

# Artificial groundwater recharge – is it possible in Mozambique?

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**Cover Picture:** Map of Mozambique.

# Artificial groundwater recharge – is it possible in Mozambique?

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**Abstract:** The amount of clean drinking water varies across different parts of the world. For example is groundwater a big resource in Sweden and stands for 50% of the drinking water, both artificially and naturally recharged. The corresponding fraction is only about 6% in Mozambique and considering that 47% of the population in Mozambique lacks clean drinking water artificial recharge might be a good option. Different ways and reasons to artificially recharge aquifers are summarized in this literature study. Seven of them were selected because they seemed relevant when investigating the potential for suitable areas in Mozambique to initiate artificial recharge. The systems work in different ways; either the water infiltrates permeable soil before reaching the aquifer or the water is led down a borehole straight to the aquifer. This depends on the sediments underneath the surface, how much space that is available on the surface and the water quality that needs to be achieved. There are also different reasons for artificial groundwater like; refill an aquifer and clean the water at the same time, to stop saltwater intrusions, fill an aquifer to make sure that subsidence does not occur or to fill the aquifer during the rain season to save the water for drier seasons. Mozambique has got potential but it takes more than geological and hydrogeological maps (e.g. field-work) to locate one single place where a artificial recharge system would work, instead two different areas were chosen as possible candidates.

**Keywords:** Artificial recharge, water quality, Mozambique.

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# Förstärkt grundvattenbildning – är det möjligt i Moçambique?

JOHANNA ALEXSON

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**Sammanfattning:** Tillgången till rent dricksvatten varierar mellan olika delar i världen. Till exempel är grundvattnet en stor resurs i Sverige där det står för 50 % av dricksvattnet, både artificiellt och naturligt bildat. Den siffran är endast 6 % i Moçambique och med tanke på att 47 % av populationen i landet saknar rent dricksvatten kan artificiell grundvattenbildning vara ett bra alternativ. Det finns olika anledningar till varför man använder sig av artificiellt infiltrerat ytvatten som med hjälp av olika processer blir till grundvatten och de summeras i denna litteraturstudie. Det finns många olika tillvägagångsätt av förstärkt grundvattenbildning, av vilka de sju som tas upp i den här rapporten valdes ut för att de verkade relevanta i utredningen ifall det går att använda förstärkt grundvattenbildning någonstans i Moçambique. De olika sätten att infiltrera vatten beror på sedimenten under ytan, hur mycket plats som finns tillgänglig på ytan och vilken vattenkvalitet som ska uppnås. Orsakerna för användning av förstärkt grundvattenbildning är bland andra att; fylla på en akvifär och samtidigt rena vattnet, stoppa saltvattensintrusion, fylla på en akvifär för att undvika subsidens eller infiltrera vatten under en regnperiod för att sedan utnyttja vattenkällan under en torrare period. Moçambique har potential till att använda sig av förstärkt grundvattenbildning men det krävs mer än geologiska och hydrogeologiska kartor (ex. fältarbete) för att lokalisera en specifik plats grundvattenbildning skulle kunna tillämpas, istället valdes två områden ut som möjliga kandidater.

**Nyckelord:** Artificiell grundvattenbildning, vattenkvalitet, Moçambique

**Handledare:** Helena Alexanderson

**Ämnesinriktning:** Kvärtärgeologi

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# 1 Introduction

Of all the water on this planet freshwater only represents 2%. Two thirds of that is solid (ice) and of the rest non-solid, groundwater stands for 96.3%, that equals approximately 8 000 000 km<sup>3</sup>. Groundwater is the greatest source of water on this planet (Seiler and Gat, 2007), and with a steady population growth around the globe the same amount of water has to be enough for more and more people and because the groundwater source is not endless it will come to an end. With the help of artificial recharge that problem may be solved. Infiltrate water for recharging the aquifers could be the answer. Poor water quality is also an issue, which can be enhanced if the soil (that the water infiltrates through) has the right kind of properties and then people might be able to drink the water straight from the well. There are many benefits with artificial recharge, it can work as a storage, which could be beneficial for arid areas where it can infiltrate during the wetter seasons and be used during the dry seasons, no evaporation and it is fairly cheap. But it needs some experience and maintenance so that the system will not clog and become unusable.

The questions in this report are as follows:

- What are the different purposes of artificial recharge, and what are the different types of artificial recharge systems?
- What is required for successful infiltration of surface water to create good quality ground water? In terms of
  - Sediment properties
  - Surface- and ground water chemistry and availability
  - Improvement options
- Based on the above requirements, can suitable sites for surface water infiltration be located in Mozambique?

These questions and their results will be addressed below in chapters 3, 4 and 5 respectively.

## 2 Methods

A literature study was the logic choice for this project, given its overview nature and the limited amount of time and money available. To make the results accessible to an international audience, I decided to write the report in English. The study includes books, reports and suitable webpages about this subject. It is based on experiences from Sweden where artificial recharge has been used for over a century, but also facts from all around the world since Sweden's and Mozambique's conditions and climates are very different.

The purpose of this paper was to first get an overview

of how artificial recharge and the different systems work to determine if artificial recharge is a good option in Mozambique.

## 3 Artificial recharge systems and their purpose

### 3.1 Different purposes

The use of artificial recharge (AR), also called Managed Aquifer Recharge (MAR) (Dillon, 2005), is not only for the purpose of producing drinking water; it can also be used to control the level of groundwater. That is done to make sure that subsidence does not occur, if a confined aquifer is drained the formation could collapse and the damages could be major (Hanson, 2000).

Artificial recharge can also act as a hydraulic barrier for countries situated by the coast that have problems with saltwater intrusion. Saltwater is heavier than fresh water so the fresh water will "lay" on top of the salt water and drinking water can be taken from the top of the aquifer (Hanson, 2000).

This report will focus on different artificial recharge systems that are used to infiltrate or inject freshwater down a borehole for drinking water supply, to refill the water in the aquifer and to enhance the quality of the water by infiltration by mixing freshwater and groundwater (Hanson, 2000). Table 1 shows how different water supply sources can be compared, both their economic cost and how much knowledge that is needed (Dillon, 2005). Artificial recharge is not the easiest or cheapest way to get drinking water but as can be read from the table, it is a good option in dry areas because it does not fail in droughts (Dillon, 2005). For example dams have problems with evaporation and in comparison to artificial recharge, the space that is needed does not need to be that big compared to dams because the space that is needed is under the surface (see artificial recharge systems below).

### 3.2 Artificial recharge systems

Since the beginning of the 1800s artificial recharge has been applied in Europe. Groundwater accounts for 50% of the drinking water in Sweden, both naturally and artificially infiltrated (Hanson, 2000). There are different types of artificial groundwater recharge systems that can be used depending on the properties of the location in question, and depending on what kind of system that is used, the outcome varies. System 1, 2, 3, 6 and 7 recharges the aquifer and enhances the water quality at the same time, while 4 and 5 only recharges the aquifer (see details below). Depending on the permeability of the soil, infiltration can start from the surface, or if the topsoil layer is impermeable it can be removed and infiltration can start a bit further down (Bouwer, 2002). It is also possible to inject water directly into a fractured rock aquifer (Dillon, 2005), but this will exclude the cleaning process that the soil provides, but it is a good option for storing water in arid areas. All the different ways of

Table 1. Summary of various water sources that supply different sized populations (below “Typical scale” column) with drinking water. The scale is yearly based and the dollar sign (\$) is a measurement of money for the “relative capital cost” and the “relative investigation costs” column. For the “relative technical knowledge needed” and “relative regulation difficulty” column, the dollar sign is a measurement of knowledge; the more dollar signs the more knowledge is needed and the more difficult the system is. The table is adapted from Dillon (2005).

