RAPPORT

ANNEE 2016 -2017

TITRE :
Design and Construction of Cascade Sand Filter

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Abstract (English)

The provision of safe clean water is one of the paramount responsibilities of all governments. This is more difficult to achieve in rural communities, hence the need for a simplified and economic design of a filtration system. A team of engineers and volunteers field-tested the water in a small community in rural Uganda and came up with the solution of building a filter. The central design was a rapid sand filter, which initially was planned to be built in 4 different locations. Due to cultural issues, that was not possible at all locations. For this reason, a common decision was made to build a filter in a spring, which was a source for more than 4 small villages in the area. This filter showed great improvement by reducing turbidity and subsequently, after chlorination, showed a considerable reduction in bacteria, from thousands of colonies to 3-4 colonies or less. In this project, in addition to the technical part, which is important, there are 2 more aspects that are crucial for an engineer to learn: one is adaptability to the conditions and the culture, and the second is creativity in finding solutions for different spontaneous problems in unusual construction environment.

Abstract (French)

L'approvisionnement en eau propre est une des responsabilités principales des gouvernements. Cette tâche est plus difficile en milieu rural, d'où la nécessite d'une conception simplifiée et économique d'un système de filtration. Une équipe d'ingénieurs et de volontaires a contrôlé la qualité des eaux et a proposé la mise en place d'un filtre. Le design central était un filtre à sable rapide qui, initialement, devait être construit dans 4 endroits différents. Pour des raisons de différences culturelles, cela n'a pas été réalisé. Une décision a donc été prise pour construire un filtre au niveau d'une source, qui constitue un point d'approvisionnement en eau pour plus de 4 petits villages de la région. Ce filtre a permis de réduire considérablement la turbidité, ainsi que la quantité de bactéries qui est passée de milliers de colonies à moins de 3 ou 4 colonies après la chloration. Dans ce projet, hormis la partie technique qui est importante, deux aspects supplémentaires sont cruciaux pour l'ingénieur : le premier est l'adaptabilité aux conditions et à la culture et le deuxième est l'aptitude à trouver des solutions face aux différents imprévus dans un environnement de construction inhabituel.

Acknowledgment

I would like to express my gratitude to the following people, which made this thesis possible.

Eng Michael Ottensmann who tutored me throughout all the internship with patience and guided me to learn the important aspects of being an engineer. Without your passion and hard work this thesis wouldn’t have been possible. Another special thank you is for helping me proof reading this report.

Also, I would like to thank everyone else involved in Mission Uganda Project (April Whitbeck, Daniel Kaufmann, Florian Singer, Kevin Martin and Natalija Milanovic) for making this trip unforgettable journey

I would like to thank everyone in Uganda as well for being so welcoming and caring for us by giving their help and support during our field work.

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1. Introduction

Water is a fundamental human need. Each person on earth requires at least 20 to 50 litres of clean, safe water per day for drinking, cooking, and simply keeping themselves clean.
Polluted water isn’t just dirty—it’s deadly. Some 1.8 million people die every year of diseases like cholera. Tens of millions of others are seriously sickened by a host of water-related ailments—many of which are easily preventable. Mostly the countries affected by these diseases are in developing countries; one of them is Uganda. Uganda has been independent since 1962 but the government structure is still changing and many people have no access to basic water and sanitation facilities. Around a quarter cannot access clean water. Without access to safe water, Uganda’s many farmers struggle to grow crops or earn a living. There are also many nomadic communities who are difficult to reach with services. The lack of clean water and safe sanitation traps them in poverty. In urban areas, large slums exist without proper drainage or toilets, leaving waste to gather in and around people’s homes.

Approximately 22 children die each day from diseases caused by using unsafe water. Rural Uganda suffers from contaminated water supply mainly from bacteria. The main, and often only, water supplies for the villages are the surface water springs which are fed by ground water and surface runoff. The surface runoff brings all the faeces and pesticides into the surface spring contaminating the water. The approach of this thesis in this context is to develop a system to treat the water. Therefore the idea and development of a chlorination system was the first priority. The first trip to Uganda was conducted to test the developed salt chlorination system. It is important to mention that the system worked very well, but was limited by the current situation and condition of the local water there. After several tests were performed, it was noticed that the bacteria reappeared over time. This happened because the water was very dirty and after the chlorination, the bacteria would disappear in the first 30 min to 1 h hiding in the dirt particles and show up again thereafter. Clearly, additional measures were needed. Initially, based on the local situation, it was decided to build a rapid sand filter and a cascade sand filter on a stream. An initial cistern rapid sand filter was constructed in a local village. However, due to some cultural issues, this idea could not be fully implemented and consequently a cascade sand filter on a common spring for several villages was constructed. Throughout the report, the process of design, decision making and construction will be explained in detail. All the problems faced will be mentioned as well and how to deal with them in such a situation. Most importantly, this report will serve as a guideline of how to adapt a design within the environment of the work and budget.

2. Water Situation in rural areas of Uganda

This project was implemented in one of the deepest rural areas of Uganda called Kalangaaloo. This area is part of Mityana District and is located in the central region of Uganda as it seen in the figure below:

Figure 1. Location of Kalangaaloo, Uganda

Figure 2. Ugandan carrying 20L Jerry Can

There are around 30.000 people living in Kalangaaloo itself. One village within Kalangaaloo has between 50-200 habitants, except Kyamagamule, which also has a school of 150 students. The vast majority of the economy is maintained by farming. Consequently the volume of needed drinking water in this area is high. Almost all the available resources are used, in some cases extensively, for drinking water supply

More than 5000 of the households are using unprotected water sources. Based on Uganda Bureau of Statistics (UBOS) the protected sources are: pipe water, boreholes, well/springs and bottled water. (See Annex A)

Statistics and on-site impressions shows that the drinking water situation in rural Uganda is poor compared to WHO standards. Most of the people take their water from surface water ponds or contaminated springs carrying a jerry can of 20L up to the village every day. Particularly in Kyamagamule the water supply is a well and the natural water springs. Both of them have unsafe contaminated water. Locals use the boiling procedure to kill the bacteria. Boiling water is a method that has proved to have effective results but the disadvantage of this method is that it is a long process and in the long term, is not seen to be practical. In addition to that, the surface water is turbid water with either organic or inorganic components, which makes this water not enjoyable in taste and appearance. The wells and springs are very vulnerable to contamination. This is due to the way of construction and damage of extensive every day use. As can be seen in the picture below the result of the water from the well is not clear. On the other hand, one can think of repairing them.

But thinking cost effectively, repairs require around 70% of the initial price that was used to build it, and the result cannot be guaranteed due to the fact the environment itself is not clean.

Figure 3. Deep Well Water

Figure 4. Rainwater collection tank at Zinga Island

Uganda as a tropical country has a relatively high annual precipitation in most regions. This fact makes the country highly suitable for domestic rainwater harvesting. Increasingly, residents take up the mass produced plastic tanks (see Figure 4) to collect rainwater. For the moment, that is a safe source and enjoyable to drink because it does not have colour nor taste. But it is worth mentioning that it is not a permanent source in situations of draught.

And the last source would be the usage of bottled water, which is widely used. But using it to fulfil the everyday life domestic needs, it is quite expensive and does not solve all the problems; they will still have to use unsafe water for other needs like washing, showering and farming.

3. Part I: Rapid Sand Filter

3.1. Importance of water treatment

Water is found almost everywhere on Earth. Water resources like rivers, lakes, which provide water, contain a lot of pollution, garbage unfit for consumption. To be clean, the water should undergo a number of treatments necessary to make it drinkable. This life-threatening problem makes you wish to follow the water treatment actions to fight back. Water purification is the best and recommendable action of water treatment which gives you safe, clean and pure water to consume.

Water purification is very important treatment done by people for many reasons below:

- ✓ Through water purification, we can avoid drinking impure and contaminated water, which causes many epidemic diseases and is unsafe for healthy life.
- ✓ It removes all unnecessary bacteria and viruses from the water, which is hazardous for our health. Through the advanced technology, it purifies or filters all the bacterial diseases, which may also lead to death.
- ✓ The filtration not only removes the toxins and makes the water clean and pure but also improves the flavour and appearance. To make the water drinkable and consumable with no unpleasant odour; the water purification plays the vital role in doing so.

