It seems the level is beginning to stabilize the last day before the monitoring was stopped to get ready to pumping test 3. During the monitoring we observed some dips in the water level of up to 4 cm. This happens in the early day until 16:00. This corresponds to the use of the manual pump during school and working hours at the construction site by the main hall. The level then rises again in the evening and is steady declining through the night. The continuous lowering of the water level over the monitoring period, may be caused by less rain in the period leading up to the monitoring period compared to the weeks before where the precipitation was heavy.

Pumping Tests

The manual pump was locked down before the pumping tests. This was done to eliminate the variation of discharge. Because the manual pump was locked the locals were asked to use the water coming from the pumping test, but this caused the hosing to be used extensively which led to multiple pump failures.

Pumping Test 1

In pumping test 1, seen in Figure 10, there are some drawdown variations in the start. This is due to issues with the pumps where one pump broke down after 17 min (1000 sec). The pumping rate after changing pumps was 1350 l/h. The pumping rate became more stable, and the test ran for 3 hours before another pump broke down and the pumping test was halted. The total drawdown of the test was 3 cm where it seems to be stabilized after 2,5 hours. This stabilization could come from one of the pumps started to have issues, ending in the pump breaking down 30 min later.

The pumping test setup were changed between pumping test 1 and 2 to optimize pumping rate from 1350 l/h to 1450 l/h.

Pumping Test 2

Pumping test 2, seen in Figure 11, shows the same drawdown curve as pumping test 1, but having a lower resolution. This change in resolution was done in hope of obtaining a longer pumping test and making sure to having space for saving all data. One of the pumps lost its pumping rate after 3 hours, like in pumping test 1. This made the discharge lower than the inflow and the water level began to rise again. The pumping rate measured after the pump broke down was unstable, but between 800 and 1200 l/h. Total drawdown after 3 hours was 5 cm.

The breakdown of the pumps in pumping test 1 and 2 was often connected to people using the discharge hose for filling water. There were also some instances children were playing with the hose. To prevent local's interference the manual pump was unlocked for pumping test 3 and 4. We still experienced some interference from the locals, as they had been used to use the test pump's water supply.

Pumping Test 3

Logging of pumping test 3, seen in Figure 12, started about 20 min (1500 sec) before the pumping started. The pumping test lasted for 30 min (until 4000 sec) before one of the pumps broke down. The pumping test was then halted for one hour, to let the water level in the well come to rest before starting the test again (8000 sec). This made the start of the drawdown of pumping test highly variable and should not be used for analysis. The discharge of the test was, from the restart and onwards, stable. After 5-7 hours from logging start (18000 sec to 25000 sec) we can see a small jump in the water level of 2 cm. This sudden shift in water level was probably caused by manual water level readings hitting and changing the elevation of the diver or baro. The baro and diver were connected through the same opening in the well casing as the manual readings were done. Manual reading was done at both these time steps, both when the shift started and returned, indicating this was the cause of the change. The water level also had the same trends fitting between the levels before and after the shift indicating a small escarpment. From about 5 hours (20000 sec) into the logging, we can see a small incline of the water table, going from -4,5 to -2 cm. This increase in water table is probably connected to less frequent use of the manual pump after the work and the construction site and school ended in the afternoon. This small change in discharge because of the pumping may have drawn the water table just enough down for the pups to not have effect to hold the table there alone over time. The changes in water level would for this reason go slowly up because of the high storage volume in the well.

Pumping Test 4

Pumping test 4, shown in Figure 13, started with some issues with the pumps, but stabilized after pumping for 2 hours. For this reason, the first 2 hours of pumping test 4 could not be used for analysis. The pumping rate was then stable through the pumping test. The drawdown of pumping test 4 have small oscillations in the first 5 hours and with smaller changes the next 5 hours until it became stable until the next morning. These fluctuations were probably caused by manual pumping, with most pumping in the early day until 16:00 when school was over. The same fluctuations appeared after 27 hours (10^5 sec) when the school starts next day. The pumping test lasted for 2 full days until the pumps broke down in the evening of the second day. After 30 hours (about 110000 sec) we could see the water level rapidly rising. This was caused by loss of power. But it was fixed within a short period of time (less than one hour). The same happened at the end of the pumping test after 170000 sec, were the power cut out for a few hours. Pumping test 4 showed increasing water level of about 2 cm during the test period. The manually cross-check showed a decline in the water level. This difference may be caused by an increase in the background water level which was higher than the lowering rate. This may have been possible because the pumping rate was close to the yield of the well. This means a small increase of inflow could overcome the pumping capacity. Another possible explanation may be a drift in the measurements in the diver. To adjust the measurements in pumping test 4 to manual measurements the graph in Figure 14 is rotated to fit the manual readings of the water level. This way of adjusting the measurements causes the water level values to be placed earlier in the timeframe, but the main trend can be extracted. For this reason, the pumping test 4.2 values are extracted from the tilted pumping test in Figure 13 for every 5000 sec. This new dataset holds the same trends as the raw data of pumping test 4, and are adjusted for manual readings. Pumping test 4.2 is for this reason used instead of pumping test 4 for analysis because of positive drawdown does not make any readable values for T and S.

The pumping tests have a drawdown of 3-6 cm. Comparing this to the background fluctuations of 2 cm over a period of two days there is a chance some of the fluctuation is influencing the results, but probably less than 2 cm. Due to the issues of pumps breaking down the pumping test 1 and 2 are best for analyzing early parts of the drawdown while pumping tests 3 and 4.2 are better for late time drawdown analysis. The small changes in drawdown also indicates that the pumping rates in the tests are equal or slightly less than the actual discharge capacity of the well. This must be taken into consideration when analyzing.

Theis Method

Theis curve fitting method was used for early parts of the drawdown curve for pumping test 1 and 2 and for late time for pumping test 3 and 4. The curve fitting of pumping test 1 and 2 gave high correlation between drawdowns and the Theis fitting curve. Curve fitting of pumping test 4 gave no correlation following the Theis fitting curve. This was expected due to the negative drawdown. Instead pumping test 4.2 was following the curve to a high degree for late time of the pumping test. The values for S were above 1 for all pumping tests. This gives no value because S have to be $0<1$. This is expected when taking into consideration that the method is made for wells where the storage in the well is neglectable, which is not the case in the well of Nyenga foundation. The values for T given by Theis curve fitting method had some variation with values ranging from 0.0012 m/s and 0.0014 m/s for the fitting of early drawdown in pumping test 1 and 2, and 0.0021 m/s for late time drawdown in pumping test 3. Values for T in pumping test 4 was 0.0026 m/s, but this should not be taken into consideration due to the small correlation between drawdown and fitting curve. Pumping test 4.2 gave a T value of 0.00096 m/s which is closer to the values of the early drawdowns in pumping test 1 and 2 than late time in pumping test 3.

Jacobs Method

Values expected from Jacobs method is the same as for Theis due to Jacobs method is a continuation of Theis equation. Jacobs method gives a linear function. Drawdowns in pumping test 1 and 2 are linear to a high degree. The lines used in estimates with Jacobs are manually plotted and may include some uncertainty. The T values from pumping test 1 and 2 show 0.0021 m/s and 0.0013 m/s which is a small difference and within expected difference when taking into consideration the uncertainty of manual curve fitting. The variation is bigger than in Theis, but not with a big difference. For pumping test 3 we got two lines, where one followed the initial drawdown while the second followed the drawdown in the shifted part of the graph. The T values from the two lines gave 0.0018 m/s and 0.0019 m/s which indicates that the second curve was as discussed earlier just an offset. Pumping test 4.2 gave a T value of 0.0012 m/s for late time of the pumping test. Comparing to Theis this is close and within expected difference.

Boulton-Streltsova Method (BS)

BS is composed of two curve fittings, one for early part of drawdown and one for late time drawdown. Because of the pumping test duration and issues with pumping continuity early time curve fittings should be based on pumping test 1 and 2, while late time should be based on pumping test 3 and 4.2. Due to small differences between different curves, the manual overlay may cause some uncertainty. Due to this and the positive drawdown in pumping test 4, only 4.2 should be used for continued discussion. The T values in the three first pumping tests are ranging from 6.63e-5 m/s to 1.56e-5 m/s, while pumping test 4.2 got the value of 5.10e-6 m/s which is 1 order of magnitude smaller.

Because BS is made for large radius wells, we also got a value for S when combining the k values calculated for both early and late time drawdown. This gives S values of 2.51 to 2.65 for pumping test 1-3 and 0.01 for pumping test 4.2.

All the methods used to analyze the results from the pumping tests have some criteria which is not fulfilled by the pumping test setup or well construction. This causes the results to have some higher uncertainty and are subject of subjective judgement out from the border conditions and observations done in field. As mentioned earlier the drawdowns of the different pumping tests are more representative for certain time steps of the pumping duration due to pumping test resolution and different variation in drawdowns caused by issues with the pumps. Pumping test 1 and 2 are more representative for early drawdown while pumping test 3 and 4.2 are more representative for late time drawdown. When comparing the results between different analytical methods the results show a higher value of K for the methods constructed for small radius wells while the BS method show a K more than 2 magnitudes smaller. The variations between pumping tests are small which indicate that the condition of groundwater supply was stable over the period when the pumping tests were done.

Hydraulic Head (h)

To be able to calculate the ground water velocity we need to know the gradient of the water table. As input to this, the likely flow path is first found by following the topography. This line is then divided into 100 parts were each value is assigned a height value. This is then set into eq 1 to find the ratio of N/K by adjusting until the head values are right in the wells at Nyenga foundation and elevation of the Chairman's well.