Water supply sources	Typical scale measured in m <sup>3</sup> /year	Limitations	Relative capital costs	Relative investigation costs	Relative technical knowledge needed	Relative regulation difficulty
Rainwater tanks	Family 10 <sup>1</sup> –10 <sup>2</sup>	Fails in droughts	\$	\$	\$	\$
Springs	Family/ village 10 <sup>3</sup> –10 <sup>4</sup>	Can fail in droughts	\$\$	\$	\$	\$
Ground-water	Village/ town 10 <sup>4</sup> –10 <sup>6</sup>	Needs aquifer	\$\$\$	\$\$	\$\$	\$\$
Artificial recharge	Village/ town 10 <sup>3</sup> –10 <sup>6</sup>	Needs aquifer	\$\$\$\$	\$\$\$	\$\$\$	\$\$\$
Dam and treatment plant	Region 10 <sup>7</sup> –10 <sup>9</sup>	Needs dam site	\$\$\$\$\$	\$\$\$\$	\$\$\$	\$\$\$
Desalination	Town/ region 10 <sup>3</sup> –10 <sup>7</sup>	Needs power and brine discharge	\$\$\$\$\$	\$\$	\$\$\$\$	\$\$

infiltration have one thing in common though; the need of a high quality freshwater source (Bouwer, 2002).

The different infiltration systems are described below:

1. **Basin (surface) infiltration** is when surface water is led to a basin and infiltrated down through the soil to an unconfined aquifer (Hanson, 2000), see Fig. 1:1. The soil has to be permeable and the vadose (unsaturated) zone has to connect to an unconfined aquifer where the surface water becomes groundwater (Bouwer, 2002). The vadose zone has to consist of coarse sediments that are well sorted and free from fine-grained particles such as clay and silt. Further explanations are found under section 4.2.1 (Hanson, 2000). This way of infiltrating takes up considerable surface space, one basin is usually 20×40 m. For example Vombverket, which provides part of southern Sweden with drinking water, takes up an area of 0.4 km<sup>2</sup> with their 52 basins (Hanson, 2000).
2. **Vadose zone infiltration** can be a good option when the soil underneath the surface is not permeable enough. This can also be a solution if surface space is an issue, because this is a vertical infiltration system (Fig. 1:2), and the diameter on the surface is only around one meter. A well or a trench is built, depending on how far down the vadose zone (with the right permeability) can be found. This system is quite cheap but it clogs easily so it has to have maintenance (Bouwer, 2002).

3. **Induced infiltration or bank infiltration** must have a surface water source that is in contact with an aquifer. A well will pump up the groundwater, which will cause the water from the surface water source to leak into the aquifer and become an artificial recharge source, see Fig. 1:3. This system needs information about the hydraulic boundary between the surface and groundwater and knowledge about the chemistry of the water, both ground and surface water (Hanson, 2000).
4. **Artificial recharge well** is an option when the soil on top of the aquifer is not permeable enough. The water is put into the well and is put straight into the aquifer (Fig. 1:4). This way of artificial recharge will not purify the water because it lacks the cleansing infiltration process, so the water has to be clean before it is pumped into the aquifer if the purpose is drinking water. In some cases the water is just used for irrigation and it might not need purifying. Clogging is a problem with this system as well, but can be avoided by “backwashing” which is done by pumping the system (the well) 2-3 times a day for 15 minutes (Bouwer, 2002).
5. **Aquifer storage and recovery (ASR)** is when fresh water is put in and taken out from the same well (Fig. 1:5), to either recover the water loss of an aquifer or to store the water for drier seasons (Dillon, 2005).
6. **Aquifer storage transfer and recovery (ASTR)** is a system where the water is put in one well and is withdrawn from another one

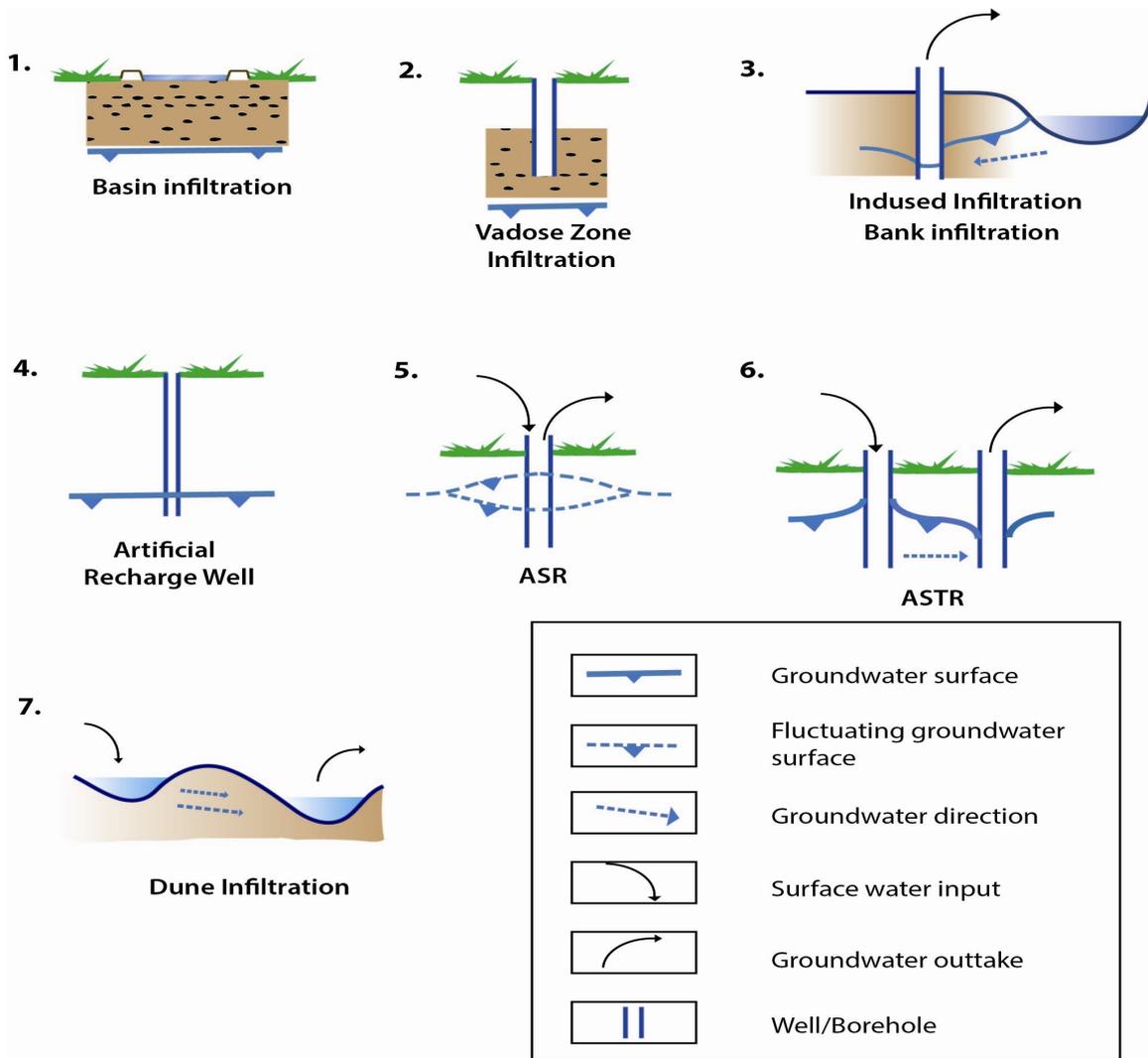


Figure 1. Different kind of artificial groundwater recharge systems that are described in section 3.2 are presented in figures made in illustrator. Number 1-4 are based on figures from Mays (2012) and number 5-7 are based on figures from Dillon (2005).

further away, see Fig. 1:6. This is done for the same reasons as ASR, but also to increase the quality of the water (Dillon, 2005).

7. **Dune infiltration** is a way to conserve the water from a rain season for the drier season and to enhance the quality of the water. Compared to what the glaciers and ice sheets did during the ice ages with the sorted sand and gravel deposits, the wind has sorted and deposited the sand in the form of dunes (Fig. 1:7). Fresh water is infiltrated through the sand from dams that are situated between the dunes and withdrawn from wells or dams that are situated at a lower level between the dunes (Dillon, 2005).

thorough study of the hydrology of the area is also advised before a location is determined. When a decision has been made, the place in question has to undergo many studies before making the artificial recharge a reality (Hanson, 2000). It is also required of the hydro-geologist to make a judgement of what type of artificial recharge that is the most suitable for a specific place. If the system is not taken care of, maybe because of lack of knowledge, the consequences can be devastating with damaging of the aquifer, loss of money because of useless systems if it clogs or the turn out could be even worse if the water quality is so bad that peoples health are at stake (Dillon, 2005).

