

**Hydrogeological Assessment and Aquifer Recharge Potential within  
the Lephalale (Ellisras) Local Municipality Area**

**Phase 3: Artificial Recharge and Geochemistry**

**Report Nr: PWMA 01/A42/00/02209\_02**

Prepared by

VSALEBOA CONSULTING

For the

Directorate: Water Resource Planning Systems (WRPS)

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**10 June 2010**





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<b>Authors:</b>	<i>S Veltman      Veltwater Groundwater Specialists</i>  <i>Reviewers:</i> <i>J Fourie                      Geostratum</i> <i>R Murray                      Groundwater Africa</i>
<b>GIS:</b>	<i>AM Cronje                      VSA Leboa Consulting</i>
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VSA Leboa Consulting (Pty) Ltd  
Approved for VSA Leboa Consulting (Pty) Ltd

.....  
Director/Project Manager:  
**VSA Leboa Consulting (Pty) Ltd**  
**Mr RV Weidemann**

.....  
Project Manager:  
Department of Water Affairs  
**Mr Fanus Fourie**

Department of Water Affairs  
Water Resources Planning Systems

Approved for the Department of Water Affairs

.....  
Director:  
Water Resource Planning Systems  
**Dr Beason Mwaka**

.....  
Deputy Director:  
Water Resource Planning Systems  
**Mr Elias Nel**



water affairs

Department:  
Water Affairs  
REPUBLIC OF SOUTH AFRICA

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**Professional Service Provider:**

*VSA Leboa Consulting*

*VSA Leboa Consulting (Pty) Ltd*



Plot 41  
Tweefontein  
Polokwane  
0700

PO Box 222  
Polokwane  
0700

Tel: 082 315 2977  
Fax: 0866857724

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### **Note on the Department of Water Affairs (DWA)**

The Department of Water Affairs (DWA) was until recently known as the Department of Water Affairs and Forestry (DWAF). The Department of Water Affairs is part of the Ministry of Water and Environmental Affairs, under a single Minister. The acronyms “DWA” and “DWAF” both appear in this report, the latter mainly as references to past work done when the Department was known as the Department of Water Affairs and Forestry.

## EXECUTIVE SUMMARY

The town of Lephale is situated in the northern part of South Africa, 200 km north-west of Pretoria in a semi-arid climate zone. The Mokolo River flows through the area, joining up with the Limpopo River in the north. Lephale is a major role-player in economic development within Limpopo and continual economic development requires development of sustainable water resources. VSA Leboa was appointed by the Department of Water Affairs and Forestry to characterise the aquifers, determine the groundwater potential and the artificial recharge options available to Lephale.

Various artificial recharge (AR) options looks promising from the aquifer properties, but all the aquifers at Lephale should be developed and storage created through abstraction from it for any AR scheme to become useful. Based on previous information up to 5.4 Mm<sup>3</sup>/a of storage can be created in the Waterberg aquifer. The abstracted water will need to be utilised and because of the fluoride content can only be introduced into drinking water supplies if fluoride has been removed from the groundwater. However, it is possible to distribute this as part of the water supply to the industrial users, if no other water quality constraints from these users are applicable.

Run of river excess, in the form of high flows during the rainy season, to the volume of 1.3 Mm<sup>3</sup>/a from the year 2010 and >4.5 Mm<sup>3</sup>/a from 2015, as well as return flows, in the form of treated effluent and storm water, to the volume of 5.5 Mm<sup>3</sup>/a from the year 2015 is available as sources of water for artificial recharge in the Lephale area.

AR options in the Waterberg aquifer include Aquifer Storage Recovery, Aquifer Storage Transfer and Recovery, Soil Aquifer Treatment and Infiltration ponds. The geochemical simulations all show some elements deteriorating *in situ* as a result of these options, but most elements are still within ideal drinking water quality, with iron within the good drinking water quality. All the simulations showed an *in situ* lowering of fluoride concentrations to below 6 mg/l and sodium/chloride to within ideal drinking water standards and therefore, mixing this lower fluoride concentration into drinking water supplies becomes a much more feasible option. Clogging of the aquifer might occur as a result of kaolinite and calcite precipitation.