The ratio giving the best fit between head values and levels measured in the wells were N/K=0.015. Assuming an infiltration of 400-800 mm/year gives a k of 8e-7 m/s to 1.5e-6 m/s. Assuming this ratio between N/K is right and inserting k=2e-5 m/s from the results of the pumping tests gives a infiltration of 7100 mm/year which is more than total precipitation.

Since the results from the head value calculations do not take the topography into consideration, the head value is probably only correct for a short area around the two adjustment points (the two wells). As seen in Figure 22, the head value is over the ground level without having any water above the surface in reality. The groundwater is also in the model becoming very deep when moving more than 1000 m from the Nyenga foundation well. This is at a point where the topographic gradient increases.

Hydrologic Conductivity (K)

The analytical methods show a K of 10-e3 m/s for Theis and Jacobs while BS give a K of 10-e5 m/s. The geological conditions in the area gives high variations of properties. This makes both values possible were K 10e-3 m/s normally indicates very coarse sand or grave, while 10e-5m/s normally is values found in well sorted sand. Both are found possible values since the aquifer is manly fracture based and is less based on matrix-based flow. When taking the analytical methods into consideration the values from BS are probably more likely because Theis method have more extensive conditions changes. A value of 10e-3 m/s also seems extreme. This is also substantiated by theoretical k values of 10e-6 m/s when calculating the head values using water levels in the two wells and Nyenga foundation and the Chairman.

Storativity (S)

BS method was the only analytical method which gave a value for S within $0<S<1$. The Theis and Jacobs methods had neglected well storativity as a condition. This was not the case at Nyenga foundation. The BS method gave values of S between 0.01 and 0.04. This value is small, but extends the expectation of fractured aquifers, since the only option for water storativity is in the cracks were the water is flowing and no storage is in the aquifer matrix. Since the aquifer is fracture based, the storativity is less impactful when looking at the short time well yield. The fast water transport will cause the well to drain from a bigger area. This also means the total storativity in the ground is less in total, but out from water usage at Nyenga foundation and surrounding community use, it is a very small chance of groundwater levels are being inflicted to a degree where it effects the ground water level.

Water Quality

Physical properties

the water had normal values for alkalinity, turbidity and conductivity. The pH was a bit lower than neutral, but within the recommended pH values of drinking water of 4.5-8.5 (Folkehelseinstituttet, 2018).

Nutrients: P and N

The readings of P and N in the water samples were extremely low with samples around the detection limit of the analytical methods. Sample 4 had some higher values than 12 and 3, which was expected, due to the higher water velocity and thus particles and the fact this was surface runoff, and not direct groundwater.

IC: Ion Chromatography

Most issues regarding water ion content is related to corrosion of pipes and water taste. For this reason, some recommended values for most ions are set. This does not mean values over or below leads to health risks. Most problems connected to water comes from usage disadvantages as miss coloring and felling. Results showed in Table 8 is from IC of water sample 2. The results show fine values for ions connected to felling like calcium, magnesium, sodium, and potassium. Substances connected to water taste also looks fine with values within recommendations for chlorine, sulfate, and nitrates. There is no set recommendation for carbon, total nitrogen and hardness. Hardness is often connected to Mg values which is lower than recommended value. High values of carbon do not directly correspond with health risk but can give some water taste. It can also give better conditions for algae and bacteriological growth under high light conditions and in water with low circulation.

Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

All measured metals are below the recommended value except for Cu and Cr in sample 1,3 and 4. These samples are probably polluted by dissolved metals from the sample bottles when it was conserved. The sample without added HNO3 does not have high values. For that reason, the Cu and Cd content should be taken from sample 2 which is 1/9 of recommended for Cu and 1/20 for Cd. For Fe and Mn, the content is high, but this is expected for the high Fe content in the soil of the region. The amount of Fe and Mn in the samples is not dangerous but can lead to some discoloring when used. This is also the case for Ca. The values measured for Ca is a bit lower than expected and well beneath values for problematic for use (10-25 mg/l) (Folkehelseinstituttet, 2018). For the heavy metals As and Sb values were by the detection limit and within recommended value.

The water sampling and analysis form this study estimates that the water quality at Nyenga foundation is good. The bacteriological count is low and metal analysis show a low concentration for most metals except for Fe and Mn, which is expected out from geological conditions. For the nutrients there are extremely low values for both P and N. There is some carbon, but still low values. Out from the nutrient levels there is a low chance of algae growth in both the well and the sampled spring. The levels measured in the wetland is higher than the water sampled in the spring and well which is expected due to higher water speeds in the drainage ditches with increases erosion and particle transport. The levels measured for P and N is low compared to industrial farmland and contaminated waters and is not in need of measures for lowering the nutrient levels.

Yield Estimation

Out from the rain conditions leading to the pumping tests we can assume the result from the analysis show the maximal yield of the well. The big variations in values for K and S resulting from the analysis makes it hard to come to an exact yield. The small drawdown also makes it hard to get an exact reference point of stable water level versus pumping rate. To make an estimate we used the equations for Jacobs and Theis. First, we adjusted K and S to fit the drawdown s to the Q used in the pumping test. Then we increased the time of pumping to the extent where the water level gets stable before beginning change Q until we get a drawdown of 2.5 m, which is the depth until the well is dry.

The S used in calculations is 0.04 out from the pumping test analysis. Because of the small drawdown, the value for k have to be 0.01 m/s for both Theis and Jacobs when solving for s. Out from these results the Q is far above what is possible to get the drawdown fit what was measured. Instead of using this approach with fitting the values to the drawdown observed, the value of k was set to 0.002 m/s which is between the value found with analysis and the value used to fit the s to observed drawdown. By using this value of K, we are getting a Q of 1350 l/h-1500 l/h depending on small shifts in K.

Risk Assessment

The biggest risk for the water supply from the well at Nyenga foundation is from local pollution caused by heavy local activity around the well. This is regarded as a risk because the well is shallow. The drainage area of the well have little anthropogenic activity, but there is some activity in the areas closest to the well. This is also the area with the highest risk factor due to smaller residence time before the water is entering the well. From anthropogenic activities, the highest contaminant risk is probably agriculture in form of fertilizer nutrient, pesticides, and livestock manure. However, the fertilizer usage in the area is low. The most used fertilizer nutrient is phosphorus which is easily bound to soil particles which means nutrient pollution must come from a source very close by. The biggest concern of transported pollution at moderately distance comes if the usage of pesticides increases. The high transitivity and low storativity makes the risk area larger due to the well having a larger drainage area, if the well is in heavily used over a longer period. The risk of the well running dry is low, due to the high recharge rate and large storage volume in the well and lack of continuous pumping, giving the well time to recharge in the night.

The risk of microbial pollution of the well is mainly from close infiltration (Figure 23). The growth conditions in the well is low with small amounts of nutrients and no access to light because the well is closed. These conditions make the main contaminant risk coming directly from infiltration of bacteria or chemicals.

Figure 23: A cow was chained to the well to grace close to the well. This is highly problematic with regards to contamination risk due to the shallowness of the well.

The risk area of the well in this thesis is based on 60 days residence time. Calculations using the T values from the analysis of the pumping tests gives a risk distance of 0.4 m and 1.5 m for min and most likely values for K. For highest value for k, the risk distance is 208 m (Table 5). All these values have some uncertainty because of the assumptions in the pumping test and subjective selection of most likely values. All these uncertainties make the decision of increasing the risk area of the most likely risk area to 10 m to have a bigger buffer for contamination. (Figure 24)

Figure 24: Risk map. Nyenga foundation well is placed at blue square while blue line is flow path from Figure 21. The red area shows the area regarded as high contaminant risk (10m). The yellow area shows a theoretical area of contamination out from the uncertainty of T and S (208m). The risk area is a subjective area out from the topographic characteristics in the area and may be larger due to geological features.

Recommended Measures

Based on the contamination risk, we recommending to avoid transporting and holding livestock in the area around the spring and well at Nyenga foundation, shown in the risk areas shown in Figure 24. This is especially important in the areas closest to the well and spring. We are assuming the same risk distances for the spring and well because of the proximity. In the risk areas livestock should not be held over longer periods of time. This increases the risk of bacterial contamination dramatically.

Furthermore, heavy use of pesticides in the flow path of the groundwater should also be avoided. Pesticides do not have the same degradation rate for hygienization as bacteria. This means knowing what pesticides are used in the drainage area and the pesticide degradation rate is important to take into consideration when thinking about the potential pollution risk.

Conclusion

The results from the analytical solutions used in the thesis show some differences in estimated transmissivity and storativity. When compared to calculated head values, the best subjective guess is based on results and observations of a T of 10e-5 m/s and S of 0.04. These results have some uncertainty because of adjustments of theoretical assumptions to fit the available data. The calculated well yield under the conditions of the pumping tests are 1350-1500 l/h. This is probably the max yield of the well. We estimated two risk areas from the estimated values for T and S. This is because of the uncertainty of T and S. The estimations gave a high risk distance of 10 m around the well. The water in the well hold good chemical quality with no high values of the measured metals and no registered bacterial growth from water samples. The same results were shown in the spring closest to the well of Nyenga foundation. The contaminant risk of the well seems small, but the biggest concern is point sources of bacterial of chemicals, as feces of livestock. We recommend therefore to limit livestock activity in the risk areas close to the well.

Further Work

The main of the uncertainty for the well yield calculations is based on the low response in drawdown. This means a pumping test with a pump with higher capacity is probably the best way to get a more exact value. A geological survey with georadar is also possible to get a better understanding of aquifer stratification. This is especially interesting for how the water flow in the cracks. A simulation of groundwater flow is also possible by using the data from the pumping test and the yield from the springs.