## 4 Requirements

### 4.1 Experience

Geological experience and detailed geological and hydrogeological maps are needed in the process of deciding on a site for a artificial recharge system. A

### 4.2 Soil properties and problems

#### 4.2.1 Soil

The sediment properties can not be summarized into one specific soil because of the different recharge systems which have different requirements so below are a few examples of what to think about:

When using artificial recharge that involves infiltration through soil the stress on the soil is much greater compared to natural recharge. The infiltration rate is thousands of times bigger; usually between 1-3 m per day compared to 1 mm per day for natural infiltration, depending on the climate (Hanson, 2000). Depending on the reason for artificial recharge the soil qualities vary. To get the best artificial recharge result when enhancing the quality of the water the unconfined aquifer should be underneath sediments that are unconsolidated and have a hydraulic conductivity that ranges from  $10^{-2}$  m/s to  $10^{-5}$  m/s (Seiler and Gat, 2007).

Due to the amount of water that infiltrates every day, the soil will eventually lose all the different minerals that help surface water to convert into groundwater (see differences between 4.4.2. and 4.4.3). This can be helped with the right kind of knowledge (Hanson, 2000). For example if the infiltrated water uses all the calcium carbonate ( $\text{CaCO}_3$ ), because of the fast infiltration rate, the pH will lower and the water gets aggressive (see 4.4.1), which can be solved by adding  $\text{CaCO}_3$  (Cech, 2003).

If a vadose zone is a part of the artificial recharge system it is important that the soil consists of sorted sand and gravel deposits and that no finer particles are to be found. In countries like Sweden those deposits are quite easy to find due to the sorted glaciofluvial material but countries that lack that kind of geological formations can use other sand and gravel deposits such as coarse river sediments (Hanson, 2000).

One thing that all of the artificial recharge systems have in common is that the soil has to be clean so that no toxins will spread down to the groundwater (Bouwer, 2002).

#### 4.2.2 Clogging

Clogging is a very common problem that happens for different reasons and occurs in every infiltration system but with the right kind of knowledge the problem can be taken care of. The clogging can take place on different depths, and the costs get greater with depth; the deeper the clogging occurs the more expensive it gets (Hanson, 2000). A thin layer of bioskin, which is a layer that forms from organic material in the water, is good for the quality of the water but when it gets too thick clogging occurs. To prevent clogging the basin is left to dry out and then the bioskin is removed as well as the top layer of the sand. The sand is washed and put back or the sand can be replaced. The clogging in the top layer is solved this way, but when the clogging occurs further down the soil has to be dug up and washed, or replaced (Hanson, 2000). In the text below different kinds of clogging processes are explained:

##### - Mechanical processes

Smaller fractions like silt or clay can clog the system, especially if the turbidity is high (for example after a storm) which can be helped by stopping the infiltration when the raw water source is too turbid. This can also

happen if the filter material contains finer grains that can infiltrate further down in the formation and clog the system at a greater depth (Hanson, 2000).

##### - Biological activity

A great amount of biological activity can cause oxygen depletion out which can lead to gas-formation that can get trapped between the sand and gravel grains and that can lead to clogging. Aeration is a good and cheap option to take care of that problem (Hanson, 2000).

##### - Organic material

Micro sieve is a good option for getting rid of plankton (the organic material), as well as a "fastfilter" but it will not work as well on the smaller mineral (inorganic) fractions like clay or silt, so they could still clog the system (Hanson, 2000).

##### - Chemical processes

Oxygen in the water can lead to precipitation of iron and manganese, which can clog the system. A lack of oxygen makes these substances dissolve in the water instead and the system will not clog. If the water contains too much of these substances aeration can be an option to make them precipitate closer to the surface (Hanson, 2000).

### 4.3 Surface- and groundwater chemistry and availability

#### 4.3.1 Water chemistry

##### *pH*

pH is a measurement of the hydrogen ion activity. This water characteristic, which helps to find out the quality of the water, should be measured in the field. It should be done directly because the pH changes as soon as the water is taken from its source, for example an aquifer. Temperature is one thing that rapidly will alter the pH and so is the  $\text{CO}_2$ -

of calcium carbonate ( $\text{CaCO}_3$ ) in the soil leads to a low pH in the water because the soils can no longer buffer (resist pH changes) and the pH drops, and the water becomes acid. This is not a problem for humans when it regards a short term intake; pH in soda can be as low as pH 2-4 (Cech, 2003) but the problem with a low pH is the corrosion that can occur inside the pipes that transport the drinking water. The metal pipes can corrode and if that happens, metals will contaminate the water. If the pipe contains for example lead, that could be dissolved from the pipes and spread to the drinking water, and could cause lead poisoning. This can occur even if the pH is not extremely low (Cech, 2003). The pH in good quality drinking water should be around 8-8.5 (Hanson, 2000).

##### *Iron (Fe) and manganese (Mn)*

Aesthetic drawback, discolouration and an unpleasant flavour are a few of the problems with much iron and manganese in the water, but it is also a technical issue because it could clog the infiltration soil (cf. 4.2.2

above) (Frycklund, 1992). Iron and manganese will precipitate in the water when the oxygen level is high which makes the levels of iron and manganese low in the water. This could lead to clogging of the infiltration system, and depending on how far down the oxygen level is high, the clogging can occur at a great depth and can be very expensive to remove.

If the ratio between oxygen and iron/manganese changes, for example; a change in pH will lead to a lower oxygen level which in turn will make iron and manganese dissolve again and the levels in the water will rise. High levels can also cause problems when the water is transported because precipitation can occur inside the water pipes, which will be very expensive to replace (Hanson, 2000).

In Sweden, for example, the levels of iron need to be less than 0.10 mg/l and manganese has to be less than 0.05 mg/l in the drinking water, but this varies between different countries (Frycklund, 1992).

### Hardness

The softness and hardness of water is a characteristic that depends on how much calcium and magnesium that is dissolved in the water. Hard water has more dissolved substances than soft water and can cause problems with precipitation of these substances in the pipes but can be softened with filtration through salt. This solution is not suitable for drinking water. With soft water the negative part is that soap is tougher to wash off (Cech, 2003), and the hardness can for example be increased by adding lime to the soil that the water is infiltrating (Hanson, 2000).

The scale of water hardness (according to Cech (2003)) is based on the amount of CaCO<sub>3</sub> and MgCO<sub>3</sub> and is shown in Table 2 below:

Table 2. Different hardness categories (from soft-very hard) are determined from the amount (mg/l) of CaCO<sub>3</sub> and MgCO<sub>3</sub> in water (Cech, 2003).

<b>Very hard</b>	> 300 mg/l
<b>Medium hard</b>	75-150 mg/l
<b>Hard</b>	150-300 mg/l
<b>Soft</b>	0-75 mg/l

### Microorganisms

A shared word for microorganisms such as parasites, bacteria and viruses are pathogens. Over 2.3 billion people on this planet suffer from diseases because of these small organisms in the drinking water. Diarrhoea is a big issue for areas that lack a proper sewage system because the pathogens spread rapidly and approximately 3-4 million people die each year because of this. But even with a proper sanitary system some of

Microorganisms are found in all water. Fresh, salt, river, lake and groundwater all contain a certain

amount of these small organisms that are usually smaller than 100 µm (almost equivalent to the diameter of a human hair). The very small viruses can be as tiny as 0.004 µm compared to protozoans that are usually up to 15 µm.

When measuring the content of microorganisms they are measured all together, because a single test for every single type would be very expensive. For the measuring one indicator organism is used; total coliform, which is a good way to measure if the water has some kind of unsanitary issue. Water samples are taken to a warm lab and colonies that “grow” are counted. Different countries have different standards but in the USA the USEPA Safe Drinking Water Act has a standard that says if more than 40 tests a month are taken a maximum of 5% of these are allowed to have a positive result of total coliforms, and the ones that are tested positive need to be further tested for Fecal coliform (one kind is *Escherichia coli*, also known as *E. coli*) which kill a lot of people around the globe each year because of the severe diarrhoea and kidney damage it can cause (Cech, 2003).