One of the most important decisions for any site is the choice of the most appropriate type of treatment. In general, in underdeveloped areas, there are three options: 1. drilling a well, 2. building a cistern sand filter or 3. Building a cascade sand filter. Each can be an appropriate choice based on the site conditions described below. In the vast majority of cases, chlorination will be a requirement, both to disinfect the water supply and to provide an additional measure of protection through disinfection residual. The site for this thesis was in some small villages in a rural area. Each of these villages used to take water from the spring downstream, collects rain water and some had a well. Rain water and the water from the well was the clearest water that they had. But the water being clear does not necessarily mean that is free from contaminants such as bacteria. Several tests were performed for all the three sources of water and all of them had too-numerous-to-count (TNTC) harmful bacteria (yellow coliforms). Even though the local mentality is that having a well which provides them clear water solves all their problems, that is not always the case. Three existing wells had contaminated water. One of them has also coloured water. This comes as a consequence of the maintenance and at the same time proves that the aquifers are not always clean and uncontaminated. In addition, in the local area, the cost of drilling a well locally is about 10 times the cost of building a filter. Therefore, under these circumstances, it was better to build a filter.

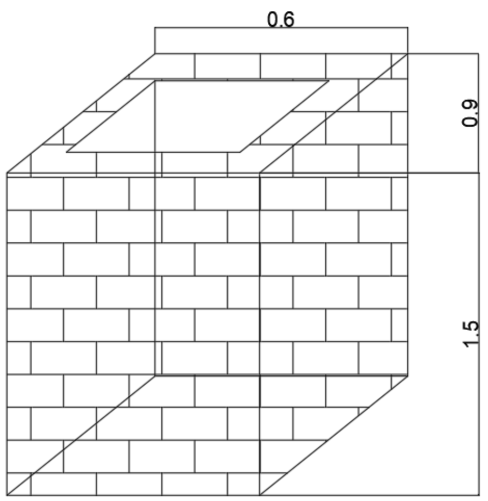

Figure 5. Representation of designed filter

3.2. Rapid Sand Filter

3.2.1. Prototype of rapid sand filter

Rapid sand filtration is a purely physical drinking water purification method. Rapid sand filters (RSF) provide rapid and efficient removal of relatively large suspended particles. Two types of RFS are typically used: rapid gravity and rapid pressure filters. Based on the site conditions, it was better adapted to a gravity sand filter. Initially the design consisted in building a frame from bricks and mortar of a size of inner width and length of 90 cm and 60 cm and height of 1.5 m as shown in the Figure 5.

These dimensions were chosen for maintenance purposes, since the maintenance would be simple and mechanical. A person has to remove the top layer. The opening size makes it possible for a person to fit inside the filter and remove the clogged sand. A prototype was built in Germany with a sand of a size range between 0.3-0.8 mm and a size range of gravel between 1.0-50 mm. The result was fascinating. The filter reduced the turbidity by 98%.(See Annex D) A cross sectional cut of the prototype filter is illustrated in Figure 6.The dark solid line between the two layers represents the filter cloth.

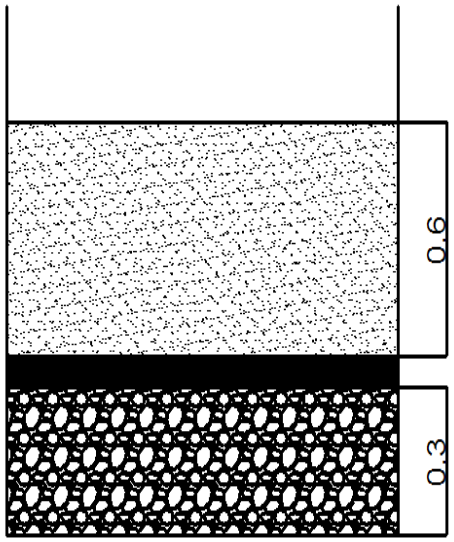

Figure 6. Cross sectional view of RSF

Figure 7. Rapid Sand Filter on site

3.2.2. Rapid sand filter on site

The filter that actually was built in Uganda was the same principle but different manner of building it. The idea was adapted to the environment and the resources. Firstly, it is important to be mentioned that it was quite hard to find the right grain size of the sand, and the frame of the filter was not built as a box of brick and mortar but rather a water storage tank as shown in Figure 7.

Besides these two constraints, the principle remains the same and here is where the adaptation to the resources available takes place. Initially the proper size of sand was not available so a sand of granular size between 0.5 - 1.2 was used. A second layer of coarse sand was laid under 60 cm of sand as the design required. Below there were two more layers as it can be seen in Figure 8. The reason behind adding more layers is to have a better result of the filtered water since the conditions and the dimensions of the initially planned design were not 100% correctly implemented. The layer of 0.08 m of fine gravel in this case serves as a filter cloth, as a separation between the sand and the stones in order to avoid loss of the material and eventually to have a better filtered water quality. The last layer of 0.26 m is a stone layer to increase the flow through the outlet pipe.

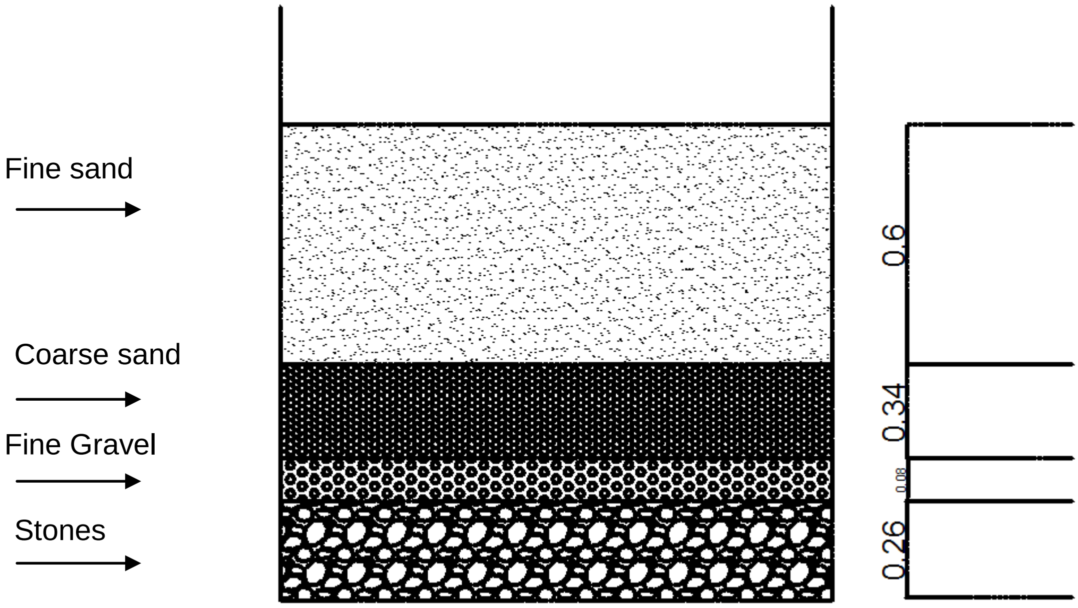

Figure 8. Sketch of rapid sand filter

3.3. Water quality (WHO Standards)

WHO produces international norms on water quality and human health in the form of guidelines that are used as the basis for regulation and standard setting worldwide.
The Guidelines for drinking-water quality (GDWQ) promote the protection of public health by advocating for the development of locally relevant standards and regulations (health based targets). Based on WHO there are three basic indicators to define the safety of water, physical, chemical and microbial. Physical parameters include pH, turbidity, and electrical conductivity, and chemical parameters include all chemical compounds found in water such as chlorine, arsenic, fluoride, fluorine, ammonia, sodium, potassium, calcium, magnesium and iron. These compounds are considered to have less influence on the human health compared to microbial contamination. The reason behind this is because most of the times they are found in very small negligible amounts and even if they are above the WHO standards, they only cause health issues in the long term but not immediate death. For this reason, in this project, treatment and purification of water from microbial requirements is most important and consequently turbidity.

3.3.1. Microbial water requirements

The use of bacteria as indicators of the sanitary quality of water probably dates back to 1880 when Von Fritsch described Klebsiella pneumoniae and K. rhinoscleromatis as microorganisms characteristically found in human faeces (Geldreich 1978). Coliforms, as part of the same family, are a broad class of bacteria found in our environment, including the faeces of man and other warm-blooded animals. The presence of coliform bacteria in drinking water may indicate a possible presence of harmful, disease-causing organisms. Testing for bacteria is the only reliable way to determine if the water is safe or not. On site, the testing of the bacteria performed by using Wagtech devices (Wagtech Potatest). (See Annex B) The main concept is to adapt the laboratory testing on site. The device is as shown in the figure below.