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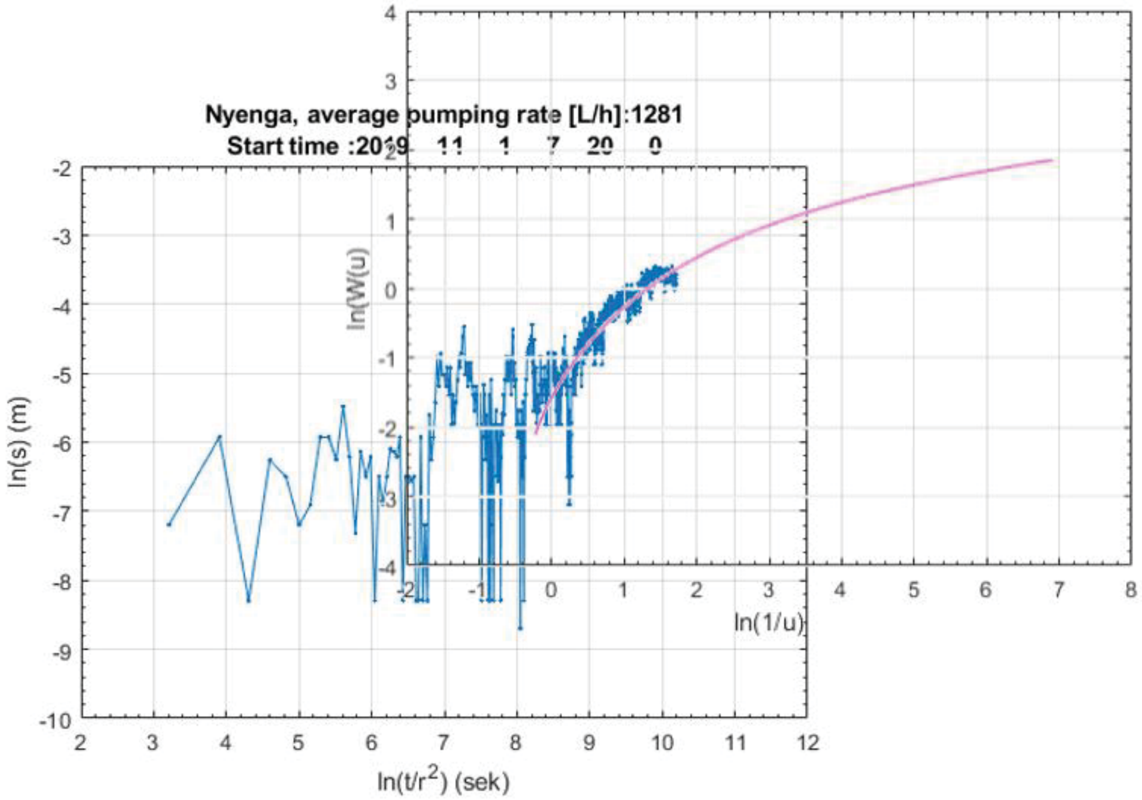
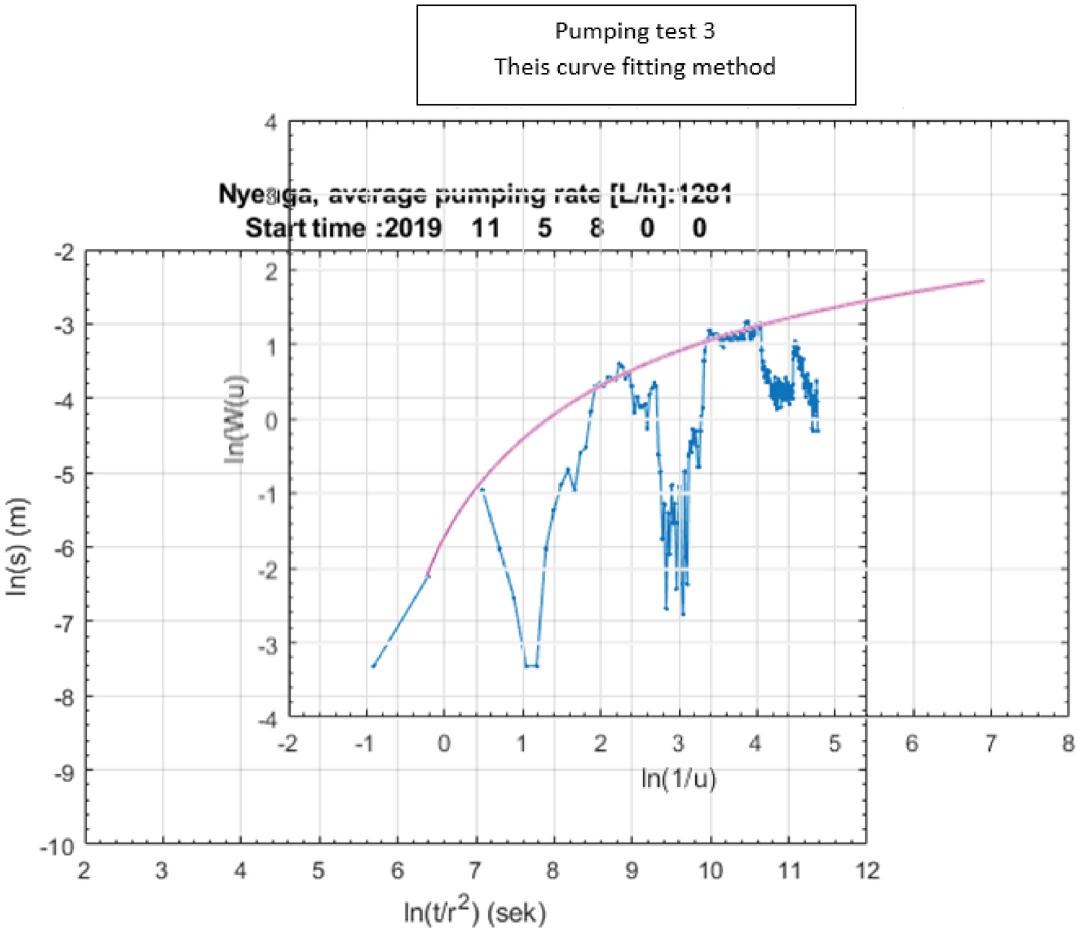
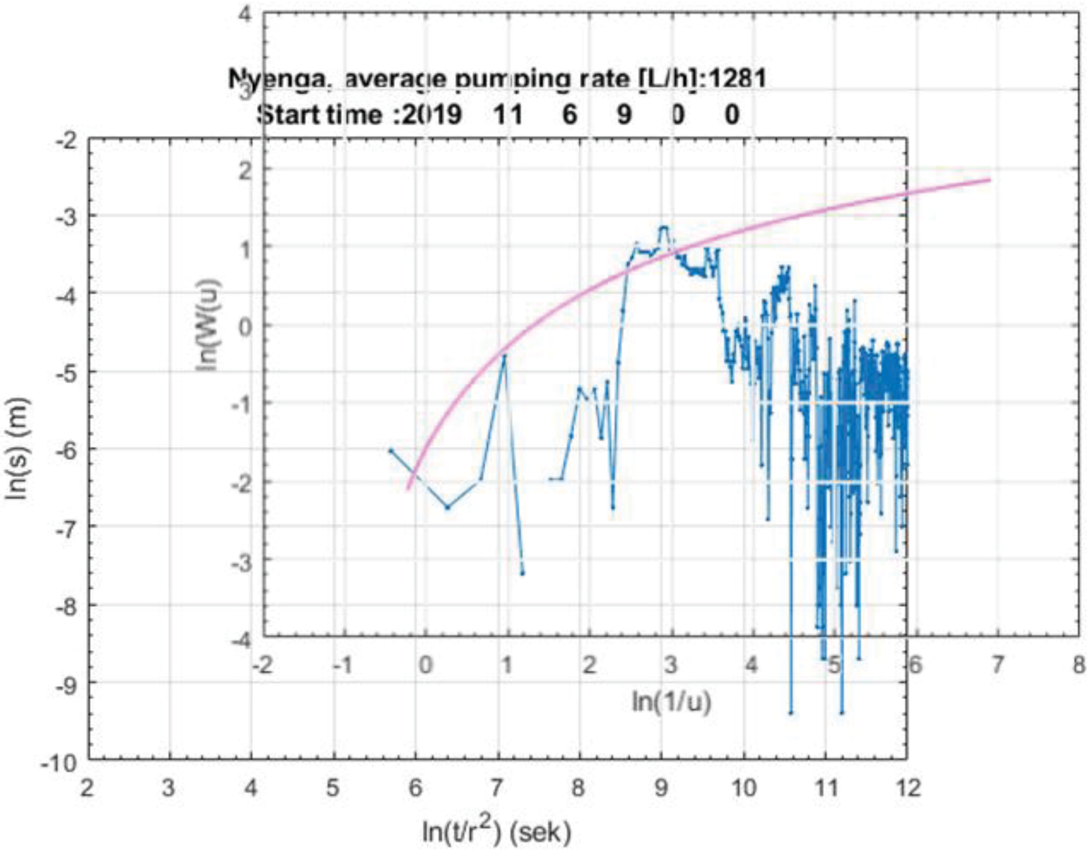
Appendix 1: Theis curve fitting method