Some of the microorganisms can not survive more than a few weeks down in an aquifer so if the water is stored under ground for that amount of time, this will enhance the quality of the water. There are a few viruses that can survive in an aquifer for years, so it is important to test regularly and to get the right kind of

2009). For different disinfection examples, see section 4.5.2.

### Turbidity

Turbidity is a measurement of the amount of particles that is in suspension in the water. A low amount of particles gives clearer water and a lower turbidity number. The turbidity of the water matters to a great extent when it comes to artificial recharge, because the small particles can easily clog the infiltration system (Cech, 2003). The effectiveness of the infiltration system can be indicated from how much turbidity that is measured in the water after infiltration, water with

2009). Another disadvantage with particles is that toxic chemicals can adhere on the small particles and, as a result, transfer those toxins from the water into humans and other living things (Cech, 2003).

### Temperature

Depending on the temperature, the water has different viscosity. At a low temperature the viscosity is higher and the water moves at a slower pace (Frycklund, 1992). This needs to be taken into consideration when calculating the timeframe and the amount of water that needs to be infiltrated for a specific area so that the water that is being taken out of the aquifer does not exceed the infiltrated water.

Much of the water characteristics are dependent on the

temperature of the water, the warmer the water is the less dissolved oxygen it can hold, and that will change the pH (see pH section above). Surface water has a wide temperature range, while groundwater is more stable with, depending on the depth of the aquifer, almost the same temperature all year around which makes the water characteristics more stable and suitable for drinking (Cech, 2003).

In Sweden a temperature guideline is set to 12°C for the drinking water that is being transported from the water plants. This is to minimize the danger of growth of microorganisms, but also to avoid an unpleasant flavour and smell (Hanson, 2000).

#### Mineralization

Mineralization is a measurement of the residue that is left after water evaporation and is a water quality indication. If there is too much minerals (salts and other minerals) in the water it becomes undrinkable (Ferro and Bouman, 1987). Table 3 shows different limits for different uses:

Table 3. Mineralization of water in Mozambique is measured in mg/l and the limits for different uses. Based on Ferro and Bouman (1987).

Use	Limit in mg/l
All use	500
Irrigation use	1000
Domestic use	1500
Domestic use, semi-arid area	3000
Livestock, semi-arid area	5000

#### 4.3.2 Surface water chemistry

The surface water that will infiltrate down to the aquifer should go through tests to show if, and what kind of treatment, the water needs before and after the infiltration.

There are different substances like; oxygen, chloride, organic material, suspended particles and chemicals that vary with individual surface water source (Frycklund, 1992, Hanson, 2000).

There are also toxic substances that should be taken into consideration. Most of them are only dangerous when ingested by food, but there are a few substances that should be looked in to before deciding on a surface water source: for example fluoride and arsenic (World Health Organization, 2011).

Common for surface water are a few characteristics (Hanson, 2000) here below and they were described more thoroughly in the previous section (4.4.1)

- Low pH
- Soft (high amount of calcium and magnesium)
- Low content of iron and manganese
- Low alkalinity (low buffering ability)
- High content of microorganisms and organic material

- High turbidity (large amount of suspended particles in the water)
- High oxygen level
- Varying temperature

All of these characteristics should be measured, and if the water infiltrates these will change and become more like groundwater characteristics that are described here below:

#### 4.3.3 Groundwater chemistry

Depending on the water infiltration velocity, the chemistry of the groundwater will vary because the infiltration changes properties like the organic content, turbidity and the iron/manganese content.

The characteristics of groundwater are usually quite the opposite from the surface water with (Hanson, 2000):

- Higher pH level
- Hard (lower amount of calcium and magnesium)
- High content of iron and manganese
- Low content of microorganisms and organic material
- Low turbidity
- Low oxygen level
- Stable temperature

#### 4.3.4 Availability

When finding a fresh water source for the artificial recharge system, certain qualities have to be considered. Knowledge about yearly precipitation and runoff are important to take into account as well as where the water is coming from and where it is going. Dillon (2005) explains that if water is taken from a river the downstream users needs to be considered so that they do not run out of water.

Stormwater (precipitation during storms) can also be used as a freshwater source. This water can be collected and infiltrated with suitable artificial recharge system (e.g. basin or well) (Dillon, 2005).

### 4.4. Water improvement options

#### 4.4.1 Oxidation

This is used to improve the water quality and can be done in a few different ways. **Aeration** is the easiest option and it is a way to get more oxygen in the water and decrease substances like carbon dioxide. The structure is usually as simple as a man made waterfall. This will lower oxidised arsenic, iron and manganese by precipitation of the substances. **Chlorine** is another way of oxidizing the water, as is **ozone**

#### 4.4.2 Disinfection

To make sure that the water is clean from microorgan-

isms before it is used for drinking, the water it is usually disinfected. There are different kinds, primary and secondary disinfectants, and one that can act as both is **chlorine**. Chlorine is effective on microorganisms but unfortunately it is not the answer for all the microorganisms in the water, for example the *Cryptosporidium parvum* (Crypto) which has a hard shell that can resist the chlorine.

### Ozone

2009). New water treatments are constantly being discovered so before deciding on a treatment, further investigations should be done to make sure that the water for the specific site gets the right treatment to avoid a poor water quality.

#### 4.4.3 Corrosion correction

If the water is too soft, corrosion of the pipes can occur. This is an economical problem because the lifetime of the pipes decreases and the metallic pipes can

2009). If the water is too soft it lacks calcium (Ca) and magnesium (Mg), but those levels can easily be raised with the help from lime. Lime can for example be put in the infiltrated sediments and the water will harden (Hanson, 2000). A low pH in the groundwater does the same thing as soft water, the solubility characteristics

## 5 Conditions of Mozambique

### 5.1 Settings

#### 5.1.1 Mozambique

The country of Mozambique is located in southern eastern Africa (Fig. 2), just by the coast of the Indian Ocean with South Africa in the south, Tanzania in the north, Malawi, Zambia and Zimbabwe in the west and Swaziland in the south-southwest (Fig. 2). Mozambique used to be a Portuguese colony but got independent in 1975. After the breakup from Portugal the country suffered many years from civil war (between the years of 1977-1992) that led to a severe overall poverty and Mozambique was the 165:th poorest country out of 169 countries in total that in 2010 (Bertelsmann Stiftung, 2012).

Today (2013) the population of Mozambique is estimated to 24 million people, and in the capital Maputo (Fig. 2) lives almost 1.6 million people according to Central Intelligence Agency, (2013). It has also been calculated that only 47% of the population had access to clean water and the rural areas account for 29% of that (Central Intelligence Agency, 2013).

#### 5.1.2 Climate and water resources

The climate varies from tropical to subtropical with a rain season that lasts from October until April and the

annual precipitation on a yearly average is 1032 mm, but it varies in different parts of the country (Aquastat, 2005). In some parts of the country, for example in the southwest, the precipitation can be as little as 400 mm/year and up north it can rain as much as 2000 mm/year (Aquastat, 2005). The hydrogeological map of Mozambique (Ferro and Bouman, 1987) used Köppen's climate classification to divide the country into different climate zones. That division can be seen in appendix 1:

- 60% has a tropical rain savanna (Aw) a the region by the coast and the north



Figure 2. Mozambique map with cities pointed out and surrounding countries. From <https://www.cia.gov/library/publications/the-world-factbook/geos/mz.html>

- 28% has a dry savanna (BSw) à the central inland region and the south
- 10% has a humid temperature climate (Cw) à the highland
- 2% has a dry desert climate (BWw) à this is a little area by the Limpopo border (see appendix 2 for Limpopo river)

Mozambique has about 104 rivers which drain into the Indian Ocean. The discharge in almost every river correlates with the seasons; higher flows during the rain season and lower during the dry season (Aquastat, 2005). About 70% of the surface flows occur in the rain season (United Nations, 1989). There are a few bigger rivers that transport surface water from bordering countries around Mozambique and the river Zambezi (see appendix 3) carries about 85% of that water alone (United Nations, 1989).

