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Water Well Investigation in Nampula Province
Slug Tests in Weathered Crystalline Rock

A Minor Field Study

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Water Collection in Matibane, Nampula Province. Photo: Sofia Hallerbäck

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Undersökning av vattenbrunnar i Nampula Provinsen

Slugtester i vittrad kristallin berggrund

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Summary

In Nampula Province, Mozambique, locating productive wells is a problem due to the heterogeneity in local geology, which consists of mainly weathered crystalline rock. This study estimates hydraulic conductivity of 10 hand pumped water wells in rural areas of Nampula Province using slug tests, and is a follow up of Andersson and Björnström (2013) and of Enkel and Sjöstrand (2013).

This thesis aims to increase the knowledge of these aquifers and similar aquifers. The thesis will help to describe the hydrogeological properties of the area in a bigger attempt to in the future find better methods of finding safe and easily accessible water in areas of similar geology.

At each site 6-10 slug tests were conducted, resulting in 68 tests in total for the 10 sites covered. The slug test data was interpreted using Bouwer and Rice (1976) and Cooper et al. (1967) solutions, using the standard commercial software Aqtesolv. Moreover the hydraulic conductivity was estimated using the specific capacity, where the specific capacity was assessed from previous pumping test conducted during the drilling process.

The hydraulic conductivities are estimated to be around 0.2-3.9 m/day using the Bouwer and Rice (1976) solution and 0.2-9.7 m/day using the Cooper et al. (1967) solution. The results using the specific capacity gave lower hydraulic conductivities ranging from 0.1-0.6 m/day. However, the results are all within the range of values from fractured igneous and metamorphic rock (Domenico and Schwartz, 1990). The three sites with highest hydraulic conductivity were Camaculo, Muriaze and Naholoco EP1-2, which were in different regions. It is found that water wells in this area that are geographically close may not at all be close in terms of hydraulic conductivity, most likely explained by the local and heterogeneous weathering process. We also show that similar rock types can yield a quite big difference in hydraulic conductivity.

The study demonstrated that slug test may very well be a suitable method in similar geological environment, however with strong recommendations of high safety precautions, especially regarding contamination via equipment and risk to ruin pump parts. Moreover, the Cooper et al. (1967) and the Bouwer and Rice (1976) methods are both developed for porous aquifers, but it is found that the methods may be applied for weathered rocks as well.

Keywords

Slug tests, Hydraulic conductivity, Weathered crystalline rock, Water Resources, Safe Drinking Water, Mozambique, Hand Pumped Water Wells

Sammanfattning

I Nampula Provinsen, Moçambique, har det tidigare varit problem att lokalisera produktiva platser att placera grundvattenbrunnar på grund av den heterogena berggrunden, bestående till största delen av vittrad kristallin berggrund. Denna studie undersöker den hydrauliska konduktiviteten av 10 handpumpade dricksvattenbrunnar med hjälp av en slugtest metod, och är en uppföljningsstudie på samma platser som tidigare undersökts av Enkel & Sjöstrand (2013) och Andersson & Björkström (2013).

Målet med studien är att uppskatta den hydrauliska konduktiviteten av dessa dricksvattenbrunnar. Studien strävar efter att öka kunskapen om dessa och likande akvifärer, vilket förhoppningsvis kan leda till att bättre identifiera produktiva brunnsplaceringar.

Totalt utfördes och analyserades 68 slugtester, där av 6-10 stycken slugtester utfördes vid varje brunn. Dataanalysen av slugtesterna gjordes genom Bouwer och Rice (1976) och Cooper et al. (1967) metoden, med hjälp av programvaran Aqtesolv. Dessutom uppskattades den hydrauliska konduktiviteten från tidigare pumptester genom att använda den specifika kapaciteten.

Det är den hydrauliska konduktiviteten i det vittrade berget har uppskattats mellan 0.2-3.9 m/dygn genom Bouwer and Rice (1976) metoden, och mellan 0.2-9.7 m/dygn med Cooper et al. (1967) metoden. Den hydrauliska konduktiviteten beräknad utifrån den specifika kapaciteten varierar mellan 0.1-0.6 m/dygn, vilket är lägre i jämförelse med värdena uppskattade från slugtesterna. Alla resultat är inom rimliga gränser för en sprickrik berggrund bestående av magmatiska eller metamorfa bergarter (Domenico och Schwartz, 1990). Tre brunnar hade extra hög hydraulisk konduktivitet jämfört med de andra; Camaculo, Muriaze och Naholoco EP1-2 men var inte geografiskt närliggande. Hittat i studien är att brunnar som är nära geografiskt eller liknande ur ett litologiskt perspektiv behöver inte vara nära beträffande hydraulisk konduktivitet, vilket troligen förklaras av den lokala och heterogena vittring processen.

Resultaten visar att slugtest metoden fungerar i dessa berggrunder, förutsatt att man i dricksvattenbrunnar ser över säkerhetsåtgärderna, speciellt med risk för korskontaminering och risk att skada pumpdelar. Det har även vistats att Cooper et al. (1967) och Bouwer och Rice (1976) metoder för att analysera slugtester, vilka är framtagna för porakvifärer, även kan tillämpas för att analysera tester utförda i en vittrad berggrund.

Nyckelord

Slugtest, hydraulisk konduktivitet, vittrade magmatiska och metamorfa bergarter, säkert dricksvatten, Moçambique, handpumpade vattenbrunnar

Contents

1 Background

1.1 Safe Drinking Water

Access to safe drinking water is a basic human right and is essential to sustain life (WHO, 2011). Water is not just important for health, but a basis for all kind of growth and development. The Millennium Development Goals and World Health Organization divide water sources into improved drinking-water sources and unimproved drinking-water sources (WHO, 2011). To find, sustain and transport safe drinking water is a challenge, especially if infrastructure is limited and if no water treatment is available. There is a big difference in urban compared to rural areas in terms of access to improved water sources. In 2010 about 786 million people did not have access to safe drinking water, and of this 653 million live in rural areas. (UN, 2012)

Improved drinking-water sources:

- Piped water into dwelling, yard or plot
- Public tap or standpipe
- Tubewell or borehole
- Protected dug well
- Protected spring
- Rainwater collection

Unimproved drinking-water sources:

- Unprotected dug well
- Unprotected spring
- Cart with small tank or drum provided by water vendor
- Tanker truck provision of water
- Surface water (river, dam, lake, pond, stream, canal, irrigation channel)
- Bottled water

(WHO, 2011)

Moreover, in rural areas there is a connection between the distance to water collection public health risk and amount of water collection (WHO, 2011). When waters is collected more than 1 km or more than 15 min away from household the likely water volume collected is 5 l per capita and the public health risk from poor hygiene is very high (WHO, 2011).

This project investigates hand-pumped boreholes that were installed as a part of a big aid project to create improved water sources in rural areas. Before the installation the villages relied on so called unimproved drinking-water source, such as unprotected dug wells, springs and surface water.

1.2 Water scarcity Mozambique

Mozambique, figure 1-1, is one of the economically poorest countries in the world, ranked 197 out of 210 in terms of GDP and listed as 184 out of 187 in Human Development Index (Tvedten, 2012). As in many so called developing countries the population is relatively young and for Mozambique the average women give birth to 6 children while the life expectancy is about 50 years (World Bank, 2015). The mortality rate of under-5 year-olds was 237 out of 1000 in 1990, but has decreased over the last decade. Still in 2013, 87 children out of 1000 do not survive their first 5 years, which can be compared to the US with about 7 out of 1000 children. One big contribution to the high child mortality rate is lack of access to clean and safe water, estimated that about 17% of the early child death is caused by inadequate sanitation and water managing.

In 2015 only 50.1% of the population has access to safe water according to the WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply and Sanitation (WHO, 2015). Moreover the access to formal sanitation management is only about 20 % (WHO, 2015). In the Nampula Province, figure 1-1B, where this study is situated it is recently estimated that only 39% of the population have access to clean water (Noticias, 2015). However, in the rural villages only about 22% have access to improved water sources (Noticias, 2015).

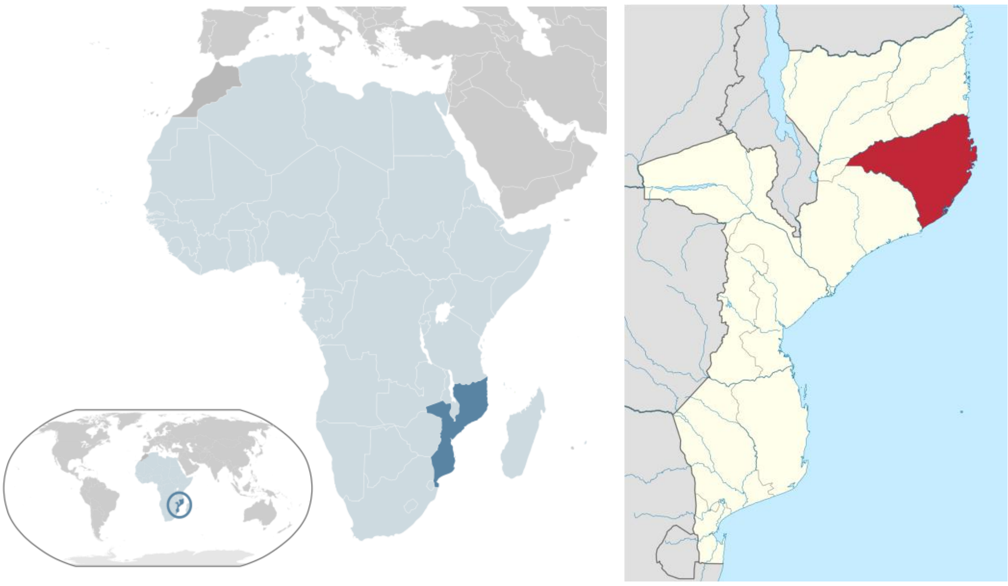


Figure 1-1 A) In red the location of the country of Mozambique. Picture: (Wikimedia, 2016) B) the location of the Nampula Province. Picture (Wikipedia, 2016)

In 2007 a development project with the aim to reduce poverty through economic growth started in Mozambique. The project was funded by the US Millennium Challenge Corporation, giving the Mozambique government a large five year grant of totally $506.9 million. The major part of the project focused on increasing the access to safe drinking water and sanitation ($231 million). As a part of this project 600 improved water points were to be constructed in the provinces Nampula and Cabo Delgado, two regions with the lowest rural water supply in Mozambique. Each water point consisted of a well, a water pump and a communal washing basin. (Hall et al. 2014, Enkel and Sjöstrand 2013, Andersson and Björkström 2013)

Open water sources such as rivers and wetlands are easily accessible but also easily contaminated. The use of the hand pumped water wells brings groundwater with a lower risk of contamination. The water from this water wells are thereby consider safe. However the geography of this Nampula Province has created difficulties in finding locations of placing the wells and the previously used methods have proven not effective.

In both Nampula and Cabo Delgado the failure rate of the water points drilled in the project has been around 25% (Cowater International Inc. and Salomon Lda., 2010). It was reported that the failure was due to the geological conditions at the well sites and that the failure rate was higher in consolidated rock areas. When choosing placement of the wells, vertical electrical sounding (VES) was used. This survey method only gives point information about the resistivity while lateral variations in resistivity are not detected, which can give misleading results especially in weathered and fractured zones. (Enkel & Sjöstrand 2013, Andersson & Björkström 2013)

However, further investigations have been carried out in the area (where of two previous MFS projects), analysing both wells with and without sufficient yield. Especially, the lateral hydrogeological variation have been interpreted using electric resistivity tomography (ERT) (Enkel & Sjöstrand 2013, Andersson & Björkström 2013). ERT was assesed to be a good method to describe the heterogeneous aquifer, but in order to make reliable interpretations of the gathered data, regional and geological information and data is needed, (Enkel & Sjöstrand 2013, Andersson & Björkström 2013). The test sites were chosen among the test sites previously visited by Enkel and Sjöstrand in Rapale and Andersson and Björkström in Mongicual.

1.3 Objectives

The aim with this thesis is to estimate the hydraulic conductivity of drinking water boreholes located in weathered fractured rocks in rural parts of the Nampula Province, Mozambique. The thesis aims to increase the knowledge about hydraulic properties of aquifers in the region. A knowledge that can be used for other aquifers located in a similar geological environment as well. The thesis will help to describe the hydrological properties of the area in a bigger attempt to develop better methods of finding safe and easily accessible water in the future in areas of similar geology.

1.4 Methodology

Field work and preparations was performed together with Elin Olsson, also an environmental engineering student at LTH, and the field study included both performance of slug test and dual induction borehole logging. This report present the results from interpretation of the slug tests, while the logging results are presented in Olsson (2016). The slug tests were performed using a solid slug. Thereafter two specific mathematical slug test solutions were used to estimate the hydraulic conductivity of the local aquifer. Moreover the hydraulic conductivity was also estimated from the specific capacity of the wells, obtained using data from the drilling reports.

1.5 Limitations

The field study was performed with a limited budget and time period of four weeks in field, where tests were performed at 10 sites. Most of the logging and slug test equipment was transported from Sweden, limiting the weight and extent of equipment.

Tests were performed in drinking water boreholes, where the population normally had no other close safe drinking water source, thereby impacted the available time period of the day where tests could be conducted as well as making it very important that the drinking water wells were left after the study in a safe and performing better or as good as before the study was conducted. Moreover the pumps were often heavily used before the measurement, impacting the results of static water level at many sites because of a slow water level recovery. Also the pump and the pump tubing were removed before testing which also caused an on-going water level recovery at these sites. Problems in the reassembling method of the pump and pump tube was found after tests had been performed at 10 sites and the remaining time of the study was used to check and evaluate all previously tested wells, in order to make sure all sites were left in a good condition.

In data analysis of the slug test there are many slug tests methods to be used, however in this analysis only Bouwer and Rice (1976), Bouwer (1989) and Cooper et al. (1967) methods were used.

2 Theory

2.1 Groundwater theory and management issues

In order to create improved water sources for the rural population of the Nampula province boreholes were drilled and provided with hand pumps. The water gained from the pumps comes from groundwater. Groundwater, or subsurface water, is a term for all water below the land surface. Nevertheless as in hydrology application groundwater is considered as the water in the so called saturated zone, which is the meaning that will be used further on in this report.

Groundwater is the largest distributed store of fresh water on our planet. This source is essential to sustain ecosystems worldwide. Humans withdraw one third of the fresh water from groundwater sources (Taylor et al., 2013). Groundwater can be used both as a source of water, a storage reservoir and as a filter plant. One great advantage of groundwater as a drinking water supply is that that annual and seasonal fluctuation in availability is not as pronounced as for surface water sources (Bear, 2012).

The geological formation or formations in the ground that permits extraction of a significant amount of groundwater are called aquifers. On the contrary formations that may contain water but that are not enabling of transmitting significant amounts of water are called aquiclude or impervious formations. Some formations are not entirely impervious but can transmit water at a very low rate and they are called aquitards, semipervious formations or leaky formations. Finally aquifuge formations can neither contain nor transmit water. (Bear, 2012)

Depending on the classification of the formations the aquifers are divided into confined and unconfined aquifers. Confined aquifers are pressurized and bounded below an impervious formation; see figure 2-1 A. On the contrary unconfined aquifers are not pressurized and have the water table as the upper aquifer boundary, figure 2-1 B. Some aquifer system may contain both an unconfined aquifer followed by one or more impervious layers with confined aquifers in between.

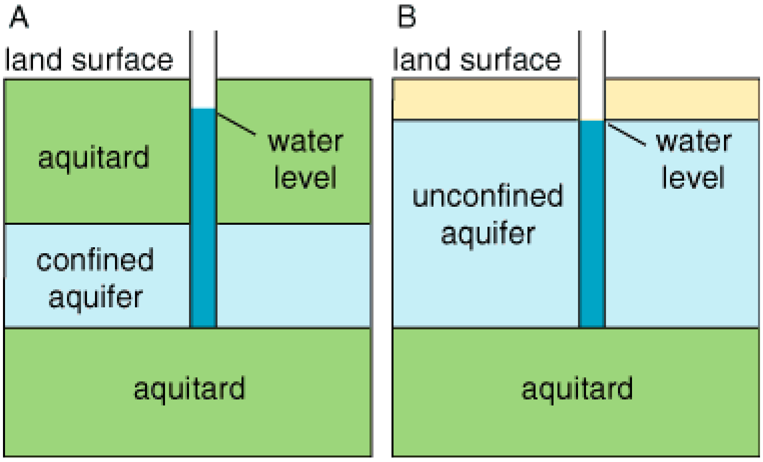


Figure 2-1 Schematic difference between a confined (A) and an unconfined (B) aquifer. Picture: Kansas Geological Survey (2016)

An aquifer can be located in both porous mediums and in fractured rock. In porous mediums the size and distribution of grain sizes will determine the hydraulic conductivity and permeability properties of soil materials. Table 2-1 present typical range of hydraulic conductivity values of different rock and soil materials using values from Domenico and Schwartz (1990).

Table 2-1 Table of hydraulic conductivity of different unconsolidated sedimentary materials and crystalline rocks (Domenico and Schwartz, 1990).

	Material	Hydraulic Conductivity - lower limit (m/day)	Hydraulic Conductivity - upper limit (m/day)
Unconsolidated Sedimentary Materials	Gravel	25.9	2592
	Sand	1.72E-02	518.4
	Silt, loess	8.64E-05	1.73
	Till	8.64E-08	0.173
	Clay	8.64E-07	4.06E-04
	Unweathered marine clay	6.91E-08	1.72E-04
Crystalline Rocks	Unfractured igneous and methamoric rock	2.59E-09	1.73E-05
	Fractured igneous and metamorphic rock	6.91E-04	25.9
	Weathered granite	0.285	4.49
	Weathered gabbro	4.75E-02	0.328
	Basalt	1.728E-06	1.73E-05

Groundwater is considered to generally be of high quality; however pollution of groundwater is possible if for example connected to polluted surface water (Bear, 2012). Sometimes dividing of surface water and groundwater can be questionable, since they are affected by each other (Bear, 2012). It is of great importance to understand the hydrogeology of the aquifer in order to assess risk of pollution.

The yield of an aquifer is the volumetric flux of water that is pumped from an aquifer. If recharge to the groundwater aquifer is slower than abstraction and this rates are of extensive areas and over a long time, than groundwater depletion will occur (Wada et al., 2010). Studies have found that the rate of groundwater depletion is increasing worldwide (Wada et al., 2010). It is very 2.1.1 crucial in groundwater management planning to consider long term development of the use of groundwater.

Important terms:

- **Homogeneous aquifer** - medium that have the same permeability in all points
- **Heterogeneous aquifer** - medium that does not have the same permeability all points
- **Isotropic aquifer** – have the same hydraulic conductivity in all directions
- **Anisotropic aquifer** – does not have the same hydraulic conductivity in all directions
- **Saturated thickness** – the saturated depth of the aquifer. For unconfined aquifers that is the length from the base of the aquifer to the water level. For confined aquifer the saturated thickness it the same as the aquifer thickness.
- **Aquifer thickness** – is the vertical length of the aquifer

2.2 Aquifer of the region

The studied boreholes are placed in a weathered crystalline rock. Acworth (1987) made a good description of these complex aquifers, see figure 2-2. As seen in the figure the solid basement of crystalline rock have a very low hydraulic conductivity. The more permeable and porous zones are created through the weathering process and this process is driven by the water chemistry and flow. Water entering the fractures in the fresh rock will start the chemical weathering process.

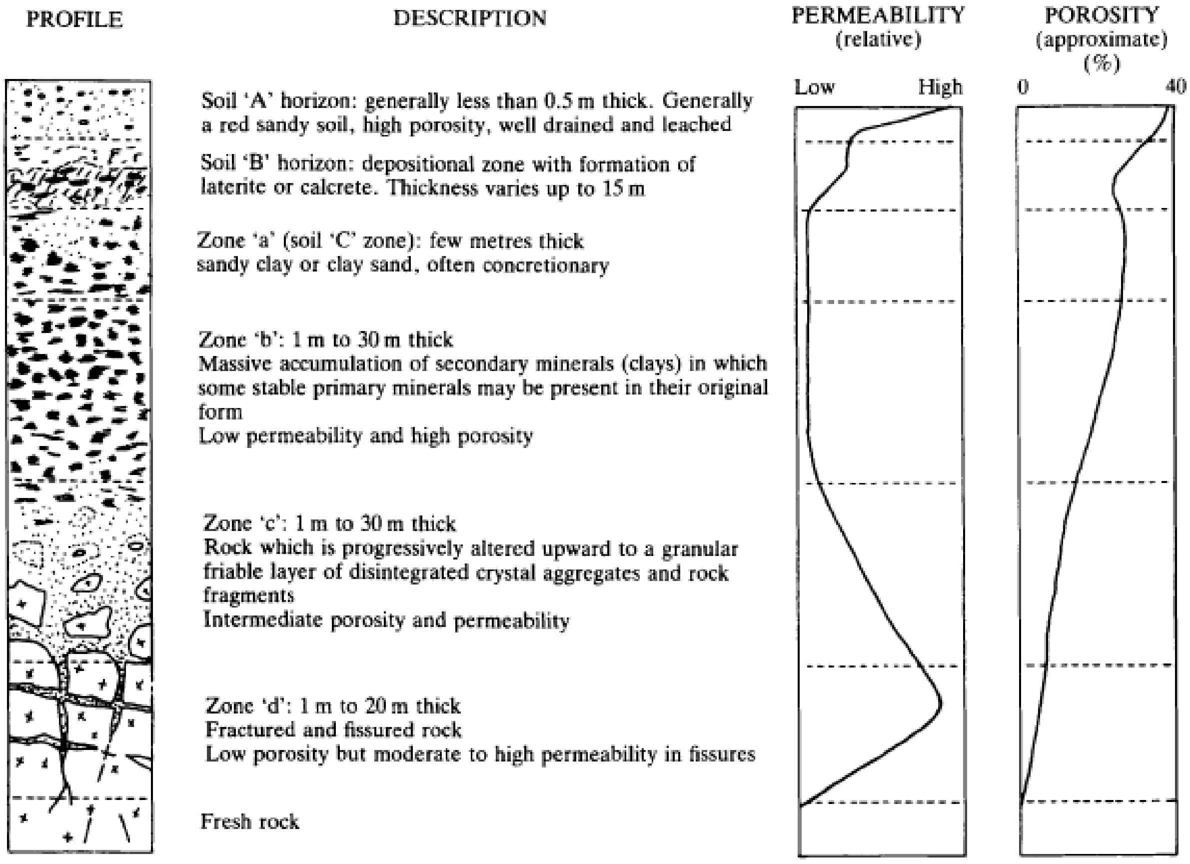


Figure 2-2 The typical weathering profile developed over crystalline basement rocks (Acworth, 1987).

"To contain significant aquifers, the weathered profile must attain a minimal areal extent and thickness and have a sufficient hydraulic conductivity and storage to yield groundwater to wells or boreholes." (Acworth, 1987)

Chemical weathering will over time generate a so called weathering profile, figure 2-2, upon the crystalline basement, where all the different zones a-d are present. However the zones may vary in size, but not in succession (Acworth, 1987). The highest permeability or hydraulic conductivities are found in zone of fractured and fissured rock, zone 'd' and in the progressively disintegrated crystal aggregates zone 'c' in figure 2-2. These zones can be used as a groundwater reserve, if the hydraulic conductivity of this weathered material is high enough. (Acworth, 1987). Also zone 'a' have a high permeability, however water from this zone is not suitable as a drinking water source due to exposure to surface contaminants.

Moreover, zone ‘b’ consists to a big range of secondary minerals, clays, with a high porosity but a low permeability. This low permeability makes this zone to normally act as a aquiclude above the highly permeable zones ‘c’ and zone ‘d’. If water is overpumped from zone ‘c’ the change in pressure may let water drain from zone ‘b’ to the well, making zone ‘b’ into a groundwater storage resource. The thickness and hydraulic conductivity of zone ‘b’ will determine if the aquifer should be considered as a confined or unconfined aquifer. (Acworth, 1987)

2.3 Water Well capacity

The goal with every groundwater pump is to be able to pump up water. The speed and amount of water that can be produced from a water well is of course limited by both pump design and performance and the aquifer properties. This thesis aims to estimate the aquifer properties using the test called slug test. In terms of the aquifer properties, one of the important aspects of groundwater management is the understanding of the hydraulic conductivity or transmissivity of the specific aquifer. These properties are basically the speed of potential water flux through the aquifer, where the transmissivity is the hydraulic conductivity times the thickness of the aquifer. Different geological materials have different hydrological conductivity. (Butler, 1998)

$$K = \frac{T}{b}$$

$$T\ is\ the\ transmissivity\ [L^2/T]$$

$$K\ is\ the\ hydraulic\ conductivity\ [L/T]$$

$$b\ is\ the\ thickness\ of\ the\ aquifer\ [L]$$

When comparing different boreholes is it easy to compare the yield of different boreholes. Nevertheless the yield from a pump is basically the pumping rate, Q. In order to better compare different boreholes the specific capacity of the well is a better method since it also considered the drawdown of the water level generated by the pumping.

$$S_c = \frac{Q}{h_0 - h}$$

$$S_c is\ the\ specific\ capacity\ [L^2/T]$$

$$Q\ is\ the\ puming\ rate\ [L^3/T]$$

$$h_0\ is\ the\ static\ water\ level\ [L]$$

$$h\ is\ the\ dynamic\ water\ level\ [L]$$

There are different solutions for estimating the transmissivity from the specific capacity. Driscoll (1986) presented the following equations for unconfined and confined aquifers. The specific capacity is expressed in m^2/day, than the transmissivity in m^2/day can be estimated as followed:

$$T = 1.385 * S_c\ (confined\ aquifer)$$

$$T = 1.042 * S_c\ (unconfined\ aquifer)$$

2.4 Slug test

Slug test is a well testing method used to estimate the hydraulic conductivity or transmissivity. Some of the advantages of the slug test method are the relatively low cost, simplicity and that it is a relatively fast method. Moreover, since a limited area in the aquifer is influenced, the method is very well suited in sites with potential groundwater contamination.