Pumping test 1
Theis curve fitting method

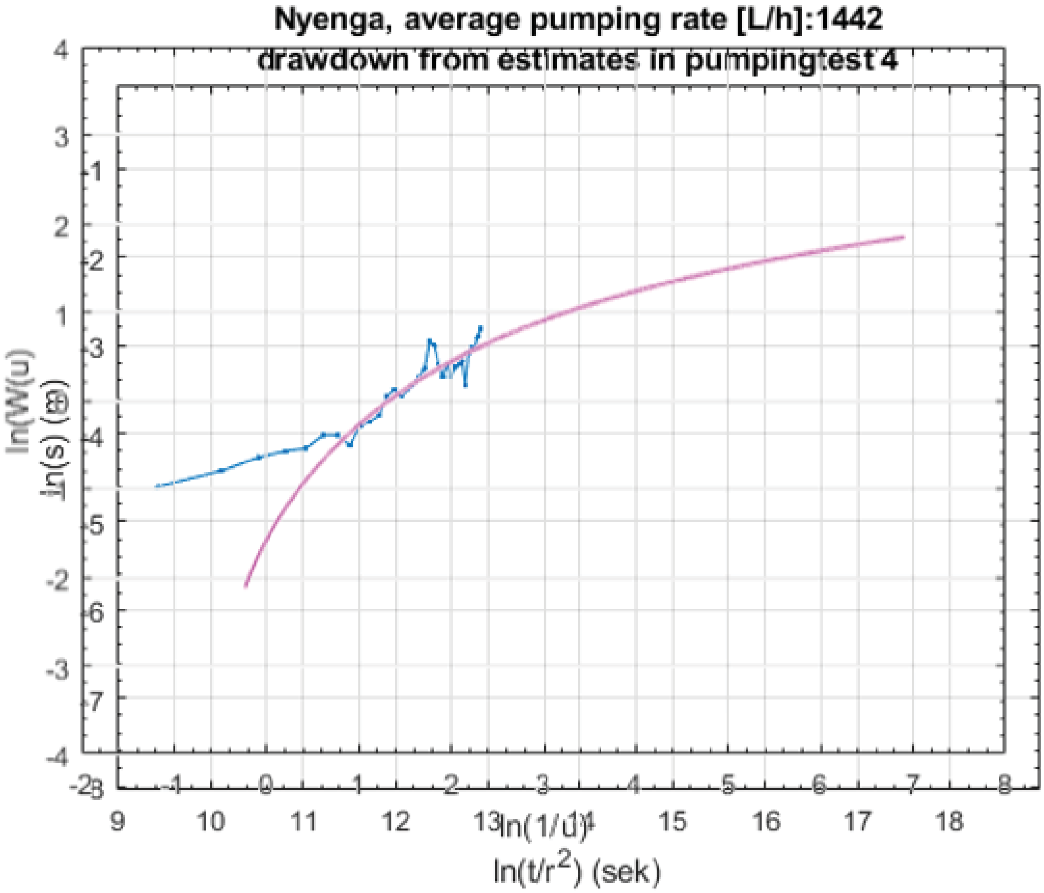



Pumping test 3
Theis curve fitting method
Nyenga, average pumping rate [L/h]:1281
Start time :2019 11 5 8 0 0
ln(W(u))
ln(1/u)
ln(s) (m)
ln(t/r2) (sek)