Figure 9. Bacteria Kit

One crucial element of bacteria tests is the incubator and its liquid nutrition media (bacteria food). The incubator simulates the temperature of a human body and the nutrient is basically made of glucose in order to have a similar simulation of the human stomach. The result was seen after the petri dishes were left for 18 h in the incubator. After the incubation time, the number of colonies which have grown in the membrane filter can be counted, because they are visible by naked eye, to determine the total coliform bacteria within the water samples. In this case, the coliform bacteria appear with yellow colour. The other bacteria species that appear with different colours such as pink or orange cannot be exactly determined. Based on Wagtech 2013 instructions those are harmless bacteria that can be taken as negligible compared to the coliforms.

Figure 10. Incubator and petri dishes (left) bacteria result (right)

3.4. Recommendations and results

In general, for a given pre-treatment of raw water and at a given filtration rate, coarse media will permit longer filter runs between washings when compared to fine media. With good pre-treatment facilities and close technical control, coarse media will yield water of satisfactory quality. With all other conditions fixed, removal of particulate matter is a function of both media size and filter bed depth, and removal generally improves with greater filter depth or with smaller media size, or both.

The coarse-to-fine grading tends to combine the longer filter runs characteristic of coarse media, with the superior filtration characteristic of fine media for improved overall performance. Proper selections of particle size range and specific gravity for the different layers of media are necessary to maintain the coarse-to-fine gradation during filtration.

a) Media size

Initially, the size of sand used, which was 0.5-1.2, showed great improvement in the effluent of the rapid sand filter.(See Annex D) But the turbidity of the filtered water did not drop down to the desired levels. For this reason, it was important to come up with another solution.

The first 30 cm of the top layer of the sand were replaced with a finer sand of diameter 0,5-0,8 mm. This improved the performance of the rapid sand filter. We have several data points (see Table 1) from before the sand was replaced regarding the turbidity (+/- 40 NTU) and the bacteria after chlorination. In most of them, the number of the bacteria were reduced significantly, but there were still some remaining and the cause of that is yet to be analysed. It is important to note that the growth media for the bacteria took on an odd colour and strong odour in the course of the tests on the 7 May. However, there is one last data point where the turbidity has dropped to 10 NTU (after replacing the sand) where you can see no bacteria after chlorination. For further explanation, the bacteria test was taken every 30 min and 1 hour after chlorination. The growth media was replaced on the 9^{th}.

b) Filter surface area

The bigger is the surface area of the filter the more discharge there is at the end, but on the other hand, water should be equally distributed over the top layer of sand. In the initial case, the water would be manually poured on top of the filter, which consequently wouldn't be equally distributed. For this reason a 20 cm diameter PVC pipe is placed on top of the filter and spread with two ends, from which water can be distributed over the top layer of sand (see Figure 11).

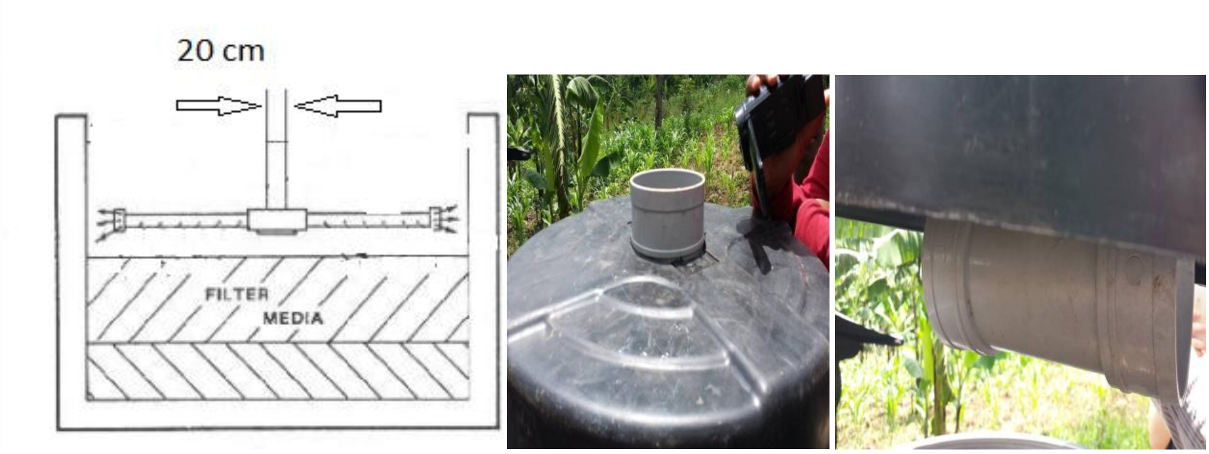

Figure 11. Sketch of water distributor (left), filter surface area (middle), distributor (right)

Date	Village	Sample	Turbidity (NTU)	Bacteria pre- and post-Chlorination (cfu/100ml)
05/05/2017	Kyamaga-mule	Filtered water over night	31	tntc; no coli visible
05/05/2017	Kyamaga-mule	Filtered water over night chlor. 2mg/l 30 min	31	20; no coli
05/05/2017	Kyamaga-mule	Filtered water over night chlor. 2mg/l 60 min	31	14; no coli
05/07/2017	Kyamaga-mule	Raw water for filter	42.2	tntc; no coli visible
05/07/2017	Kyamaga-mule	Filtered water over night	9.17	tntc; no coli visible
05/07/2017	Kyamaga-mule	Filtered water after change of sand (fine sand)	31.4	tntc; coli !
05/07/2017	Kyamaga-mule	Filtered water over night chlor. 2 mg/l 30 min	9.17	tntc; coli !
05/07/2017	Kyamaga-mule	Filtered water after change of sand (fine sand) chlor. 2 mg/l 30 min	31.4	6; no coli
05/07/2017	Kyamaga-mule	Filtered water over night chlor. 2 mg/l 60 min	9.17	about 200
05/09/2017	Kyamaga-mule	Filtered water (fine sand) over night for 2 nights	9.5	tntc; coli
05/09/2017	Kyamaga-mule	Filtered water (fine sand) over night for 2 nights; chlor. 2mg/l 30 min	9.5	30; 2 coli
05/09/2017	Kyamaga-mule	Filtered water (fine sand) over night for 2 nights; chlor. 2mg/l 60 min	9.5	1; no coli

Table 1. Results of turbidity and chlorination

c) *Rate of filtration*

Flow rate in rapid filters vary widely. In this case, after several data points and average was taken and as a result to fill a jerry can of 10 L was needed 3.2 min. This value is approximately equal to 0.05 l/s. Having the filter surface area it is possible finding the velocity using the continuity equation.

$$Q = V * A$$

And as a result, the velocity of the water through the filter is approximately 1.5m/h. Normally for many installations the downward filter velocity through the media varies from 4- 12 m/h but considering the size of the filter and the adaptation to the environment this is quite an acceptable result.

Figure 12. Outlet of the filter

4. Part II: Cascade Sand Filter

The present design relates to water filtration systems in which water is filtered through granular media to remove dissolved and suspended material from the water. Water to be treated is passed through the granular media and material dissolved or suspended in the water collects in the granular media. The first goal was to make a system of rapid sand filters in four different locations. Due to the negative social aspect and the fear that the filter component would get stolen or poisoned, this initial plan got cancelled. It was important to take into consideration their suggestions and the local way of thinking of those who actually are the ones going to benefit from this project. Hence a second decision was made to build a cascade filter in the common spring that more than 4 villages will use. This also came to be of more benefit for a larger amount of people.

4.1. Site description

A spring is a water resource formed when the side of a hill, a valley bottom or other excavation intersects a flowing body of groundwater at or below the local water table, below which the subsurface material is saturated with water. A spring is the result of an aquifer being filled to the point that the water overflows onto the land surface. They range in size from intermittent seeps, which flow only after much rain, to huge pools flowing hundreds of millions of gallons daily.
The spring on which the cascade filter was designed and built was surrounded by mud and was influenced by surface water. Consequently, there were a lot of dirt and faeces and chemicals contaminating the spring as it can be seen in Figure 13.

Figure 13. Spring in Kyamagamule, Uganda

4.2. Data from the site

Spring discharge, or **resurgence**, is determined by the spring's recharge basin. Factors that affect the recharge include the size of the area in which groundwater is captured, the amount of precipitation, the size of capture points, and the size of the spring outlet. Water may leak into the underground system from many sources including permeable earth, sinkholes, and losing streams. In some cases entire creeks seemingly disappear as the water sinks into the ground via the stream bed.