AR options in the alluvial aquifer include Bank filtration and Infiltration ponds along the Mokolo River alluvium. This is considered feasible since water quality in the

alluvium is similar to the Mokolo River and clogging as a result of increased load of suspended solids on the alluvial aquifer is considered the only limiting option. However, these options were not looked at in detail due to a lack in information and will need to be re-investigated as soon as information from a Groundwater Reserve study, done by GeoAfrica, for the Mokolo River is complete and environmental risks can be defined. The greatest benefit in both these options will be to increase retention time of excess river run off closer to Lephalale, minimise losses of surface water to the downstream river environment and increase infiltration to the Waterberg aquifer.

The alluvial groundwater users north of the Eenzaamheid Fault and Lephalale will be impacted upon through abstraction from the Waterberg with a reduction in surface water flow, if this reduction cannot be supplemented by upstream releases from the Mokolo dam storage.

Based on the available source water volumes and water quality artificial recharge is a feasible option to explore further for water conservation and demand management in the Lephalale area, including the new developments occurring in the area to the west of the town of Lephalale.



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## **1 INTRODUCTION**

The town of Lephalale is situated in the northern part of South Africa, some 200 km north west of Pretoria (see Plan 1, Appendix A). The town is situated in a semi-arid climate zone, with an average annual rainfall less than 400 mm and an annual evaporation higher than 2000 mm, making water highly vulnerable to droughts. The Mokolo River is flowing through the study area, joining up with the Limpopo River in the north.

Lephalale is a major role-player in economic development within Limpopo. Local coal deposits are leading to industrial and mining development and this continual economic development requires development of sustainable water resources and therefore the need to investigate every possible water resource option. As a result, Lephalale Local Municipality is constantly investigating new augmentation options, and these options include use of groundwater and aquifer storage and recovery of storm water and/or return flows. VSA Leboa was appointed by the Department of Water Affairs and Forestry to characterise the aquifers, determine the groundwater potential and the artificial recharge options available to Lephalale.

### **1.1 Objectives**

The main objectives of the study are to review the regional hydrogeological conditions at Lephalale, investigate the linear structures within the vicinity of the town, at various depths, to determine the possibility of supplying sufficient potable water from groundwater sources and the possibilities of artificial recharge of the groundwater at Lephalale. The study was divided into four phases and will take two years to complete. The following phases were identified:

- Phase 1 Installation and testing of monitoring wells;
- Phase 2 Detail assessment of local hydrogeology;
- ***Phase 3 Detail assessment of artificial recharge potential;*** and
- Phase 4 EIA study.

This report deals with **Phase 3** and the objectives of this phase was:

- To assess the various artificial recharge systems proposed in the previous phases on a pre-feasibility level;
- To sample, analyse and evaluate water quality of the various sources' water; and
- To do limited geochemical modelling to test interactions of the source water and limitations to the different proposed artificial recharge systems.

Due to various constraints the DWA decided not to go on with Phase 4 and this report is considered the final report for this study.

## 2 ARTIFICIAL RECHARGE OPTIONS AT LEPHALALE

It is expected that Lephalale will in future be under severe stress in terms of water supply, because of the economic growth occurring in the area. Aquifers at Lephalale have not been utilised on a scale where an impact can be observed and this resource needs to be utilised before artificial recharge (AR) can occur. This also makes it an ideal time to start proper planning, development and phasing in of AR schemes, while at the same time testing the response of the aquifer to the use.

Boreholes drilled in the previous phases of this project have reasonable yields (greater than 2 L/s), but yield poor quality water, the limiting factor for use to be quality rather than quantity. The poor quality may also be enhanced by low rainfall and high evaporation, making it ideal to investigate artificial recharge as a future augmentation option, storing good quality water in saline aquifers and using it during peak demands.