Pumping test 4
Theis curve fitting method

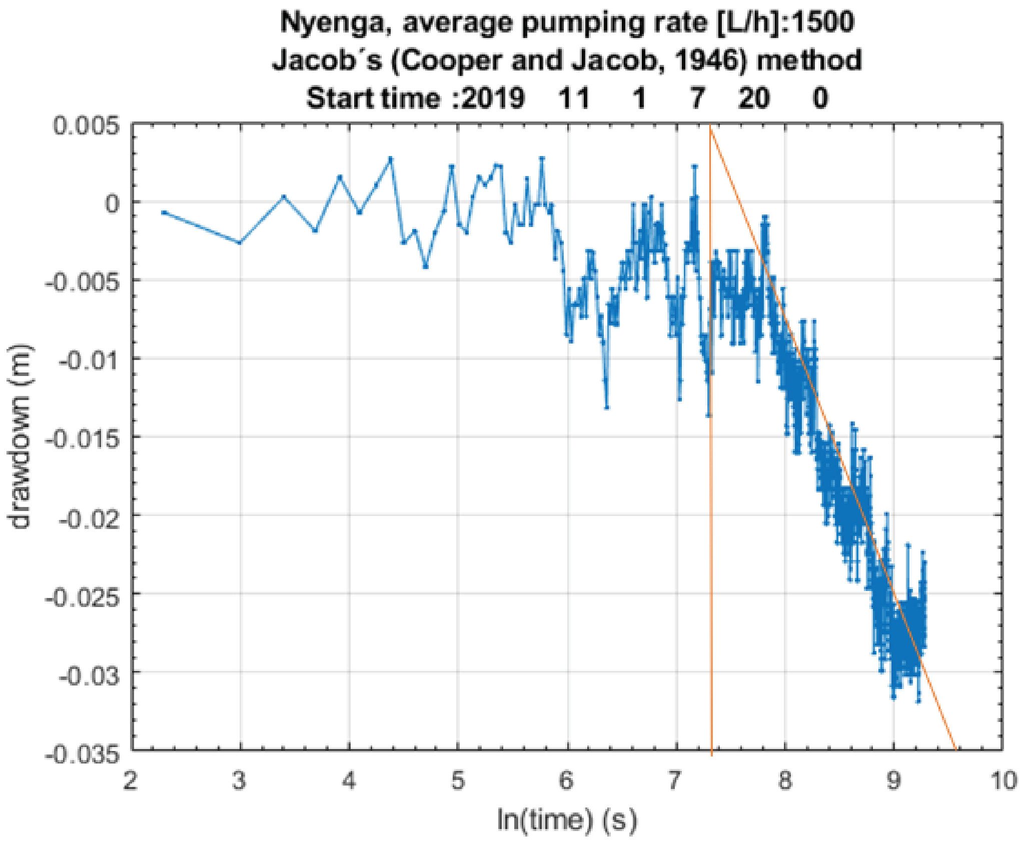


Pumping test 4.2
Theis curve fitting method

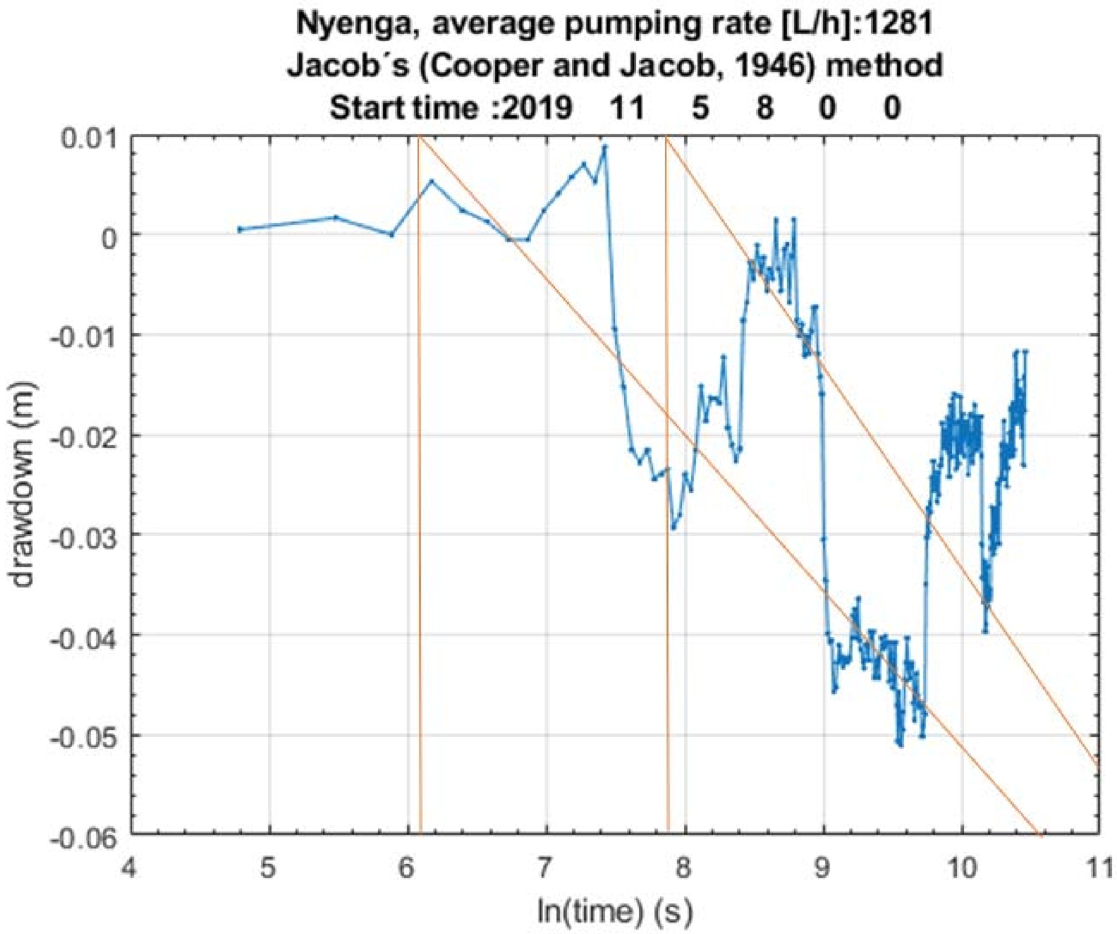


Appendix 2: Jacobs method

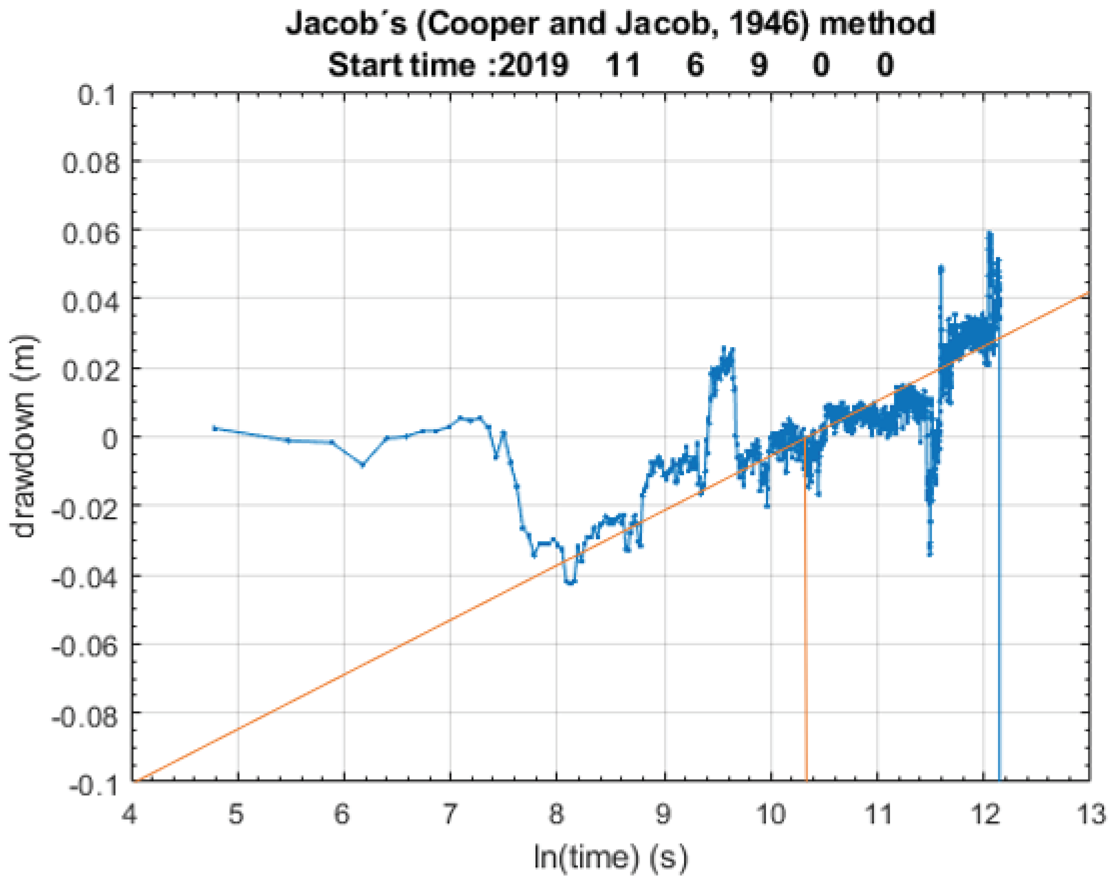
Pumping test 1
Jacobs method



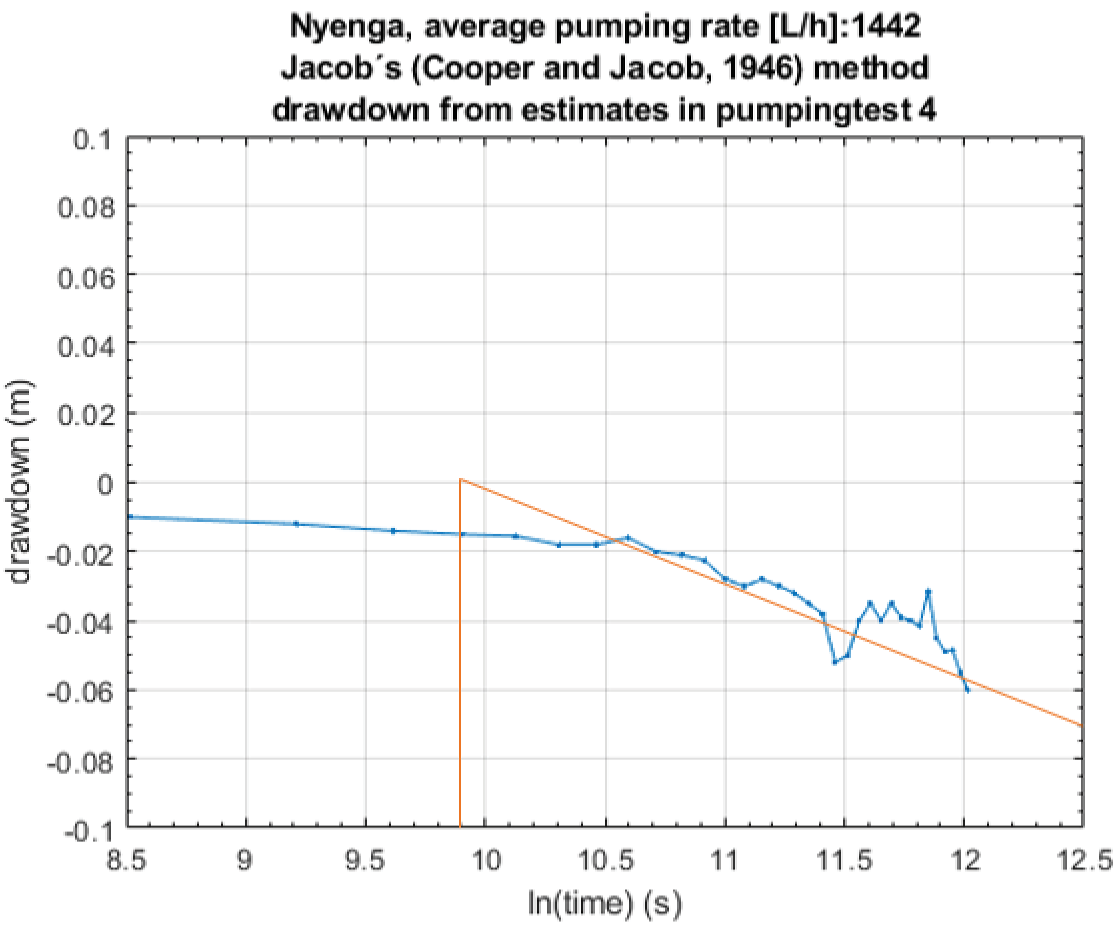
Pumping test 3
Jacobs method



Pumping test 4
Jacobs method



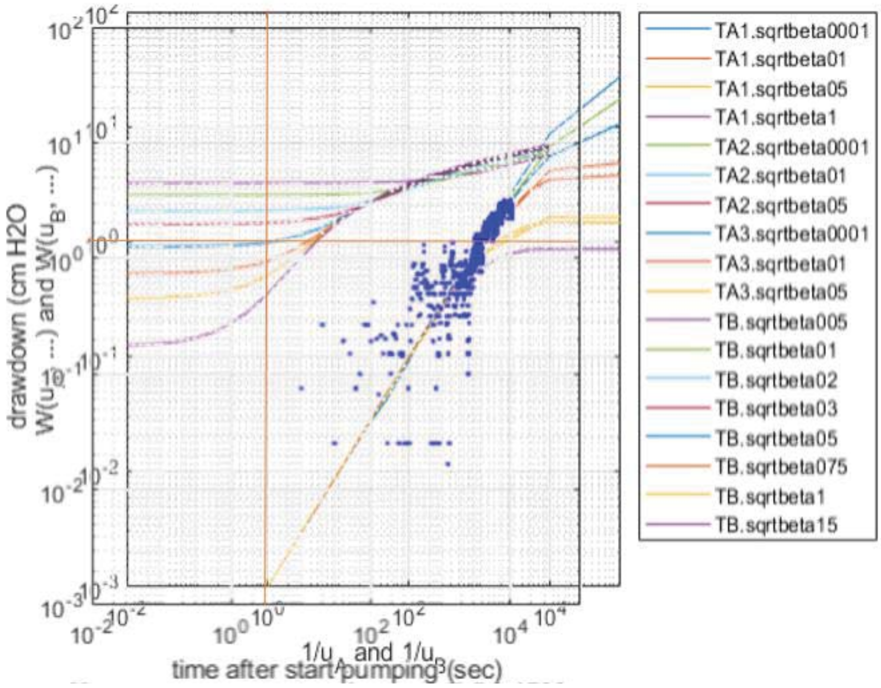
Pumping test 4.2
Jacobs method

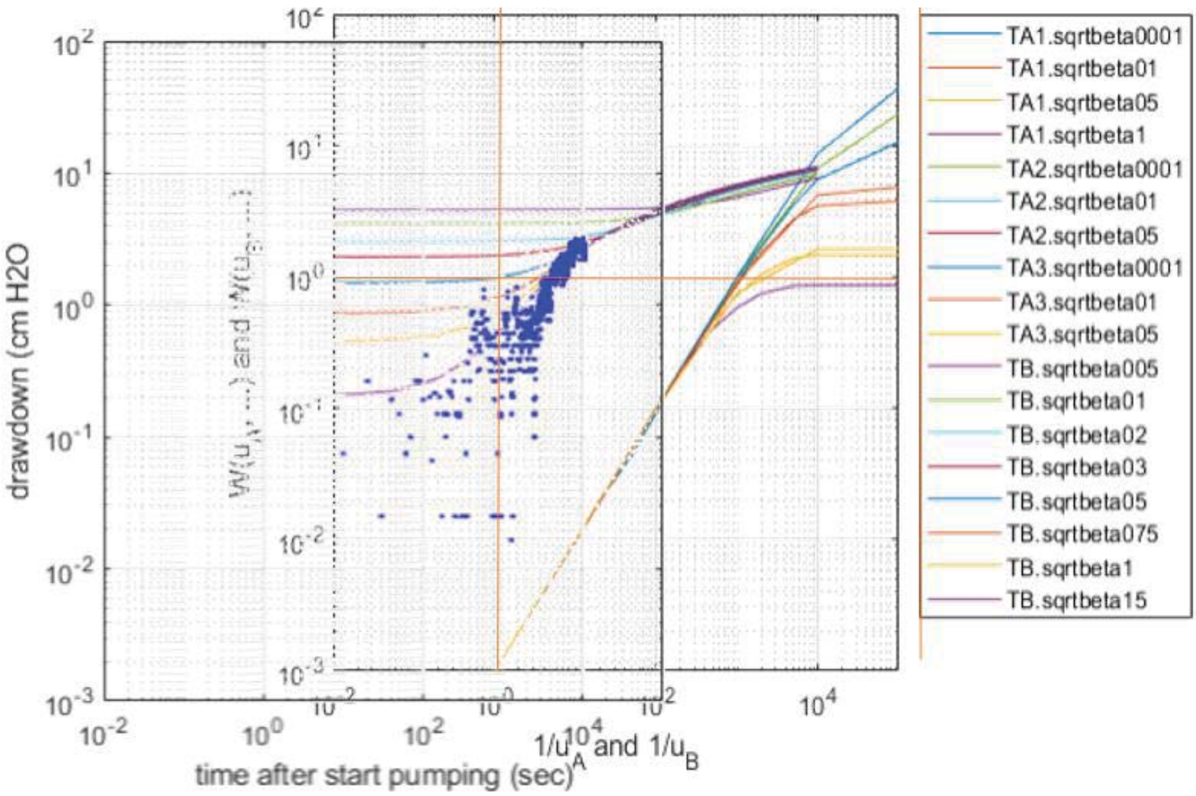


Appendix 3: Boulton-Streltsova curve fitting method

Boulton-Streltsova curve fitting method

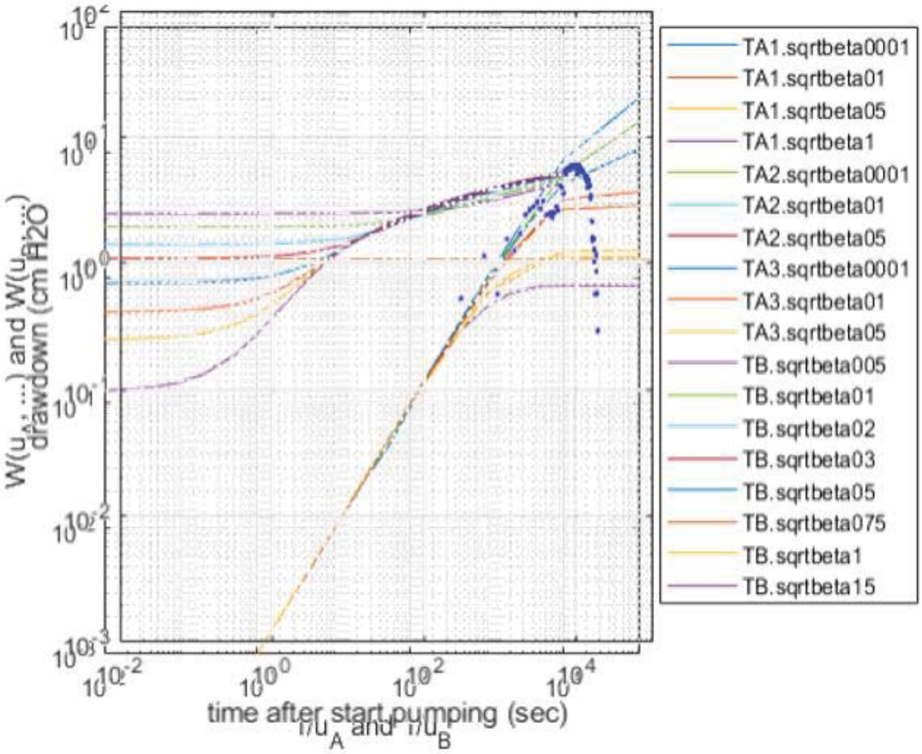
Pumping test 1

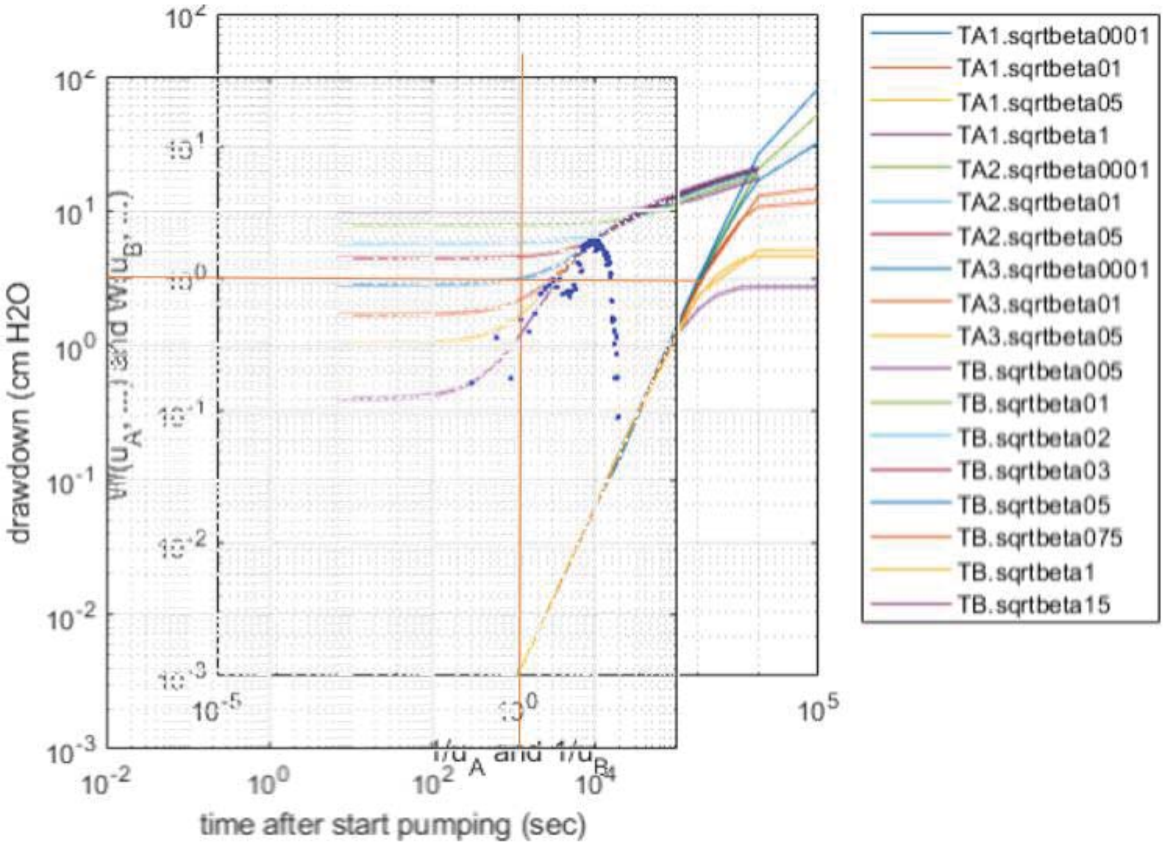




Boulton-Streltsova curve fitting method

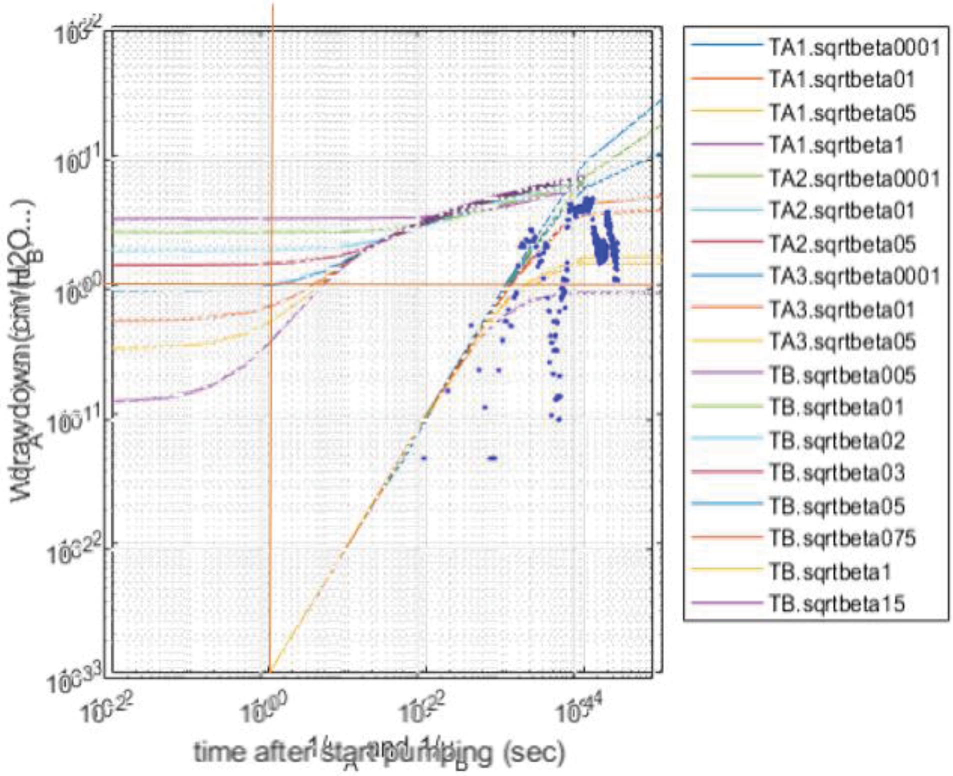
Pumping test 2

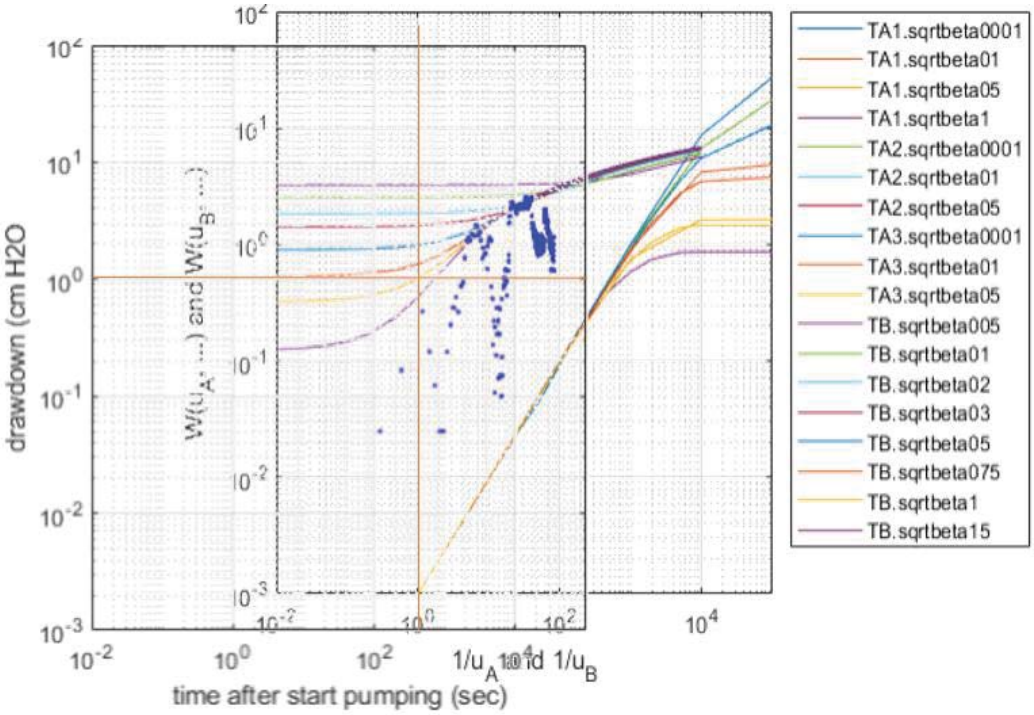




Boulton-Streltsova curve fitting method

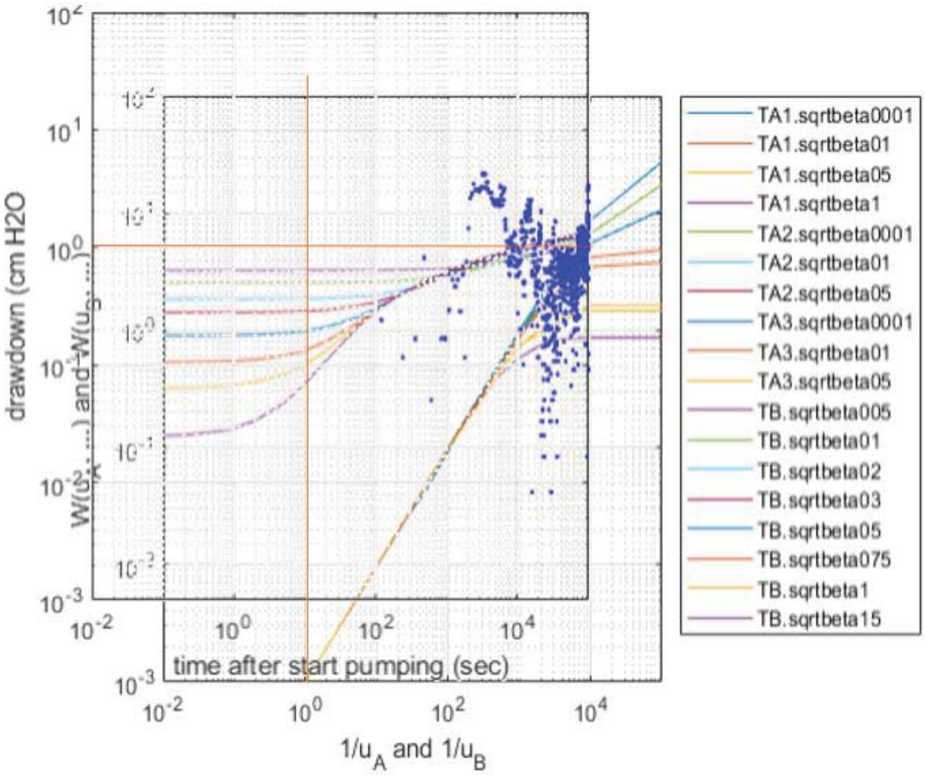
Pumping test 3

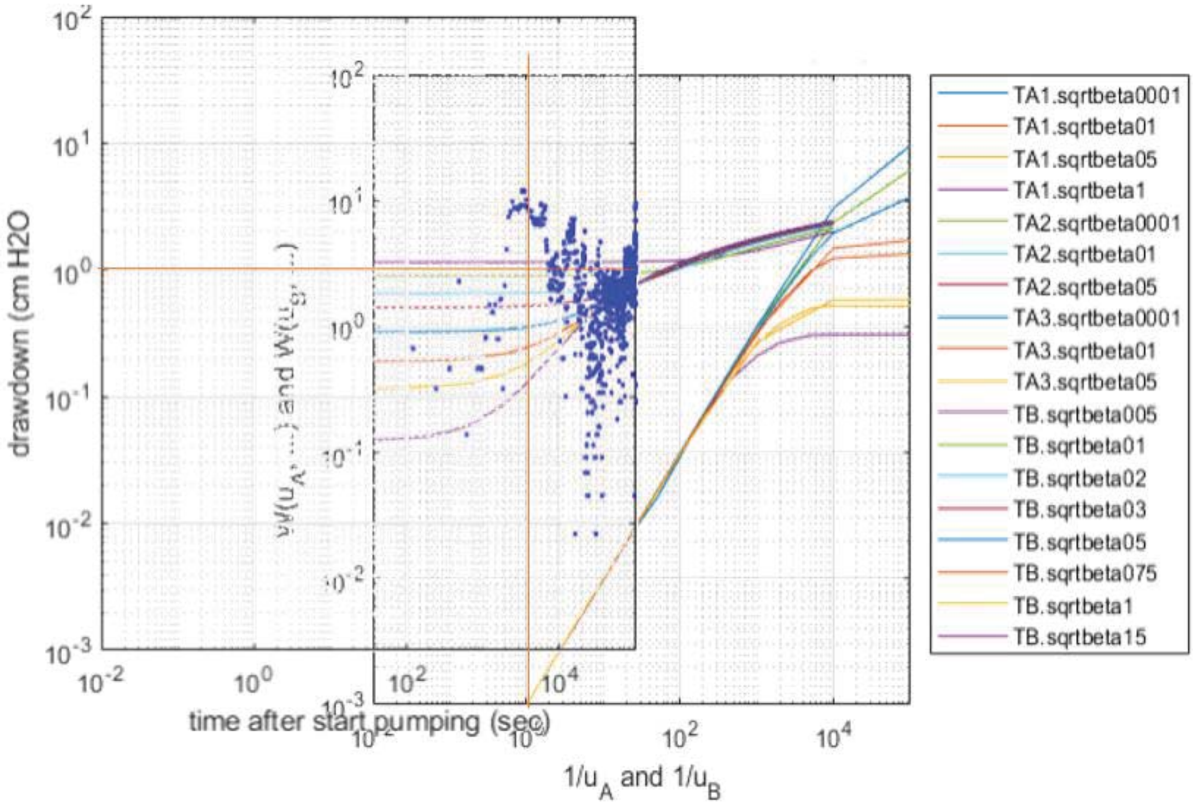




Boulton-Streltsova curve fitting method

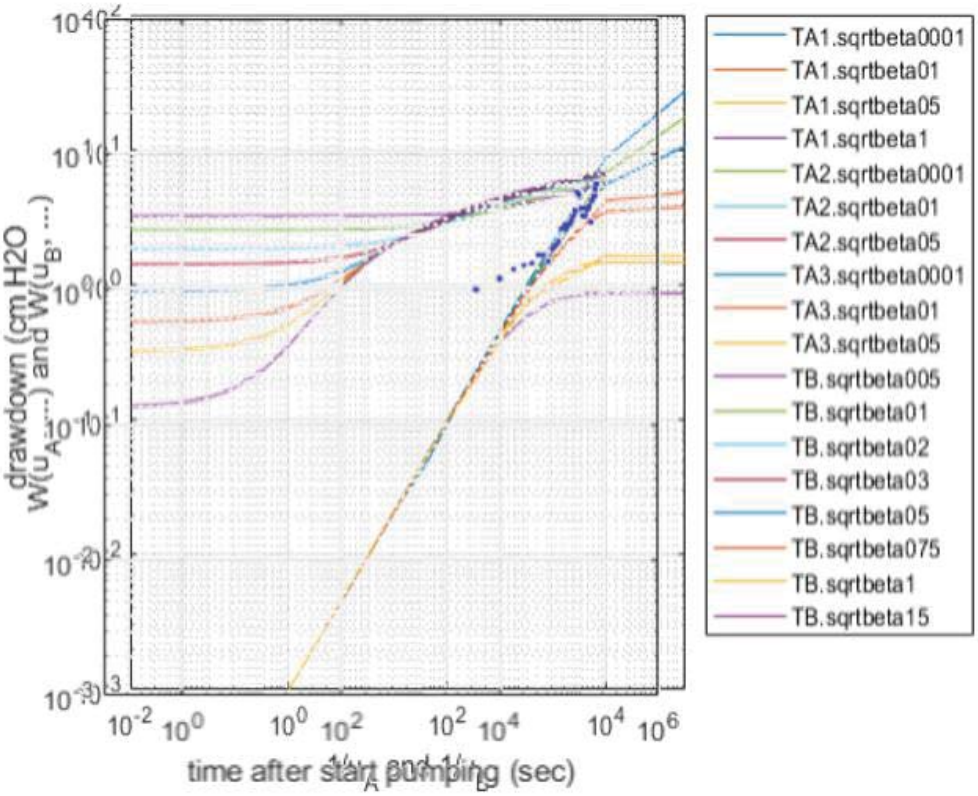
Pumping test 4

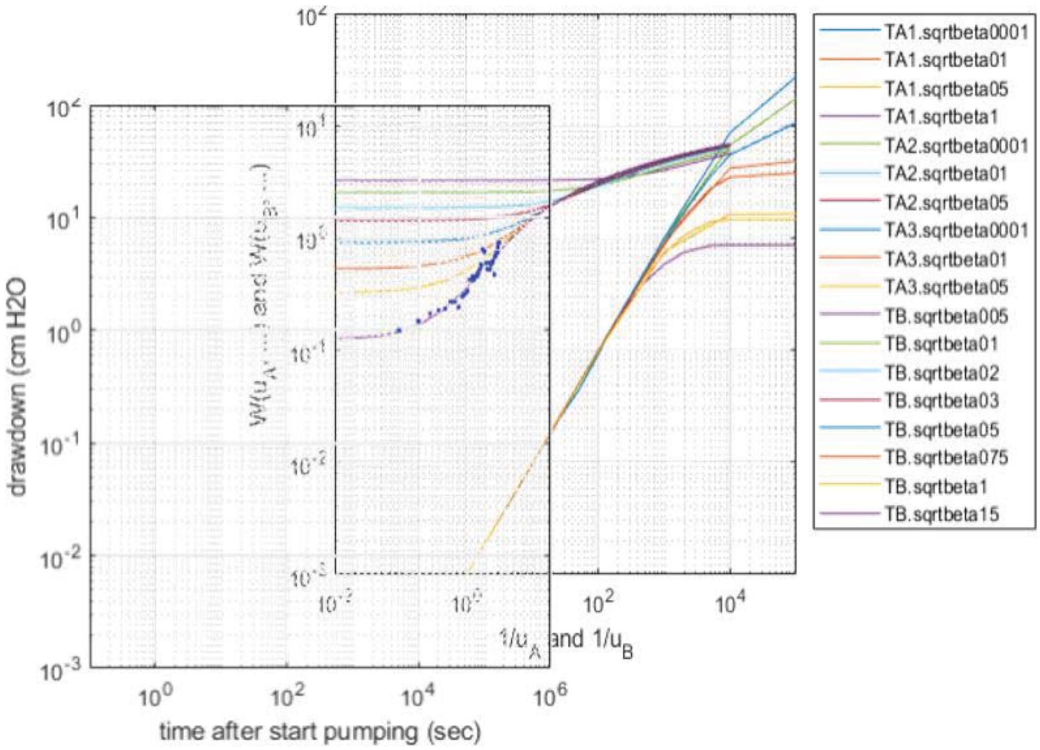




Boulton-Streltsova curve fitting method

Pumping test 4.2





Appendix 4: Photometer measurements

Photometer measurements for dissolved phosphorus

Sample nr.	Average of 3 reads	SD
Blank 1	0.00023	0.00011
Blank 2	-0.00029	0.00004