Local spring dimensions:

- Width: 54 cm
- Depth: 46 cm
- Depth after 18 min: 16 cm
- Length: 79 cm

Based on these characteristics, the resurgence of the actual spring was calculated

$$Q = V/t$$

- V=0,54*0,79*(0,46-0,16)
- $t = 18min * 60$ s
- $Q = 0{,}0001m^3/s$(0.1L/s)

Based on this result, the spring is classified as a first magnitude spring

.

In a filtration system, pressure drop is crucial because fluid flows through the filter medium by virtue of a pressure differential across the bed. Studying the pressure drop across the bed is therefore essential to determine filtration efficiency and expected time span before excessive build-up of filtered material occurs. Packed beds can be made in various forms that are designed in accordance with their application. The flow is considered laminar because the space between the particles is small, so the velocity is so small

4.3. Design Calculation

4.3.1. Structure of the filter

The cascade sand filter designed consisted of three boxes of different size granular media where the water filters through, like in the Figure 14. In essence, it is the same principle of a reversed sand filter. The first two boxes of media are gravel and coarse sand and the last one is the fine sand. It is important to be mentioned that the more stages the water passes through, the better the likelihood is to have non-turbid clear water at the outlet, but on the other hand one should not forget that, under different situations and site conditions, it is necessary to adapt to the resources given.

In this case, the resources were limited. From a technical point of view, looking at the local site conditions, the spring discharge was not big enough to pass through more than 3 layers of media. Moreover, the placement of the media starts from the coarser to the finest. The reason behind this is to minimize the maintenance process. Since the water coming from the spring is not only turbid, but has also large particles of dirt and mud, it would clog the sand in the course of few days and taking into account the working mentality of the locals, that would not only not be a solution, but also prevent them from using the water source like they had done it before. Another crucial aspect of the cascade sand filter is the civil structure. The structure chosen were the gabion walls and a retaining wall at the outlet.

There are two reasons why is important to have this civil structure. One is the stability of the media and the second one is in the hydraulic point of view. The movement of water in this cascade filter is horizontal. In other words, without an additional structure, this means that the water would flow underneath each box without being filtered properly.

The gabion wall blocks the path of the water by raising its level up to 30 cm which is enough for the water to be spread through the filter surface of each box by being filtered through and passed to the other filter box.

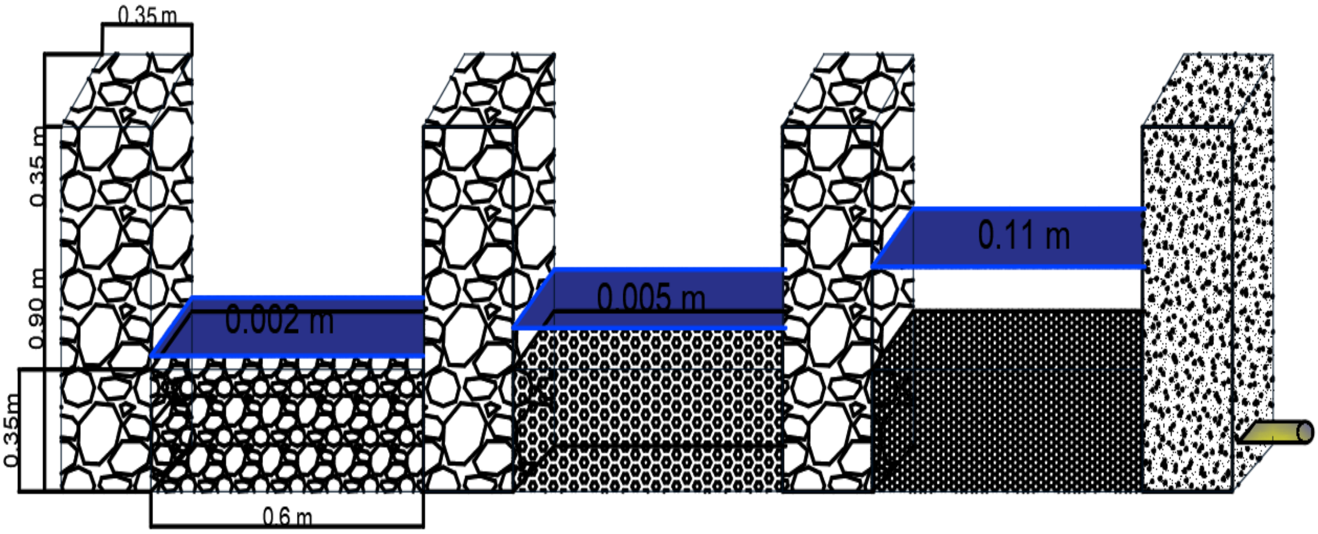

Figure 14. Representation of Cascade Sand Filter

4.3.2. Inlet Control

Inlet control represents a more complex hydraulic environment than outlet control, and it cannot be strictly mathematically modelled to obtain headwater depths. Under inlet control, the flow patterns at the entrance to the culvert may be three dimensional with vortices or other unpredictable features. These patterns are influenced by a number of factors, the most important of which are inlet geometry, wing wall configuration, culvert shape, and degree of bevelling. Fortunately, culverts operating under inlet control can be modelled using regression equations. Inlet control represents the case where the culvert barrel will convey more flow than the inlet will accept. The culvert normally will not flow full for its full length, thereby resulting in a free water surface that exists along the length of the structure. Under inlet control, the culvert entrance may either be unsubmerged or submerged. At low flows, the culvert entrance is unsubmerged and the discharge through the culvert entrance behaves like weir flow. A weir is a flow control cross-section where the discharge and depth of water are related to one another through some predictable relationship. One example of where inlet control occurs is when there is a mild channel slope upstream of the culvert that transitions to a steep culvert slope (Norman, et al, 1985) Figure 15

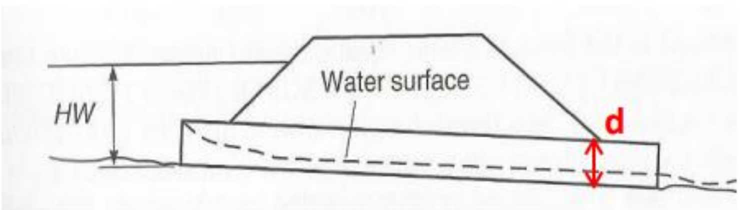

Figure 15. Submerged Inlet Control

In the design of the cascade filter a derivative of Norman equation was used.

$$y_h = D(C_4 * A * \left(\frac{4Q_p}{\pi D^{\frac{5}{2}}}\right)^2 + C_5 + C_3 S_p$$

- D: Diameter of the pipe
- Qp: Discharge
- Sp: Slope of the pipe
- $C_4 = 0{,}0379$
- $C_5 = 0{,}69$
- $C_3 = -0{,}5$

Initially a diameter was assumed in order to have a back check if the water head y_h would go over the banks. This allows cross-checking of whether the dimensions chosen for the gabion walls would support the flow of water. Based on the results shown in table 2, the value of the water head is small enough to not flood the banks.

Parameters	Values	Units
D	0.02	m
П	3.14159265	
Qp	0.0001	m/s3
C3	-0.5	
C4	0.0379	
C5	0.69	
yh	0.0176	m

Table 2. Norman eqn results

4.3.3. Pipe culvert sizing

When the culvert entrance is submerged, a different equation must be applied to find the headwater depth under inlet control.

$$\frac{HW}{D} = c\left(\frac{Q}{AD^{0,5}}\right)^2 + y - 0{,}5S$$

- HW: Water Head
- Q: Discharge
- A: Area of the model
- D: Diameter
- S: Slope channel
- Y and c are inlet control regression coefficients for submerged conditions.

An iteration process is used by means of Norman equation to find a proper diameter for the outlet pipe. Two parameters that were fixed were the water head and the designed discharge. The design discharge was initially taken as the measured discharge seen in section 4.2.

Fixed Parameters	
Hw (m)	0.41
Q(m3/s)	0.0001

The water head is fixed based on the pressure drop in m of the fine sand plus the elevation of the pipe. Whereas the discharge is fixed based on the discharge of the spring itself, at the same time it is very important to take into consideration the social point of view. In other words $0.0001m^3$/s is equal to 6 l/min and this makes a strong point for the locals that are going to use this filter. In less than 2 minutes they are able to fill a 10L jerry can and this is a good way of measuring if they are going to be satisfied with the result.