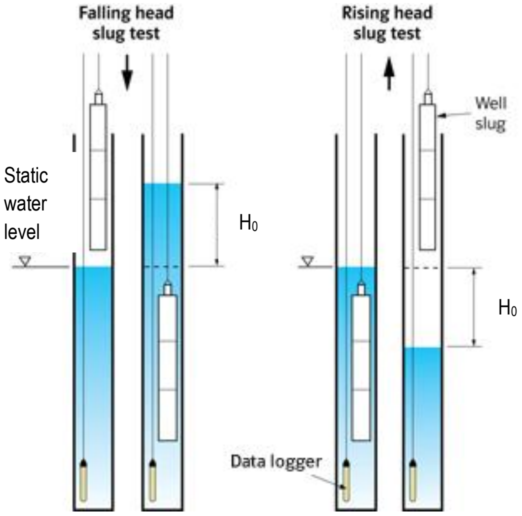


Figure 2-3 Falling head slug test and rising head slug test method.

The slug tests are basically measuring the recovery on a near-instantaneous change in water head. This change in head is created by introduction or reduction of a known volume or pressure to the water column in the well, see figure 2-3. This can be done for example by rapidly introducing a solid object, a so called solid slug. When the slug is inserted rapidly below the water level the water level will primarily rise, see figure 2-3, indicated as H_0 the initial displacement. The increased water level will create a higher water pressure that over time will be equalized into the surrounding formation. Thereby the pressure and water level will slowly decrease. This response is called a falling head slug test. When the water level has returned to initial conditions a rising head slug test can be performed by rapidly removing the slug and thereby initially lower the water level in the well, also indicated in figure 2-3 as H_0. The formation will thereafter respond so that water will flow into the well.

As seen in figure 2-3 the data is being stored in a data logger or pressure memory gauge. In figure 2-4 the water level response to falling head and rising head slug tests is shown as a change of meter of water column above the pressure gauge. The measured pressure is recalculated into water depth above sensor via the density of the water and acceleration of gravity.

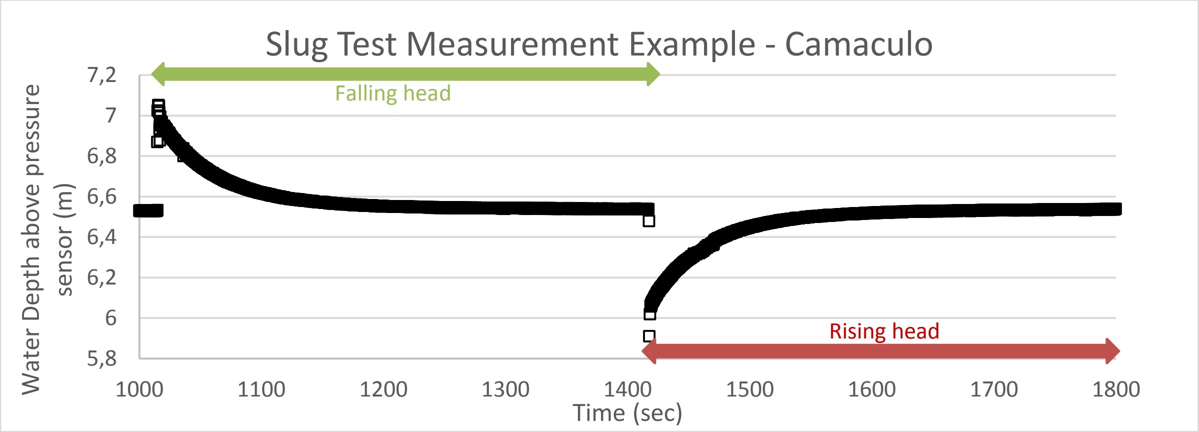


Figure 2-4 Example of slug test measurement results, with water depth above pressure gauge is plotted as a function of time. Example taken from measurement at the waterwell in Camaculo test site.

This study used solid slug equipment and a pressure sensor and cable. A major advantage with solid slug tests is that no water needs to be handled. Moreover the construction can be made with low costs. Moreover the expected initial displacement can very accurately be measured. Also the method can be used for both falling and rising head tests. (Butler, 1998)

The speed of which the water level return to static conditions after the induced head from the slug are connected to the hydraulic conductivity or transmissivity of the formation (Butler, 1998). Based on different assumptions there are many different methods to find this desired estimated value, for example the Bouwer and Rice (1976) solution and the Cooper et al. (1967) solution used in this study. Unfortunately no specific method is developed for weathered crystalline rock. The Aqtesolv product have a method for fractured rocks (Barker and Black, 1984), however too much initial parameters are needed to use the method in this study.

2.5 Expected initial displacement

The expected initial displacement, H^*_0 represents the height the water level theoretically should rise or fall when the entire slug is primarily inserted in the water or removed from the water. The expected initial displacement can be calculated using the volume of the slug and the radius of the water well casing, according to the equation below, where V_{slug} represents the volume of the slug and r_{casing} radius of the casing.

$$H_0^* = \frac{V_{slug}}{\pi r_{casing}^2}$$

$$H_0^* \textit{ is the expected inital displacement } [L]$$

2.6 Series of slug test

To ensure testing quality it is recommended to perform a minimum of three tests with at least two or more different slug volumes (Butler, 1998). In theory performance of multiple slug test in a well should give equal response of time vs. displacement (Butler, 1998). Also in theory, if the formation is uniform to inflow and outflow, displacement curve from both the falling head test and the rising head test should be similar. Furthermore, performing slug test with different volumes should give equal response if the results are normalized using the initial displacement. In order to compare the different tests the results for each falling head and rising head test are normalized using the value of the static level and the initial displacement.

$$H_{norm} = \left|\frac{h_p - h_{p0}}{H_0}\right|$$

$$H_{norm} \mathit{is\ normalized\ head\ values}\ [-]$$

$$h_p \mathit{is\ the\ height\ of\ water\ column\ at\ the\ end\ point\ of\ the\ test}\ [L]$$

$$h_{p0} \mathit{is\ the\ height\ of\ water\ column\ at\ the\ start\ point\ of\ the\ test}\ [L]$$

In order to verify well development during test one must perform the first and last test using the same slug volume, initial displacement. Thereby for example gaining information about potential clogging or improvement of the hydraulic properties of the well as a result of the testing (Rosberg, 2010). The end point is normally chosen as the point when the water level have recover to the static water level within a 5% margin (Butler et al., 2009). Moreover the start point is normally chosen at the peak of the initial displacement where time is set to zero (Butler et al., 2009).

2.7 The Bouwer and Rice (1976) slug test solution

One commonly used slug test solution is the Bouwer and Rice (1976). One of the big advantages with the Bouwer and Rice (1976) solution is that the same solution can be used for both confined and unconfined aquifers, as well as for fully or partially penetrating wells. The equation used in Bouwer and Rice (1976) is based on the assumption that the aquifer is homogeneous, have uniform thickness and infinite areal extent. The method is also assuming instantaneous injection into or discharge from the well. The method is a quasi-steady-state model, whereby assuming that the hydraulic head in the aquifer varies with time but the specific storage is neglected. Since the slug test method itself is a relatively short and local method estimations of the specific storage are not normally trusted.

To describe the water flow, Q (L^3/T) into a well for different drawdowns from the static level, h (length), the Thiem equation can be used.

$$Q = 2\pi KL \frac{h}{\ln(R_e/r_w)}$$

The rate of rise of the water level is connected to the water inflow divided by the cross-sectional area of the well where the water is rising, r_c.

$$dh/dt = -Q/\pi r_c^2$$

Combining this two equations give the following relationship

$$\frac{1}{h}dh = -\frac{2KL}{r_c^2 \ln(R_e/r_w)}dt$$

This can be integrated into

$$\ln h = -\frac{2KLt}{r_c^2 \ln(R_e/r_w)} + constant$$

Using the boundary conditions that at t=0 then h = H_0 and that at t=t, h = h(t)

$$K = \frac{r_c^2 \ln(R_e/r_w)}{2L}\frac{1}{t}\ln\frac{H_0}{h(t)}$$

Which can be rearranged into

$$\ln(H_0) - \ln\left(h(t)\right) = \frac{2KLt}{r_{ce}^2 \ln\left(\frac{R_e}{r_{we}}\right)}$$

$$r_{we} = r_w\sqrt{K_z/K_r}$$

h_t *is displacement at time* t $[L]$
H_0 *is inital displacement* $[L]$
K, K_r *is radial hydraulic conductivity* $[L/T]$
K_Z *is vertical hydraulic conductivity* $[L/T]$
L *is screen length* $[L]$
r_{ce} *is effective casing radius* $[L]$
R_e *is external radius* $[L]$
r_w *is well radius* $[L]$
r_{we} *is equivalent well radius* $[L]$
t *is time* $[t]$

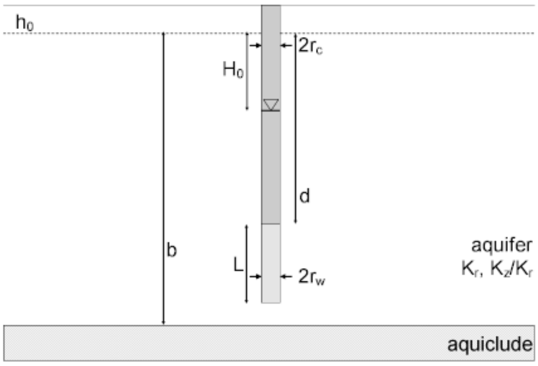


Figure 2-5 Geometrical parameters used in Bouwer and Rice (1976) solution, represented for an unconfined aquifer. Source: Aqtesolv

As seen in the equations above the hydraulic conductivity calculated using the Bower and Rice (1976) method requires the measurements of displacement initialized by the slug test and as a function of time, as well as the initial displacement, H_0. The solution also requires information about the casing and well radius as well as the depth to the top of the well screen, d and screen length, L see figure 2-5. Moreover information is needed of the saturated thickness, for unconfined aquifers, or thickness of aquifer, for confined aquifers, b. For partially penetrating wells there is a need of the hydraulic conductivity anisotropic ratio K_y/K_x. The Bouwer and Rice (1976) method results in an estimation of the hydraulic conductivity, K and the intercept of line with the y-axis, y_0.

Graphically the method fits a straight solution line from the displacement curve as a function of time, using logarithmic y-axis scale, see example in figure 2-6 from the first Bouwer and Rice article (1976).

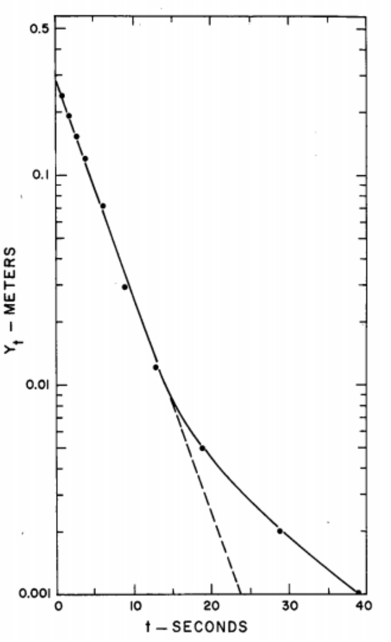


Figure 2-6 Example of displacement y versus time t fitted with the straight dotted line using the Bouwer and Rice (1976) solution.

In the article by Bouwer (1989) the double straight line effect was described. The double straight line effect was introduced since during some measured slug tests, see figure 2-7, the response is divided into a primary higher slope (AB) and a secondary lower slope (BC). For these wells the analysis is best done using the Bouwer (1989) double straight line method.

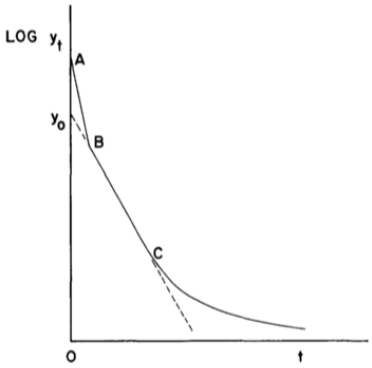


Figure 2-7 Schematic figure of the double straight line effect (Bouwer, 1989).

The main explanation for these double straight line responses is the impact of a high permeable zone surrounding the well, normally the gravel pack or developed zone (Bouwer, 1989). When conducting the slug test the first responses, representing line AB in figure 2-7, is the drainage of highly permeable zone, resulting in the high sloping line representing a high K value. Thereafter the surrounding formations are drained at a slower rate, representing the lower K value of the second line, BC. The same responses are found in the rising head test.

2.8 Cooper et al. (1967) slug test solution

The Cooper et al. (1967) is another frequently used slug test method. The model is developed for fully penetrating wells in confined aquifers. However, Butler (1998) is suggesting the use of this method for all unconfined and confined aquifers with overdamping response. Overdamping is typical for formations in low to moderate hydraulic conductivity. The model is based on the typical assumptions such as that the aquifer has infinite areal extent and is homogeneous, isotropic and of uniform thickness. Most different from the Bouwer and Rice (1976) is the use of the specific storage parameter, S.

The Cooper et al. (1967) method is based on the following equations, presented as in the description from Aqtesolv:

$$\bar{H} = \frac{H_0 r_w S K_0(rq)}{Tq[r_w q K_0(r_w q) + 2\alpha K_1(r_w q)]}$$

$$q = (p\,S/T)^{1/2}$$

$$\alpha = \frac{r_w^2 S}{r_c^2}$$

$\bar{H}$ $is\ the\ Lapace\ transformation\ of\ the\ head\ in\ the\ well\ [L]$
K_i $is\ the\ modified\ Bessel\ function\ of\ second\ kind, order\ i\ [L/T]$
$p\ is\ the\ Laplace\ transformation\ variable$
$r_c is\ the\ casing\ radius\ [L]$
$r_w is\ the\ well\ radius\ [L]$
$S\ is\ the\ storativty\ [dimensionless]$
$T\ is\ transmissivity\ [L^2/\mathrm{T}]$
$t\ is\ the\ elaped\ time\ since\ initation\ of\ test\ [T]$

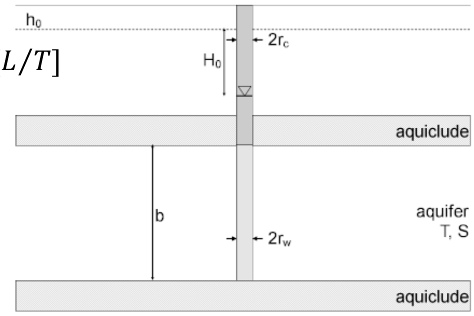


Figure 2-8 Geometrical representation of parameters defined for confined aquifers using the Cooper et al. (1967) solution. Source: Aqtesolv.

The estimated parameters are the transmissivity and storativity. In order to estimate the hydraulic conductivity from the Cooper et al. (1967) solution the aquifer thickness value, b is used. Moreover data of the initial displacement, casing radius and well radius are needed just as for the Bouwer and Rice (1976) method. However the Cooper et al. (1967) solution does not require depth to top of well screen and screen length, see figure 2-8, since it assumes a fully penetrating well.

One of the benefits of plotting slug test measurements using the Cooper et al. (1967) solution is that one can easily compare the test in order to assess well development during a series of slug tests performed in a well. As seen in figure 2-9 higher transmissivity values represent a faster response, curve moving down-left, compared to lower transmissivity values moving to up-right. Higher transmissivity values represent higher conductivity values, if the aquifer thickness is the same.

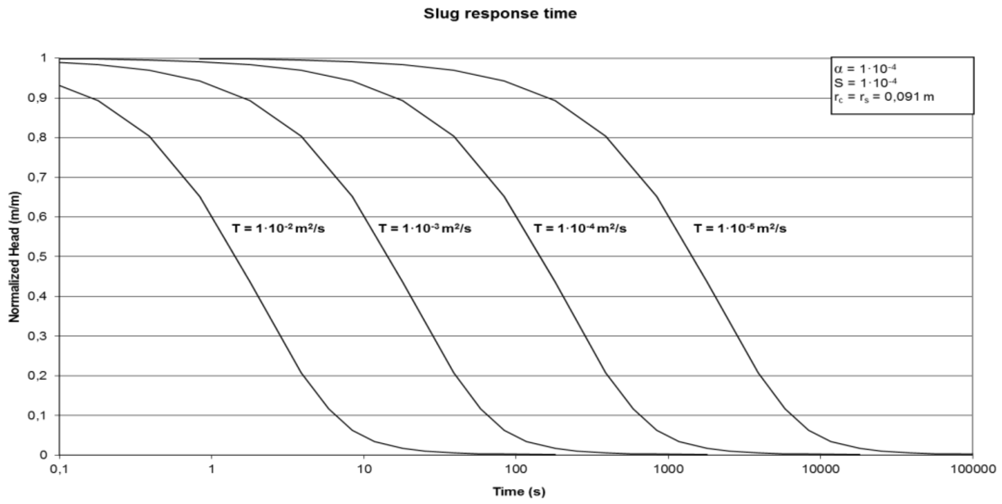


Figure 2-9 Using the Cooper et al. (1967) solution for different transmissivity values (Rosberg, 2010).

2.9 Water pump design

The well design and development is of great importance in slug test analysis. The investigated wells are constructed with a PVC pipe well casing, see figure 2-10. The well casing ends with a casing sump where finer grains will settle. The casing is open at the well screen where water enters the well. The well screens are hopefully placed at the depths of the most potential production zones. For the slug test analysis it is important to know the size and positions of the well screens. It is also curtail to know the dimensions of the well casing in order to estimate the slug test results using both Bouwer and Rice (1976) and Cooper et. Al (1967). Around the well screens a high conductivity material, usually gravel, is placed, and called the gravel pack. The dimensions of the gravel pack might also be of importance for the analysis. The development of the well such as clogging of the screens etc. is also of interest.

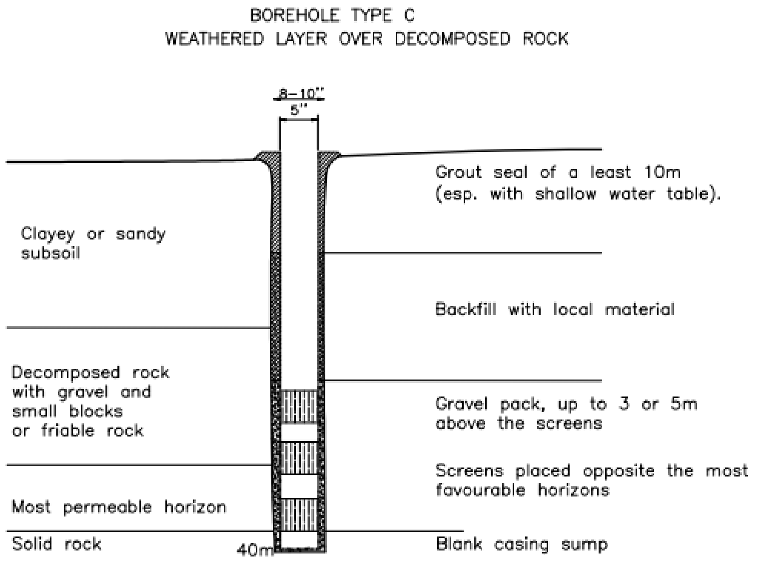


Figure 2-10 Basic well design parameters and geology of a weathered layer over decomposed rock usually found in the Nampula Region. (Salomon Lda, 2010)

A partially penetrating well has a length of screens less than the saturated thickness of an unconfined aquifer or less than the length of the aquifer thickness for confined aquifers. While a fully penetrating well has the same length of screen as the saturated thickness of an unconfined aquifer or of the aquifer thickness for a confined aquifer.

3 Method and Equipment

3.1 Equipment and preparations

In order to create two different displacement volumes two slugs where constructed that was able to be screwed together into one or used separate. The two slugs with the same dimentions, where constructed by Johan Kullenberg, Engineering Geology, LTH, using PVC-pipe, see figure 3-1. The slugs were both used as one single slug and could be connected to a "double" slug to induce a bigger displacement. In order for the slugs to sink into the water they need a higher density then water. The slug test filling was primarily tested in Lund using sand filling of the slug, as proposed in Rosberg (2010), but in order to avoid the screw threads to jam and to make the slug easier to clean, metal sticks where instead used inside the slugs. As mentioned by Butler (1998) there is a risk that the solid slug can be a source for cross contamination if not properly cleaned from one well to another. Precautions for this were made by carefully cleaning the equipment between each site.

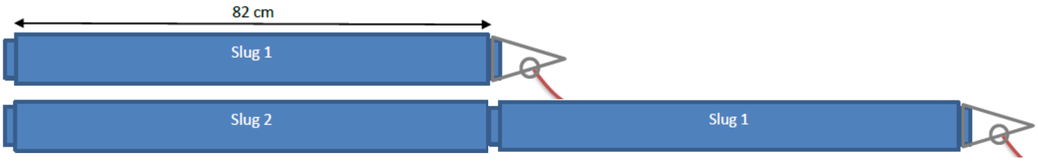


Figure 3-1 Schematic figure of the two slugs used in the field study, used as a single slug(upper) using only slug 1 and a double slug (lower) using both slug 1 and 2.

An alternative to solid slug test method is to use a so called bailer that collects water (Butler, 1998). The known volume of water is thereafter removed rapidly to create this change in head. However this method requires direct handling of the water and can only be used for rising head tests. Moreover there are uncertainties in determining the expected initial displacement. However, a bailer pilot pump that could be used on the slug was included in the equipment to the Nampula Province just in case is would be beneficial to use.

Other methods for initiating slug tests are pouring water into the well or by rapid pumping the well. However pouring water is not optimal from a water safety perspective, due to the risk of spreading contaminates. Other examples of slug test methods is pneumatic slug test, where pressure is induced into the well. That method requires minimum amount of contact with the water, minimizing the risk for cross contamination, but unfortunately that method required more extensive and reliable borehole information then to be found for this study. More especially information about the location of the screens is critical, since the pneumatic method cannot be used if the well is screened above the water table, since than the well cannot be pressurized.

Figure 3-2 Dippmeter (left) and pressure gauge communication cable, pressure gauge and where the cable is connected to the computer (right). Photo: Sofia Hallerbäck

Radius, length and volumes of the single and double slug and the well casing radius, which were same at all sites, are found in appendix. The expected initial displacements were found to be 46 cm and 94 cm for the single slug respectively for the double slug, calculated as described in chapter 2.5 and presented in table 3-1.

Table 3-1 Calculated expected initial displacements for one slug and double slug.

$H_0{*}_{one}$ (cm)	46
$H_0{*}_{double}$ (cm)	94

To measure the displacement of water the pressure was measured at a certain depth below the water column. The dipmeter, shown in figure 3-2, was used to get the water level from the reference point on the top of the well to the water level. WinSitu program in the computer was connected through a communication cable to the pressure gauge, seen in figure 3-2. The pressure gauge has the following specifications:

Level Troll700
Pressure range: 0 -70 m
Accuracy: 35 mm
Resolution: >3.5 mm
Sampling rate: 4 per second

The sampling rate was set to 4 per second for the entire test periods. The pressure gauge was connected to a computer and the measurements were plotted in real time using the WinSitu software. After the measurements the results was downloaded from the pressure gauge also using the WinSitu software.

3.2 Test Performance

The slug testing was performed at 10 sites. To make sure the right drinking water well was analysed the series number on the well was compared to the number presented in Enkel & Sjöstrand (2013) or Andersson & Björkström (2013). After that the hand pumped well was tested by the technicians, helping with the research performance, and thereafter the pump was dismantled. After that the pump tubing was also taken up from the well. This was done by pulling up around 4-5 m of the pump tubing and then cutting it, and thereafter take up another 4-5 m and so forth until the whole pump tubing was up, see figure 3-3 A.

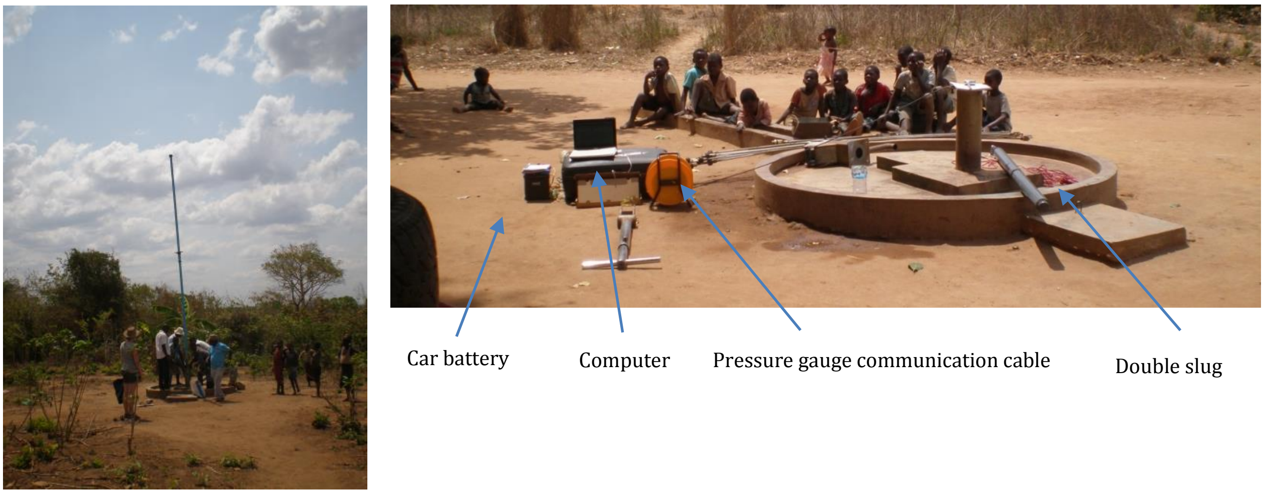


Figure 3-3 A) Pump tubing dismantled from the well in Nampawa. B) Setup during slug test performed showing the car battery used to the computer, the computer connected to the Pressure gauge communication cable. Photo from Naholoco Communidade. Photos: Sofia Hallerbäck

When this was done the water depth was measured using a dipmeter. Secondly one slug was used as a borehole dummy to ensure the borehole depth and quality before the logging sond was to be used. Thereafter the logging equipment was prepared and borehole logging was performed, presented in the report by Olsson (2016). When the logging was completed the slug test was prepared by primarily inserting the pressure gauge. The slug test set up is shown in figure 3-3 B, showing the computer which is charged using a car battery, and the pressure gauge communication cable connected to the computer and on the other end connected the pressure gauge in the well. Moreover, figure 3-3 B also show the double slug. Before the slug tests the water depth was once again measured and at the same time the pressure gauge depth was also noted. Comparing the two water depth measurement and the time in between gave an understanding of background recharge. After inserting the pressure gauge around 5-7 m below the water level and waiting 10-20 min till the temperature and water level was relatively steady, the first slug test was performed by inserting the first slug just below the water column. This was the first falling head test.