Blank 3	-0.00092	0.00003
Blank 3	-0.00091	0.00015
Sample nr.2	0.00066	0.00006
Std	0.26076	0.00006
Std	0.26381	0.00003
Std	0.26531	0.00002

Photometer measurements for total phosphorus

Sample nr.	Average of 3 reads	SD
Blank 2	-0.00077	0.00006
Blank 3	-0.00041	0.00011
Std	0.22363	0.00013
Std	0.22012	0.00006
Std	0.21936	0.00028
QC	0.53706	0.00025
Sample 1	-0.00063	0.00003
Sample 2	0.00390	0.00011
Sample 3	0.00177	0.00004
Sample 4	0.00702	0.00009
Blank 2	0.00038	0.00002
Blank 3	0.00117	0.00009

Photometer measurements of $NH4^+$

Sample nr.	Average of 3 reads	SD
Blank 1	0.02841	0.00005
Blank 2	0.02899	0.00006
Blank 3	0.02991	0.0002
Sample 2	0.03316	0.00005
Std	0.18775	0.00011
Std	0.18799	0.00002
Std	0.18686	0.00008

Appendix 5: ICP results

Ank 5/8 19

ENVIRONMENTAL MATRIX REFERENCE MATERIAL

ION-96.4 lot 0618

Product Information Sheet

A River Water Sample

Issue Date: 26-JUN-19

Environment and Climate Change Canada matrix reference materials (RMs) are collected in bulk from various locations across North America. ION-96.4 was collected from the mouth of the Grand River in Southern Ontario during 2009. The bulk sample was centrifuged to remove particulates and filtered through a 0.2 µm sterilizing filter to remove bacteria. This bulk Major Ions and Nutrients in water RM is stored in a dark cold room and is unpreserved.