For purposes of calculation, the slope channel is considered as zero and the regression coefficient are considered as one. The value of the diameter for which the water head was most close to the fixed value is 0.014m. This value of diameter is close to the initial value chosen 0.02 m. Typical commercially available pipes are 0.016 and 0.020m diameter, so the actual choice of initial diameter would be one of these two values. The results are represented in more detail in the Table 3.

Parameters	Results
Hw (m)	0.41
Q(m3/s)	0.0001
c	1
y	1
D (m)	**0.014**
A(m2)	0.000154
(Q/A*D^0.5)^2	30.14255
Hw/D	31.14255
Hw (m)	0.435996

Table 3. Diameter of the outlet pipe

4.3.4. Flow through a packed bed.

As a fluid passes through a packed bed it experiences pressure loss due to factors such as friction. The relationships required to predict the pressure drop for a fluid flowing through a packed bed have been known for some time, with Darcy observing in 1896 that the laminar flow of water through a bed of sand was governed by the following relationship:

$$-\frac{\Delta p}{H} \sim U$$

The pressure drop for laminar fluid flow through a randomly packed bed of mono-sized spheres with a certain diameter may be calculated using the Carman-Kozeny equation as follows:

$$-\frac{\Delta p}{H} = 180\frac{\mu U(1-\varepsilon)^2}{x^2 \varepsilon^2}$$

In this case, the pressure drop is calculated for the three medias using different porosity, for fine sand, coarse sand and gravel as it can be seen in the Table 3.

Parameters	Symbols	Units	Gravel	Coarse Sand	Fine Sand
Viscosity	µ	pa.s	0.001	0.001	0.001
Superficial Fluid Velocity	U	m/s	0.00020576	0.00020576	0.00020576
Porosity	ε		0.35	0.45	0.25
Middle Grain Diameter	x	m	0.002	0.00085	0.0006
Pressure Drop	Δ p/h	pa	91.24284634	170.171263	3703.703704
Pressure in Column meter	Δ p	m	0.002791254	0.005205792	0.113301801

Table 4. Pressure drop results

These results give a clear idea of the head losses, which consequently will be an important point to cross check, the choice of the pipe diameter in the first place. The pressure in column meter is represented in the figure below.

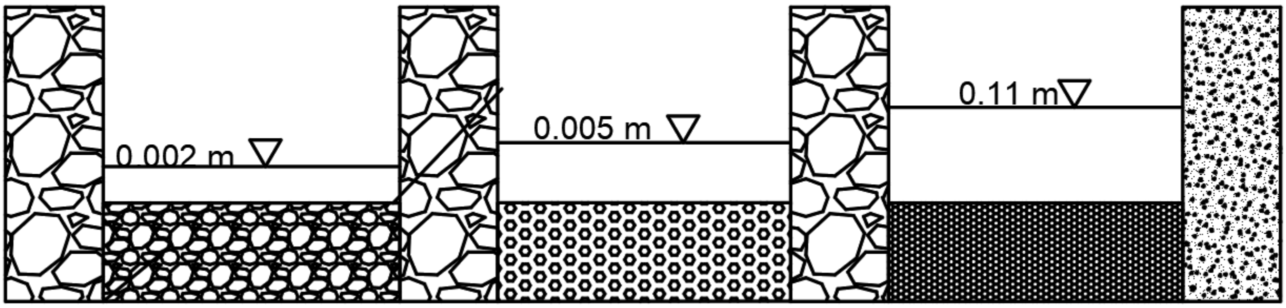

Figure 16. Pressure in column meter

4.4. Sensitivity analysis

This analysis is crucial in a study to check the uncertainty in the output of the mathematical calculations. Even though this case is a small model with a limited number of parameters, it is important to stage the output by focusing on the sensitive parameters.

4.4.1. Porosity

When working in such conditions, most of the values needed for the design are not as accurate as one would like to have. To be close to reality, using only the literature review is sometimes not enough. One good example of that is the porosity of the sand. This is one of the crucial parameters to determine the pressure drop in the filter. Literature values for the porosity of sand range from 0.20 to 0.5. Using the minimum porosity of 0.25 results in a flow head of 0.25 m A porosity of 0.25 results in a flow head of 0.11 m. A simple change of the porosity to 0.35 changes the flow head to 0.03 m. Using the wrong assumption of porosity could result in building unnecessary protection methods or, worse, neglecting to build protective measures based on a poor assumption of porosity. But there is often an on-site solution to find out the closest value to reality and that is by experimentally measuring it.

Porosity or **void fraction** is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0 and 100%.

$$P_t = \frac{V_p}{V_t}$$

To measure the porosity, a random bucket with dimensions 0.22*0.27*0.3 was taken. The bucket was filled up with sand and then water was poured until it was filled to the top.

This volume of water is assumed to fill all the voids therefore is considered as the volume of voids itself. While pouring the water, sand started to compact on both sides of the bucket. In order to have a more accurate measurement, a mean of the three cases was taken, first without compaction, then with compaction on the right side and last with compaction on the left side.

Table 5. Porosity Results for three cases.

Without compaction	
Volume of sand (m3)	0.01782
Volume of Water (m3)	0.006
Total Volume (m3)	0.01782
Porosity	0.2518
Without compaction left side	
Volume of sand (m3)	0.016632
Volume of Water (m3)	0.006
Total Volume (m3)	0.0226
Porosity	0.265
Without compaction right side	
Volume of sand (m3)	0.0154
Volume of Water (m3)	0.006
Total Volume (m3)	0.0214
Porosity	0.2797
Average Porosity	
0.265	

4.4.2. Regression Coefficient

In this case is important to determine the value of the pipe diameter when knowing the water depth. In the equation there are presented y and c, which are two regression coefficients. Regression is used to predict the value of one variable based on the value of a different variable. This means predicting diameter while knowing the water depth. The coefficient “c” is a sensitive parameter. For a value of c equal to 1, the water head is 0.43 m and for a value of c equal to 0.5, water head drops to 0.22 m.

To better interpret the regression coefficient the Norman formula is taken as linear and the coefficient “c” itself is seen as a slope. This regression coefficient represents the mean change in the response variable for one unit of change in the predictor variable while holding other predictors in the model constant. This statistical control that regression provides is important because it isolates the role of one variable from all of the others in the model. Based on this regression analysis, a value of 1 for c was used.

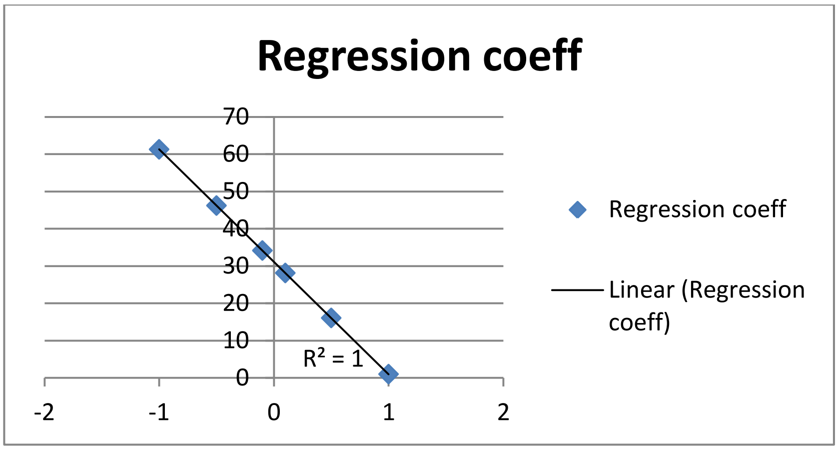

Figure 17. Linear Regression Coefficient

4.4.3. Stream Cascade prototype

For the prototype, the water was pumped from a well with high clay content, which made it very turbid. As it can be seen in the figure below, the cascade is made of two steps which are gravel and two which are sand. A weir is placed in the sand to prevent the sand from coming from one box to the other. A filter cloth was also placed in the sand boxes.
The cascade sand filter removed 99% of the turbidity. (See Appendix D)

Figure 18. Cascade Sand Filter prototype

5. Construction process

The construction process in itself is the process of identifying activities and resources required to make a design a physical reality. The first step is to make sure one can provide all the materials required. The second step is to come up with a solution of accessing the site and bringing all the materials needed. The third step is to provide manpower and financial support to cover all the expenses.