Mozambique has two big lakes that are both located in the north/northwest, just on the border to Malawi. Lake Malawi is the biggest lake and has a surface area of 30 800 km<sup>2</sup> and almost 6500 km<sup>2</sup> of those are on Mozambique's land. The other big lake is called Lake Chilwa and has a surface area of 750 km<sup>2</sup> but only 29 km<sup>2</sup> of those are in Mozambique (both lakes can be found in the map in appendix 2) (Aquastat, 2005).

### 5.1.3 Geology

The map is found in appendix 3.

#### **Precambrian Basement Complex (covers 57% of the lands surface)**

Greenschist and metamorphic rocks make up the Mozambique metamorphic belt and it consists of gneiss and gneiss-granite-migmatite. This formation covers most of the northern parts of the country and can be seen as the "Gneiss granite complex" in appendix 3 (Ferro and Bouman, 1987).

#### **Karoo supergroup (sedimentary formations, rhyolite, basalt) (covers 5% of the lands surface)**

When Gondwana was broken up, sediments started to fill out the basins that were left from the split of the continent. The sediments that filled the basins are called "continental Karoo sediments" in the geological map of Mozambique from 1987, and starts with finer sediments that form mudstone and more sand higher up in the stratigraphy (Ferro and Bouman, 1987).

#### **Post Cambrian (Volcanic and igneous rocks) (covers 3% of the lands surface)**

The end of the Karoo period was characterized by volcanic activity that resulted in bedrock made of rhyolite and basalt (Ferro and Bouman, 1987).

#### **Meso-Cenozonic sediments (covers 35% of the lands surface)**

Two sedimentary basins cover 35% of the country.

They have sequences of sediments that reveal the marine transgression that occurred when the basins were filled. More inland the sediments are made of sandstone and towards the coast of the Indian Ocean are mainly marine sediments.

East African Rift Systems tectonics made the sediments fault but folding has occurred very little.

On top of the sedimentary basins (calculated to be on 70% of the basins) lies a thick layer, between 5-10 meters of weathering material, mostly in the form of sand and clay (Ferro and Bouman, 1987).

### 5.1.4 Hydrogeology

The hydrogeological map of Mozambique from 1987 (Ferro and Bouman, 1987) indicates that the prospects for finding good quality groundwater are not great, about 75% of the land area is classified as local, limited or no recourse of groundwater at all, and 40% of the sedimentary basins have got brackish water which only leaves 17% of the country that has groundwater resources of drinkable water at a decent flow (over 3 m<sup>3</sup>/h) and a mineralization of less than 1500 mg/l (see 4.4.1).

The Pleistocene transgression accounts for a lot of saline intrusion in groundwater because of the fluctuating sealevel rise that filled the sediments with salt water. Places with high mineralization are found with over 30 000 mg/l (Ferro and Bouman, 1987).

Since the 1950:s the search for groundwater has been going on in Mozambique (United Nations, 1989). Groundwater is the solution to get drinking water in rural areas (76% of the rural population lacks a good quality water (Aquastat, 2005)) but one problem is that crystalline rocks cover 60% of the country and the groundwater is situated in the weathered zones where the permeability is poor because of fine-grained particles. The other problem is the high mineralization content of the water (Groundwater, 2002).

The amount of groundwater that can be taken from an aquifer has some guidelines in Mozambique. For a **medium scale** water outtake the rate needs to be at least 10 m<sup>3</sup>/h (that covers a family's yearly water use, see table 1) and the mineralisation (a measurement of residue that is left after water evaporation) should be no more than 500 mg/l.

In rural areas in Mozambique the quality-guidelines for drinkingwater changes. The water withdrawal can be as low as 0,8 m<sup>3</sup>/h and the mineralisation can be as high as 3000 mg/l for a **minimum scale** outtake, which is the limit in semi-arid areas for domestic use (see 4.4.1) (Ferro and Bouman, 1987).

Mozambique is divided into seven different hydrogeological provinces (Fig. 3) depending on the geological formation. They are presented here below:

1. **Basement Complex** from Precambrium
2. **Volcanic Terrains** from post-Cambrian
3. **Middle Zambeze Sedimentary Basin** from Karoo
4. **Maniamba Sedimentary Basin** from Karoo

5. **Rovuma Sedimentaru Basin** from Meso-Cenozoic
6. **Mozambique Sedimentary Basin** North of the Save River (see App.2 for location) from Meso-Cenozoic
7. **Mozambique Sedimentary Basin** South of the Save River from Meso-Cenozoic

Mozambique artificial groundwater recharge may be applied. The table is put together with facts from the geological map of Mozambique from 1987 (Ferro and Bouman, 1987) and notice the different amount of fact that is provided for the different zones, for example; much testing had been done in province 6 and 7 therefore a greater amount of groundwater facts. See next page for summarized Table 4.

The seven different provinces can be found in figure 3 that is a hydrogeological map of Mozambique where the provinces are numbered. The same map can also be found in appendix 4 (hydrogeological map of Mozambique) in a larger scale. They are also summarized (separately) in Table 4 to get an overview of where in

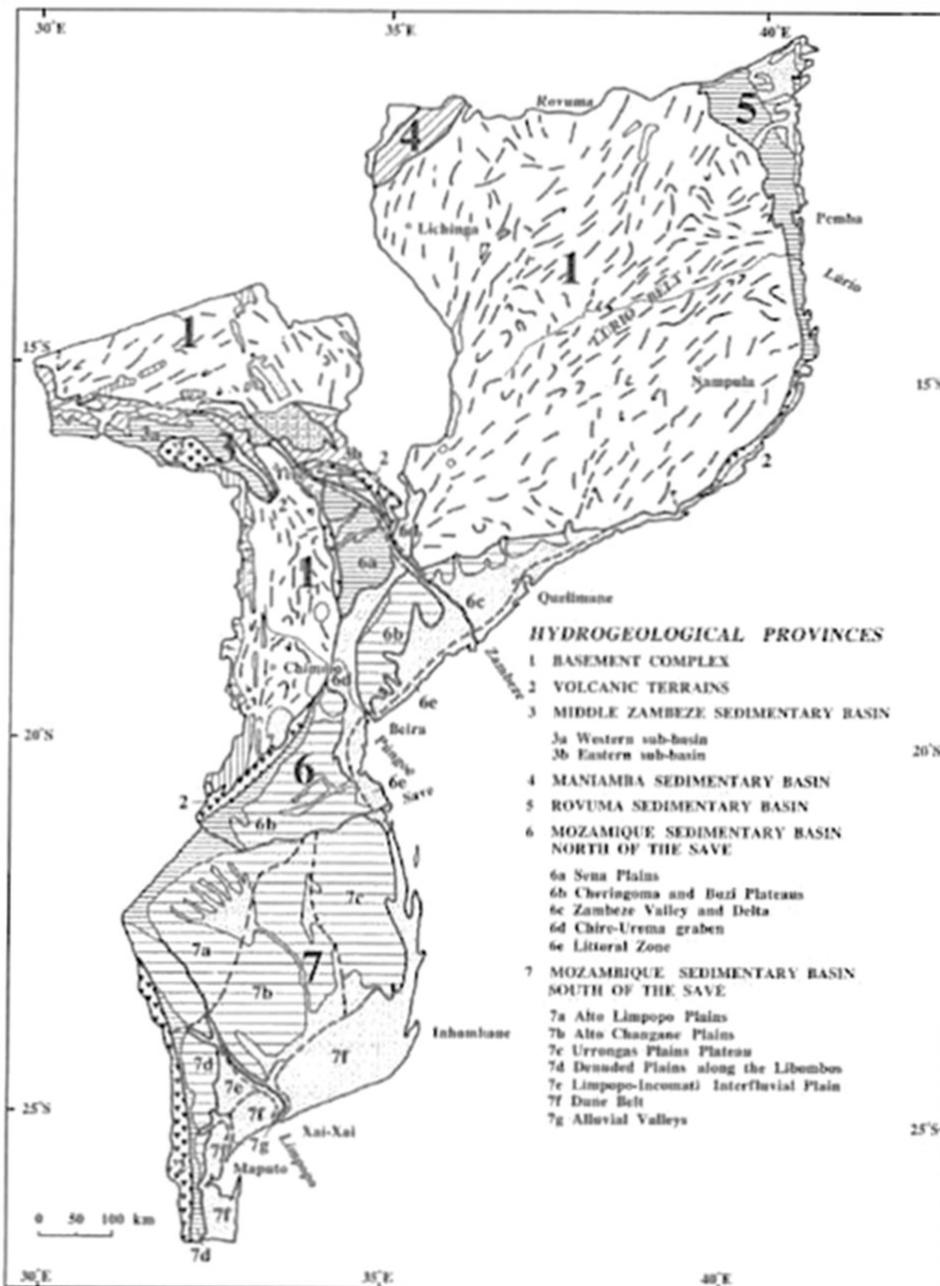


Figure 3. A map of Mozambique is divided into seven hydrogeological provinces. (Ferro and Bouman, 1987).