Thereafter the initial displacement and the 5% limit to steady state were calculated. The first removal of the slug was performed when the water level had returned within 5% of the static level or if the well was experiencing high amount of recharge the well might not return to the same level and then the shape of the curve was used as an indicator of when the next test could be initialized. The slug was thereafter taken up from the water and all the way to the ground. This was the first rising head test. Since the slug did take in a small amount of water the water intake was measured. Next test was performed when the water level was within the 5% of the static level.

The test performance was done with primarily one slug, then double slug and finally one slug again, giving a minimum of 6 tests performed. Always return to one slug at the end is important in order to assess well development throughout the test. At sites with fast recovery or when there was extra time more tests were performed. If extra tests were performed then one more single slug tests were performed in the end, giving in total 8 tests, see example of the raw data from Camaculo in figure 3-4. At one site there was even more time and then the double slug was also used one more time giving in total 10 tests.

When the last test was performed the equipment was repacked for travel and the technicians had the mission of reinserting the pump tubing and the pump.

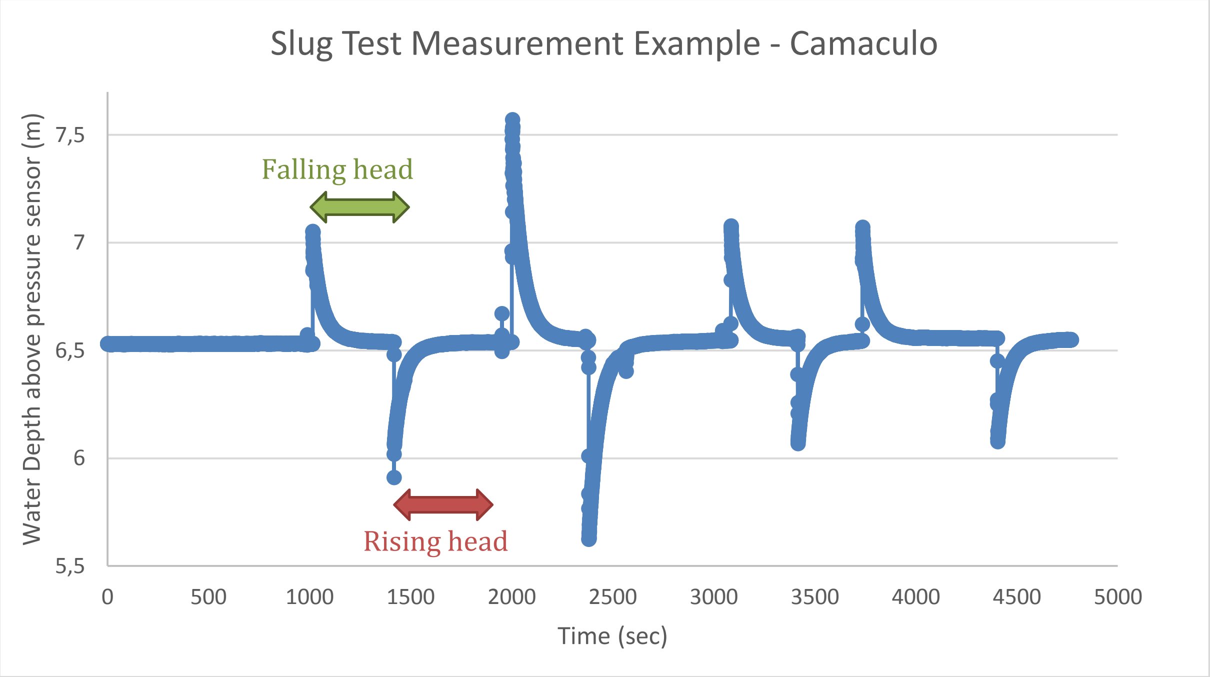


Figure 3-4 Example of slug test measurement results, with water depth above pressure gauge plotted as a function of time.

3.3 Data Analysis

The primary step in the data analysis is to determine the start and end point of each test from each site. In ideal cases the static water level can be set to a specific value for each test. However in our case the water level was not entirely static before the first tests was conducted, since many of the test sites were under the influence of a background recharge, see more discussion in chapter 5.4. Because of the background recharge the reference point before each test was specified individually and used for each specific test as the static water level from which the displacements was calculated, see figure 3-5 A. Thereafter the starting point was defined as the point after the maximum displacement without major disturbance and noise, figure 3-5 A.

Primary the method used was to define the starting point as the point of maximum displacement, however early time noise was found. According to Butler (1998) this is very common using the solid slug method. Thereby the starting point was instead chosen as the point after the noise ends, according to the recommendations from Butler (1998). This point was used as the start of both the time of the test as well as for normalization of the test.

The initial displacement was thereafter calculated as the difference between the reference point and the start point. The displacement was thereafter found by subtracting all measurement points within the test with the water depth measured at the reference point. The absolute values of the rising head displacements where further used. Furthermore the time of the starting point is subtracted from all displacement times to get the start time of each test to zero, see figure 3-5 B.

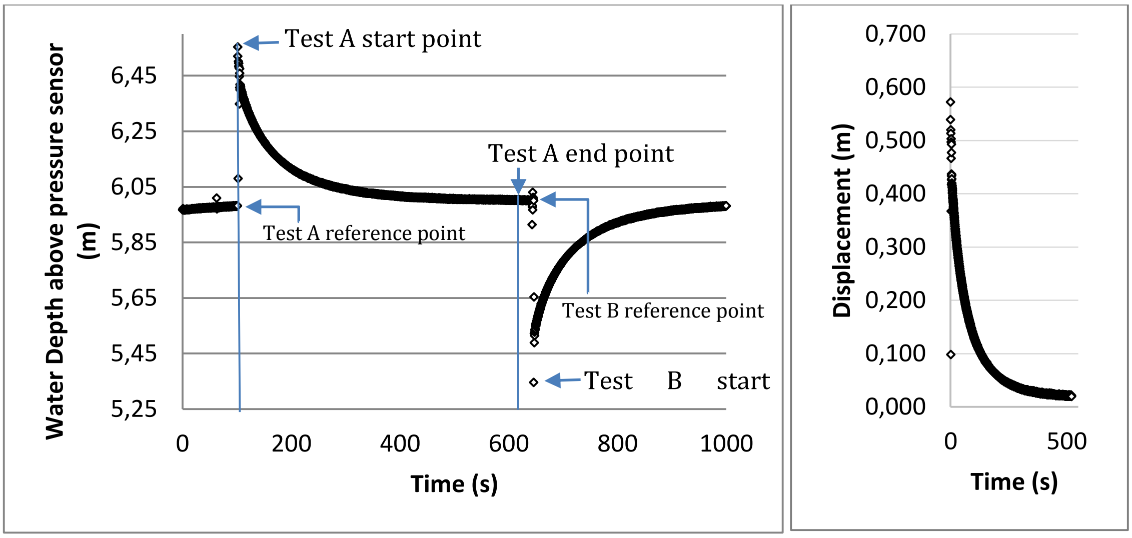


Figure 3-5 A) Diagram of how the reference, start and end point for each test was defined and B) plot of the corresponding displacement for test A.

3.4 Initial Parameters Used in Data Analysis using Aqtesolv

The data analysis was performed using Aqtesolv Slug Test Analysis solution where the methods Cooper et al. (1967) and Bouwer and Rice (1976) was used. The following parameter values are presented schematically in figure 3-6 and found in for each site in appendix B.

The static water height, H was set in the analysis as the borehole depth from the drilling report minus the water level that was observed from the dipmeter at the test site, right before starting the slug test. The length of the screens, L was chosen as the total sum of the length of the screens. Furthermore the distance to the top of the well screen, d was chosen as the length to the first screen.

Moreover the aquifer thickness, b was set as the aquifer thickness presented in the summary of drilling results, for the Bouwer and Rice (1976) analysis. However unfortunately it is not properly described how the estimate of the thickness of the aquifer was derived in the summary of drilling reports. However in the analysis using the Cooper et al. (1967) solution to translate the transmissivity, T value to the hydraulic conductivity the b value was set to the length of the well screening, since the Cooper et al. (1967) method is developed for fully penetrating wells.

As for the well radius values, the inside radius of well casing r(c) and well r (w) was 4'', which represents 0.1016 m. Since no information was found of the outer radius of well skin the radius of the well skin was set as double the well radius, which was found reasonable.

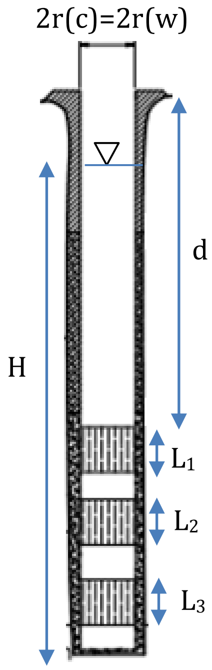


Figure 3-6 Representation of the parameters used in the slug test data analysis. Well casing radius r(c) and well radius r(w), distance to the screening d and static water head H. Length of well screen chosen as the sum of the length of the well screens, here represented as L_1, L_2 and L_3.

3.5 Test Sites

Tests were performed in both the Nampula water district and Mongicual water districts, see indicated in figure 3-7 below. Furthermore the test sites are shown in figure 3-8, also with indications of different rock types.

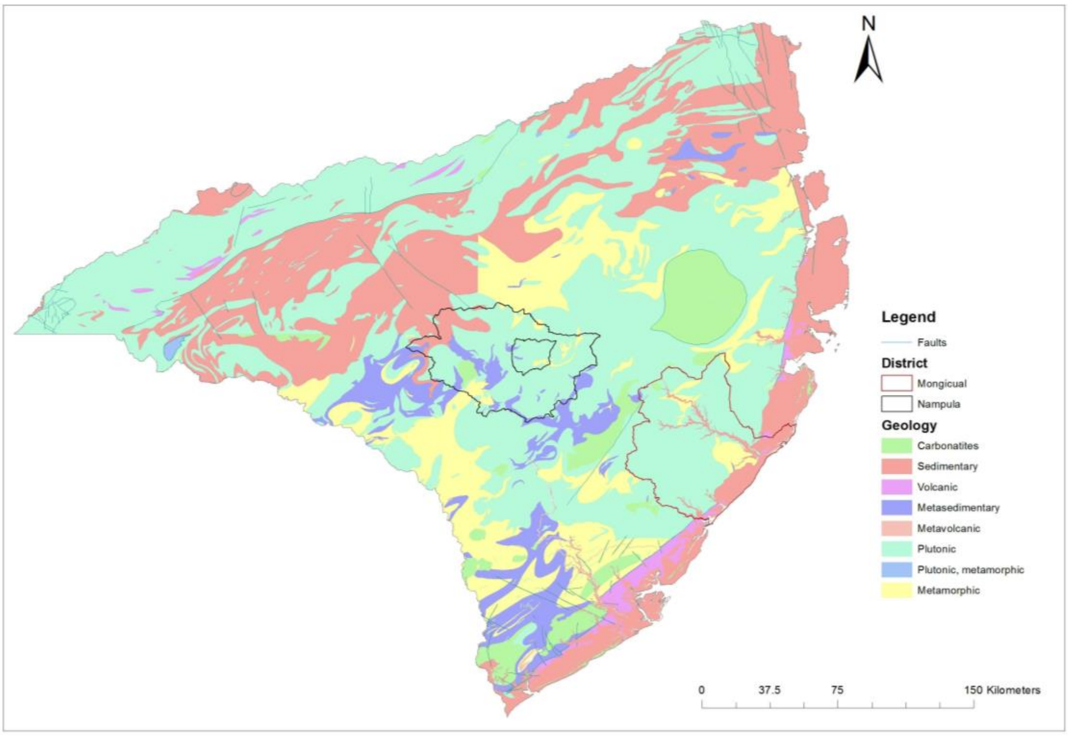


Figure 3-7 Map of Nampula Province including geology, faults and the districts of Nampula (left) and Mongicual (right). Constructed in Arc-GIS, using data from DNG (1989).

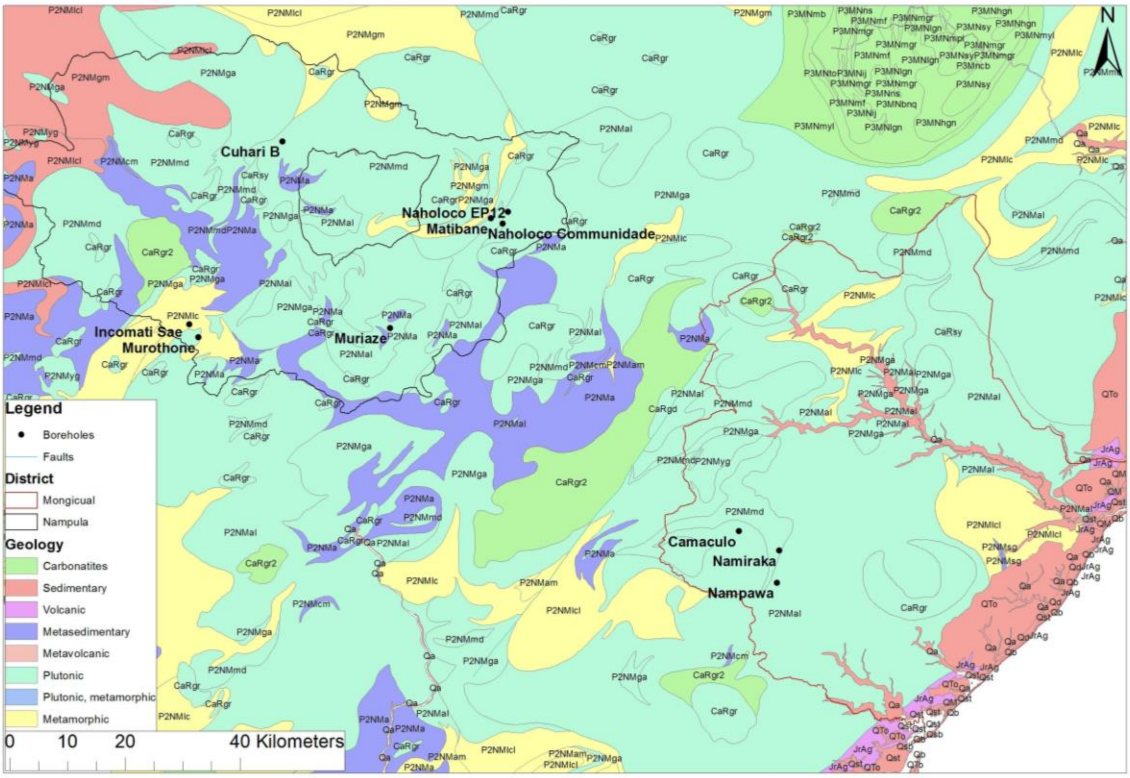


Figure 3-8 Map showing the 10 visited test sites in Nampula and Mongicual and the geology of the area. Rock type labeling: CaRgr: Equigranular medium-grained leucratic granite, P2NMal: Leucratic streaky augen granatic gneiss, P2Mmd: Hornblende-bearing granodioritic tonalatic gneiss, P2NMga: Augen granatic Gneiss, P2NMa: Amphibolitic gneiss, garnet amphibolite and P2Mlc: Medium-grained leucogranitic gneiss, migmatitic. Constructed in Arc-GIS, using data from DNG (1989).

4 Results

At each site 6-10 tests were conducted, resulting in 68 tests in total for the 10 sites covered. Each test was evaluated using Aqtesolv and the two different methods as described earlier, resulting in 136 method evaluations. Primarily the results are presented from each test site in the following order:

- Short overview of the site, borehole information, slug test specifications
- Normalized head of all test sites presented in two figures; A) using logarithmic normalized head axis and B) using logarithmic time axis, thereby represent the Bouwer and Rice (1976) solution and the Cooper et al. (1967) solution method.
- Comments of potential well development and test performance limitations
- Results of estimated hydraulic conductivity values from Bouwer and Rice (1976) and Cooper et al. (1967).
- Initial displacement from each test is presented
- Graphic examples of displacement and solutions from these two methods
- Analysis of method performance
- Comparison of falling head and rising head test

Thereafter the specific capacity and the hydraulic conductivity calculated from the specific capacity are presented for all sites. Finally the result section includes an overview of the average hydraulic conductivity from all sites calculated using slug test methods Bouwer and Rice (1976), Cooper et al. (1967) and using the specific capacity from previous pump test data.

The following information is found in appendix:

- Drilling report information including administrative post location, drilling date, borehole depth, static water level, dynamic water level, thickness of aquifer, yield, casing details, screens and gravel pack. This information was gathered from the summary of drilling report information from the Salmon Ida Company.
- The screen placements were not included in the summary of drilling reports and unfortunately the original drilling reports were not found. However the screening placement was found in the previous studies from Enkel and Sjöstrand (2013) and Andersson and Björkström (2013).
- Slug test specifications including; test date, water level primarily measured, number of tests and height from ground to reference point at the top of the metal outer casing. In addition at all test sited (excluding Cuhari B and Murothone) a water depth right before the slug test was also included, coupled with the time of both water depth measurements. To clarify, the primary water depth measurement was measured before the logging test performance and thereafter the secondary measurement was performed before the slug test.
- The data analysis parameters are also found in appendix, calculated according to the method described previously, under" Initial Parameters Used in Data Analysis using Aqtesolv".
- Aqtesolv data analysis results from given methods presenting output solution parameters and RSS values, in addition mean and standard deviation between these tests are displayed.

4.1 Cuhari B, Nampula

Cuhari B is located approximately 18 km northwest of Nampula City, find location and geology in figure 3-8. A series of 6 slug tests were conducted on the 9 of September 2015. The normalized head over time for all tests are presented in figure 4-1. The borehole was drilled in December 2010 and resistivity analysis was done by Enkel and Sjöstrand (2013). Local water government, Rapale was informed and local water committee was present at test performance. The pump was well performing and widely used according to the local population. The pump was used in the morning prior to testing.

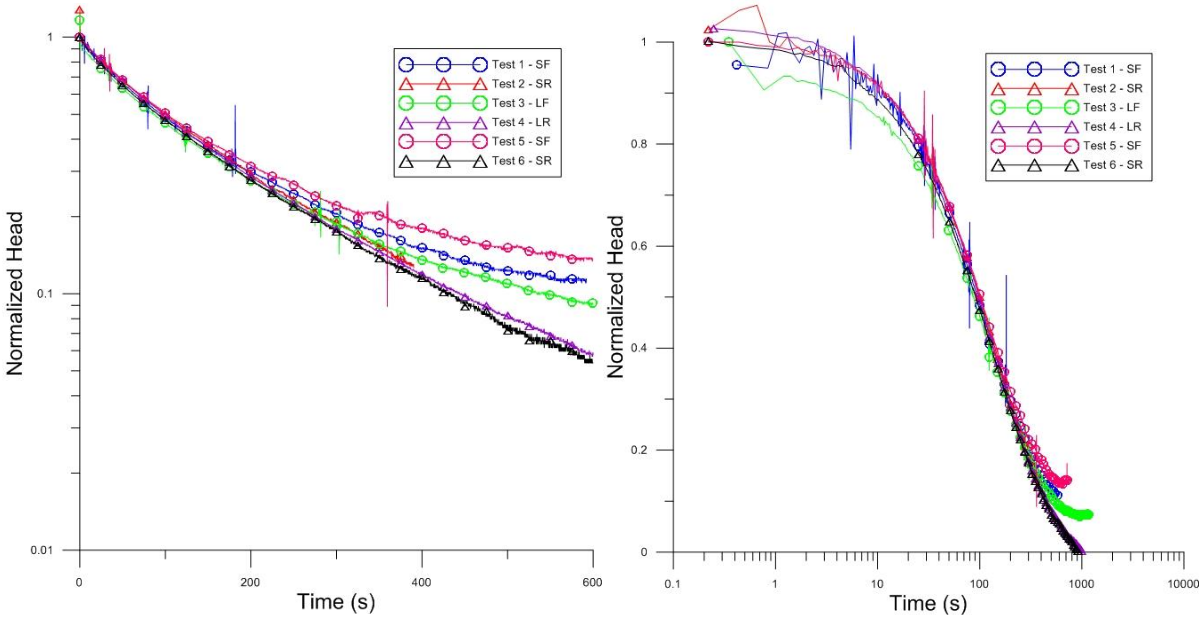
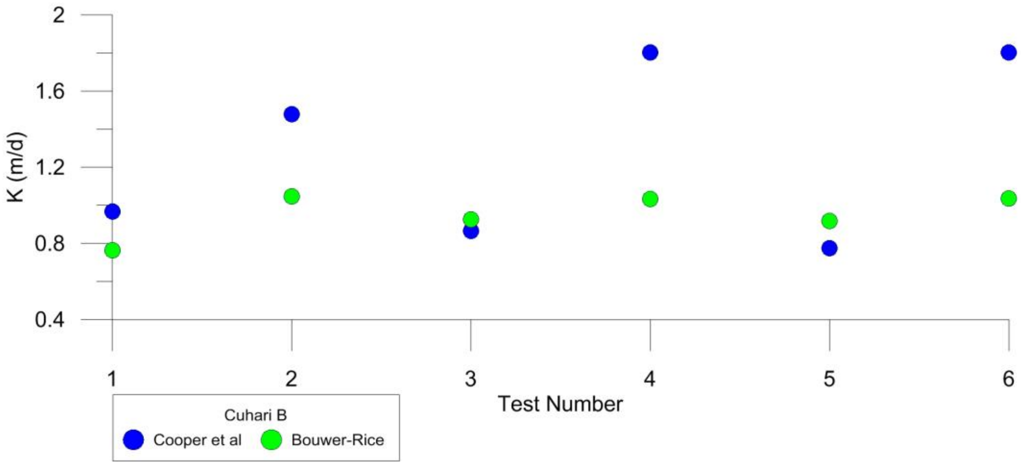


Figure 4-1 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.

No distinct changes in terms of well development from test 1 and test 6 are found in figure 4-1B. This might be due to sensitivity in set of the first test point, and thereby the set of initial displacement. Distinct early time noise in data was found at all test except test number 4 and 6. There was a slight background recharge during the test where the water level did not stabilize at the same level but was subject to a slight increase over time. The “static” water column rise from 5.63 m to 5.83 m over the test period, representing a 20 cm increase over 1 hour and 35 min. In figure 4-1A all falling head tests have a lower and a less linear decline after about 300 second, compared to all the rising head tests, possibly an effect of the background recharge.



Test	H_0 (m)
1F	0.49
2R	0.499
3F	0.96
4R	0.975
5F	0.471
6R	0.503

Figure 4-2 A) The results of hydraulic conductivity from the test using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

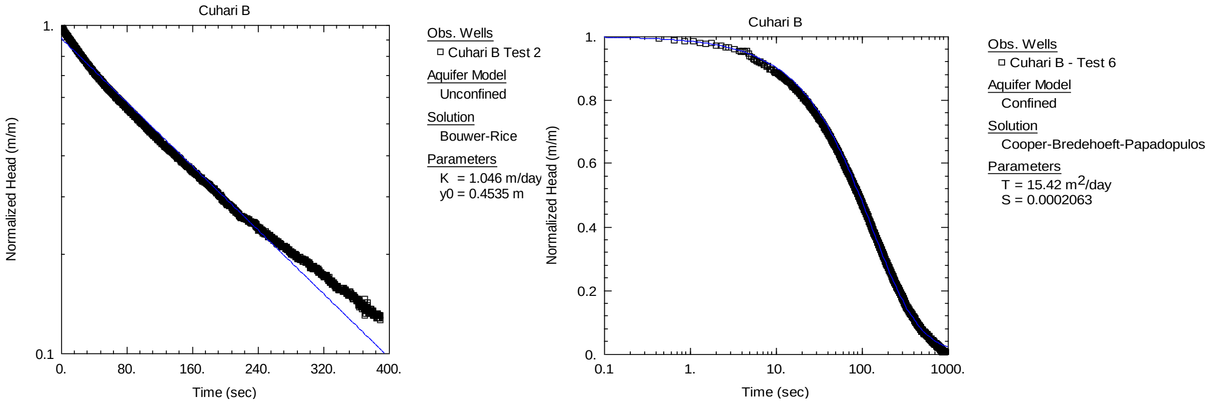


Figure 4-3 Measured normalized head as a function of time (squares) and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right.

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-2. Figure 4-3 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head at the Cuhari site using Aqtesolv. From the Bouwer and Rice (1976) method the mean hydraulic conductivity from all test where 0.954 m/day, and from the Cooper et al. (1967) the mean value was 1.282 m/day. The standard deviation between the Bouwer and Rice (1976) solutions was more than 4 times less than the standard deviation between the Cooper et al. (1967) solutions, 0.10 vs. 0.43. In terms of estimated hydraulic conductivity there was a difference between the rising and falling head tests, especially using the Cooper et al. (1967) method. The falling head tests had a mean hydraulic conductivity value of 0.869 m/day and 0.868 m/day using Bouwer and Rice (1976) respectively Cooper et al. (1967). While the rising head tests had a mean value of 1.03 m/day and 1.695 both using Bouwer and Rice (1976) respectively Cooper et al. (1967).

4.2 Murothone, Rapale

Murothone is situated about 36 km southwest of Nampula city, find location and geology in figure 3-8. A series of 6 slug tests were conducted on the 10 of September 2015. The normalized head over time for each test are presented in figure 4-4. The borehole was drilled in December 2010 and resistivity analysis was performed by Enkel and Sjöstrand (2013). Local water government, Anchilo was informed however no local water committee was found for this pump. No maintenance was previously done at the site. The pump gave water but was not well performing and not used as drinking water because of salty tasted water according to the local population.