The various artificial recharge options for consideration at Lephalale (Figure 1) were identified in Phase 1 & 2 of this study (DWA, 2010) and will be discussed in more detail in the sections to follow, in terms of the pre-feasibility stage discussed in Murray, *et. al*, 2007 and checklist parameters listed in DWA, 2009.

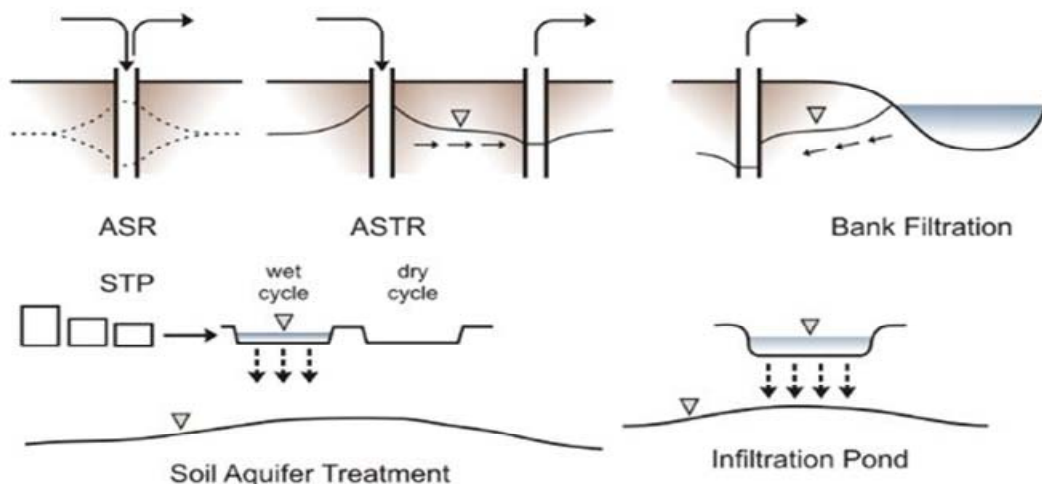


Figure 1: Schematic examples of ASR, ASTR, Bank filtration, SAT and Infiltration ponds (Dillon, 2005)

## 2.1 Sources of Water

The various sources of water available for AR at Lephale includes treated effluent from the sewage works return water dam, storm water run-off, excess river run-off, treated surface water at / from Zeeland and increased natural recharge. The increased recharge will occur as soon as the aquifer (currently full) is utilised and storage becomes available for infiltration to take place. Infiltration is expected to be rapid because of the coarse gravel on top of the fractured rock aquifer, especially in the Eenzaamheid Fault System (EFS), since transmissivity values of the vertical structures are extremely high (see hydraulic parameters in DWA, 2010).

The quantity and quality of the source water are discussed in the sections to follow. H21-0671 was sampled to have a comparative analysis of the deep groundwater with the rest of the sources at the same time and is considered a typical groundwater sample of the Waterberg fractured rock aquifer. Chemical analyses for the treated river water (Zeeland Raw and Zeeland Drink) were obtained from the Zeeland Water Treatment Works (via Exxaro Coal (Pty) Ltd). All analyses were performed by the accredited laboratory UIS Analytical Services, Pretoria.

### 2.1.1 Water Quantity

Limited information was available at the time of printing regarding volumes of source water available. Table 1 shows the volumes for the different sources and all of these was deduced from information contained in the planning scenarios of the MCWAP, 2010 study.

**Table 1: Volumes of source water available for artificial recharge of the Waterberg aquifer**

Source	Volume (m <sup>3</sup> /d)	Volume (Mm <sup>3</sup> /a)	Date available	Comment
Treated effluent	13500	4.95	2015	As total volume of return flows on planning tables
Storm water	1500	0.55		
Run off river excess	3500	1.3	2010	Taken as 10% loss on expected demand
Run off river excess	12300	>4.5	2015	

### 2.1.2 Water Quality

Table 2 to Table 6 shows the different water quality parameters for the water sources and only problematic concentrations are highlighted. Those not highlighted are within ideal drinking water quality ranges as specified in DWA, 1998.