5.1. Materials

In such place as Uganda, flexibility is essential. For example, finding all the necessary materials can be more difficult than one might think. The process of finding sand started in a traditional fashion by going to different locations and checking the grading of the sand by using 0.3-0.8 mm sieves. In most of the cases, the sand grade varied considerably. Another solution was to buy the sand. Searching for the suppliers was not difficult but none of the places had the required sand parameters. Additionally, locals were convinced that there was no such sand that was asked for, a cultural factor not to be ignored. Therefore one point worth mentioning is how important it is to redirect the locals thinking because they are the only ones who could help finish this project with success by getting the necessary materials. By asking for pool suppliers who might have filter sand, rather than simply asking for sand resulted in finding a pool supplier who was found able to supply 0.5 to 1.2 mm sand which was close but not the desired grain size and not sufficiently graded. Ultimately, the required grading was acquired by special order from a local quarry, at the cost of a week's time. Finding the coarse sand and the gravel was much easier, as the grain sizes required were readily available. Other necessary materials such as wires to build the gabion walls, cement, plastic sheeting and empty sand bags, were locally available.

5.2. Transportation to the site

The site as seen in the figure below the location is not easily accessible area by car. The terrain was steep, with grades as high as 30%. There was no roadway to the filter site. It is worth mentioning here that for a small truck to be able to come to the spring, creating a small and easy track through the local farms was needed. For that, it was important to take the opinion of all the locals. Some of them did not want to cut some of their crops. This was a very important learning through process to see how they discuss with each other and what their priorities are. The vast majority of the locals that would profit by building the cascade sand filter gave a positive final decision, which made possible the transportation of the materials.

5.3. Construction

The construction of the filter itself started with pumping out the water from the spring and excavating the mud and possible dirt that was around like shown in the picture below:

Figure 19. Water being pumped out from the spring (right) empty pit (left)

The second step was placing large rocks at the bottom of the pond to minimise the mud and dirt being lifted up by the water. Once done, the area of the pond where the spring was, was reduced, and a channel was artificially created for directing the water where it should go. The area was reduced by placing soil in sand bags and placing these sand bags around the sides of the spring, which also helped the stability.

But before that, all the area around the pond (the walls) was covered with plastic sheeting. This has two benefits: one is avoiding loss of water outward through the soil and the second one is protecting from the intrusion of dirt and mud. Even though the spring water was not clear, having the plastic wrapped around would avoid the big amount of dirt and at the same time would help the filter to have a longer lifespan before being clogged.

Figure 20. Front view of the channel where the filter is placed

Figure 21. During the process of reducing the pond of the spring

Once this process was over, the channelizing of the water started, by building stone walls in the pit. This way the water would be free of mud and dirt and a smaller surface would provide a rapid raise of water to the level of the surface in order to go through the filtering channel, see figure below.

Figure 22. Final view of the spring pit after water channelization

Figure 23. Placement of the gabion walls

The last two steps of the construction process were the placement of the media between the gabion walls, building the retaining wall at the far end of the filter and placing the outlet pipe.

Figure 24. Top view of cascade

Figure 23 shows a top view of the cascade. In this picture you can see the two gabion walls and the sand media. Plastic sheeting is wrapped around it to isolate the water and prevent loss of water through leaking or penetration in the banks. In the figure 24 (left) can be seen the channelizing and reduction of the surface of the pond in order to direct the water to the channel where the cascade is, and on the right can be seen the concrete wall built at the outlet end of the cascade.

Figure 25.Final views of the cascade

5.4. Other considerations

5.4.1. Emergency overflow

In the cascade filter, the emergency overflows main function is to divert the excess water away from the filter in case of a strong rainfall event or in case of a higher amount of discharge is coming from the spring. This prevents washout of the filter media. This is the reason for calculating the 0.11 m of head loss above (see section 4.3.4). Another pipe is placed in the concrete retaining wall to release all the extra volume of water that would not be able to be filtered.

5.4.2. Structural stability

One of the most important points in a design is the structure stability of the filter itself. In this case, due to a very low discharge of water, the pressure of water acting horizontally on the gabion walls and the concrete retaining wall is considered negligible. This simplifies a lot the construction process in the field under difficult conditions. Under larger flow conditions, a structural analysis and dam design analysis would need to be performed prior to construction. Failure to do so could result in catastrophic failure and injury or loss of life.

5.5. Future research

There is always place to improve in engineering, the same principle works for this design as well. There are several aspects where the cascade can be improved. Starting with the emergency overflow. Two pipes were placed provisionally at the top of the concrete retaining wall for any additional flow above the calculated level to be removed from the filter. But emergency overflow needs to be calculated separately and a better solution found of how to deviate the extra volume of water coming from the spring, especially in rainy days.

Additionally, backwashing is a crucial point to be taken into consideration. As dirt accumulates in the filter bed, resistance to flow increases, which causes a reduction in water discharge to the outlet. When the flow is insufficient for proper water circulation, it’s probably time to routinely clean the filter. Another necessary time to backwash your water is after killing an algae bloom or when treating cloudy water. Presently, the cleaning of the filter is performed manually; this applies to the rapid sand filter as well. The top layer will be removed and washed, afterwards replaced back with the other media. The aim in the future is to find an automated, but mechanical, way of doing the backwashing.

Lastly as future research, there is also building a cascade in a stream or a river. During the trip in Uganda, there was a site where there was a continuous flow in a stream. The water did look clearer because it was continuously flowing (see Figure 26)

Figure 26. Stream in a village, Kalangaloo District

After performing several quality and bacteria tests, the results showed that the water needed treatment. The slope was measured for future feasibility. After measurements, the slope was determined as shown.

From upstream to downstream		From downstream to upstream		From downstream to upstream	
X(cm)	Y(cm)	X(cm)	Y(cm)	X(cm)	Y(cm)
0	65.5	0	76	0	71
50	66.7	40	75	50	69
100	66.5	90	73	100	67
133	65	140	72	150	70
183	66	190	69.8	200	69.8
233	64.5	240	67.5	250	69.5
283	66.8	290	69.0	300	69.0
333	65.5	340	66	350	69.4
383	69.5	390	65	400	68.6
433	70.3	440	67	450	66.5
483	72.2	490	65	500	66.4
533	73.4	540	64.5	550	65.5
573	75.5	Slope	**0.021**	600	62.8
Slope	**0.016**			632	63.5
				Slope	**0.011**
Average	**0.016**	**0.021**	**0.011**	Sum=0.048	**0.016**

Table 6. Slope of the stream data points and result

6. Conclusion

The microbial testing of water on site in Uganda has shown that is contaminated with organic and inorganic waste but especially faeces. On some sites, these indicators have shown high levels and in others, just few colonies of harmful bacteria. But this will not make a big difference health wise. As long as they are there, they cause a lot of health issues and very often lead to death for the consumers.

Based on this result, the first solution was chlorination of the water. The system of chlorination consists of a solar panel, car battery, electrodes and a bucket of salt water. This makes possible the production of chlorine. The produced chlorine is used to purify the water and remove all the bacteria. The salt chlorination system proved easy to use by the local population and provided effective disinfection of the local water supply. The acceptance level of the chlorination process was high. The addition of solar power provided the side benefit of an electrical source for villagers.

Wherever the water source had turbidity of less than 5 NTU, the disinfection was complete. Even where the turbidity was higher than 40 NTU, the reduction in bacteria count was substantial, from thousands to roughly 5. Even though these are desirable results they do not completely solve the problems. The best way for the chlorination to be efficient is to first filter the water.

The main technology is this study was building a rapid sand filter in a very traditional fashion, simple to build and maintain. Compared to the literature review, the filter media was important to be between 0.5-0.8 mm but this gradation was not easy to find. Initially the grain size found varied from 0.5-1.2, that was the closest to the one needed. The turbidity reduced to around 10 NTU but that was not the desirable values. The only solution was to adapt to these conditions and start sifting. After the first 30 cm were replaced with the initial designed grain sand size the results were improved. Most importantly, the water results after the chlorination showed no bacteria. But one thing important to mention is the time and the adaptability. Because the water that was used to clean the sand in the first place was the dirty water. Consequently it took more time to see the results compared to the prototype.

This rapid sand filter was planned to be built in four different locations. Due to cultural point of view of having this filters in less secured area than the one already built, the locals denied the construction. This was a challenge to overcome. The sites had been previously chosen and all the water sources were already known. The team decided to build the cascade filter in the spring downhill from the village. This spring was a water supply for more than 4 villages around. Consequently, this was a better solution because it would come to help of more people.