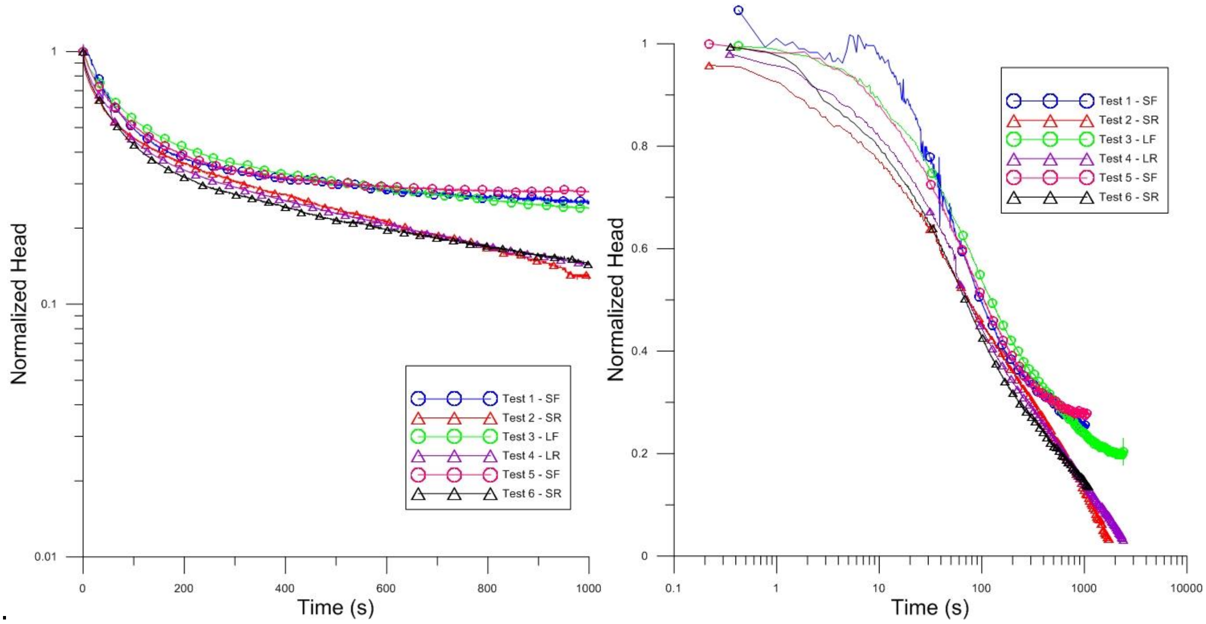
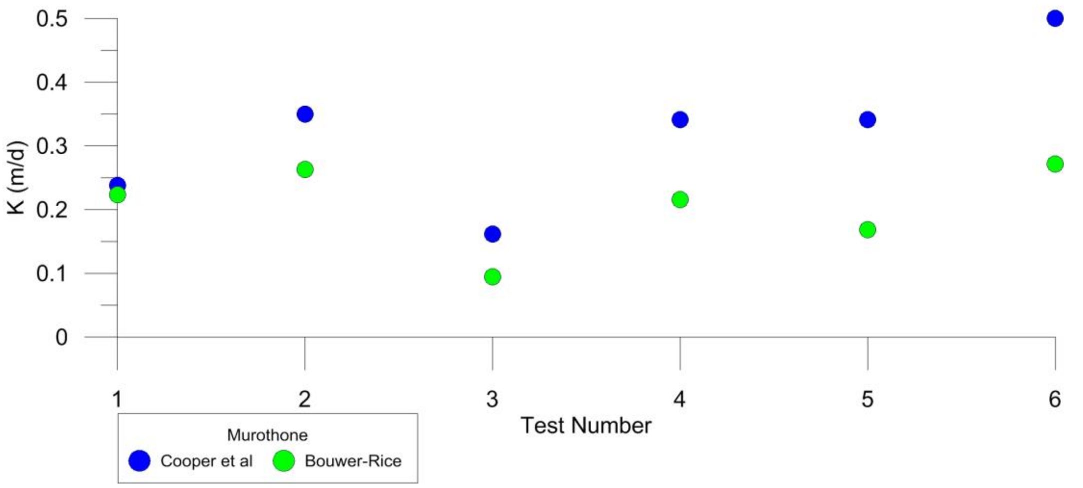


Figure 4-4 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.

Very slow recovery of the site coupled with a high background recovery complicated the test performance at this site. From the drilling report the static water level was at 2.5 m and the dynamic water level at 29.89 m. The water depth before logging was around 21 meter. Since the first screen is placed between 22.19-27.89 m from the reference point the pressure gauge was unfortunately located at the depth of the screening, at about 27.6 m depth. Also, potentially the dismounting of the pump tubing, the logging and/or slug test performance may have unclogged the well casing given the ongoing recovery during the test. According to local sources, the pump was performing better days after the test than prior to the testing. An interesting note from the test site, just about 100 m from the well there are hand dug water wells and a sump land, where the water level is just 50-0 cm from the ground and water is used for both drinking and cleaning of clothes. A quite big difference from the water level at 21 meter found in the well prior to testing.

During test performance the water level after the rising head tests did not stop rising, however the test was ended within 5% of the measured initial displacement. However for the falling head test the water depth did not return to 5% of the initial displacement and test was ended when water level was considered stable. First stable point before first slug test measurement was with 6.59 m of water column above the pressure gauge, and the last stable point measured was before the last rising head measurement and at 6.93 m, representing an background increase of 34 cm during the 4 hours of total slug test time. Comparing the falling head and the rising head test there was a difference in slope in the end of the recovery from the test probably due to the faster rising head test recovery because of background recovery, see figure 4-4 A and B. More specifically the rising head tests 2, 4 and 6 flattens out in the end of the test. Early time noise was found at all test except test number 2. Seen in figure 4-4 B is that test 1 was quite noisy for a very long time period, however a starting point was chosen when the noisiest part was taken away.



Test	H_0 (m)
1F	0.289
2R	0.351
3F	0.779
4R	0.863
5F	0.381
6R	0.458

Figure 4-5 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

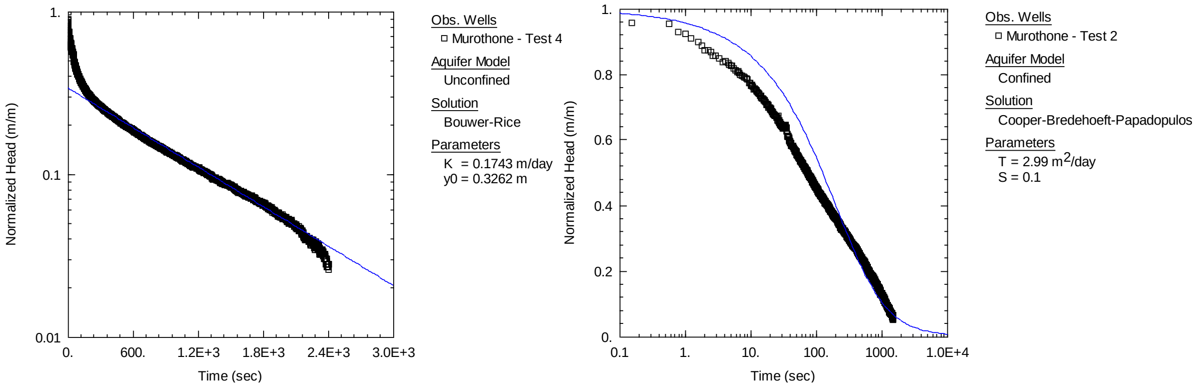


Figure 4-6 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-5 A. Figure 4-5B shows the measured initial displacement after removal of early time noise. Figure 4-6 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv.

The double straight line method (Bouwer, 1989) was needed in order to estimate the hydraulic conductivity using Bouwer and Rise (1976). This may be due to the placement of the pressure sensor at the same level as the screens, potentially making the response from the gravel pack appear more in the measurements (Butler, 1998). The primary slope, according to Bouwer (1989) probably representing the gravel pack had a mean hydraulic conductivity of 1.43 m/day. The slope that more probably is representing the formation was found by fitting the line to the range from 0.20-0.30 normalized displacement, according to Bouwer (1989). This method yielded a mean hydraulic conductivity from the Bouwer (1989) solution of 0.21 m/day. The mean value of the hydraulic conductivity using the Cooper et al. (1967) was 0.32 m/day.

Moreover in the data analysis the results of hydraulic conductivity is higher for the rising head test then for the falling head test, for both methods and all data analysis, except when test using the initial slope in the Bouwer and Rice (1976). The difference is also seen in the solutions, where the mean value for falling head was about 0.162 m/day and 0.322 m/day, while the mean value was 0.250 m/day and 0.397 m/day for the rising head test, for Bouwer and Rice (1976) respectively Cooper et al. (1967).

4.3 Naholoco EP1-2, Anchilo

Naholoco EP1-2 is situated about 25 km east of Nampula city, find location and geology in figure 3-8. A series of 6 slug tests were conducted on the 11 of September 2015. In particular the order was single slug, double slug and then single slug again. All performed with both falling head then rising head test. The normalized head for each test are presented in figure 4-7. The borehole was drilled in February 2011 and resistivity analysis was done by Enkel and Sjöstrand (2013). Local water government, Anchilo was informed. The pump was well performing and widely used according to the local population. The pump was used in the morning before testing.

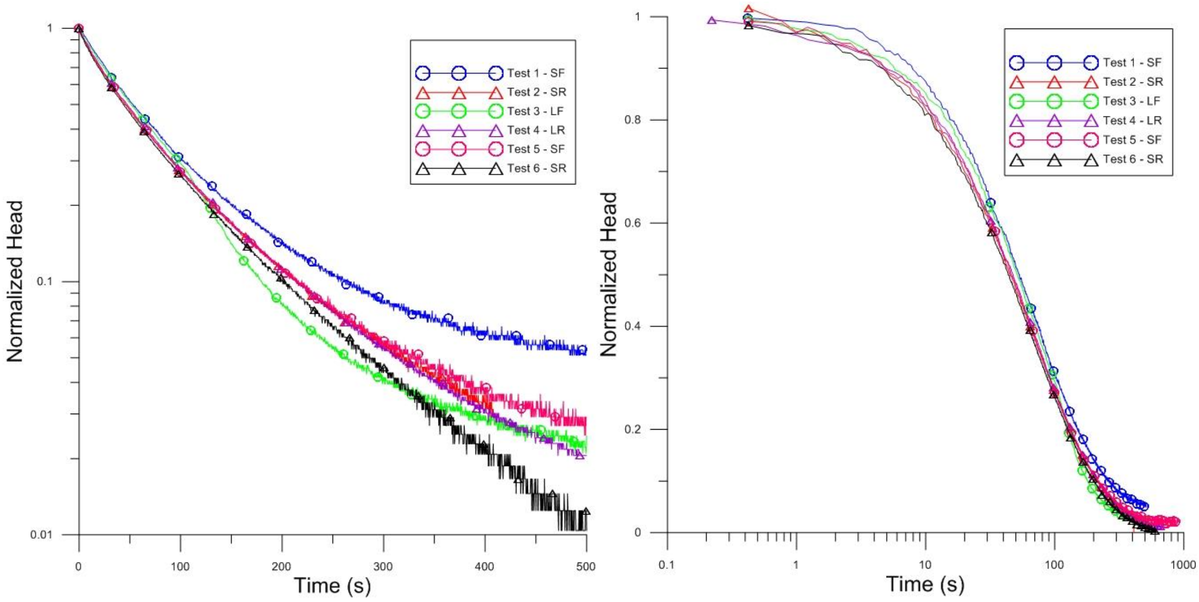
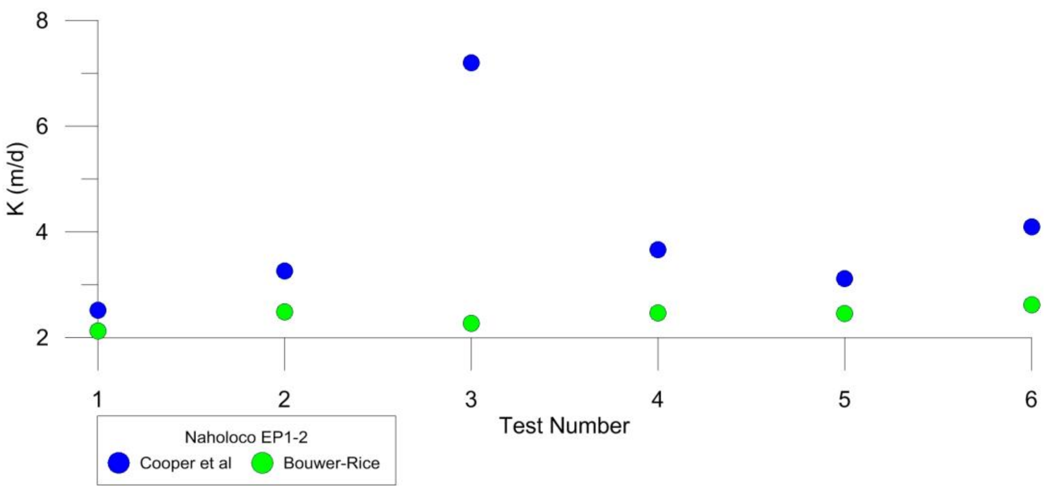


Figure 4-7 Normalized head using Bouwer and Rice (1976) to the left and Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.

The Naholoco EP1-2 borehole had a quick response and the entire test was performed during 1 hour. If trusting the chosen starting points a potential positive well development can be seen in figure 4-7 B, since test 1 is above test 6. However noted should be that early time noise was found and disregarded in all tests.

The Bouwer (1989) method was not found to be needed. The borehole was deep, 45.42 m and with the primary screening at 32.3 m depth, and thereby not close to the water level at 13.73 m depth before slug test. There was no distinct increase in background water level, first stable measurement was 5.98 m of water column above sensor and last stable water measurement as 6.00 m of water column above sensor.



Test	H_0 (m)
1	0.391
2	0.478
3	0.812
4	0.817
5	0.445
6	0.481

Figure 4-8 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

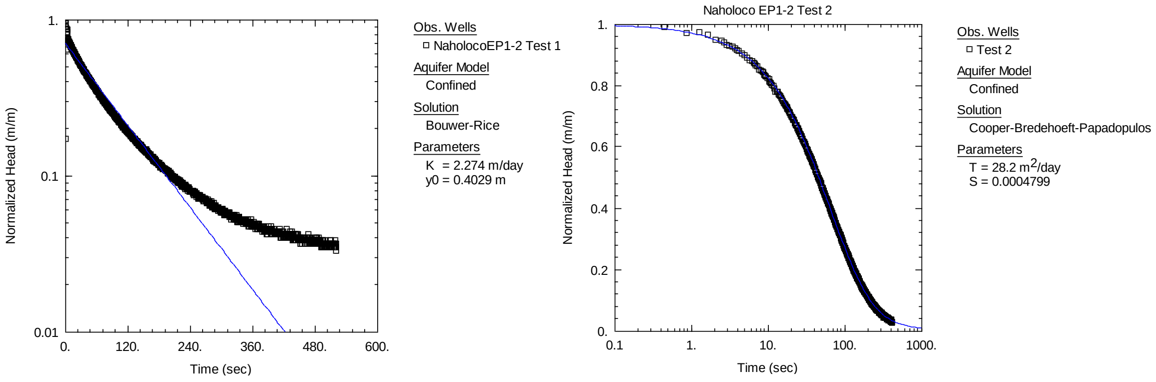


Figure 4-9 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-8 A. Figure 4-8B shows the measured initial displacement after removal of early time noise. Figure 4-6 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv. However test 3 had a special development see test 3 in figure 4-7 A. After about 150 sec the displacement decrease dramatically and then it evens out, perhaps this is due to a measured infiltration into the slug of about 4 dl of water during this test. This test will be disregarded in the results section. Thereby the mean hydraulic conductivity from the Bouwer and Rice (1976) analysis was 2.40 m/day, standard deviation between the tests was 0.165. From the Cooper et al. (1967) solution the result had a mean value of 3.33 m/day; standard deviation between the tests was 0.53. Including test 3 gives the results of the mean hydraulic conductivity from the Bouwer and Rice (1976) analysis was 2.40 m/day, standard deviation between the tests was 0.16. Form the Cooper et al. (1967) solution the result had a mean estimated hydraulic conductivity of 3.975 m/day; standard deviation between the tests was 1.52.

No persistent difference between falling head and rising head nor single and double slug form the data analysis hydraulic conductivity results. However, the mean hydraulic conductivity estimated from the falling head tests was lower than the mean of the rising head test.

4.4 Naholoco Communidade, Anchilo

Naholoco Communidade is situated about 25 km east of Nampula city, find location and geology in figure 3-8. A series of 8 slug tests were conducted on the 12 of September 2015. In particular the order was single slug, double slug and then two single slug measurement. All performed with both falling head then rising head test. The normalized head over time for each test are presented in figure 4-10. The borehole was drilled in February 2011 and resistivity analysis was done by Enkel and Sjöstrand (2013). Local water government, Anchilo was informed and local water committee was present at test performance. The pump was well performing and widely used according to the local population. The pump was used in the morning before testing.

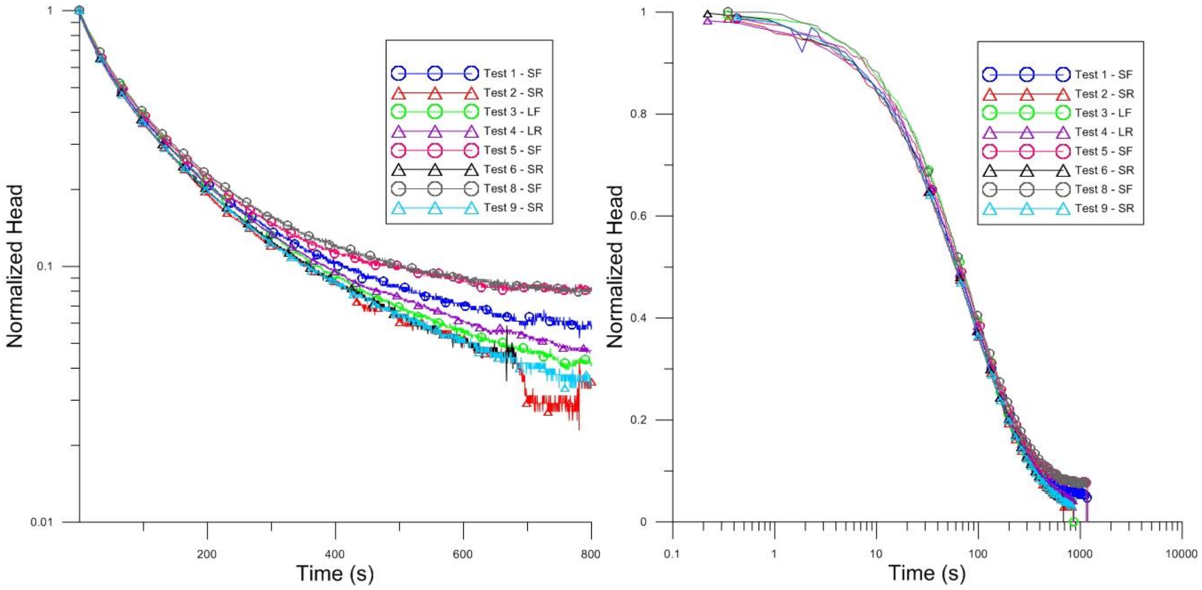
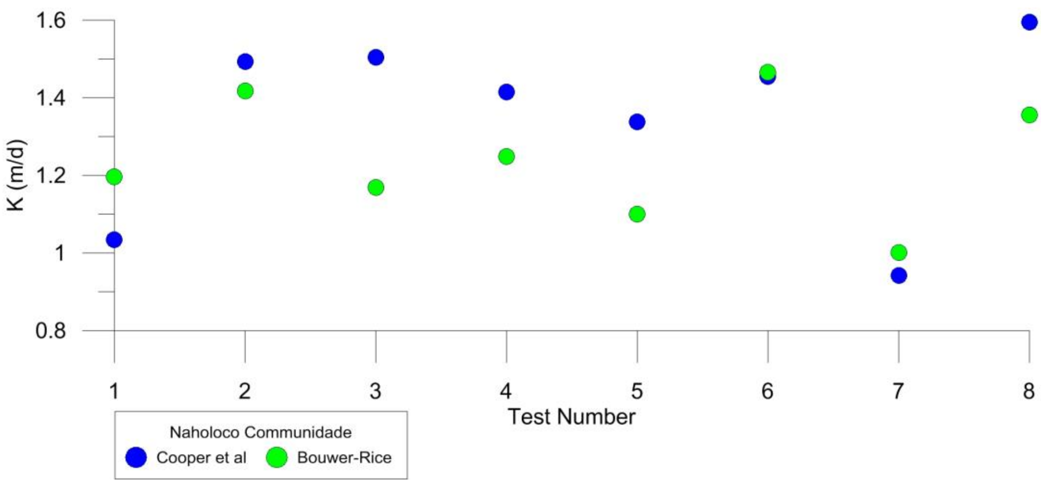


Figure 4-10 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.

No distinct well development was found from the figure 4-10 B, however in figure 4-10 A it seen that the rising head test separates generally from the falling head test in the later parts of the tests. The background recharge is of about 7 cm for the test period of 2 hours. In terms of initial displacement the falling head have a generally higher value then the rising head in all tests except the first test using Bouwer and Rice (1976) and the last test using Cooper et al. (1967). There was only a slight water intake into the slug of about 1.5, 2, 0.5 and 0.3 dl found when pouring out the water in the slug after the each uptake of the slug between the rising and falling head test. The pressure gauge was situated at 19.67 from the reference point, well above the first well screen at 24.3 m below the reference point for the borehole of totally 38.6 m depth.



Test	H_0 (m)
1	0.458
2	0.48
3	0.835
4	0.939
5	0.447
6	0.477
7	0.427
8	0.477

Figure 4-11 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

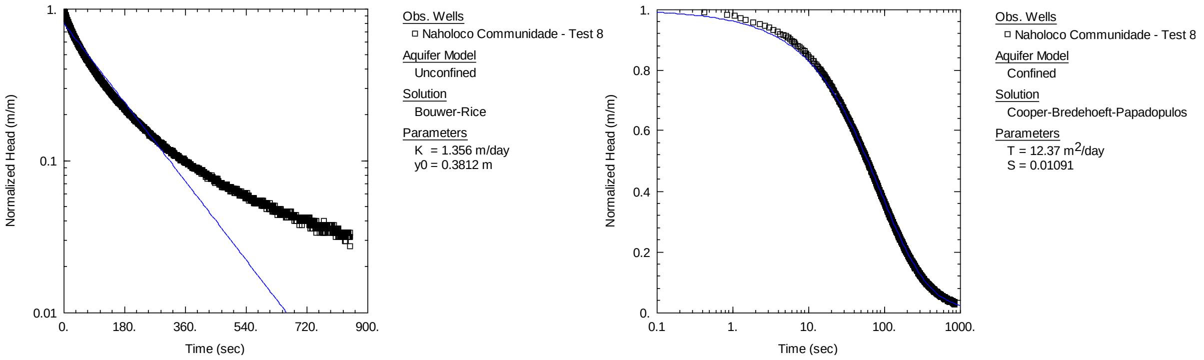


Figure 4-12 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-11A. Figure 4-11 B shows the measured initial displacement after removal of early time noise. Figure 4-12 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv.

Cooper et al. (1967) method gave a good fit using automatic fitting option in Aqtesolv. However the 0.2-0.3 normalized head was used according to the double straight line effect (Bouwer, 1989) Mean hydraulic conductivity from Bouwer and Rice was found to be 1.24 m/day and 1.34 m/day using Cooper et al. (1967). The standard deviations between the tests were 0.15 for Bouwer and Rice (1976) and 0.22 using Cooper. Moreover the mean hydraulic conductivity value for falling head tests are found to be lower than the mean value for rising head test, 82% (Bouwer and Rice, 1976) and 81% (Cooper et al., 1967) of the mean values for the rising head.

4.5 Nampawa, Luipo

Nampawa is situated about 11 km south of Luipo, find location and geology in figure 3-8. A series of 6 slug tests were conducted on the 15 of September 2015. The normalized head of all tests are presented in figure 4-13. The borehole was drilled in November 2012 and resistivity analysis was done by Andersson and Björkström (2013). Local water government, Luipo was informed and local water committee was present at test performance. The pump was well performing and widely used according to the local population. The pump was used in the morning before testing. Noted was that there were also many hand dug wells in the local village.

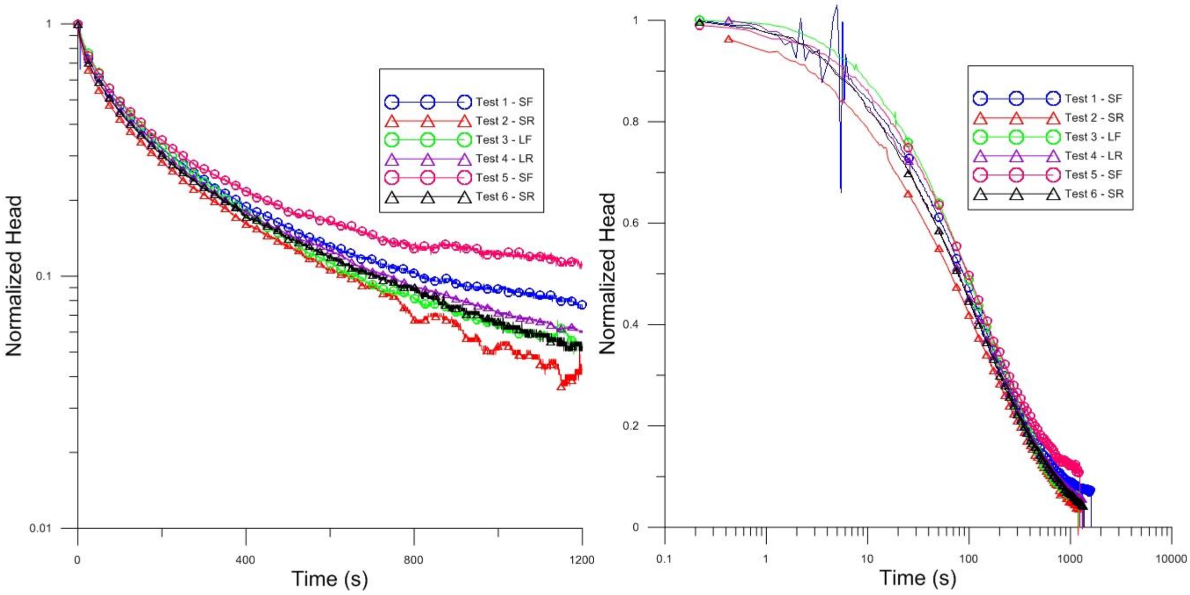
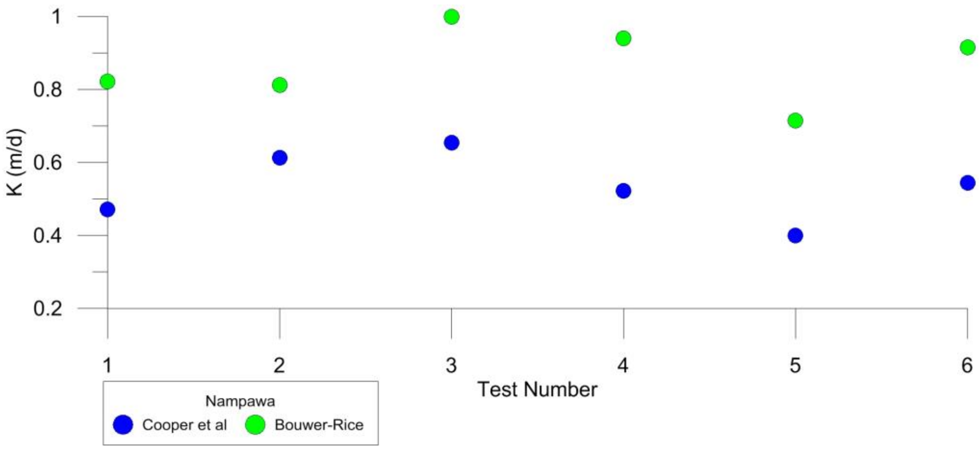


Figure 4-13 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.