Table 4. The hydrogeological provinces from the geological map from 1987 (Ferro and Bouman, 1987) are summarized (each province has one horizontal column) and the facts are divided into four groups for a better overview of the different areas.

Hydro geological Provinces	Physical Geography	Geology	Groundwater	Generally
<b>1.</b>  <b>Basement-Complex</b>  <b>(Pre-Cambrian)</b>	<ul style="list-style-type: none"> <li>• 57% of the country</li> <li>• Mountains and plateaus</li> <li>• Weathered rocks (mountains) leaving thick (sometimes 50m) sediments on plateaus</li> <li>• Lots of rain</li> <li>• Good recharge</li> <li>• All year around rivers in rainy areas</li> </ul>	<ul style="list-style-type: none"> <li>• <i>Early Precambrian</i> (part of the Zimbabwe Craton)</li> <li>• Greenschists, limestone, conglomerates, marbles, quartzite's</li> <li>• <i>Later Precambrian</i> (Part of the Mozambique Metamorphic Belt)- gneiss, granite, migmatite</li> </ul>	<ul style="list-style-type: none"> <li>• Poor water-carrying formations</li> <li>• Limited aquifers</li> <li>• Low (&lt;600 mg/l) mineralization</li> <li>• Higher (500-1000 mg/l) mineralization in arid areas</li> <li>• Medium-high hardness</li> <li>• pH 7.0-8.3</li> </ul>	<ul style="list-style-type: none"> <li>• Sediments are porous and impermeable (much clay)</li> <li>• Permeable zone by the parent rock that is still intact</li> <li>• Most prolific aquifers are in the marbles</li> </ul>
<b>2.</b>  <b>Volcanic Terrains</b>  <b>(Post-Cambrian)</b>	<ul style="list-style-type: none"> <li>• Fractured eruptions, lead to volcanic rock terrain</li> <li>• Easily weathered rock, mountains has been formed</li> <li>• Weathered material formed a dark and clayey soil</li> </ul>	<ul style="list-style-type: none"> <li>• Rhyolites</li> <li>• Basalt</li> <li>• Alkaline rocks</li> </ul>	<ul style="list-style-type: none"> <li>• Great quality groundwater in rhyolites, low hardness, low mineralization (&lt;500 mg/l)</li> <li>• Poor quality groundwater in basalt, harder, mineralization high (8500 mg/l)</li> </ul>	<ul style="list-style-type: none"> <li>• Large amount of clay in the ground, impermeable</li> <li>• Less than 10 m weathered material</li> </ul>
<b>3.</b>  <b>Middle Zambeze Sedimentary Basin</b>  <b>(Karoo)</b>	<ul style="list-style-type: none"> <li>• Belongs to the Karoo basin</li> <li>• Quite dry, precipitation between 500-700 mm/year</li> </ul>	<ul style="list-style-type: none"> <li>• Quaternary</li> <li>• Conglomerates and tillites made from mud, silt and clay stones</li> </ul>	<ul style="list-style-type: none"> <li>• Lack of knowledge</li> <li>• Probably low water withdrawal capacity because of fine course material. Better by fractures</li> <li>• Mineralization, 400-800 mg/l</li> <li>• Quaternary sand formations might work as local wells</li> </ul>	<ul style="list-style-type: none"> <li>• Quaternary formations, from sand, silt and clay</li> <li>• Thick sediments can be found, over 300 m</li> </ul>
<b>4.</b>  <b>Maniamba Sedimentary Basin</b>  <b>(Karoo)</b>	<ul style="list-style-type: none"> <li>• Belongs to the Karoo basin</li> <li>• Much precipitation, between 1100-1400 mm/year</li> </ul>	<ul style="list-style-type: none"> <li>• Quaternary</li> <li>• Conglomerates from sand, mud and siltstones,</li> <li>• Shales</li> </ul>	<ul style="list-style-type: none"> <li>• Lack of knowledge</li> <li>• Probably low water withdrawal capacity because of fine course material.</li> <li>• Mineralization, 400-800 mg/l</li> <li>• Quaternary sand formations might work as local wells</li> </ul>	<ul style="list-style-type: none"> <li>• Quaternary formations from sand, silt and clay</li> <li>• Very thick sedimentary structures,</li> <li>• 2000 m has been found</li> </ul>

Hydrogeological Provinces	Physical Geography	Geology	Groundwater	Generally
<p><b>5.</b></p> <p><b>Rovuma Sedimentary Basin</b></p> <p><b>(Meso-Cenozoic)</b></p>	<ul style="list-style-type: none"> <li>Plains and low plateaus</li> <li>Precipitation; 800-1200 mm/year</li> <li>High recharge capacity in the north, low in the south because of clayey soils</li> </ul>	<ul style="list-style-type: none"> <li>Cretaceous marlstone</li> <li>Plateaus are covered with sand, 20-40 meters thick</li> <li>Coast is covered with 30-60 m thick sandstone</li> </ul>	<ul style="list-style-type: none"> <li>Brackish water</li> <li>Impermeable cretaceous marlstone</li> <li>Good quality (mineralization 100-300 mg/l)</li> <li>Medium outtake</li> <li>Deep aquifers, outtake of 30 l/s but water has a low pH and is very soft (leads to corrosion)</li> </ul>	<ul style="list-style-type: none"> <li>Eluvial formation, clean water but not much outtake</li> <li>Alluvium formations has better yields, but sometimes brackish water</li> </ul>
<p><b>6.</b></p> <p><b>Mozambique Sedimentary Basin (North of the Save)</b></p> <p><b>(Meso-Cenozoic)</b></p>	<ul style="list-style-type: none"> <li>Plains, plateaus and valleys</li> <li>More rain by the coast (1400 mm/year), less inland (700-900 mm/year)</li> <li>Overall good recharge</li> </ul>	<ul style="list-style-type: none"> <li>Cretaceous sandstones, as thick as 2500 m</li> <li>Sandstone</li> <li>Limestone</li> <li>Marl</li> </ul>	<ul style="list-style-type: none"> <li>High mineralization (&gt;8500 mg/l),</li> <li>60% brackish water, 40% fresh water</li> <li>Better quality on the plateau, mineralization; 350-1500 mg/l</li> <li>Shallow water table can be found on plateaus, very low pH (problem with corrosion)</li> <li>Productive wells can be found in the valleys, might be to mineralized</li> </ul>	<ul style="list-style-type: none"> <li>Good sand formations, might be to shallow on some places</li> <li>A 300 m thick sand formation has been found on top of clay formation</li> </ul>
<p><b>7.</b></p> <p><b>Mozambique Sedimentary Basin (South of the Save)</b></p> <p><b>(Meso-Cenozoic)</b></p>	<ul style="list-style-type: none"> <li>Plateaus and valleys</li> <li>Dune area by the coast (30 km in average width)</li> <li>Precipitation; coast:700-1000 mm/year inland: 350 mm/year</li> <li>Recharge is best by the dunes (by the coast), least inland</li> <li>Main rivers , but they dry out during the dry season</li> <li>700 lakes, only 8% are permanent</li> </ul>	<ul style="list-style-type: none"> <li>Limestone in the north-east</li> <li>Sandstones dominates inland</li> <li>Shales, marls, sandstones from cretaceous</li> <li>Thick sandstones (up to 1500 m)</li> <li>Tertiary formations of calcarenous and sandstones</li> <li>Quaternary sediments cover 70% of basin</li> </ul>	<ul style="list-style-type: none"> <li>Best prospects by the alluvial and dune areas</li> <li>Big saline problems (high resistivity) because of the Pleistocene transgression and the arid conditions</li> <li>Contains a big fresh water aquifer called "Limpopo aquifer" which might run out if over exploited</li> <li>Well explored place, many aquifers</li> <li>Salinity is a common issue</li> </ul>	<ul style="list-style-type: none"> <li>Dunes can be found, up to 100 m. The sand is sorted (medium to coarse) and it is clean</li> <li>Up to 60 m thick alluvium deposits can be found by the big rivers</li> <li>Problems with clay in the sandstone at places</li> </ul>

## 5.2 Relevant examples of artificial groundwater recharge

### 5.2.1 Large scale

One useful source is to look at how they use artificial recharge in a town in South Africa called Atlantis that has an artificial recharge system that has been operating since 1979. They infiltrate stormwater runoff and treated domestic wastewater that becomes drinking water. The water that does not have good enough quality is diverted and recharged near the coast to prevent seawater intrusion. This South African example can be of much help since they are near Mozambique and have the same kind of difficulties with seawater intrusion and both countries have a lot of crystalline formations.