The Waterberg fractured aquifer groundwater quality has elevated NaCl (sodium-chloride) and very high levels of F (fluoride). Very low levels of heavy metals and microbiological constituents were observed.

The other sources of water have elevated heavy metals (aluminium, iron and manganese) and very high levels of microbiological contamination. The treated effluent had no microbes because of the high dosage of free chlorine in the water (field observation at the time of sampling).

**Table 2: Source water - physical water quality properties**

<b>WATER SOURCE</b>	pH	EC [mS/m]	TDS [mg/l]	Suspended Solids [mg/l]	Alkalinity [mg/l CaCO <sub>3</sub> ]	Total Hardness [mg/l CaCO <sub>3</sub> ]
<b>Groundwater H21-0671</b>	8.52	150	950	1.8	143.24	20.17
<b>Lephale Treated Effluent</b>	7.37	52	314	25.8	94.96	80.33
<b>Lephale Storm water</b>	7.24	66	392	67.4	230.04	104.96
<b>Mokolo River</b>	7.49	7	42	2	20	17.57
<b>Zeeland Raw</b>	8.88	7	46	-	27.5	-
<b>Zeeland Drink</b>	9.59	9	72	-	34.2	-

**Table 3: Source water - chemical water quality (Cations)**

<b>WATER SOURCE</b>	pH	Ca [mg/l]	Mg [mg/l]	Na [mg/l]	K [mg/l]	Si [mg/l]
<b>Groundwater H21-0671</b>	8.52	7.68	0.24	324	2.95	8.3
<b>Lephale Treated Effluent</b>	7.37	24.7	4.53	65.8	12.3	8.5
<b>Lephale Storm water</b>	7.24	34.2	4.75	61.5	13.3	7.3
<b>Mokolo River</b>	7.49	3.41	2.2	5.89	0.98	4.38
<b>Zeeland Raw</b>	8.88	8.05	1.74	6.86	0.88	2.24
<b>Zeeland Drink</b>	9.59	12	1.7	8.63	0.9	2.14



**Table 4: Source water - chemical water quality (Anions)**

WATER SOURCE	pH	F [mg/l]	Cl [mg/l]	NO <sub>3</sub> as N [mg/l]	PO <sub>4</sub> [mg/l]	SO <sub>4</sub> [mg/l]
Groundwater H21-0671	8.52	10.93	303.92	<0.3	<0.8	169.78
Lephale Treated Effluent	7.37	0.11	76.24	0.78	<0.8	30.93
Lephale Storm water	7.24	0.14	41.76	<0.3	<0.8	13.04
Mokolo River	7.49	0.03	8.18	<0.3	<0.8	2.28
Zeeland Raw	8.88	<0.1	5.72	<0.3	-	6.18
Zeeland Drink	9.59	<0.1	6.99	<0.3	-	5.22

**Table 5: Source water - chemical water quality (Metals)**

WATER SOURCE	pH	Al [mg/l]	Ba [mg/l]	Fe [mg/l]	Mn [mg/l]	Pb [mg/l]
Groundwater H21-0671	8.52	<0.05	0.08	0.06	<0.05	<0.05
Lephale Treated Effluent	7.37	0.12	0.06	0.67	0.09	<0.05
Lephale Storm water	7.24	0.92	0.1	0.87	0.16	<0.05
Mokolo River	7.49	0.07	0.05	0.64	<0.05	<0.05
Zeeland Raw	8.88	<0.05	0.06	0.35	<0.05	<0.05
Zeeland Drink	9.59	<0.05	0.18	0.14	<0.05	<0.05

**Table 6: Source water - microbiological water quality**

WATER SOURCE	pH	Coliforms [Colonies/100ml]	Faecal Coliforms [Colonies/100ml]	Escherichia coli [Colonies/100ml]	Dissolved Oxygen [mg/l O <sub>2</sub> ]
Groundwater H21-0671	8.52	6	0	0	8
Lephale Treated Effluent	7.37	0	0	0	8.1
Lephale Storm water	7.24	>30000	>30000	>30000	1.2
Mokolo River	7.49	4300	87	39	7.9
Zeeland Raw	8.88	1600	0	0	-
Zeeland Drink	9.59	0	0	0	-