This Reference Material is intended for the verification or development of analytical methods for environmental analysis. It is not intended for use as a calibration standard.

MEASURAND	VALUE IN MG/L		µ	N
ALKALINITY, TOTAL (AS $CACO_3$)	245	±	12	116
BORON	0.0430	±	0.0058	50
CALCIUM	95.4	±	7.3	129
CHLORIDE	74.0	±	3.8	128
COLOUR (HAZEN UNITS)	14.0	±	3.7	79
CONDUCTIVITY (µS/CM, 25°C)	829	±	30	145
DISSOLVED INORGANIC CARBON (DIC)	57.1	±	6.3	59
DISSOLVED ORGANIC CARBON (DOC)	4.64	±	0.70	94
FLUORIDE	0.123	±	0.034	77
HARDNESS, TOTAL (AS $CACO_3$)	342	±	25	77
MAGNESIUM	25.4	±	2.0	126
NITRATE + NITRITE (AS N)	2.87	±	0.28	149
PH (UNITS, 25°C)	8.40	±	0.17	142
POTASSIUM	3.51	±	0.29	122
SILICA (AS SI)	0.275	±	0.033	85
SODIUM	43.0	±	4.2	126
SULFATE (AS SO_4)	76.1	±	4.0	123
TOTAL NITROGEN	3.21	±	0.32	101

Outliers of >3 standard deviations (SD) are excluded and calculated with 'Robust Analysis' Annex C, ISO DIS 13528:2015(E).

The uncertainty µ represents the +/-2 standard deviation limit for an individual measurement. The 95% confidence interval on the population mean is (SD x 1.96) ÷ √N.

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Appendix 6: Spring measurements

Spring nr	Date	Time	sec/10L	vannføring l	Note
1	03.nov	09:00	33,75	1066,667	white
			33,75	1066,667	
			33,25	1082,707	
1	03.nov	15:00	34	1058,824	color white
			33,75	1066,667	
			34,5	1043,478	