A prototype had been built in Germany in advance for a stream. The situation was different, but the principal remained the same. The only difference is that the medias are separated from one other with a gabion wall and they start from the gravel to fine sand. The reason behind this organisation is to make possible water rising till the top level and to have a vertical movement in order to be filtered and the second is for maintenance. Due to the fact that the spring is surrounded by mud, having the gabion walls and the gravel first will slow down clogging.

In the cascade, due to the short time and the lack of supervision after the senior engineer returned to Germany, some decisions were made that materially affected the functionality of the filter. The emergency overflow, for example, was placed above the level of the banks.

However water problems in developing countries cannot be solved by individual water treatment alone and it requires more than the 4 weeks of time available to construct, supervise and test the results of the plant, which is the filter in this case, but also the chlorination. The chlorination itself has other issues to be taken into consideration, like the life span of the battery, the concentration of chlorine generated and the time required to generate the concentration. This provides another good example of adapting to local conditions: How do you teach Ugandans living in the deepest village with no cell phone how much an hour is?

This journey was not only to grow as engineer and to learn the technical point of view and different aspects of design and construction. This journey was also about adaptability and creativity. Drinking water purification systems should be designed for every region under special considerations of natural resources, technical, social, economical and cultural aspects.

This project is a successful example that shows improvement in water quality of a developing country. But one can only judge the success of the project when the locals are happy with it and they continuously use it.

7. Recommendation

No matter the success one should never simply be satisfied and not move out of their comfort zone. There is still a lot of place for improvements. Having passed through such an experience, the things that are helpful for others doing the same mission is given as a recommendation.

Initially, the organisation, is a very crucial aspect in such projects. Before undertaking this big step of going somewhere and giving promises to people in desperate times, one needs to be sure they have clear goals. Even though sometimes things that are not expected happen, for example the locals did not want to build other filters, organisation helps. If the site for the cascade was not previously known by the locals, perhaps building the cascade in a spring would not have come up as an idea.

Assigning tasks to different groups to maximize time is an important component. Making technical decisions and sticking with them is also essential. For example, once the senior engineer was gone the gravel pack that should have been used to cover the outlet pipe was substitute by a filter cloth. This resulted in clogging the outlet through the accumulation of fine particles.

And most importantly, patience. In different countries the working habits are different. That is why patience is needed to start directing the peoples' thinking to what is needed to get a project done!

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9. Annexes

ANNEX A : Relevant Page from UBOS 2016

ANNEX B : Bacteria test procedure in pictures WAGTECH 2013

ANNEX C: Chlorination equipments photo

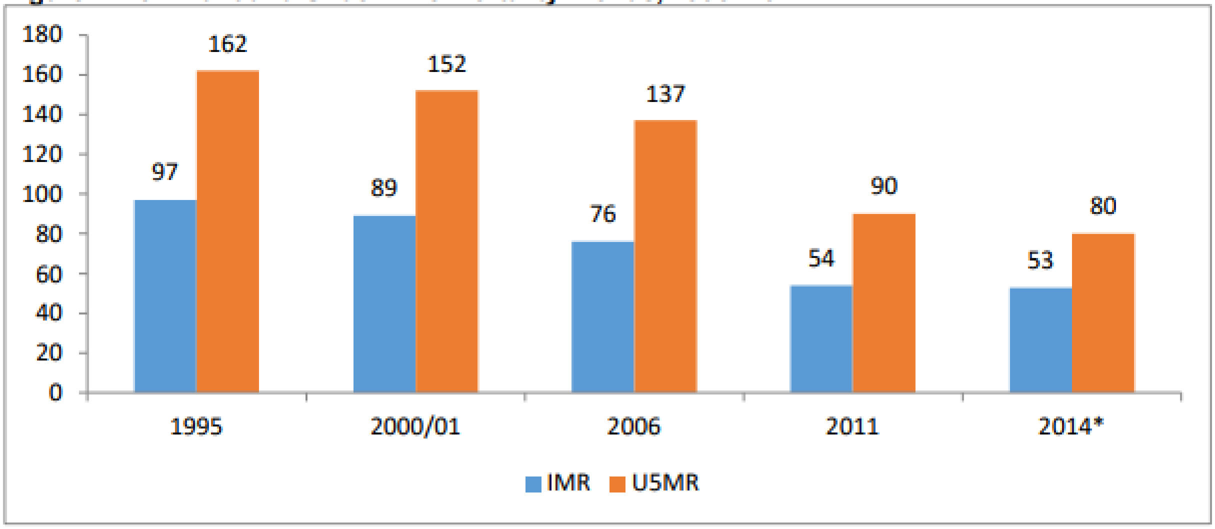
ANNEX D : Prototype turbidity results

ANNEX E : Data from the site

ANNEX A

Mortality Trends

Figure 2.1.5: Infant and Under Five Mortality Trends, 1995- 2014



Population Characteristics

Table 2.1.1: Population size, Inter-censal Population increases and average annual growth rates, 1911-2014

Census year	Male	Female	Total	Intercensal Period	Average Annual Increase (000's)	Average Annual Growth Rate (%)
1911	1,116,903	1,349,422	2,466,325			
1921	1,320,286	1,534,322	2,854,608	1911-1921	39	1.5
1931	1,707,437	1,834,844	3,542,281	1921-1931	68	2.2
1948	2,481,394	2,477,126	4,958,520	1931-1948	83	2.0
1959	3,236,902	3,212,656	6,536,616	1948-1959	143	2.5
1969	4,812,447	4,722,604	9,535,051	1959-1969	300	3.9
1980	6,259,837	6,376,342	12,636,179	1969-1980	262	2.7
1991	8,185,747	8,485,558	16,671,705	1980-1991	367	2.5
2002	11,824,273	12,403,024	24,227,297	1991-2002	647	3.2
2014	17,060,832	17,573,818	34,634,650	2002 - 2014	882	3.0

Source: Uganda Bureau of statistics.