The various options for AR at Lephale will be discussed in more detail in sections 2.2 and 2.3 and detail on mixing concentrations of the different blend options will be dealt with in section 3. It can already be noted that a 1:1 blending of groundwater with river water will potentially half the concentrations of NaCl and F in the groundwater as well as the heavy metals in the river water. This will better the water quality of both the groundwater and river water. However, the river water will have to be treated to eliminate microbiological contamination to the groundwater system.

The potential clogging of the Waterberg aquifer will also be dealt with in section 3 as a result of both physical properties of the source waters and possible mineralogical changes that may occur with the sandstone host rock.

## **2.2 AR Options in the Waterberg Aquifer**

Water levels in the Waterberg aquifer are generally not deep, except where dewatering has taken place. Close to the town of Lephale water levels are less than 2 meters below surface. Therefore, it is critical that abstraction takes place before AR schemes can be implemented. However, this also provides the opportunity to properly plan and implement AR schemes in a timely fashion to maximise water conservation and demand management in an area dependant on highly variable rainfall run-off.

The aquifer hydraulics and groundwater quality of the Waterberg fractured rock aquifer was described in detail in DWA, 2010. During the exploration phase of this study, the Waterberg semi-confined and confined aquifer was confirmed as an aquifer that has major yields associated with boreholes drilled on feasible structures and an aquifer that has a vast amount of water in storage. The numerical modelling showed that the proposed well-field from the existing exploration boreholes, Table 7, creates storage in the order of 1700 m<sup>3</sup>/d (0.6 Mm<sup>3</sup>/a) and if the rest of the EFS are developed storage of 7000 – 15000 m<sup>3</sup>/d (2.5 – 5.4 Mm<sup>3</sup>/a) can potentially be created.

When comparing this to the potential source water volumes that will become available, Table 1, it is clear that AR can play an important role in water demand management and conservation in this area in the near future.

**Table 7: Current accessible groundwater from Waterberg aquifer (single borehole pumping)**

Aquifer	Drill Site ID	Water Level (mbgl)	Pump Depth (mbgl)	24h Yield (L/s)	Volume (m <sup>3</sup> /m)	Volume (m <sup>3</sup> /a)	Total (m <sup>3</sup> /a)
Semi-confined Waterberg Eenzaamheid Fault System	H21-0637	1.4	120	4	10,368	124,416	<b>1,088,640</b> <b>(excl H21-0638)</b>
	H21-0638	0.5	120	7.5	19,440	233,280	
	H21-0663	1.9	120	3	7,776	93,312	
	H21-0665	1.3	119	14	36,288	435,456	
	H21-0700	4.6	119	9	23,328	279,936	
	H21-0666	34.2	102	3	7,776	93,312	
	H21-0712	3.3	76	2	5,184	62,208	
Confined Waterberg	H21-0671	0.3	119	9	23,328	279,936	<b>342,144</b>
	H21-0702	2.5	118	2	5,184	62,208	

At this stage, prior to large-scale testing, it will be assumed that the same amount of water can be injected for the storage created. The potential AR rate depends on the regional permeability of the aquifer and the number and spacing of artificial recharge infrastructure (density of injection boreholes, etc). Whilst this will only be confirmed after testing, it is evident from the large abstraction potential, that a significant volume of water can potentially be stored in the aquifer once space has been created after times of large-scale abstraction. In times of high rainfall, excess runoff needs to be captured and stored in the aquifer, and used again in times of drought. By abstracting this water from the aquifer at high rates when water shortages are experienced, space will be created in the aquifer for the next round of artificial recharge.