The pressure gauge situated at a depth from the reference point of 11.63 m, compared to that the first well screen was situated at 27.2 m depth for the total water depth of 33 m. The pressure gauge was thereby not placed close to the screens. The borehole had a background recharge of about 7 cm during the total test performance of 2 hours and 15 min. Well development in figure 4-13B is difficult to estimate due to early time noise. In figure 4-13A the two single slug falling head tests, test 1 and 5, are not declining as fast as the other tests. The double slug falling head test, test 3 better follows the rising head tests.



Test	H_0 (m)
1	0.429
2	0.491
3	0.776
4	0.92
5	0.411
6	0.455

Figure 4-14 The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

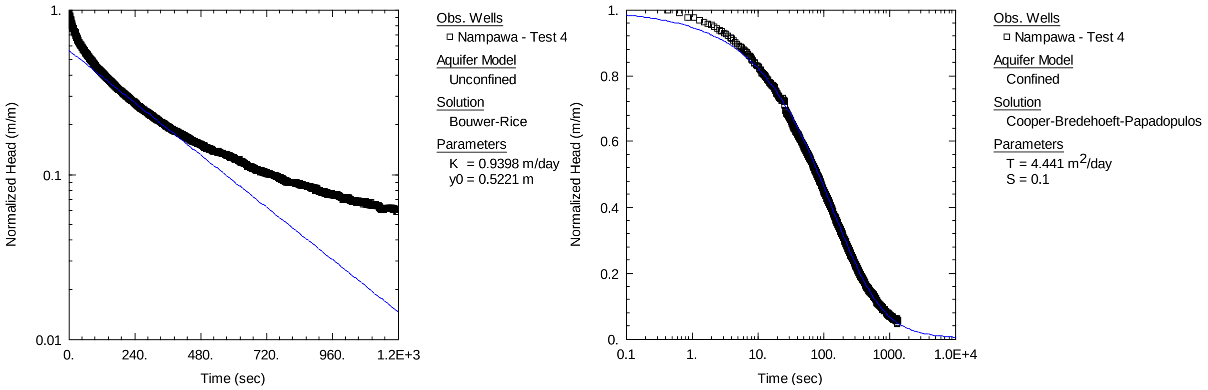


Figure 4-15 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-14A. Figure 4-14B shows the measured initial displacement after removal of early time noise. Figure 4-15 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv.

The double Bouwer and Rice (1976) solution was used. The mean hydraulic conductivity using the Bouwer and Rice (1976) solution was found to be 0.87 m/day. Using the Cooper et al. (1967) yielded a mean hydraulic conductivity from the tests of about 0.53 m/day. The standard deviations between the tests are 0.09 and 0.08 for Bouwer and Rice (1976) resp. Cooper et al. (1967). There is a slight increase in conductivity values for rising head tests, where the falling head tests have an average value 95% (Bouwer and Rice, 1976) and 91% (Cooper et al., 1967) of average for the rising head tests. More specifically the estimated hydraulic conductivity values for rising head test are higher for the single slug tests, however this is not true for the double slug tests., see figure 4-14.

4.6 Namiraka, Luipo

Namiraka is situated about 6 km south-west of Luipo, find location and geology in figure 3-8. A series of 6 slug tests were conducted on the 16 of September 2015. The normalized head for each test are presented in figure 4-16. The borehole was drilled in October 2012 and resistivity analysis was done by Andersson and Björkström (2013). Local water government, Luipo was informed and local water committee was present at test performance. The pump was well performing according to the local population. However complains were made about the water tasting salty, however the water is used as drinking water. The pump was used in the morning before testing.

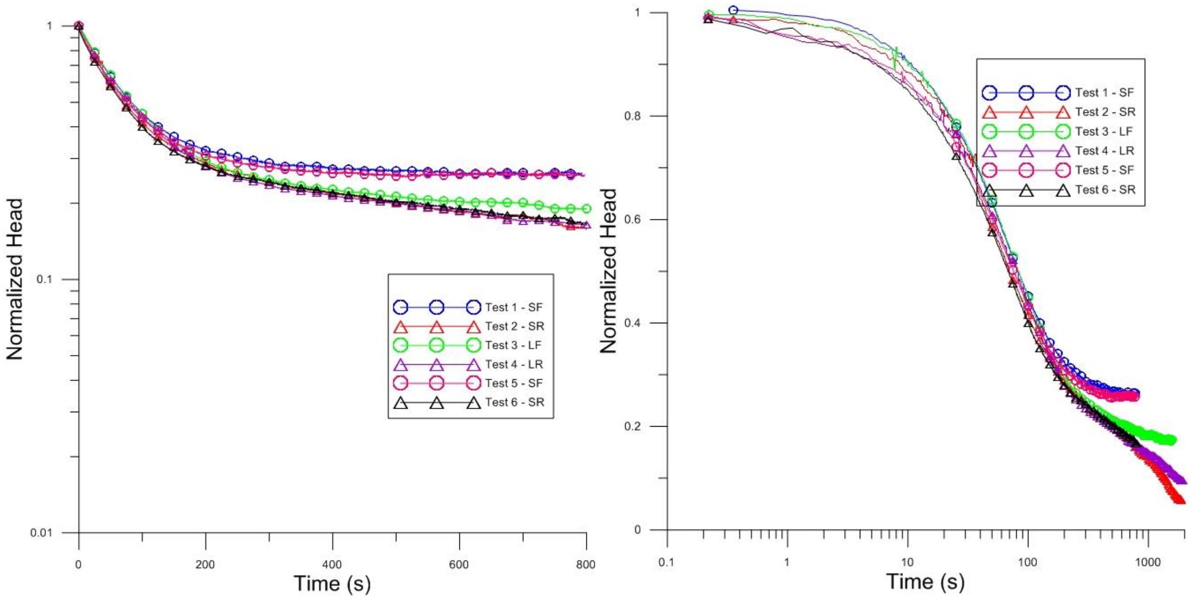
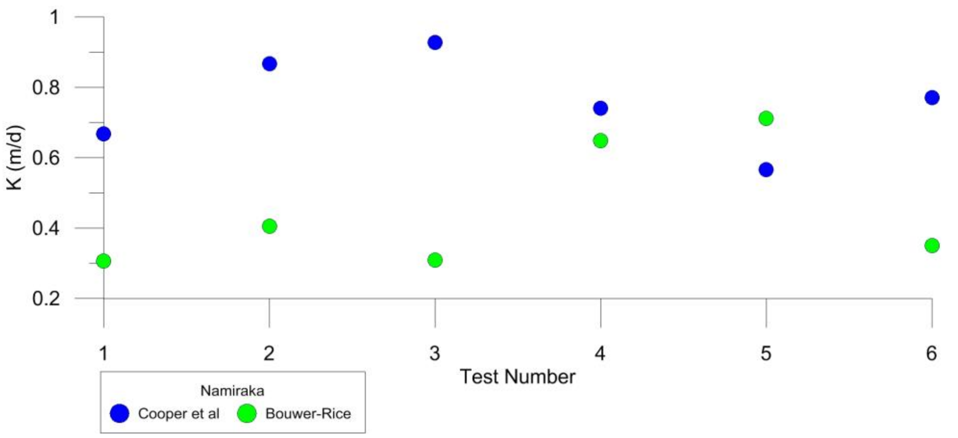


Figure 4-16 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.

The pressure gauge was at a position about 14.39 m below the reference point, while the first screen was at a position of 32.2 m below the reference point, in the 38.9 m deep borehole. Thereby not close to the screen. During testing there was a background recharge of about 27 cm during about 3 hours and 15 min of testing. It is difficult to estimate well development using figure 4-16B, due to early time noise. Figure 4-16A show that the two single slug falling head tests deviate from the rising head test, and never reaches 0.2 of the normalized head. The double slug falling head test deviate a slightly from the rising head tests.



Test	H_0 (m)
1	0.425
2	0.458
3	0.814
4	0.944
5	0.458
6	0.47

Figure 4-17 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

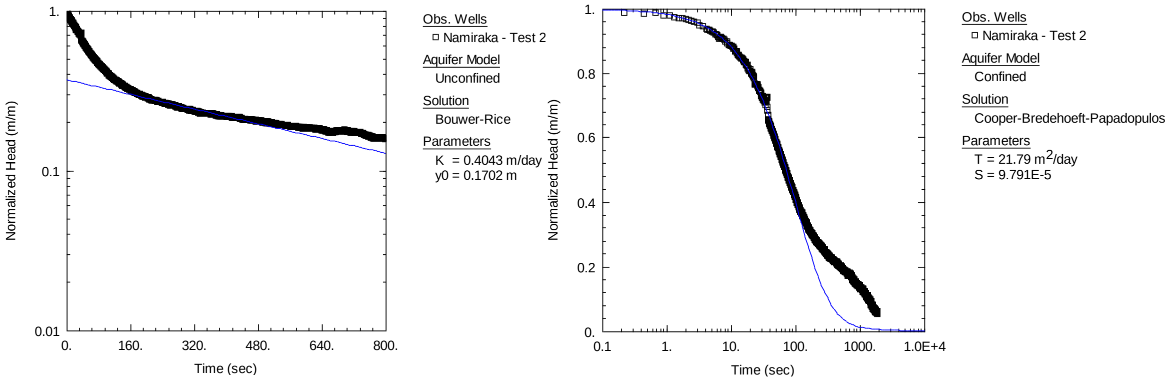


Figure 4-18 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-17A. Figure 4-17B shows the measured initial displacement after removal of early time noise. Figure 4-18 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv. The normalized head using log scaled y-axis, figure 4-16A, had very steep initial slope following a very low later slow and it was unclear which slope best represented the formation. The automatic fit did not give a good graphical result for this test. The 0.2-0.3 normalized head for double slug test from Bouwer (1989) was used. However the single slug falling head tests was fitted at 0.3 normalized head since they never reach 0.2 normalized head.

The estimated mean hydraulic conductivity using the Bouwer (1989) update of the Bouwer and Rice (1976) method was 0.46 m/day. Using the Cooper et al. (1967) yielded a mean hydraulic conductivity from the tests of about 0.76 m/day. The standard deviations between the tests are 0.16 and 0.12 for Bouwer (1989) resp. Cooper et al. There is a slightly higher conductivity values for rising head tests, where the falling heads tests have an average value 95% (Bouwer, 1989) and 91% (Cooper et al., 1967) of average for the rising head tests. More specifically the estimated hydraulic conductivity values for rising head tests are higher for the single slug tests, however for the double slug test estimated from the Cooper et al. (1967) solution and the two last tests for Bouwer (1989) the falling head test where estimated to have higher values.

4.7 Camaculo, Luipo

Camaculo is situatedabout 10 km west of Luipo, find location and geology in figure 3-8. A series of 8 slug tests were conducted on the 17 of September 2015. In particular the order was single slug, double slug and finally two single slug measurement. All performed with both falling head then rising head test. The normalized head of the displacement over time for each test are presented in figure 4-19. The borehole was drilled in December 2012 and resistivity analysis was done by Andersson and Björkström (2013). Local water government, Luipo was informed, however unclear if the local water committee was present at test performance. The pump was well performing and widely used according to the local population. Pump was used in the morning before testing. Unfortunately this village was not informed the day prior to our visit, however thereby the pump was probably not as heavily pumped in the morning.

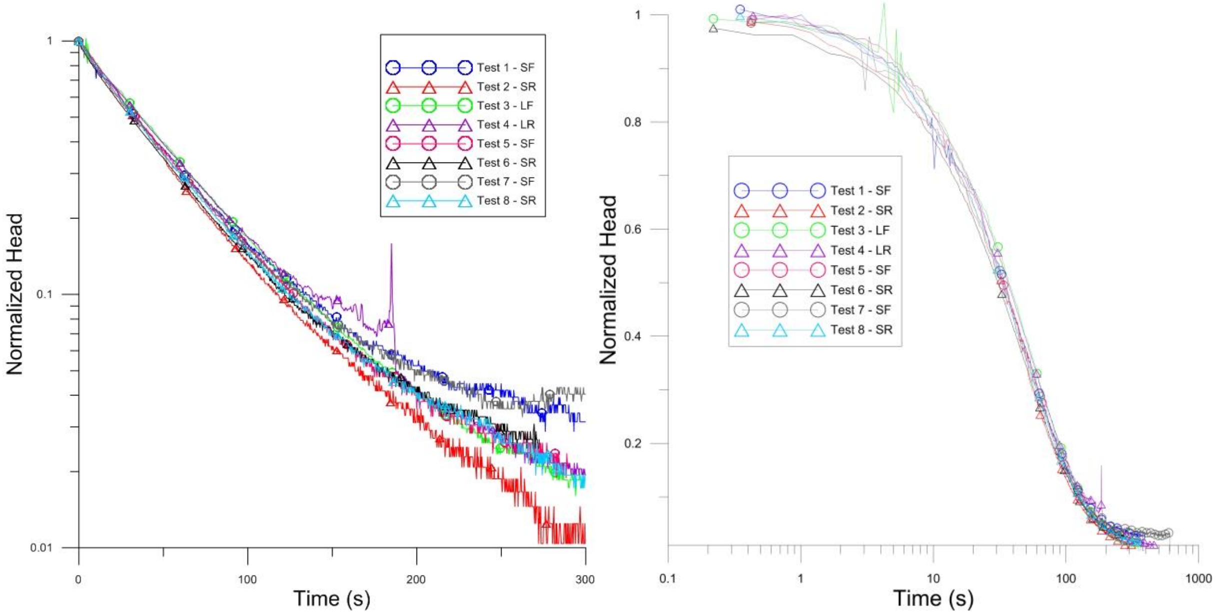
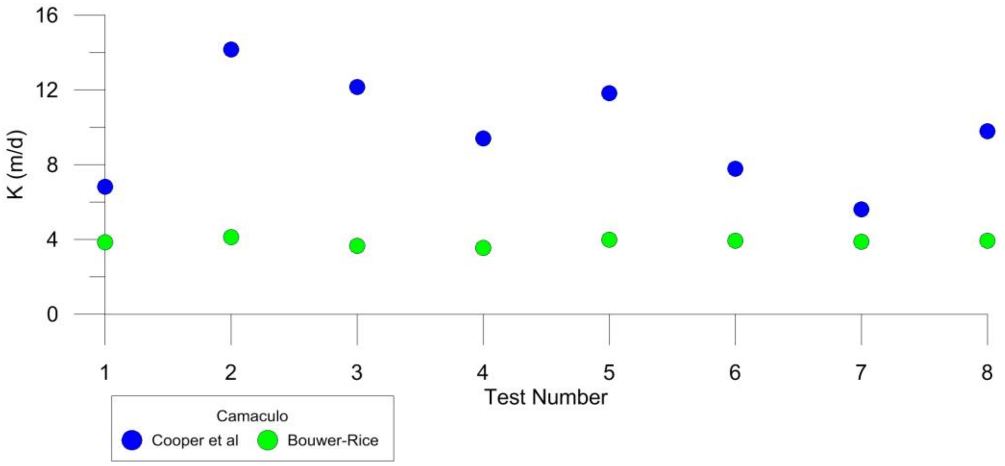


Figure 4-19 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.



Test	H_0 (m)
1	0.382
2	0.481
3	0.81
4	0.926
5	0.424
6	0.486
7	0.396
8	0.465

Figure 4-20 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

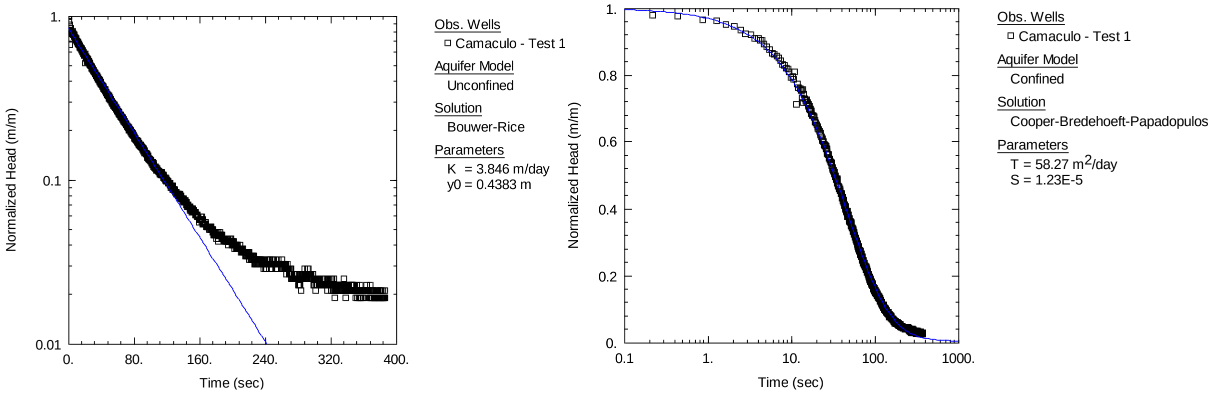


Figure 4-21 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-20A. Figure 4-20B shows the measured initial displacement after removal of early time noise. Figure 4-21 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv. The results fit very well to both methods in terms of sum of squared residuals. More stable results from the Bouwer and Rice (1976) method, with a mean K value of 3.4 m/d.

At this site the highest estimated values in terms of hydraulic conductivity was estimated compared to the other visited sites. Mean estimated hydraulic conductivity values was 3.85 m/day using Bouwer and Rice (1976) and 9.69 m/day using Cooper et al. (1967). The standard deviation between the tests was 0.17 for the Bouwer and Rice (1976) and 2.72 for Cooper et al. (1967). Comparing falling and rising head the rising head tests yielded higher hydraulic conductivity values, 8.87 and 7.44 m/day for Bouwer and Rice (1976) resp. Cooper et al (1967). The Falling head test had an average of 3.83 resp. 5.36 m/day. Seen is that the Bouwer method presented more consistent results, with lower standardisation between the tests than the Cooper method at this site. However both method gave good results in terms of low RSS values.

4.8 Matibane, Anchilo

Matibane is situated about 22 km east of Nampula city, find location and geology in figure 3-8. A series of 6 slug tests were conducted on the 21 of September 2015. The normalized head of the displacement over time for each test are presented in figure 4-22. The borehole was drilled in December 2012 and resistivity analysis was done by Enkel and Sjöstrand (2013). Local water government, Anchilo was informed and local water committee was present at test performance. The pump had not been functioning for 1 year prior to our visit because of a crack in the pump pipe, however the technicians managed to remove the found crack in the pump tubing and leave a working pump for the village, figure 4-23.

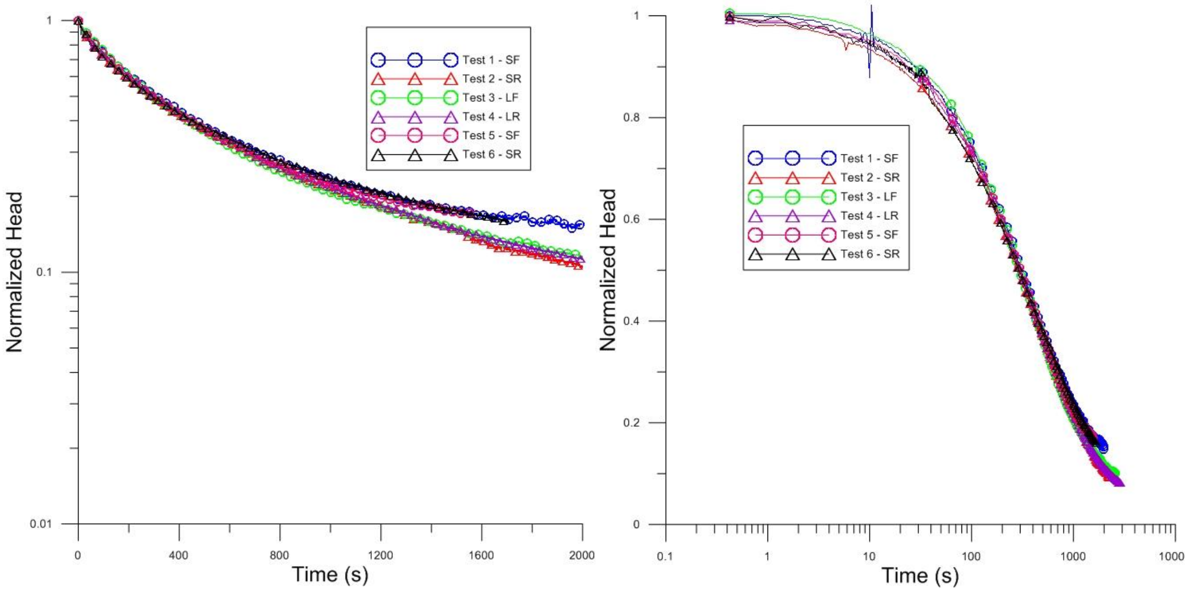
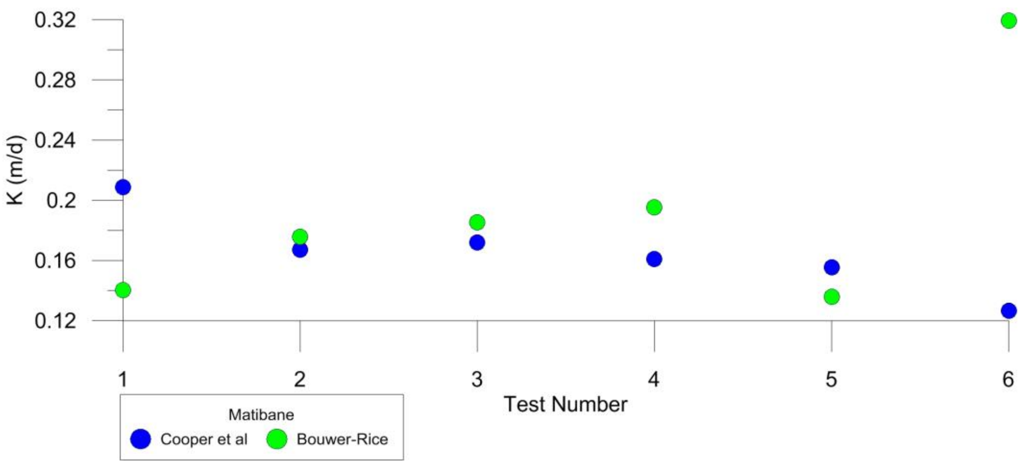


Figure 4-22 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.

Figure 4-23 The crack in the pipe that made the pump non-functioning for a year prior to testing (left) and the now used pump (right).



Test	H_0 (m)
1	0.467
2	0.498
3	0.895
4	0.964
5	0.477
6	0.501

Figure 4-24 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

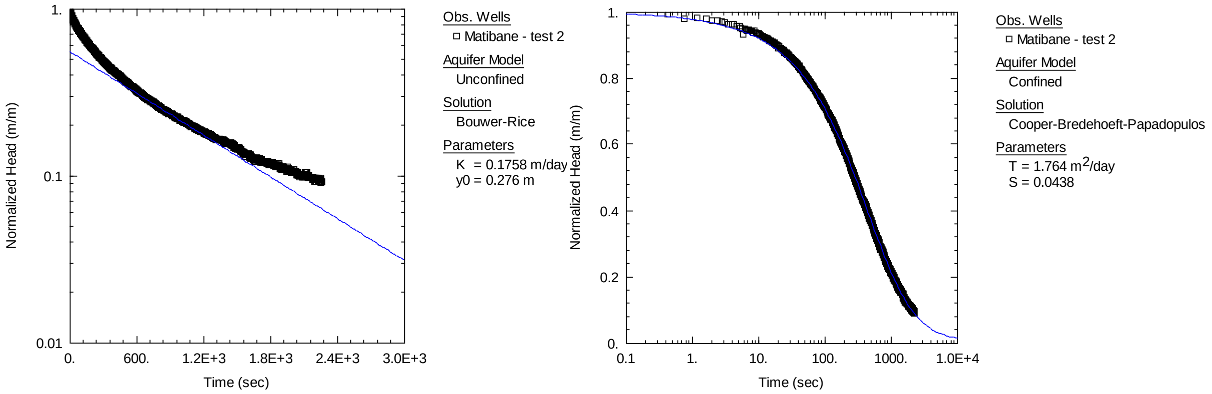


Figure 4-25 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-24A. Figure 4-24B shows the measured initial displacement after removal of early time noise. Figure 4-25 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv.

The placement of the pressure sensor at 15.2 m was high above the first well screen, placed at a depth of 34.35 m. Even so, the double Bouwer (1989) method was used since a higher slope was found in the beginning of the test compared to the later part. The primary slope was found to have a mean hydraulic conductivity of 0.50 m/day; however the 0.2-0.3 normalized head fitting yielded a mean hydraulic conductivity of 0.19 m/day. The standard deviation between the tests was found to be 0.05 for the initial slope and 0.06 for the 0.2-0.30 normalized head fit.

The Cooper et al. (1967) method yielded a mean hydraulic conductivity of 0.17 m/day and a standard deviation of 0.02. There is a difference in the results comparing the falling head and the rising head measurements. The falling heads tests have an average hydraulic conductivity value 94% (Bouwer and Rice (1976)) and 87% (Cooper et al., 1967) of average for the rising head tests.