Bacteria Procedure

Figure 1.Bacteria Food Preparation

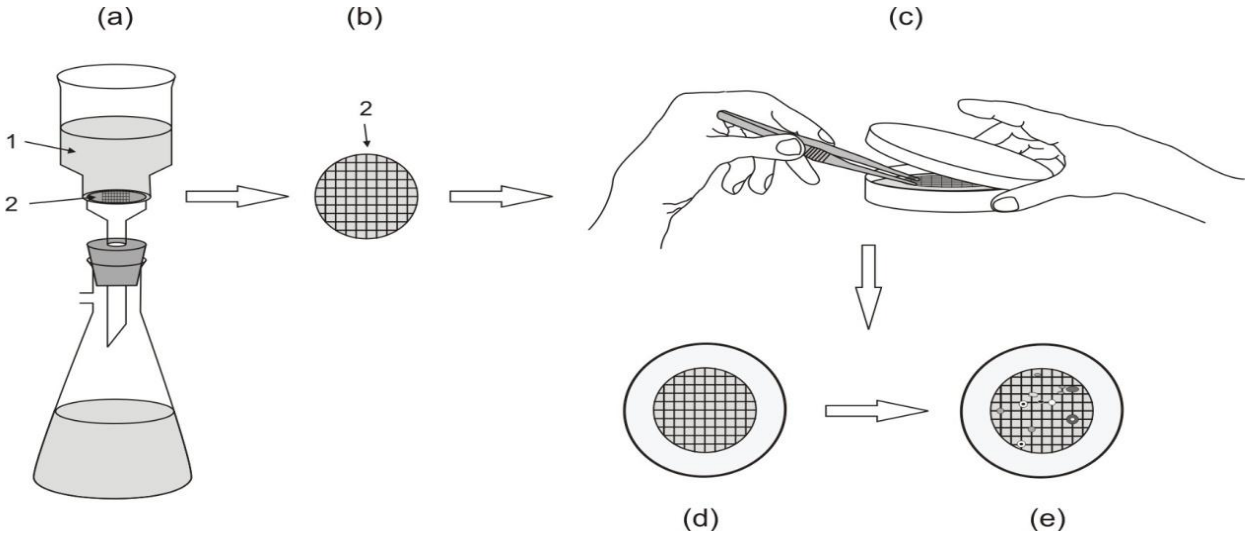


Figure 2.Membrane filter method overview

Figure 2.Disinfection process

ANNEX C

Chlorination equipments

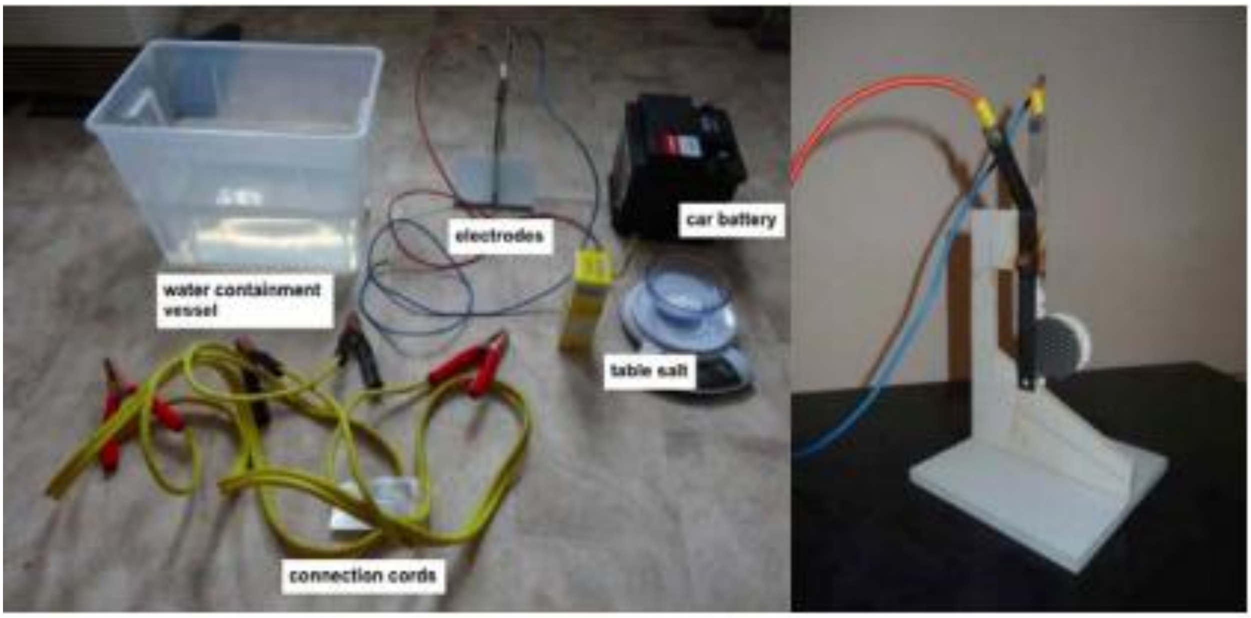


Figure1. Laboratory set up of chlorine producing

Figure 2 On site chlorine producing

ANNEX D

Prototype Turbidity Result

Time And Date	Turbidity Dirty Water NTU	Turbidity Filtered Water NTU
08/07/2016 12:55	79.6	3.06
08/07/2016 13:30	81	3
08/07/2016 12:55	144	1.03
08/07/2016 14:00	212	3.35
08/07/2016 14:30	84.1	1
08/07/2016 12:55	87.5	1.95
08/07/2016 15:00	120	0.78
08/07/2016 15:30	84.9	0.7
08/07/2016 16:00	90.4	0.24
08/07/2016 16:30	125	0

Table 1.Turbidity Result on the prototype

Figure 1.Before and after filtration

ANNEX E

On Site Data

Date	Village	Sample	Turbidity [NTU]	Electrical ConductivityEC [µS]	Temp [°C]	pH Value	Colony Forming Units	
							3M Petrifilm	Membrane Filter
12/06/2016	Namukomago	S2	44.7	56.8	27.8	7.1	860	tntc
12/06/2016	Namukomago	1 (George)	26.2	37.6	27.7	7	tntc	619
12/06/2016	Namukomago	S3	62	39.1	27.8	6.17	129	tntc
12/06/2016	Namukomago	S1	48.9	44.3	28.5	7.1	720	tntc
12/06/2016	Kalangaalo Kyamagemule	S2	28.9	63.3	27.6	6.2	8; 586; 730	4
12/06/2016	Kalangaalo Kyamagemule	S1	26.9	21.8	27.5	6.6	6	71
12/06/2016	Kabayiima	S1	67.4	72	28.1	7.12	820	tntc
12/06/2016	Kabayiima	S2	19.79	23.2	26.2	7.22	tntc	tntc
12/06/2016	Kabayiima	S1 (Juline)	85.5	67.1	26.3	7.18	tntc	180
12/06/2016	Kabayiima	S2 (Juline)	20.4	72.3	27.1	6.9	tntc	tntc
12/06/2016	Kosovo by church (downstream)	S1	1.14	150.9	25.5	6.1	51; 21; 21	285
12/06/2016	Kosovo by church (downstream)	S2	0.53	150.1	25.3	6.4	30; 44	tntc
12/06/2016	Kosovo-Kampala	S3	0.63	189.4	26.9	6	15; 8	333
12/06/2016	Enro	-	-	80.1	26.1	7	816; 627	tntc
13/06/2016	Masajja		2.67	191.6	24.7	6.4	540	784
15/06/2016	Mbiliddembiraba	S1	37.9	44.4	24.9	6.65	tntc	tntc
15/06/2016	Mbiliddembiraba	S2	44.4	42.9	25	6.52	tntc	tntc

15/06 /2016	Kalangaalo Kyamagemule	S	1.6	42.9	25	6.43	85	170
16/06 /2016	Mayobyo A	S1 (well)	49	43	24	6.1	tntc	tntc
16/06 /2016	Mayobyo A	S2 (well)	44	42	25	6.5	tntc	tntc
16/06 /2016	Mayobyo A	S3 (strea m)	27	58	24	7	485	tntc
16/06 /2016	Mayobyo A	S4 (strea m)	27.7	108.4	24.2	6.8	tntc	tntc
16/06 /2016	Kabayiima (LCI)	S	38.1	53.5	24.5	5.91	tntc	tntc
16/06 /2016	Namukomago	S1	28.5	291	24.1	6.05	tntc	tntc
16/06 /2016	Namukomago	S3	78.5	106.2	24.3	5.6	tntc	tntc
16/06 /2016	Kabayiima	S1	69.9	164.4	24.3	6.87	tntc	tntc
16/06 /2016	Kabayiima	S2	13.49	65.4	24.3	6	tntc	tntc
16/06 /2016	Mbiliddembiraba	S1	26	52.8	24.4	6.86	tntc	tntc
16/06 /2016	Mbiliddembiraba	S2	25.4	55.1	24.3	6.66	tntc	tntc

Table 1.Data of 4 sites, raw water

Date	Village	Chlorine doze	Aerobic Heteretrophic , Plate counts cfu/ml	Membrane Filter Method, Total Colifroms cfu/100ml
20/06/2016	Mbiliddembiraba	chlorinated 1 mg/l 3 h		no visible coliforms
20/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 1 h		no visible coliforms
20/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 2 h		no visible coliforms
20/06/2016	Mbiliddembiraba	chlorinated 1 mg/l 2 h		no visible coliforms
20/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 1h		8
20/06/2016	Namukomago	chlorinated 1 mg/l 2 h		12

20/06/2016	Namukomago	chlorinated 1 mg/h 3 h		no visible coliforms
20/06/2016	Namukomago	chlorinated 2 mg/l 3 h		no visible coliforms
20/06/2016	Namukomago (left well)	chlorinated 2 mg/l 1/2 h		no visible coliforms
21/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 1/2 h	16	
21/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 1 h	8	
21/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 2 h	4	
21/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 3 h	14	
21/06/2016	Mbiliddembiraba	chlorinated 2 mg/l 4 h	3	
21/06/2016	Namukomago	chlorinated 2 mg/l 1/2 h	126	
21/06/2016	Namukomago	chlorinated 2 mg/l 1,5 h	110	
21/06/2016	Namukomago	chlorinated 2 mg/l 1,5 h	85	
21/06/2016	Namukomago	chlorinated 2 mg/l 2 h	53	
21/06/2016	Namukomago	chlorinated 2 mg/l 2,5 h	77	
21/06/2016	Namukomago	chlorinated 2 mg/l 3 h	83	
22/06/2016	Namukomago	chlorinated 2 caps 3 h		2
22/06/2016	Namukomago	chlorinated 1 cap 3 h		0
22/06/2016	Namukomago	chlorinated 2 caps 2 h		1
22/06/2016	Namukomago	chlorinated 1 cap 2 h		3
22/06/2016	Namukomago	chlorinated 2 caps 1 h		0
23/06/2016	Namukomago	ultrafiltration 1	0	no visible coliforms
23/06/2016	Namukomago	chlorinated 2 caps 1 h		1
23/06/2016	Namukomago	chlorinated 1 cap 1 h		no visible coliforms

Table 2.Date after chlorination