The population of the town is around 245 000 people and the groundwater stands for almost half of the water use. The water infiltrates down to the bedrock (shale or granite) trough sand dunes that lie on top of calcrete and fluvial sand sediments (Water Affairs & Forestry, 2007).

Almost all of the groundwater they use in Atlantis comes from artificial recharge and is summarized in Table 5 below:

Table 5. Use of water and the daily infiltration rate from a artificial recharge area in Atlantis in South Africa (Water Affairs & Forestry, 2007).

<b>Yearly use of water</b>	$2.87 \times 10^6 \text{ m}^3$
<b>Yearly artificial recharge</b>	$1.5 \times 10^6 - 2.5 \times 10^6 \text{ m}^3$
<b>Daily infiltrating rate</b>	0.01 – 0.16 m

### 5.2.2 Small scale

A good example of a small-scale artificial recharge is in Kharkams, South Africa, which has a semi-arid climate. The population is 1700 people and they are being supplied with water from surface water runoff that recharge whenever possible into one of the three boreholes (the least yielding one) that connects with an underlying aquifer (fractured granite, gneiss). The surface water that is led down the borehole would have evaporated and/or transported to the ocean if not for the artificial recharge. The quality of the water is improved by the artificial recharge, probably because of the mixing of surface- and groundwater lowers the salinity of the water (Water Affairs & Forestry, 2007), which also is a problem with a lot of groundwater in Mozambique.

## 6 Discussion

### 6.1. Knowledge about artificial recharge

The different ways to artificially recharge an aquifer are many, which is why those that seemed more relevant for this thesis where chosen.

Figure 1 gives a picture of how the various systems work. In most of the systems that are described in this report, the water infiltrates the soil (for soil properties see 4.2), preferably a vadose zone, to end up in an unconfined aquifer. On this journey the characteristics of the water changes and the surface water becomes groundwater. The features that change are described under 4.4.2 and 4.4.3. The infiltration will enhance the water quality and can be done with systems 1, 2, 3, 6 and 7 (see 3.2). If the water does not need a quality improvement or if the water may be of lower quality, systems 4 and 5 (see 3.2) can be used where the water goes straight into the aquifer without the infiltration. This could be an option for water storage or to prevent subsidation.

When looking for a way to provide people with drinking water, artificial recharge is a great option but as mentioned previously in this report; it is crucial to have knowledge and experience. The experience in Sweden is over 100 years and there are still problems such as clogging (see 4.3). It is important to know that this type of system is not a solution for everywhere, for example if the soil is filled with toxins or if no one can take care of the system it should not be considered as an option. However, there are many different kinds of systems, so the artificial recharge investigation should be thorough, because there are options for water quality problems, space issues, saltwater intrusions, stormwater infiltration and to store water in an aquifer for dryer periods to name a few.

The thought with this thesis was from the beginning to form a few ground rules for artificial recharge systems (soil properties and water chemistry), but as it turned out, that is very difficult. There is however a few guidelines when it comes to the quality of the water, both for the surface and the groundwater, to make sure that the quality of the drinking water is good and to avoid corrosion of water pipes, which is summarized in Table 6.

Table 6. Guidelines for quality drinking water that does not corrode (based on Hanson (2000)).

<b>pH</b>	8-8,5
<b>Temperature</b>	12°C
<b>Oxygen level (O<sub>2</sub>)</b>	3 mg/l
<b>Coliform</b>	< 1/100 ml
<b>Calcium (Ca)</b>	>20 mg/l
<b>Oxygen O<sub>2</sub></b>	> 3 mg/l

If the water is infiltrating a vadose zone before reaching the unconfined aquifer then the soil (see section 4.2.1) need these characteristics for the best water quality result and for a well-functioning infiltration system:

- Hydraulic conductivity ranges from  $10^{-2}$  m/s to  $10^{-5}$  m/s
- No finer particles (e.g. clay and silt) in the vadose zone
- The soil consists of sorted sand and gravel deposits
- No toxins in soil, will spread to the water

Artificial recharge is not the least expensive water supply source (see Table 1), but it is a brilliant option in the long run, especially in arid areas where the other water supply sources are very effected from evaporation.

## 6.2 Possibilities in Mozambique

To get started with exploring the possibilities for artificial recharge, maps are very important, both geological and hydrogeological ones.

The maps that were used in this report are from 1987, which makes it difficult to get a true image of where in the country different systems might work, because big parts of the county was yet unexplored.

Depending on the lack of detailed maps over the geology and hydrogeology in Mozambique a comparison where made over two of the provinces in table 5, which has diverse conditions, to determine pros and cons with different locations across the country regarding artificial recharge.

### Province 1

The basement complex is situated in the north (province 1) and the area has good recharge, much precipitation, all year long rivers, the pH is excellent (between 7-8.3) and the water has a mineralization amount of less than 500 mg/l in the wet areas. On the other hand is the infiltration soil impermeable with considerable amount of clay from the weathered mountains. This makes the infiltration systems unworkable and the artificial recharge options are less to choose from. However, the positive thing is that the water seems to be of high quality and could make an artificial recharge well a great option (see 3.2) since that system can infiltrate even a confined aquifer. In Kharkams, South Africa, water infiltrates through boreholes (see 5.2.2) and that might work in this area as well.

### Province 6 and 7

The Mozambique Sedimentary basin is split in two, divided by the Save River (appendix 2) but they have similar qualities and is why they are both included here. Big sand dunes, as high as 100 meters has been found, which might make this a good place for the dune infiltration option (see 3.2). The problem is that the sand dunes are located by the coast as well as the saline groundwater. This is nothing that either of the seven infiltration systems mentioned in this report can take care of, but one solution might be to (as described in the beginning of this thesis), infiltrate freshwater

that can float on top of the saltwater, because the freshwater is lighter. Desalination is also an option but as can be seen in Table 1, this method is very expensive.

The salinity is less of a problem on the plateaus but lack of precipitation is another one. One solution could be to infiltrate stormwater like they do in Atlantis in South Africa (see 5.2.1). The water is gathered during storms and infiltrated to and aquifer and is used during the drier seasons. (Bouwer, 2002)

## 7 Conclusions

Artificial groundwater recharge is not built on one single guidebook alone, it is many endless hours searching for facts, many hours looking at maps and if a place seems suitable there are a great amount of time that will be spent in the field taking tests (e.g. water and soil). There are both negative and positive aspects of artificial recharge and a few are summarized here below:

Positive:

- if a suitable area is found, it can provide many people with clean water
- water quality can be improved
- it might a good option for aquifers that has problems with seawater intrusion
- water from rain seasons can be saved for drier seasons

Negative:

- not every area is suitable for artificial recharge
- all the systems need some sort of supervision throughout the entire use
- the water, both fresh water and groundwater has to be tested continuously for microorganisms and the different levels of substances that has guidelines

The conditions for Mozambique are split, if the soil is good, the water quality is poor, and if the quality of the water is good then the soil is impermeable. Further studies must be done, especially fieldwork because in the end, that is a very important piece of the puzzle in making artificial recharge a reality.

## 6 Acknowledgements

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### Figures:

Figure 2 is retrieved 28 May 2013 from <https://www.cia.gov/library/publications/the-world-factbook/geos/mz.html>

Figure 3 is retrieved from Ferro and Bouman, 1987.