4.9 Incomati Sae “D” (4)/(3) , Rapale

Incomati Sae “D” is situated about 35 km northwest of Nampula city, find location and geology in figure 3-8. A series of 6 slug tests were conducted on the 23 of September 2015. The normalized head over time for all tests are presented in figure 4-26. The borehole was drilled in March 2011 and resistivity analysis was done by Enkel and Sjöstrand (2013). Local water government, Rapale was informed, however it was not noted if the local water committee was present at test performance. The pump was well performing and widely used according to the local population. The pump was used in the morning before testing.

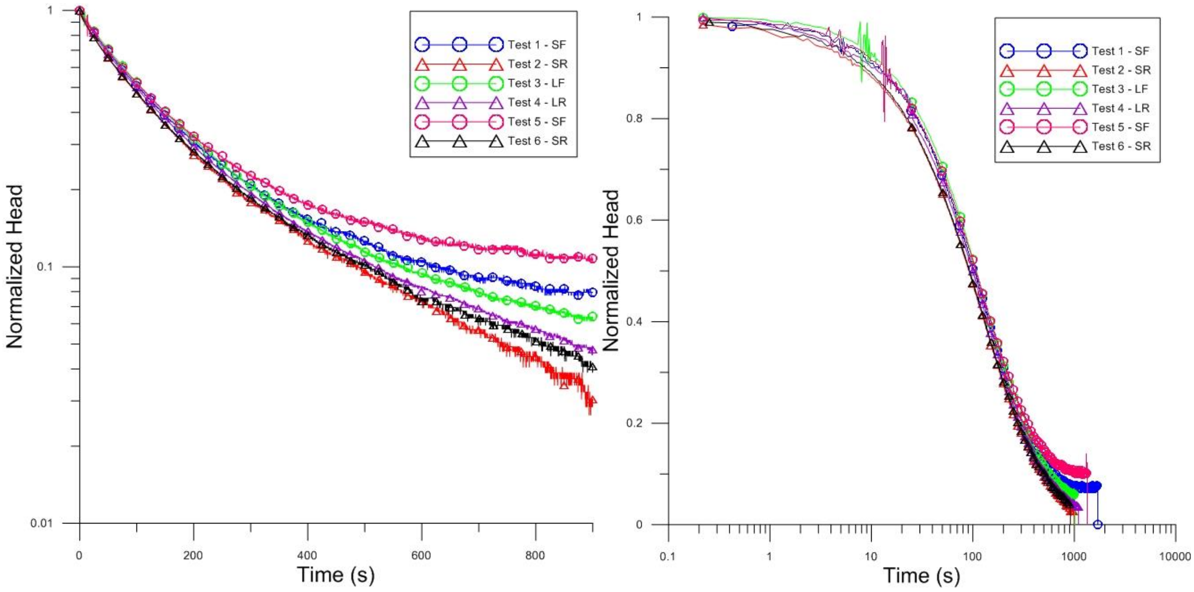
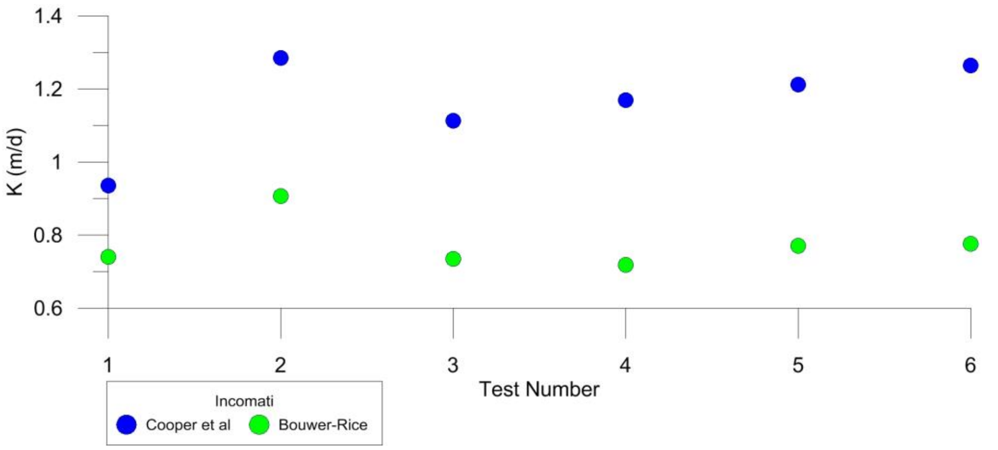


Figure 4-26 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.



Test	H_0 (m)
1	0.467
2	0.498
3	0.895
4	0.964
5	0.477
6	0.501

Figure 4-27 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

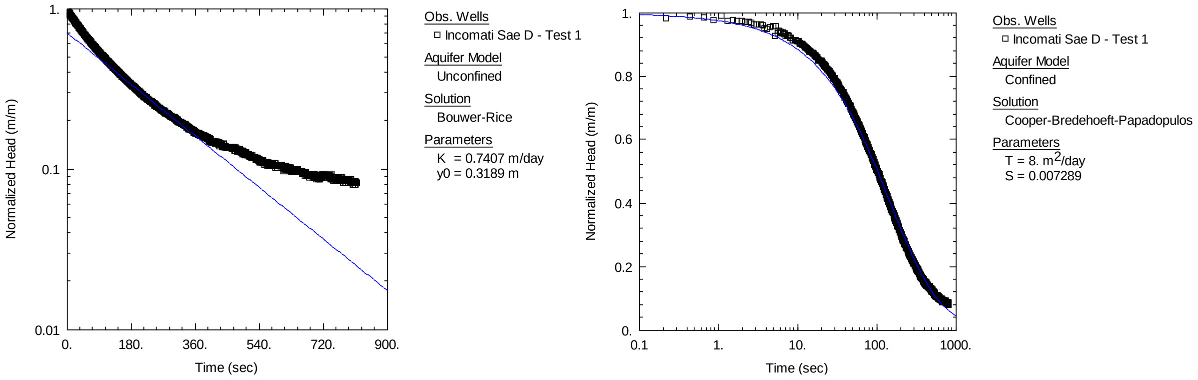


Figure 4-28 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

The estimated hydraulic conductivity values for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-27A. Figure 4-27B shows the measured initial displacement after removal of early time noise. Figure 4-28 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv.

The pressure sensor was placed at a depth of 16 meter and the first screen is placed at 20.35 m depth. Even so, at this location the double Bouwer (1989) method was used. The mean value from Bouwer and Rice (1976) was found to be 0.75 m/day with a standard deviation between the tests of 0.06. Using Cooper et al. (1967) method the K value was found to have a mean of 1.09 m/day, standard deviation of 0.12. There is a slight difference found between the falling head and rising head test. The falling head tests have a hydraulic conductivity value of 94% (Bouwer and Rice, 1976) and 87% (Cooper et al., 1967) of the average rising head tests.

4.10 Muriaze, Nampula

Muriaze is located about 30 km south of Nampula city, find location and geology in figure 3-8. A series of 10 slug tests were conducted on the 24 of September 2015. In particular the order was two single slug, two double slug and then one single slug test measurement. All performed with both falling head then rising head test. The normalized head for each test are presented in figure 4-29. Unfortunately no drilling information was found for this site. Moreover this site has not previously been investigated by Andersson and Björkström (2013) nor Enkel and Sjöstrand (2013). Local water government was informed, however unclear if the local water committee was present at test performance. The pump was well performing and regularly used according to the local population. Unclear is if the pump was used in the morning before testing.

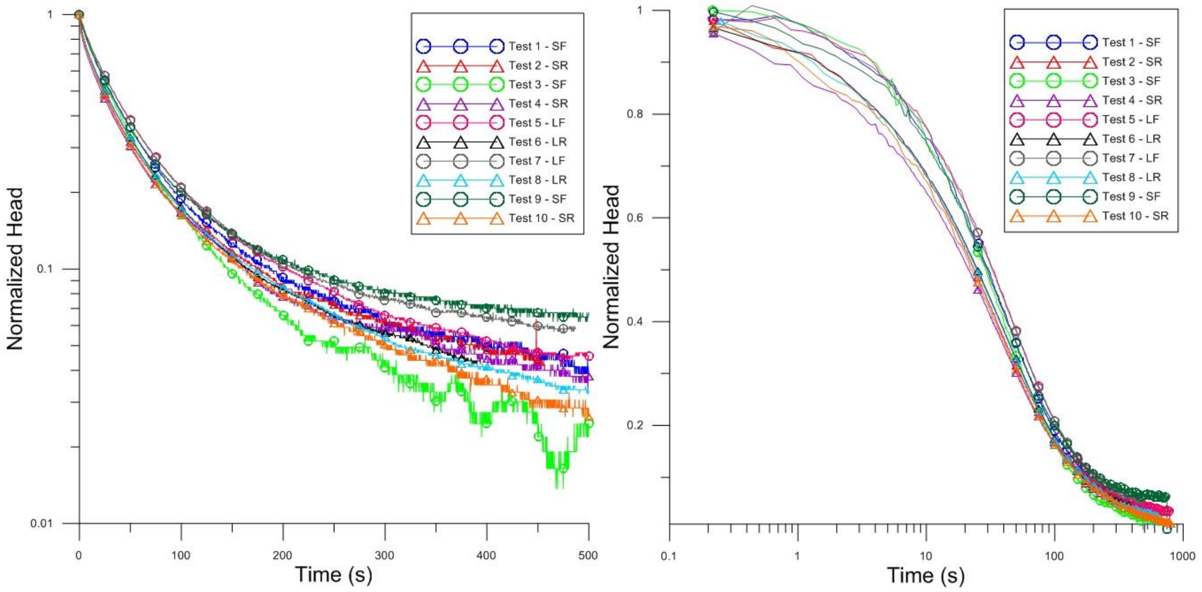
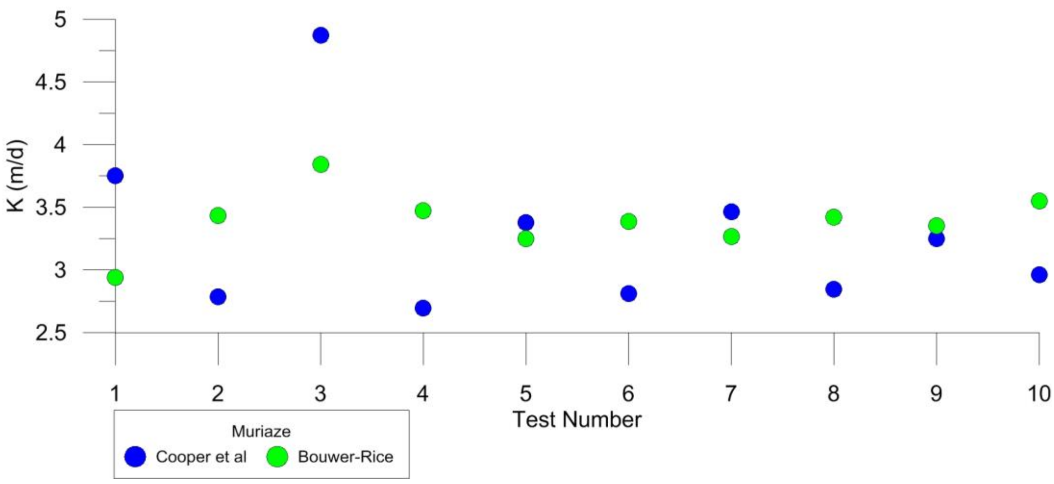


Figure 4-29 Normalized head using A) Bouwer and Rice (1976) to the left and B) Cooper et al. (1967) to the right. Legend description: S stands for short slug, L for long slug, F for falling head test (circular marker) and R for rising head test (triangular marks). Markers are set at every hundred measurement.



Test	H_0 (m)
1	0.387
2	0.456
3	0.365
4	0.475
5	0.746
6	0.895
7	0.756
8	0.895
9	0.386
10	0.457

Figure 4-30 A) The results of hydraulic conductivity from the tests using Bouwer and Rice (1976) resp. Cooper et al. (1967) method. B) Included to the right are the initial displacements with letters indicating falling (F) and rising (R) head tests.

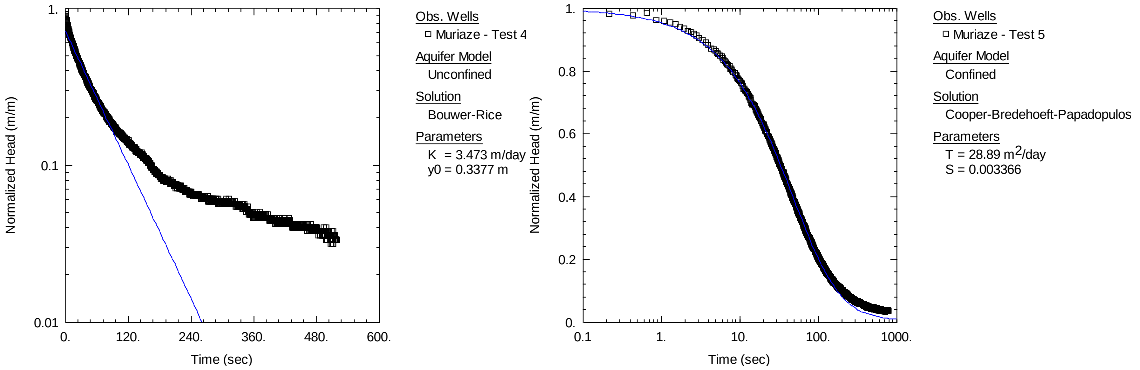


Figure 4-31 Normalized head (black squares) as a function of time and A) the Bouwer and Rice (1976) solution to the left and B) Cooper et al. (1967) solution to the right (blue line).

Since no drilling information was found the initial parameters was assumed using the following estimations. The H value, the static water level height was derived from the measurement done at the site, the depth of the well and the static water table before the slug test. Moreover the other parameters were difficult to estimate at the site and thereby the aquifer thickness, b was set to the average of the other sites, so also the depth to the first well screen, d. Finally the length of the well screens, L was set to the most common value among the other 9 tested sites, 8.55 m.

The estimated hydraulic conductivity for each test using Bouwer and Rice (1976) and Cooper et al. (1967) method are found in figure 4-30A. Figure 4-30B shows the measured initial displacement after removal of early time noise. Figure 4-31 respectively present example of A) the Bouwer and Rice (1976) and B) the Cooper et al. (1967) solution fit to the measured head using Aqtesolv.

The Bouwer (1989) method was not used. The mean value of the hydraulic conductivity was found to be 3.39 m/day, with a standard deviation of 0.22 for Bouwer and Rice (1976) and 3.28 m/day, with a standard deviation of 0.63 for Cooper et al. (1967). There is a difference found between the falling head values and the rising head estimated hydraulic conductivity values. Interestingly the difference is the opposite comparing Bouwer and Rice (1976) method and Cooper et al. (1967) method. The estimated average falling head hydraulic conductivity values was 3.33 m/day using Bouwer and Rice (1976) and 3.74 m/day using Cooper et al. (1967). The estimated average rising head hydraulic conductivity values was 3.45 m/day using Bouwer and Rice (1976) and 2.82 m/day using Cooper et al. (1967).

4.11 Water Quality

At the sites the pH, electrical conductivity and temperature were measured, given the following results in table 4-1. Two sites, Namiraka and Camaculo had a relatively high electrical conductivity. Noted should be that the water quality results were not use in the slug test calculations. However they could have been included to more accurately determine the density of the water.

Table 4-1. The pH, electrical conductivity and temperature of the water samples taken at the test sites.

Site	pH	Electrical conductivity (micro S/cm)	Temp (°C)
Cuhari B	6.2	231	26.3
Murothone	6.64	502	29.7
Naholoco EP1-2	6.2	388	27.9
Naholoco Communidade	6.62	775	25.2
Nampawa	6.54	440	25.9
Namiraka	6.62	1951	27.6
Camaculo	6.38	1444	27.6
Matibane	6.35	350	26.8
Incomate Sae D	6.1	246	30.4
Muriaze	6.45	344	27.8

4.12 Specific Capacity

From the summary of the drilling reports the following yields of the boreholes were presented from the pumping tests performed after the boreholes were drilled, figure 4-32 A. Using this information and the dynamic and stable water level information from the same reports the following specific capacities were found and sorted from highest to lowest, figure 4-32 B. In order of specific capacity Camaculo, Naholoco EP1-2 and Cuhari B had the highest specific capacity values. As described in chapter 2.3, the transmissivity values from specific capacity was estimated using Driscoll (1986) and thereafter the hydraulic capacity was estimated using the saturated thickness. The saturated thickness was set as the total length of the screens.

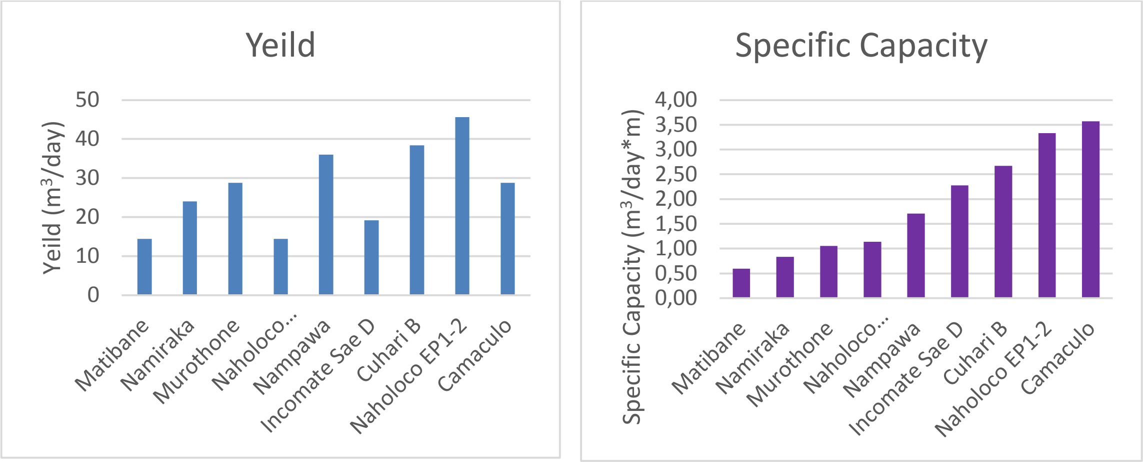


Figure 4-32 A) The Yield in m^3/day compared to B) the Specific Capacity to the left in m^3/day*m. The sites are plotted in the order of increasing specific capacity.

4.13 Summary of results

All sites were analysed using Bouwer and Rice (1976) and Cooper et al. (1967), see results in figure 4-33. Also included in figure 4-33 is the specific capacity. There is a slight correlation between high specific capacity values and high hydraulic conductivity. However in terms of the hydraulic conductivity the estimated values from the specific capacity are considerably lower than the values from this slug test analysis, plotted in figure 4-34.

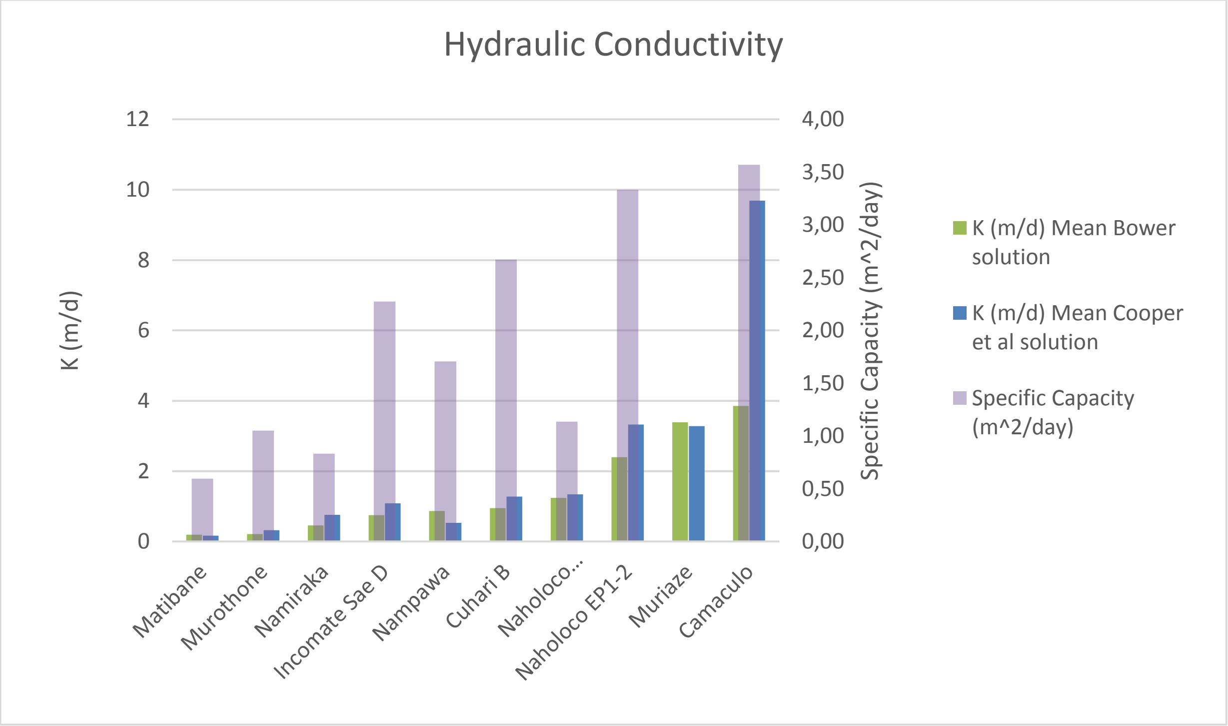


Figure 4-33 On the left axis the mean results of hydraulic conductivity from the sites from the Bouwer and Rice (1976) and Cooper et al. (1967) is found coupled with on the right axis the specific capacity at the sites.

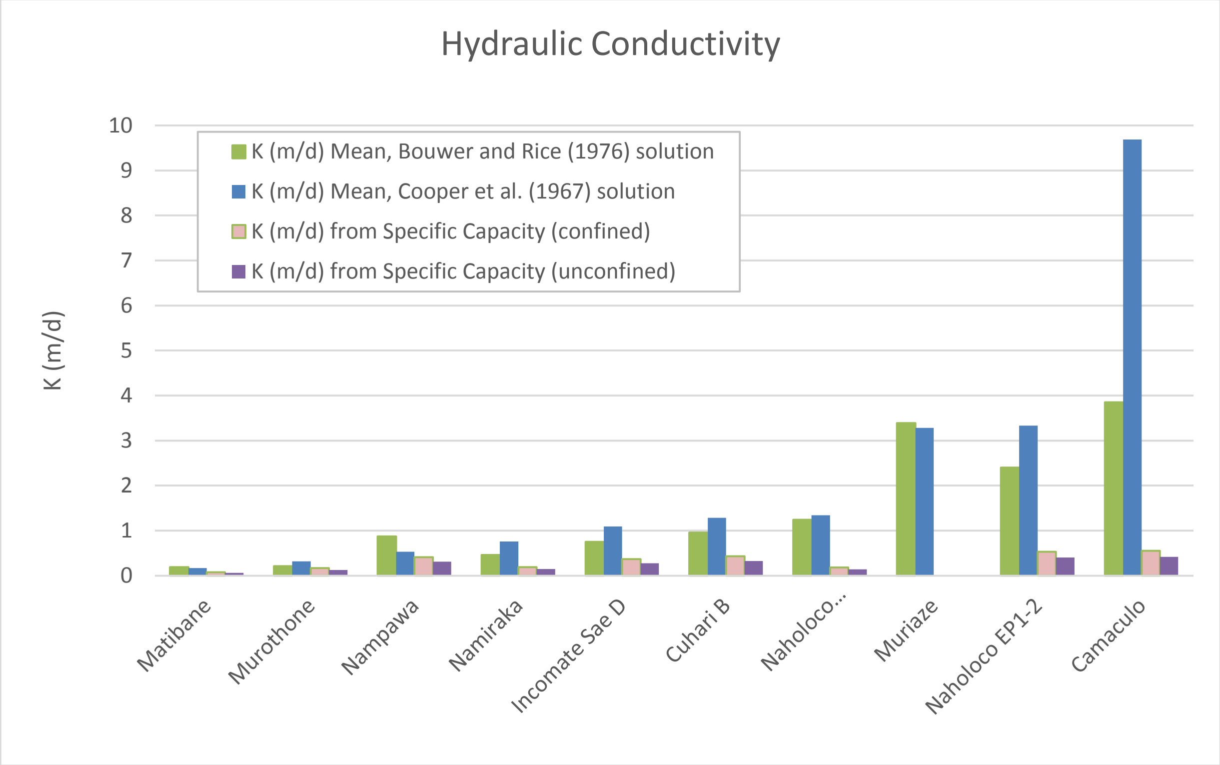


Figure 4-34 The mean results of hydraulic conductivity from the sites from the Bouwer and Rice (1976) and Cooper et al. (1967) coupled with the results of hydraulic conductivity estimated from specific capacity values.

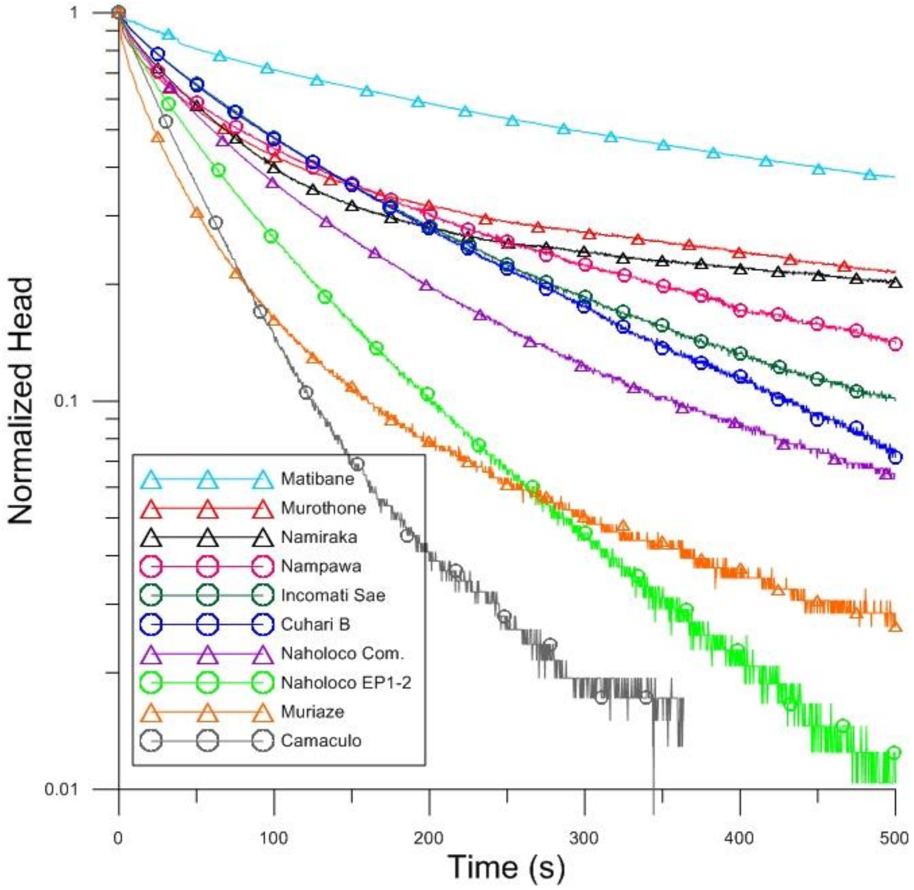


Figure 4-35 Normalized head of the displacements for the last slug test at all test sites plotted together.