1	03.nov	18:30	33,75	1066,667	white
			33,75	1066,667	
			33,25	1082,707	
1	04.nov	08:20	34	1058,824	
1	01.nov		34	1058,824	
			36	1000	
			35	1028,571	
1	02.nov		33	1090,909	white
			32	1125	
			32	1125	
1	04.nov		33,6	1071,429	tests done 4 november are done 9:30 to 11:30
			34	1058,824	
			34,2	1052,632	
2	04.nov		7,85	4585,987	
			7,5	4800	
			7,7	4675,325	
			8,43	4270,463	
			7,91	4551,201	
3	04.nov		5,77	6239,168	two pipes at spring. nr 1
			6,09	5911,33	
			6,04	5960,265	
			5,82	6185,567	
			6	6000	
			6,78	5309,735	nr 2
			6,84	5263,158	
			6,83	5270,864	
			6,63	5429,864	
			6,77	5317,578	
4	04.nov		4,51	7982,262	
			4,12	8737,864	
			4,28	8411,215	
			4,04	8910,891	
			4,44	8108,108	
			4,59	7843,137	
5	04.nov		6,5	5538,462	
			6,66	5405,405	
			6,68	5389,222	
			6,41	5616,225	
			6,67	5397,301	
			6,59	5462,822	
6	04.nov		4,2	8571,429	
			4,76	7563,025	
			4,79	7515,658	
			4,79	7515,658	
			4,34	8294,931	
			4,65	7741,935	
			4,84	7438,017	
			4,67	7708,779	
7	04.nov		10,17	3539,823	some color, white
			10,26	3508,772	
			9,68	3719,008	
			9,99	3603,604	
			9,5	3789,474	
			9,36	3846,154	

Spring nr	Location
1	Spring at Nyenga property
2	Road cross
3	across from way
4	upsteams f bridge
5	downstream from brigde
6	spring downhill frome mosc'e
7	sugercane field

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