### Appendix 3: Geological map of Mozambique

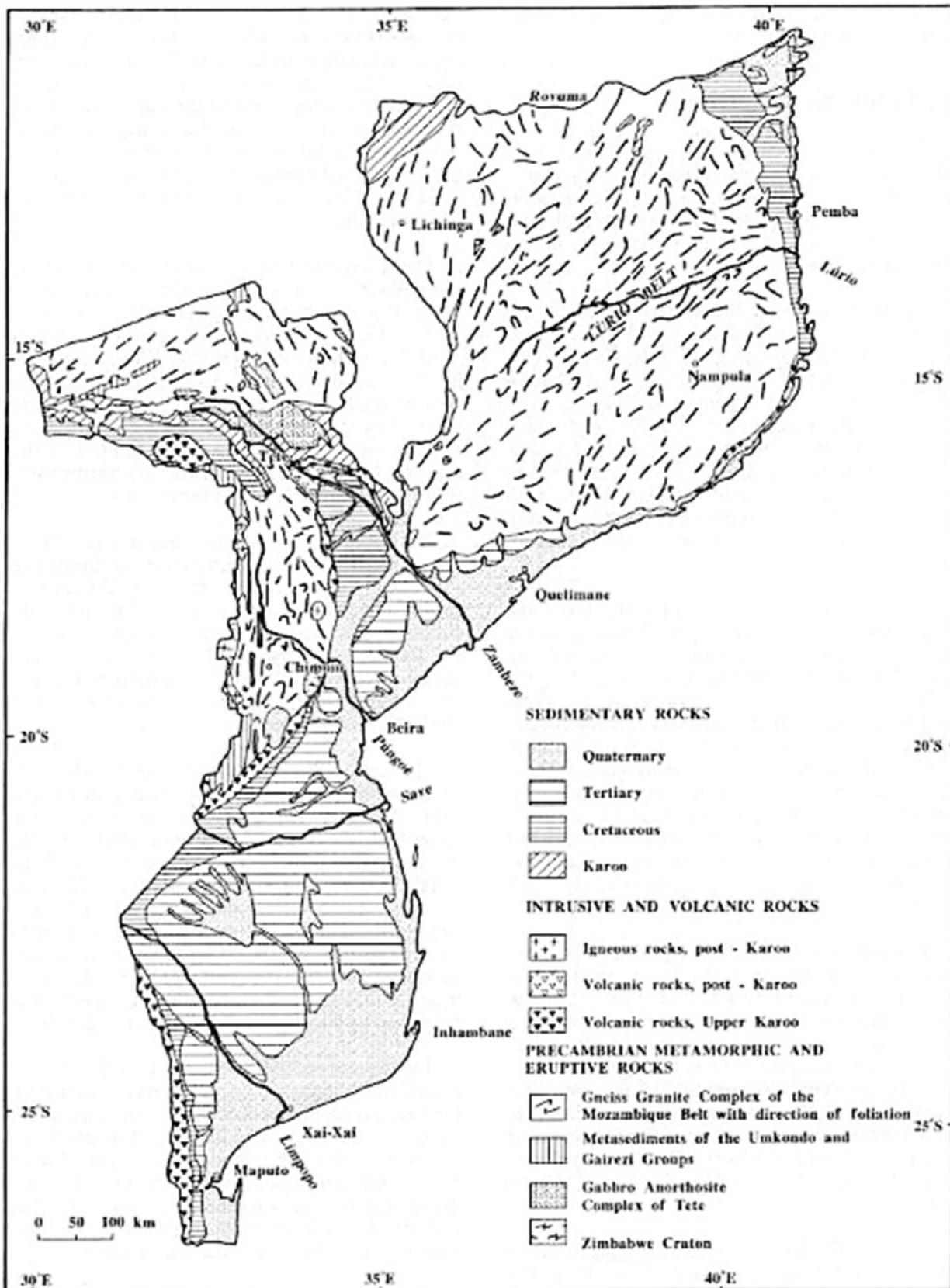


Figure 6 illustrate the geology of Mozambique and is taken from Ferro and Bouman (1987). A more detailed explanation is found under section 5.1.3.

## Appendix 4: Hydrogeological map of Mozambique

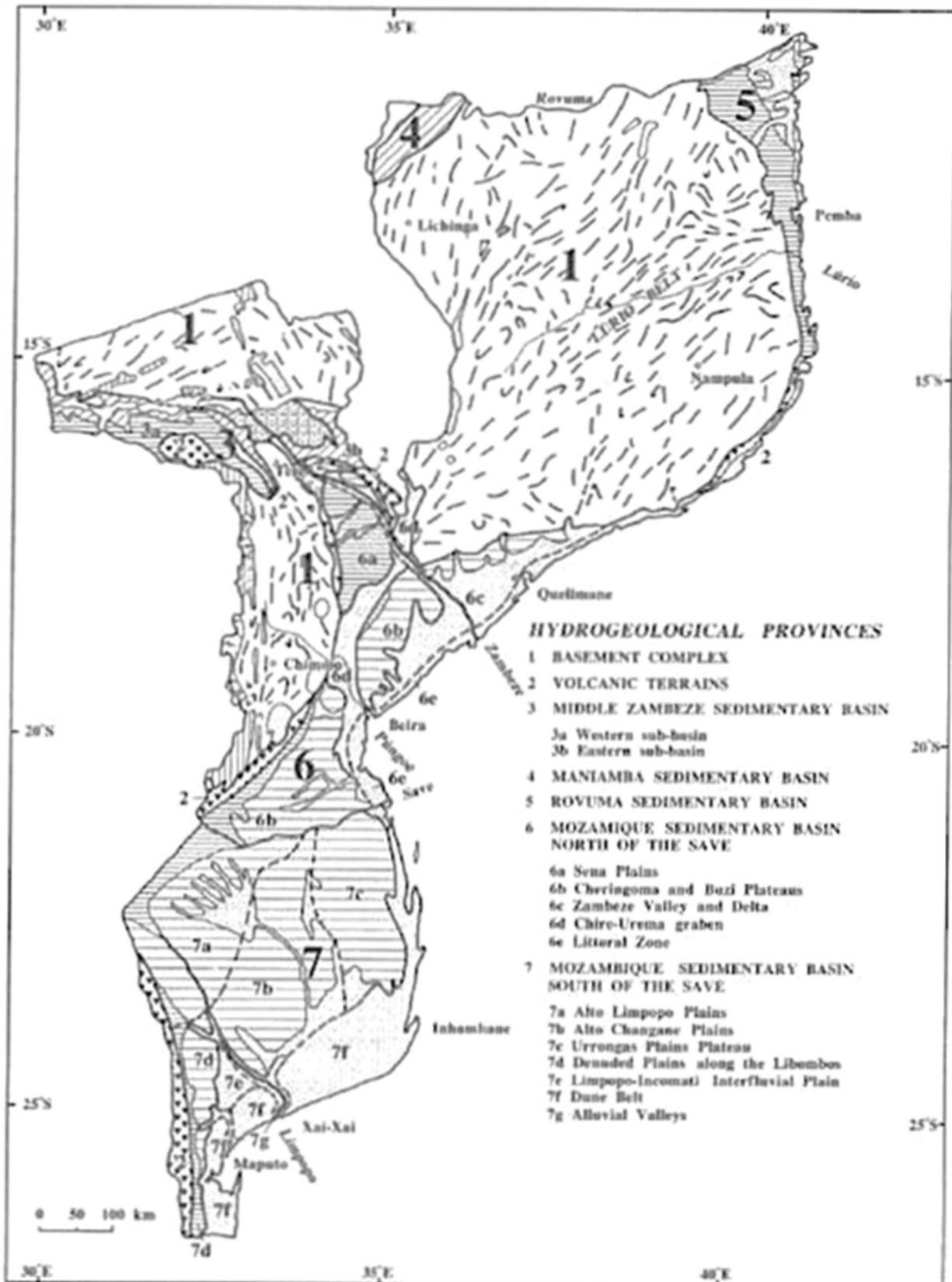


Figure 7. A division of Mozambique based on the hydrogeology of different areas. They are described in more detail in Table 4. The picture is taken from Ferro and Bouman (1987).

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