In figure 4-35 the last slug test taken at all sites are plotted normalized together, showing the slopes of the lines in a raw way. Moreover, from the figure one can also see that some sites are more divided into different slopes over time while some sites show a more linear behaviour in this log normalized plot. Corresponding to this is the use of the Bouwer (1989) double straight line method that was used at the following sites presented in table 4-2.

Table 4-2 Sites where the double straight line update Bouwer (1989) to the Bouwer and Rice (1976) was used and not used.

Bouwer (1989) was used	Bouwer (1989) was not used
Murothone	Cuhari B
Naholoco Communidade	Naholoco EP1-2
Nampawa	Camaculo
Namiraka	(Muriaze)
Matibane	
Incomate Sae D	

4.14 Problems during well re-installation after testing

After our first visits at the sites 5 out of 10 wells did not perform as good as before and 2 wells did not give any water at all. Unfortunately the communication between the local communities to the research team did not work. Therefore the problem was not heard of until the research team returned the second time to Luipo during prepared for measurements at the 11 site. When the research team heard about the problems in Namiraka it was decided to not continue with the study until the problem was identified. Moreover it was also decided in agreement with supervisor in Sweden to investigate and fix if more of the previously visited wells had problems.

Since the communication to the research team did not work the sites needed to be re-visited. Asking the villages it turned out that all problems at the sites where discovered already the day after the testing. At the sites where problems were found the casing and/or pump parts were fixed. Thereafter these sites were also revisited or contacted again to make sure the pump was now well functioning. The research team also made sure that a local contact in Nampula City can be contacted from the villages and will help if problems were caused by this study come up even later, also so that the institution in Lund can be informed about it.

Some pump parts are quite sensitive, and possibly even more sensitive if they were old and no maintenance had been performed previous to this study. Some old plastic and rubber pump part did not manage to be taken up and down when the pump and the pump tubing were lifted out from the well, figure 4-36. If similar test are to be made, one should always change every plastic and rubber part right away. The research team did change the worst looking plastic and rubber parts right away, but it was apparently not good enough.

Other and more serious problems were due to leakage of the pump tubing after re-installation. This problem was similar to the problem that caused the village of Matibane to not have a functioning well for 1 year prior to our visits. When the pump tubing is leaking the water level in the pump is constantly sinking, which make the process of pumping up water less efficient. If the hole causing the leakage is big enough, as it was in Matibane, then no water can be pumped up. The problems may have been caused because that the technicians did not wait enough time to make sure that the glue had hardened before the pump tubing was lowered into the water. The whole process of reinstalling the pump tubing was hard, heavy and time consuming. Lastly some problems were probably due to that small rubber part had got stuck into the lower intake hole of the pump. During the re-installation all pump parts that was starting to get old were exchanged for new parts. All the found problems were fixed and so far no problems have been heard from the sites. However communication can still be a problem even as arrangements were made.

Figure 4-36 Dismounting of the pump tube at Naholoco EP1-2 (left) and Camaculo (right).

Contamination risks can occur from the pump tubing being exposed for several hours. In this study, at the first sites the pump tubing were placed directly on the ground. Thereafter the pipes were stacked on wood logs, however then it was discussed that the pump tubing might start to bend in the heat of the sun. Instead it was concluded that the best option was to have the pump tubing placed on plastic tarpaulin during testing, see figure 4-36.

5 Discussion

5.1 Geographical location and estimated K values

That there was a big difference in speed of recovery between different sites. From the data analysis it was found that the highest values of hydraulic conductivity were found in Camaculo, giving a mean value of 3.85 m/day from Bouwer and Rice (1976) solution and 9.69 m/day using Cooper et al. (1967) solution. Next biggest was Muriaze, however it should be noted that no drilling information was found for this site, and thereby the initial parameters where assumed. The mean value of the hydraulic conductivity was found to be 3.39 m/day using Bouwer and Rice (1976) and 3.28 m/day using Cooper et al. (1967). Naholoco EP1-2 also had high mean values of hydraulic conductivity, with 2.40 m/day using Bouwer and Rice (1976) and 3.33 m/day using Cooper et al. (1967). Naholoco EP1-2 and Camaculo also had the highest value of specific capacity, however specific capacity data for Muriaze was unfortunately not found. The three sites are also separated from the others in the raw normalized head plotted for the last slug test in figure 4-35. However these three sites were not close geographically, see figure 5-1.

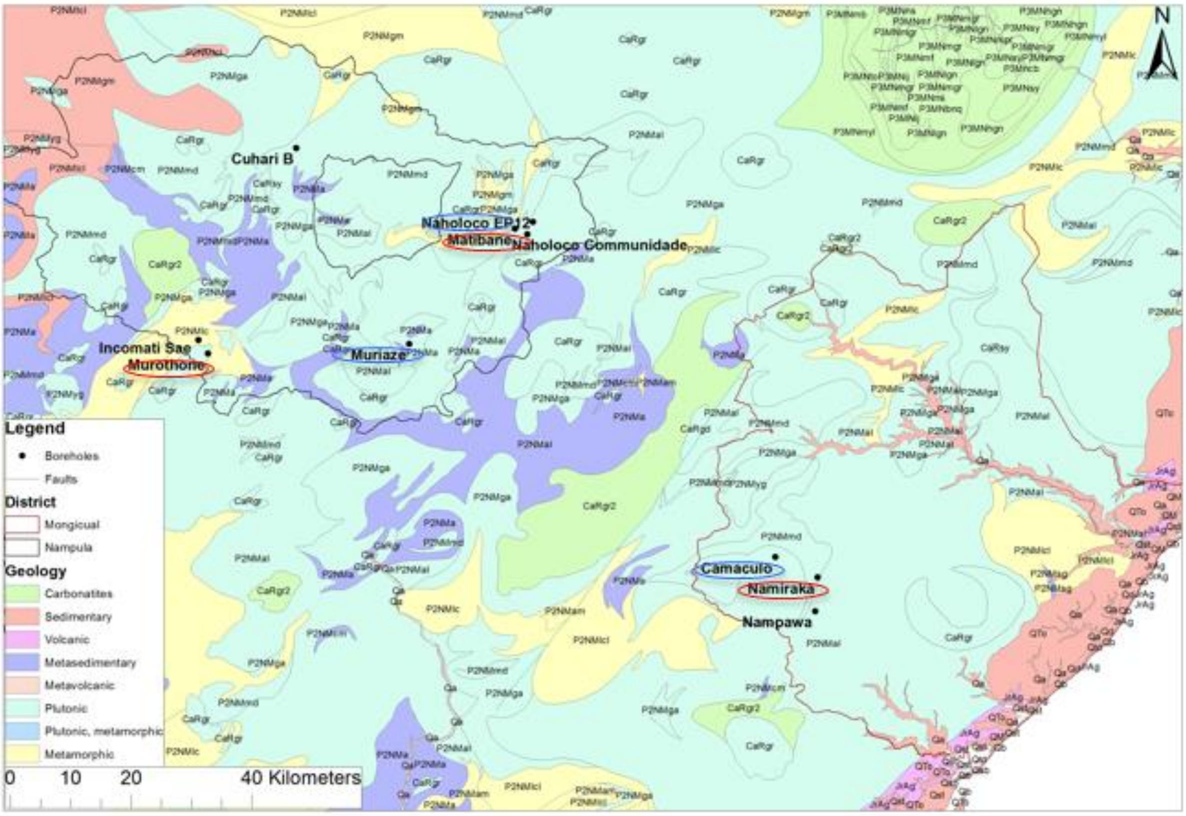


Figure 5-1 Map showing the 10 visited test sites in Nampula and Mongicual and the geology of the area. The blue circles mark the three sites with the highest estimated hydraulic conductivity and the red circles mark the three sites with the lowest estimated hydraulic conductivity. Rock type labeling: CaRgr: Equigranular medium-grained leucratic granite, P2NMal: Leucratic streaky augen granatic gneiss, P2Mmd: Hornblende-bearing granodioritic tonalatic gneiss, P2NMga: Augen granatic Gneiss, P2NMa: Amphibolitic gneiss, garnet amphibolite and P2Mlc: Medium-grained leucogranitic gneiss, migmatitic. Constructed in Arc-GIS, using data from DNG (1989).

Naholoco EP1-2 is much closer to Matibane and Naholoco Communidade, while Camaculo is much closer to Namiraka and Nampawa, see figure 5-1. Interesting is that Matibane had the lowest hydraulic conductivity (0.17 m/day from Bouwer and Rice (1976) and 0.19 m/day from Cooper et al. (1967)) of the ones investigated and also the lowest specific capacity. Noted should be that this well had not been used for 1 year previous to our test. The hydraulic conductivity was about 8% of the value from Naholoco EP1-2, and about 17% in terms of specific capacity. Naholoco Communidade was number 4 in rank of hydraulic conductivity but had about half the hydraulic conductivity as Naholoco EP1-2, and about a third the value of specific capacity.

Camaculo was close to Namiraka and Nampawa. Namiraka had about 11% of the hydraulic conductivity compared to Camaculo comparing Bouwer and Rice (1976) and about 8% comparing with the values from Cooper et al. (1967). Nampawa had closer values but still 22% comparing with the K results from Bouwer and Rice (1976) and 8% using the values for the Cooper et al. (1967) solutions.

5.2 Geological information and estimated K values

From table 2-1 it is found that fractured igneous and metamorphic rocks have a hydraulic conductivity between $6.9*10^{-4}$ to 25.9 m/day, (Domenico and Schwartz, 1990). All estimated hydraulic conductivity values from this study are within these boundaries. Coarse sand ranges from 0.078 m/day to 518 m/day, which also is within the range of these results.

The hydraulic conductivity values estimated from the slug tests are a result from the local aquifer region that was impacted by induced slug test. It is not clear how far away from the well the values represent the hydraulic conductivity. Moreover the geology is most likely not homogenous, but a mix of different grain sizes and most likely also fracture zones, as represented in the typical weathering profile (Acworth, 1987). As seen in the figure 2-2 according to Acworth (1987) the permeability varies vertically. The K values estimated from this slug test are probably representing a combination of the most permeable zones; zone “c” and “d”. Possibly also zone “b” yielded a response in the slug tests at some sites.

At the sites were the updated double straight line (Bouwer, 1989) was used in the Bouwer and Rice (1976) method, see table 4-2, the response in the log normalized displacement plot displayed a concave upward curvature which also is found at the Muriaze site. Generally this curvature will be displayed if the flow is primarily horizontal (Butler et al. 2009). If the flow is mainly horizontal can possibly for these weathered aquifers be interpreted as if the flow is mainly from the ‘c’ and/or the ‘d’ zone, seen in figure 2-2. The slope of the log normalized displacement is interpreted as the hydraulic conductivity using the Bouwer and Rice (1976) method and higher negative slope represent a higher K value. These curved log normalized displacements may thereby represent a decrease of hydraulic conductivity over time. Perhaps this can be interpreted as a representation of the vertically heterogeneous typical weathering profile. Perhaps the tail of slow response found at some wells when the normalized displacement where plotted using Bouwer (1989) was a response from zone “b”.

The values of hydraulic conductivity generated from the specific capacity generally yield lower values of hydraulic conductivity compared the ones generated by the slug tests. There are several uncertainties and the method itself is an approximation. However, perhaps the difference is explained because the pumping tests were conducted when the pump was installed 3-5 years before the slug tests, so one explanation can be that wells have been hydraulically improved. Another possible explanation is that the specific capacity from the pump tests represents a bigger aquifer volume then the K values estimated from the slug tests.

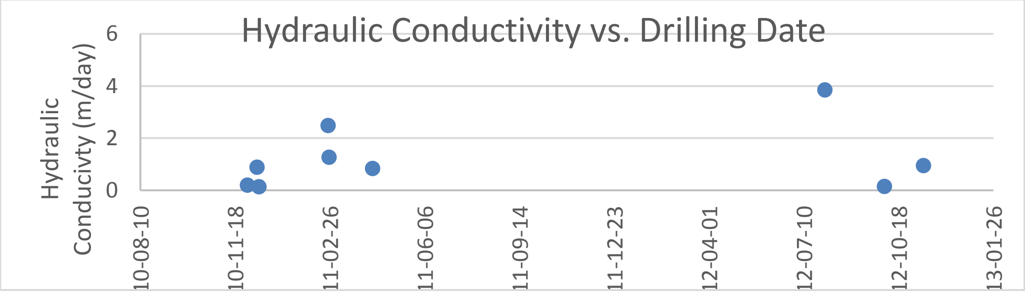


Figure 5-2 Hydraulic conductivity of the sites as a function of the drilling dates of the different sites.

According to Acworth (1987) the movement of the water is the driving geomorphological agent for the chemical weathering processes. The porosity of the rock increases continuously as the rock is weathered. As a result the hydraulic conductivity primarily increases. Perhaps the active pumping of the well can increase the rate of weathering. However of course it should be noted that there are uncertainties in the pump test performances and documentation of the primary drilling and pumping test reports. Plotting hydraulic conductivity as a function of the drilling date, see figure 5-2, no clear trend is seen. However the two sites with lowest hydraulic conductivity are among the oldest boreholes. Perhaps the change over time is negative. However to measure this performance over time one should perform the same tests in the same sites over time. This result may mainly be a result from the selection of tested well. However the weathering process is most likely a much slower process.

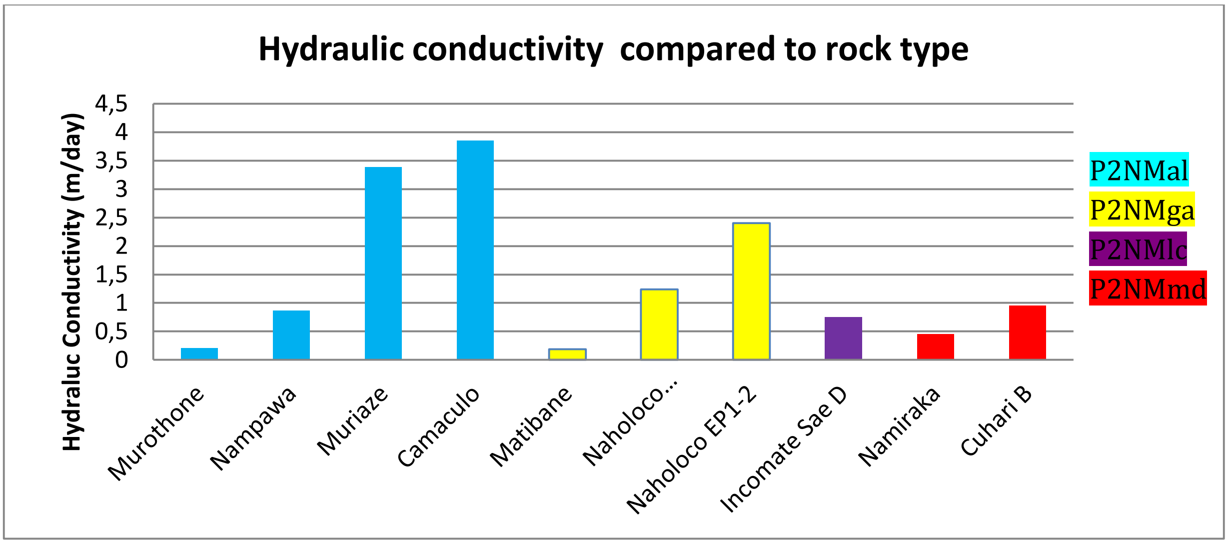


Figure 5-3 The values of hydraulic conductivity from Bouwer and Rice (1976) method compared to the different rock types of the boreholes as stated in figure 5-1. Rock type labeling: P2NMal: Leucratic streaky augen granatic gneiss, P2Mmd: Hornblende-bearing granodioritic tonalatic gneiss, P2NMga: Augen granatic Gneiss, P2NMa: Amphibolitic gneiss, garnet amphibolite and P2Mlc: Medium-grained leucogranitic gneiss, migmatitic.

In order to compare different formations and the estimated hydraulic conductivity, figure 5-3, the sites were divided into different rock types, as presented in figure 5-1. The two best performing wells where located in the leucratic streaky augen granatic gneiss, P2NMal. However the leucratic streaky augen granatic gneiss represent both the two wells with the highest estimated K value and the well with the lowest estimated K value, Muruthone. Due to the difference within the same rock type it is hard from this analysis to state that a particular rock type is better than another. Another factor is that more tests in different rock types is needed in order to make a statistical comparison. A possible explanation is that specific rock type is not the dominate factor for a productive well, however it is not known if the whole length of the borehole is represented by the specified rock type.

5.3 Early time noise in data

One of the disadvantages with slug tests using solid slug equipment is the often occurring disturbances in early time data (Butler, 1998). These disturbances are large fluctuations in the initial readings from the transducer. According to Butler (1998) two different factors are the main reason for this early time fluctuations. One factor is short-term dynamic movement pressure disturbances caused by the movement of the slug. These pressure fluctuations can be quite large. Another factor according to Butler is that the slug may hit or get entangled in the transducer and the transducer cable.

Butler suggests that to minimize this effects the slug can be designed in a more streamlined fashion. It is also suggested that if a big well is tested then the transducer may be placed separately in a smaller diameter pipe in the well. However it is not possible to eliminate this early time fluctuations entirely if not another slug test method is chosen, such as pneumatic slug tests (Butler, 1998).

The performed tests in Nampula Province also showed, in almost every test this early time fluctuations. Because of this it was harder to determine the most optimum start point for each test. According to Butler (1998) there is tree ways exclude the early time fluctuations: 1) To ignore the data primarily to point that is estimated to be without noise and set the start time to that point as well. 2) To use the expected initial displacement and ignore the early time data or 3) to use the first point without noise but keep the time to the start of the slug test injection. In this analysis the first option was used since that easily allowed for a better visual interpretation of the tests when all the normalized head results from a site was plotted together, as for example in figure 4-1.

It was found that the sensitivity of this noise has a bigger impact on fast recovering wells then slow wells, also noted by Butler (1998). Also found in the analysis was that the Cooper et al. (1967) method was more sensitive to the early time noise then the Bouwer and Rice (1976), due to a higher sensitivity to the primary part of the test and the result of the initial displacement. Perhaps this was a cause of generally a greater variability in the the results from the Cooper et al. (1967) solution.

5.4 Background recharge

There was a background recovery of the water wells at almost all sites. As discussed earlier this is probably due to heavily pumping in the morning before tests were made, but can also be due to the uptake of the pump tubing, creating a big “rising head test”. Moreover the logging test may also induce a slow “rising head test”. Due to the background recharge it sometimes can take a very long time to reach 5% from the primary initial displacement, however in the data analysis a solution could be found for every site in the end even if the initial displacement was not recovered within a 5% range.

According to Butler (1998) background changes in head can occur during test and to see the effect the water level should be measured both before and after the test. In this study the water level at most sites was measured both before the logging test, before the slug test and from the pressure gauge the water level was measured during and till the end of the test. Unfortunately the water level was not measured after the test again using the dip-meter. This could be an advice for future work, since the measured change in “still water level” over the testing period using the pressure gauge can also be an effect of changes associated with the pressure gauge, such as stretching of the cable.

5.5 Uncertainties

During the test performance the uncertainties include if the whole slug was submerged. However in the data analysis the measured initial displacement is used and then if the whole slug was introduced or not should not matter for the end result. Another thing that may have affected the result was that the slug had an intake of water during the testing period. The intake was normally around 1-2 dl, which probably had a minor effect, but as some places the water intake was around 5 dl which may have affected the result. During the falling head tests then part of the water did not infiltrate the formation rather it infiltrated the slug. Also during the rising head test at most site the slug was primarily just lifted above the water table to not get entangled with the cable. Then water may have dripped from the slug into the well. Also the on-going background recovery has affected the results. However at most sites the rising head and falling head method yielded quite similar results and by using the mean result from both rising head and falling head test hopefully most of this uncertainties was evened out, since they mainly affected one test method positive and the other test method negative.

Of course there is also a risk that at some places the cable got entangled or that the cable stretched out during the testing period. Moreover there is a limitation of 4 measures a second that may mainly affect the primary fast response in the beginning of the test period. However 4 measures a second is the best available sampling rate.

In the data analysis there are uncertainties from how start and end point where chosen, because of the early time noise and background recovery, as previously discussed. The early time noise is impacting the selection of starting point and the background recovery is probably impacting mainly the end of the test and the end point. The Cooper et al. (1967) method is more sensitive for the chosen initial displacement then the Bouwer and Rice (1976) method, both in terms of time and amplitude of the displacement.

There are uncertainties in the information from the drilling report that effect the initial parameters used in the data analysis. Moreover it was unfortunate that the actual drilling reports were not found and that only the drilling report summary was used. Even more unfortunate for the site Muriaze were no drilling report information was found. However for Bouwer and Rice (1976) the relationships with the initial parameters are linear and a simple relationship can be found if one wants to update the values. As seen in figure 4-35 the main impact is the slope itself and the initial parameters will not create changes that impact the order of these boreholes in terms of hydraulic conductivity. There is also uncertainty in how to best fit the data to the solution when the behaviour was not linear, in the log scale.

Another impacting factor is the well screening placement as well as the placement, quality and extent of the gravel pack. Well screening placement at productive positions will increase the yield and hydraulic conductivity of the well, especially when estimated using short time testing. The gravel pack may affect the results, possibly e.g. for the sites where the double straight line updated slug test method (Bouwer, 1989) where used, table 4-2. The three sites Cuhari B, Naholoco EP1-2 and Camaculo where the update was not needed, was not located closely geologically nor in closely estimated hydraulic conductivity values.

Perhaps the non-linear and more smoothly rounded displacement is a function of the heterogeneous aquifer. Perhaps this could explain why the double Bouwer (1989) method was found to be needed even at sites where the screens where not close to the location of the pressure gauge. It could be the case for sites like Namiraka and Nampawa. Maybe we can see the conductivities from first the ‘c’ and ‘d’ zone and thereafter a response from the slower ‘b’ zone, figure 2-2. However it may also be an effect of the gravel pack.

The estimate of the thickness of the aquifer used in the solutions using the Cooper et al. (1967) solutions can easy be updated if more accurate estimates are found, since the transmissivity values are given in appendix. Moreover the aquifer is not homogenous nor porous as assumed in both the Cooper et al. (1967) and the Bouwer and Rice (1976) method. However it is found that both methods can be used for the analysis of slug test data from weathered and fractured crystalline rock.

Moreover it is not determined if the aquifers are in fact unconfined or confined. For the Bouwer and Rice (1976) method the fact that the well is unconfined and confined will not matter, however the Cooper et al. (1967) method assumes a confined aquifer. However no direct conclusions regarding if the aquifer is confined or unconfined is draw directly from this results. Perhaps sites with a better fit to the Cooper et al. (1967) solution can indicate a confined aquifer. Moreover, possibly the different responses found in the normalized head plotted using the Bouwer and Rice (1976) solution may be related to that property, for example the concave shape possibly related to a more dominant horizontal flow. However possibly a pumping test analysis is a more secure method to determine the difference between a confined and unconfined aquifer, since the pumping test relates to a bigger volume of the formation and a response from a confining layer can be more clearly presented.

6 Conclusion

The hydraulic conductivities obtained from the slug tested wells are estimated to be around 0.2 - 3.9 m/day using the Bouwer and Rice (1976) method and 0.2 - 9.7 m/day using the Cooper et al. (1967) method. The Cooper et al. (1967) and the Bouwer and Rice (1976) methods are both developed for porous aquifers, but it is found that the methods can be applied for weathered rocks as well. The results using the specific capacity gave lower hydraulic conductivities ranging from 0.1 - 0.6 m/day, which is possibly explained e.g. by measurement of a bigger volume of surrounding formation. Moreover, all results are within the range of hydraulic conductivity values from typical fractured igneous and metamorphic rock (Domenico and Schwartz, 1990). The three sites with highest hydraulic conductivity were Camaculo, Muriaze and Naholoco EP1-2, which are not close geographically compared to other sites and are all in different types of gneiss formations. Furthermore water wells in this area that are geographically close may not at all be close in terms of hydraulic conductivity, most likely explained by the local and heterogeneous weathering process. Finally it is demonstrated that slug test may very well be a suitable method in similar geological environment, however with strong recommendations of high safety precautions, especially regarding contamination via equipment and risk to ruin pump parts.

6.1 Recommendations

- For future work a more extensive risk assessment should be made when working directly with drinking water, which is being used without treatment. It is my opinion that Swedish drinking water regulations and precautions should be followed for research from a Swedish University also when dealing with drinking water in Mozambique.
- For future work it is not recommended to do this kind of direct measurement in drinking water wells, especially if for example the pump tubing, as in this project, needed to be removed and placed on the ground in order to perform the test. This created risks of contamination as well as a risk that the pump tube would not perform as well as it did prior to testing. As a conclusion the pump parts and tubing must be handled very carefully and with a more equipped group of technicians.
- Another very important question is that the test equipment itself may carry microbes, especially from one water well to the next. All equipment parts in contact with water need to be able to be cleaned and disinfected effectively. The need of complete disinfection of the equipment requires other types and materials of equipment than the logging probe with the wire to the winch as well as another method than the solid slug testing, used in this project. The PVC solid slug and the simple slug rope cannot be 100% disinfected. Possibly the pneumatic method of slug testing is a more safe option, since no direct contact with the water is required. The pneumatic slug test method is possible if the well screen placements are both known and also determined to be under the water level. Also the dip meter and the used dummy (in this case the solid slug) needs to be clean. Failure to keep the equipment clean may have very serious consequences.

Examples can be cross contamination of cholera, which may have deadly consequences. Therefore the test method of current state is not recommended without further precautions.

- It has been discussed if the tests are better to be performed inside the pump tubing, so that the tubing does not need to be taken up from the well. However, then the logging probe would need to be shorter to be used safely without getting stuck inside the pump tubing. For the slug tests one have to consider that all the flow will be through the end of the pump tubing pipe, where the diameter is even less then the pump tubing itself. This should be taken into account for example since the slug tests will take longer time, note that on some sites already during these tests the time for the slug test performance was 4 hours. One also needs to make sure that the pump tubing is not damaged during this performance. Best would be to make similar tests prior to the visit to make sure it works.
- For future work it is important to make sure that the contact to the research group works. One cannot rely on that the local villages will contact their local governments and thereafter the local government will contact the research group.
- As mentioned before one need to have a great knowledge about pump construction and materials in order to make these tests. Have in consideration that a problem can be that people may state that things will work well and that they know what they are talking about when they do not.
- It would be very interesting to couple the results of the hydraulic conductivity with the resistivity profiles from ERT measurements performed by Enkel & Sjöstrand (2013) and Andersson & Björkström (2013), as well as from the geophysical borehole logging presented by Olsson (2016). One possible evaluation may be whether the water is flowing from the fracture or dominantly from the porous zone, as well as to evaluate the impact of the length of the clay layer.
- As a future research question it would be interesting to know more about potential spread of contaminants to the well from nearby located sewage “tanks”. At some places the location of this sewage storages are within 50 meter to the well. In this research it would be interesting to investigate indicator bacteria, such as e-coli. No water quality test have been performed since the installation except the pH and conductivity measurements performed by us and the pervious MFS students Enkel & Sjöstrand (2013) and Andersson & Björkström (2013). This draws back to the issues of potential cross contamination, since the wells are not previously inspected to be safe. Perhaps these slug test results of estimated hydraulic conductivities can be used in that potential assessment. Moreover, the potential spread of surface contaminants is also related to whether the aquifer is confined or unconfined.
- On another note, one impact of future climate change may be longer periods of drought. This may have a negative impact on the well capacity and the hydraulic conductivity in the “c” zone. According to Acworth (1987) when the water table is lowered by reduced recharge, for example caused by less precipitation, hydrolysis will occur in the clay rich “b” zone, bringing clay minerals to the “c” zone and reducing the capacity of the well. This may be an interesting research question for these sites.

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Ta bom!

Greetings from the research team!

Appendix A – Geometry of the solid slug

Geometric properties of the slug and water well casing used in this study.

Length one slug (cm)	82
Radius slug (cm)	3.75
Volume of one slug (cm^3)	3621
Volume of one slug, including slug ends (cm^3)*	3709
Volume of two slugs (cm^3)	7242
Volume of two slugs, including slug ends (cm^3)*	7639
Radius casing (cm)	5.08

*The volumes were calculated adding an estimation of the volume of the plastic treads.

Appendix B – Drilling report information and slug test analysis

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Cuhari B

Drilling Report Information

Adm.Post	Rapale
Drilling Date	2010-12-11
Borehole Depth (m)	34
Static Water level (m)	3,48
Dynamic Water Level (m)	17,85
Thickness of Aquifer (m)	27,52
Yield (m^3/h)	1,6
Casing details	9
Screens	3
Gravel Pack	17
Screen 1 start (m)	26,3
Screen 1 end (m)	29,15
Screen 2 start (m)	29,15
Screen 2 end (m)	32
Total Screen Length (m)	8,55

Test Specifications

Test Date	2015-09-09
Water Level primary (m)	5,8
Number of tests	6
Height to reference point (m)	0,725

Data Analysis Parameter values

Aquifer Thickness [b]	27,52
Static water column height [H]	28,2
Depth to top of well screen [d]	14,8
Length of well screen [L]	8,55

Note to all sites: The static and dynamic water level in the drilling report information is probably measured from the top of the well casing. Moreover it is not properly described how the estimate of the thickness of the aquifer was derived. Moreover how the data analysis parameters where derived is described in chapter 3.4.

Slug test analysis:

1. Cuhari B	**Observed inital dispacement**	**Bouwer-Rice (0,2-0,3)**				**Cooper-Bredehoef-Papadopulos**			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**		**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.49	0.764	0.341	0.031		8.256	0.008	0.966	0.100
2	0.499	1.046	0.454	0.163		12.640	0.006	1.478	0.267
3	0.96	0.925	0.800	3.320		7.386	0.008	0.864	3.170
4	0.975	1.033	0.856	1.130		15.420	0.000	1.804	0.304
5	0.471	0.918	0.417	0.406		6.623	0.015	0.775	0.156
6	0.503	1.035	0.440	0.295		15.420	0.000	1.804	0.098
Mean		0.954	0.551	0.891		10.958	0.006	1.282	0.682
Std		0.100	0.200	1.141		3.686	0.005	0.431	1.115
Mean falling head	0.640	0.869	0.519	1.252		7.422	0.011	0.868	1.142
Mean rising head	0.659	1.038	0.583	0.529		14.493	0.002	1.695	0.223

*The Bouwer (1989) was not used in the Bouwer and Rice.

Murothone

Drilling Report Information

Adm.Post	Anchilo
Drilling Date	2010-12-13
Borehole Depth (m)	38,44
Static Water level (m)	2,5
Dynamic Water Level (m)	29,89
Thickness of Aquifer (m)	24,5
Yield (m^3/h)	1,2
Casing details	10
Screens	3
Gravel Pack	19,19
Screen 1 start (m)	22,19
Screen 1 end (m)	27,89
Screen 2 start (m)	33,59
Screen 2 end (m)	36,44
Total Screen Length (m)	8,55

Test Results

Test Date	2015-09-10
Water Level primary (m)	21
Number of tests	6
Height to reference point (m)	0,705

Data Analysis Parameter values

Aquifer Thickness [b]	24,5
Static water column height [H]	17,44
Depth to top of well screen [d]	1,19
Length of well screen [L]	8,55

Slug test analysis:

2. Murothone	**Observed inital dispacement**	**Bouwer-Rice (0,2-0,3)**				**Cooper-Bredehoef-Papadopulos**			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**		**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.289	0.2234	0.1903	2.868		2.037	0.1	0.2382	1.37
2	0.351	0.2628	0.2001	0.87		2.99	0.1	0.3497	0.804
3	0.779	0.09487	0.3937	25.37		1.382	0.1	0.1616	25.3
4	0.863	0.2159	0.4517	11.39		2.916	0.1	0.3411	6.41
5	0.381	0.1687	0.2243	3.9		2.92	0.1	0.3415	0.174
6	0.458	0.2713	0.25	2.408		4.274	0.1	0.4999	0.326
Mean		0.206	0.285	7.801		2.753	0.100	0.322	5.731
Std		0.060	0.101	8.546		0.896	0.000	0.105	9.007
Mean falling head	0.483	0.162	0.269	10.713		2.113	0.100	0.247	8.948
Mean rising head	0.557	0.250	0.301	4.889		3.393	0.100	0.397	2.513

*The Bouwer (1989) update was used in the Bouwer and Rice estimation.

Naholoco EP1-2

Drilling Report Information

Adm. Post	Anchilo
Drilling Date	2011-02-24
Borehole Depth (m)	45,42
Static Water level (m)	14,46
Dynamic Water Level (m)	28,14
Thickness of Aquifer (m)	23,54
Yield (m^3/h)	1,9
Casing details	13
Screens	3
Gravel Pack	29,02
Screen 1 start (m)	32,2
Screen 1 end (m)	38
Screen 2 start (m)	40,57
Screen 2 end (m)	43,42
Total Screen Length (m)	8,65

Slug test performed

Test Date	2015-09-11
Water Level primary (m)	13,9
Time primary Water level	10:00
Water Level before slug test (m)	13,73
Time Start of slug test	11:50
Number of tests	6
Height to reference point (m)	0,73

Data Analysis Parameter values

Aquifer Thickness [b]	23,54
Static water column height [H]	31,69
Depth to top of well screen [d]	18,47
Length of well screen [L]	8,65

Slug test analysis:

3. Naholoco EP1-2	Observed inital dispacement	Bouwer-Rice (0,2-0,3)				Cooper-Bredehoef-Papadopulos				
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**		**T (m^2/d)**	**S**	**K (m/d)**	**RSS**	**Lenght of well screen (m)**
1	0.391	2.121	0.3439	0.294		21.76	0.0007941	2.5156	0.0365	
2	0.478	2.489	0.4182	0.162		28.2	0.0004799	3.2601	0.000221	
3	0.812	2.268	0.7738	0.256		62.28	4,975*10^-9	7.2000	0.998	*Test 3 disregarged
4	0.817	2.469	0.7311	0.532		31.7	0.000136	3.6647	0.0114	
5	0.445	2.457	0.3904	0.287		26.91	0.0006356	3.1110	0.0109	
6	0.481	2.616	0.4208	0.116		35.43	8,83*10-5	4.0960	0.0256	
Mean		2.430	0.461	0.278		28.800	0.001	3.329	0.017	*
Std		0.165	0.138	0.145		4.601	0.000	0.532	0.013	*
Mean falling head	0.418	2.289	0.367	0.291		24.335	0.001	2.813	0.024	*
Mean rising head	0.592	2.525	0.523	0.270		31.777	0.000	3.674	0.012	*

**The Bouwer (1989) update was not used in the Bouwer and Rice estimation.

Naholoco Communidade

Drilling Report Information

Adm. Post	Anchilo
Drilling Date	2011-02-25
Borehole Depth (m)	38,61
Static Water level (m)	11,97
Dynamic Water Level (m)	24,64
Thickness of Aquifer (m)	9,03
Yield (m^3/h)	0,6
Casing details	11
Screens	3
Gravel Pack	22,21
Screen 1 start (m)	24,3
Screen 1 end (m)	30
Screen 2 start (m)	33,76
Screen 2 end (m)	36,61
Total Screen Length (m)	8,55

Slug test performed

Test Date	2015-09-12
Water Level primary (m)	13,89
Time primary Water level	08:10
Water Level before slug test (m)	13,68
Time Start of slug test	10:05
Number of tests	8
Height to reference point (m)	0,75

Data Analysis Parameter values

Aquifer Thickness [b]	9,03
Static water column height [H]	24,93
Depth to top of well screen [d]	10,62
Length of well screen [L]	8,55

Slug test analysis:

4. Naholoco Communidade	**Observed inital dispacement**	**Bouwer-Rice (0,2-0,3)**				**Cooper-Bredehoef-Papadopulos**			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**		**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.458	1.196	0.362	1.750		8.839	0.032	1.034	0.220
2	0.48	1.417	0.390	0.529		12.760	0.010	1.492	0.007
3	0.835	1.169	0.601	0.001		12.860	0.005	1.504	0.095
4	0.939	1.248	0.653	0.001		12.090	0.010	1.414	0.000
5	0.447	1.100	0.288	0.000		11.440	0.107	1.338	0.001
6	0.477	1.466	0.360	0.000		12.430	0.103	1.454	0.011
7	0.427	1.001	0.321	2.200		8.057	0.100	0.942	0.351
8	0.477	1.356	0.381	0.719		13.630	0.000	1.594	0.001
Mean		1.244	0.420	0.650		11.513	0.046	1.347	0.086
Std		0.150	0.124	0.815		1.875	0.045	0.219	0.123
Mean falling head	0.542	1.117	0.393	0.988		10.299	0.061	1.205	0.167
Mean rising head	0.593	1.372	0.446	0.312		12.728	0.031	1.489	0.005

*The Bouwer (1989) update was used in the Bouwer and Rice estimation. *The RSS values for the Bouwer and Rice estimation represent RRS values for the timespan of data representing 0.2-0.3 of the normalized head.

Nampawa

Drilling Report Information

	Luipo
Drilling Date	2012-11-13
Borehole Depth (m)	33
Static Water level (m)	7,3
Dynamic Water Level (m)	28,39
Thickness of Aquifer (m)	22,7
Yield (m^3/h)	1,5
Casing details	10
Screens	2
Gravel Pack	10,8
Screen 1 start (m)	30,1
Screen 1 end (m)	30,1
Screen 2 start (m)	30,1
Screen 2 end (m)	33
Total Screen Length (m)	5,8

Slug test performed

Test Date	2015-09-15
Water Level primary (m)	7,77
Time primary Water level	08:20
Water Level before slug test (m)	7,25
Time Start of slug test	09:54
Number of tests	6
Height to reference point (m)	0,765

Data Analysis Parameter values

Aquifer Thickness [b]	22,7
Static water column height [H]	25,75
Depth to top of well screen [d]	19,95
Length of well screen [L]	5,8

Slug test analysis:

5. Nampawa	**Observed inital dispacement**	**Bouwer-Rice (0,2-0,3)**				**Cooper-Bredehoef-Papadopulos**			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**	**Time span (s)**	**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.429	0.822	0.233	0.000	200-300	4.005	0.100	0.471	0.228
2	0.491	0.812	0.223	1.670		5.205	0.100	0.612	0.088
3	0.776	0.999	0.479	0.000	200-300	5.561	0.100	0.654	0.051
4	0.92	0.940	0.522	0.000	200-300	4.441	0.100	0.522	0.135
5	0.411	0.715	0.221	0.002	200-400	3.397	0.100	0.400	0.413
6	0.455	0.915	0.246	0.000	200-300	4.627	0.100	0.544	0.018
Mean		0.867	0.321	0.279		4.539	0.100	0.534	0.156
Std		0.094	0.128	0.622		0.718	0.000	0.084	0.133
Mean falling head	0.539	0.845	0.311	0.001		4.321	0.100	0.508	0.231
Mean rising head	0.622	0.889	0.330	0.557		4.758	0.100	0.560	0.081

*The Bouwer (1989) update was used in the Bouwer and Rice estimation.
*The RSS values for the Bouwer and Rice estimation represent RRS values for the timespan of data representing 0.2-0.3 of the normalized head, time span noted in table above.

Namiraka

Drilling Report Information

	Luipo
Drilling Date	2012-10-03
Borehole Depth (m)	43
Static Water level (m)	10,07
Dynamic Water Level (m)	38,93
Thickness of Aquifer (m)	14,93
Yield (m^3/h)	1
Casing details	12
Screens	2
Gravel Pack	10,8
Screen 1 start (m)	32,2
Screen 1 end (m)	35,2
Screen 2 start (m)	38
Screen 2 end (m)	41
Total Screen Length (m)	6

Slug test performed

Test Date	2015-09-16
Water Level primary (m)	9,67
Time primary Water level	08:02
Water Level before slug test (m)	9,01
Time Start of slug test	10:05
Number of tests	6
Height to reference point (m)	0,765

Data Analysis Parameter values

Aquifer Thickness [b]	14,93
Static water column height [H]	33,99
Depth to top of well screen [d]	23,19
Length of well screen [L]	6

Slug test analysis:

6. Namiraka	Observed inital dispacement	Bouwer-Rice (0,2-0,3)				Cooper-Bredehoef-Papadopulos			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**	**Time span (s)**	**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.425	0.3062	0.169	0.006	160-300	4.005	0.100	0.668	0.228
2	0.458	0.4043	0.170	0.010	160-500	5.205	0.100	0.868	0.088
3	0.814	0.309	0.279	0.058	100-280	5.561	0.100	0.927	0.051
4	0.944	0.6485	0.412	0.024	160-320	4.441	0.100	0.740	0.135
5	0.458	0.7113	0.223	0.000	150-160	3.397	0.100	0.566	0.413
6	0.47	0.3502	0.165	0.009	160-500	4.627	0.100	0.771	0.018
Mean		0.455	0.236	0.018		4.539	0.100	0.757	0.156
Std		0.163	0.088	0.019		0.718	0.000	0.120	0.133
Mean falling head	0.566	0.442	0.224	0.021		4.321	0.100	0.720	0.231
Mean rising head	0.624	0.468	0.249	0.015		4.758	0.100	0.793	0.081

*The Bouwer (1989) update was used in the Bouwer and Rice estimation. *The RSS values for the Bouwer and Rice estimation represent RRS values for the timespan of data representing 0.2-0.3 of the normalized head, timespan noted in table above.

Camaculo

Drilling Report Information

	Luipo
Drilling Date	2012-08-01
Borehole Depth (m)	45
Static Water level (m)	19,43
Dynamic Water Level (m)	27,5
Thickness of Aquifer (m)	23,57
Yield (m^3/h)	1,2
Casing details	12
Screens	3
Gravel Pack	18,9
Screen 1 start (m)	34,5
Screen 1 end (m)	43,5
Total Screen Length (m)	9

Slug test performed

Test Date	2015-09-17
Water Level before slug test (m)	11,7
Time Start of slug test	10:55
Number of tests	8
Height to reference point (m)	0,775

Data Analysis Parameter values

Aquifer Thickness [b]	23,57
Static water column height [H]	33,3
Depth to top of well screen [d]	22,8
Length of well screen [L]	9

Slug test analsyis:

7. Camaculo	**Observed inital dispacement**	**Bouwer-Rice (0,2-0,3)**				**Cooper-Bredehoef-Papadopulos**			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**		**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.382	3.846	0.438	0.128		58.270	0.0000123	6.815	0.012
2	0.481	4.119	0.468	0.033		121.100	0.0000000	14.164	0.011
3	0.81	3.649	0.853	0.437		103.800	0.0000000	12.140	0.046
4	0.926	3.543	0.879	0.292		80.380	0.0000000	9.401	0.051
5	0.424	3.973	0.447	0.055		101.000	0.0000000	11.813	0.059
6	0.486	3.915	0.443	0.058		66.470	0.0000068	7.774	0.003
7	0.396	3.873	0.436	0.248		48.020	0.0001183	5.616	0.066
8	0.465	3.915	0.443	0.058		83.580	0.0000001	9.775	0.003
Mean		3.854	0.551	0.164		82.828	0.000	9.687	0.032
Std		0.170	0.182	0.137		23.248	0.000	2.719	0.025
Mean falling head	0.503	3.835	0.544	0.217		77.773	0.000	9.096	0.046
Mean rising head	0.590	3.873	0.558	0.110		87.883	0.000	10.279	0.017

*The Bouwer (1989) update was not used in the Bouwer and Rice estimation.

Matibane

Drilling Report Information

	Anchilo
Drilling Date	2010-12-01
Borehole Depth (m)	47,75
Static Water level (m)	10
Dynamic Water Level (m)	34,11
Thickness of Aquifer (m)	34
Yield (m^3/h)	0,6
Casing details	14
Screens	3
Gravel Pack	4
Screen 1 start (m)	34,35
Screen 1 end (m)	37,2
Screen 2 start (m)	40,05
Screen 2 end (m)	47,75
Total Screen Length (m)	10,55

Slug test performed

Test Date	2015-09-21
Water Level primary (m)	10,9
Time primary Water level	00:00
Water Level before slug test (m)	9,45
Time Start of slug test	11:11
Number of tests	6
Height to reference point (m)	0,82

Data Analysis Parameter values

Aquifer Thickness [b]	34
Static water column height [H]	38,3
Depth to top of well screen [d]	24,9
Length of well screen [L]	10,55

Slug test analysis:

8. Matibane	Observed inital dispacement	Bouwer-Rice (0,2-0,3)				Cooper-Bredehoef-Papadopulos			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**	**Time span (RS**	**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.467	0.1402	0.2346			2.201	0.014	0.209	0.019
2	0.498	0.1758	0.276			1.764	0.044	0.167	0.023
3	0.895	0.1852	0.512			1.812	0.035	0.172	1.510
4	0.964	0.1952	0.6021			1.696	0.044	0.161	0.552
5	0.477	0.1358	0.233			1.640	0.046	0.155	0.173
6	0.501	0.3193	0.4218			1.336	0.085	0.127	0.113
Mean		0.192	0.380			1.742	0.045	0.165	0.398
Std		0.061	0.143			0.256	0.021	0.024	0.529
Mean falling head	0.613	0.154	0.327			1.884	0.032	0.179	0.567
Mean rising head	0.654	0.230	0.433			1.599	0.058	0.152	0.229

*The Bouwer (1989) update was not used in the Bouwer and Rice estimation. However the solutions where obtained fitting the early time data representing 0.2-0.3 of the normalized head. *The RSS values for the Bouwer and Rice estimation represent RRS values for the timespan of data representing 0.2-0.3 of the normalized head.

Incomati Sae "D"

Drilling Report Information

	Rapale
Drilling Date	2011-04-12
Borehole Depth (m)	38,17
Static Water level (m)	6,28
Dynamic Water Level (m)	14,72
Thickness of Aquifer (m)	27,72
Yield (m^3/h)	0,8
Casing details	11
Screens	3
Gravel Pack	20,82
Screen 1 start (m)	20,35
Screen 1 end (m)	23,2
Screen 2 start (m)	25,05
Screen 2 end (m)	27,9
Total Screen Length (m)	8,55

Slug test performed

Test Date	2015-09-23
Water Level primary (m)	8,66
Time primary Water level	09:15
Water Level before slug test (m)	8,8
Time Start of slug test	11:05
Number of tests	6
Height to reference point (m)	0,765

Data Analysis Parameter values

Aquifer Thickness [b]	27,72
Static water column height [H]	29,37
Depth to top of well screen [d]	11,55
Length of well screen [L]	8,55

Slug test analysis:

9. Incomati Sae D	Observed inital dispacement	Bouwer-Rice (0,2-0,3)				Cooper-Bredehoef-Papadopulos			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**	**Time span (RS**	**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.467	0.7407	0.3189			8.000	0.007	0.936	0.109
2	0.498	0.906	0.4137			10.980	0.003	1.284	0.022
3	0.895	0.7348	0.6176			9.512	0.002	1.113	0.297
4	0.964	0.7177	0.6009			9.997	0.003	1.169	0.148
5	0.477	0.7707	0.3524			10.360	0.001	1.212	0.007
6	0.501	0.7762	0.325			10.810	0.003	1.264	0.000
Mean		0.774	0.438			9.943	0.003	1.163	0.097
Std		0.062	0.125			0.997	0.002	0.117	0.105
Mean falling head	0.613	0.749	0.430			9.291	0.004	1.087	0.138
Mean rising head	0.654	0.800	0.447			10.596	0.003	1.239	0.057

*The Bouwer (1989) update was used in the Bouwer and Rice estimation.
* No RSS values obtained for the Bouwer and Rice solutions since visual fitting method was used at this site.

Drilling Report Information - Missing!

Adm. Post	
Drilling Date	
Borehole Depth (m)*	37.18
Static Water level (m)	
Dynamic Water Level (m)	
Thickness of Aquifer (m)	
Yeild (m^3/h)	
Casing details	
Screens	
Gravel Pack	
Screen 1 start (m)	
Screen 1 end (m)	
Screen 2 start (m)	
Screen 2 end (m)	
Total Screen Length (m)	

* Measured depth 2015-09-24

Slug test performed

Test Date	9/24/2015
Water Level primary (m)	3.41
Time primary Water level	0:00
Water Level before slug test (m)	3.32
Time Start of slug test	10:52
Number of tests	10
Height to reference point (m)	0.765

Data Analysis Parameter values

Aquifer Thickness [b]**	23.07
Static water column height [H]	33.66
Depth to top of well screen [d]**	16.38
Length of well screen [L]***	8.55

** Average value for the other sites combined

*** Most common value for the other sites

Slug test analysis:

10. Muriaze	Observed inital dispacement	Bouwer-Rice (0,2-0,3)				Cooper-Bredehoef-Papadopulos			
Test	**H(0) (m)**	**K (m/d)**	**y0 (m)**	**RSS**		**T (m^2/d)**	**S**	**K (m/d)**	**RSS**
1	0.387	2.94	0.3162	0.324		32.070	0.00297	3.751	0.05300
2	0.456	3.432	0.3372	0.0194		23.790	0.03235	2.782	0.00374
3	0.365	3.841	0.3137	0.00782		41.660	0.00080	4.873	0.00030
4	0.475	3.473	0.3377	0.0176		23.040	0.04851	2.695	0.00029
5	0.746	3.25	0.6323	0.0364		28.890	0.00336	3.379	0.00140
6	0.895	3.385	0.6749	0.0491		24.030	0.02590	2.811	0.00047
7	0.756	3.264	0.6453	0.0415		29.610	0.00279	3.463	0.00252
8	0.895	3.422	0.6735	0.0467		24.340	0.02614	2.847	0.00076
9	0.386	3.351	0.3175	0.0141		27.790	0.00658	3.250	0.00103
10	0.457	3.547	0.3376	0.0153		25.320	0.02923	2.961	0.00020
Mean		3.391	0.459	0.057		28.054	0.018	3.281	0.006
Std		0.218	0.162	0.090		5.341	0.016	0.625	0.016
Mean falling head	0.528	3.329	0.445	0.085		32.004	0.003	3.743	0.012
Mean rising head	0.636	3.452	0.472	0.030		24.104	0.032	2.819	0.001

*The Bouwer (1989) update was not used in the Bouwer and Rice estimation. However the solutions where obtained fitting the early time data representing 0.2-0.3 of the normalized head.

*The RSS values for the Bouwer and Rice estimation represent RRS values for the timespan of data representing 0.2-0.3 of the normalized head.

Appendix C – Hydraulic conductivity from Specific Capacity

Yield, Specific Capacity and estimated transmissivity, T and hydraulic conductivity, K values estimated from the specific capacity.

Site	Yield (m^3/day)	Specific Capacity (m^2/day)	T (m^2/d) from Specific Capacity [unconfined]	T (m^2/d) from Specific Capacity [confined]	K (m/d) from Specific Capacity [unconfined]	K (m/d) from Specific Capacity [confined]
Matibane	14,40	0,60	0,62	0,83	0,06	0,08
Namiraka	24,00	0,83	0,87	1,15	0,14	0,19
Murothone	28,80	1,05	1,10	1,46	0,13	0,17
Naholoco Communidade	14,40	1,14	1,18	1,57	0,14	0,18
Nampawa	36,00	1,71	1,78	2,36	0,31	0,41
Incomati Sae D	19,20	2,27	2,37	3,15	0,28	0,37
Cuhari B	38,40	2,67	2,78	3,70	0,33	0,43
Naholoco EP1-2	45,60	3,33	3,47	4,62	0,40	0,53
Camaculo	28,80	3,57	3,72	4,94	0,41	0,55