It must be noted that currently groundwater is evaporating, evapo-transpiring or discharging to the Mokolo River at Lephallale, since these are the only ways water can be removed from the aquifer. In relation to retaining artificially recharged water, the Eenzaamheid Fault System (EFS) creates a natural groundwater barrier that effectively stops leakage from the aquifer. The EFS has a downthrow of 250 meters to the north, were it is overlain with impermeable Ecca layers, forming a hydraulic barrier to the north were natural groundwater drainage would have occurred. Therefore, if the groundwater levels at Lephallale are lowered and AR schemes put in place, water recharged will be dammed up against this barrier until it has risen to the piezometric level where it again would evaporate, evapo-transpire and/or discharge into the Mokolo River.

The AR schemes currently considered for the Waterberg aquifer at Lephale is shown in Figure 2 and include the following:

### 2.2.1 Aquifer Storage Recovery (ASR)

Aquifer storage recovery (ASR) occurs when water is abstracted from a water supply borehole and in times of excess the same borehole is used to inject treated water into the aquifer, see Figure 1 (Murray, *et. al.*, 2007). At Lephale, this would typically be utilised as part of the annual well-field operation of the high-yielding boreholes drilled into the EFS (see Figure 2). ASR will increase the sustainable abstraction rate of the single boreholes, since higher abstraction rates can be maintained if water taken from storage is replenished in the annual abstraction-cycle of the ASR borehole.

#### 2.2.1.1 Feasibility of ASR at Lephale

ASR is the first of the AR options that should be implemented at Lephale and serves two purposes: (1) it will increase the yields that can be abstracted sustainably from the boreholes and/or the assurance of supply from the aquifer and (2) a blending of treated river water and in-situ groundwater is expected to better both sources water quality for drinking water purposes. This is considered feasible, in terms of aquifer hydraulic properties, abstracting groundwater and injecting treated river water at the current high yielding boreholes. The feasibility of chemical and geochemical interactions in the aquifer will be confirmed in section 3.

### 2.2.2 Aquifer Storage Transfer & Recovery (ASTR)

Aquifer storage transfer & recovery (ASTR) occurs when excess treated water is injected into dedicated injection boreholes and retrieved through dedicated abstraction boreholes, see Figure 1 (Murray, *et. al.*, 2007). At Lephale, this would be considered at the end of the proposed well-field development, at the boundary of the well-field abstraction impact (see Figure 2), to increase the yield of the abstraction boreholes and better the overall water quality or decrease the impact on the surrounding users.

#### 2.2.2.1 Feasibility of ASTR at Lephale

ASTR is considered feasible during the end final stages of development of water resources at Lephale, injecting treated river water at the boundary of the abstraction impact, and is expected to better the water quality of the aquifer for drinking water purposes. The feasibility of chemical and geochemical interactions in the aquifer will be discussed in section 5.

#### 2.2.3 Soil Aquifer Treatment (SAT)

Soil aquifer treatment (SAT) occurs when treated sewage effluent or urban storm water is captured and allowed to infiltrate through constructed infiltration ponds and recovered by boreholes after a certain residence time in the aquifer. This method is highly dependent on water quality and proper treatment of infiltration water (assumed polluted to an extent) is extremely important. This method also facilitates nutrient and pathogen removal through filtration at the ponds. (Murray, *et. al.*, 2007)

SAT should be considered for the area south of the storm water dam were ponds can be constructed to capture stormwater and treated effluent from the sewage works return water dam (see Figure 2). The existing storm water dam can be utilised as a retention dam where most of the suspended solids can settle before water is channelled to the infiltration ponds.

##### 2.2.3.1 Feasibility of SAT at Lephale

SAT is only effective in areas with sufficient sand thickness and sufficient permeability to allow for effective infiltration, aquifer through flow and abstraction. From the two boreholes that were drilled in the alluvium, it appears as if this aquifer may be favourable for SAT. Geophysical surveys to determine areas of thickest sands, and additional boreholes need to be drilled to verify the suitability of the aquifer for SAT. Should the conditions prove favourable, SAT could be an effective water re-use option. Storm water and treated effluent will blend in the retention dam (current storm water dam) rendering a lower microbiological water and therefore enhance the effectiveness of treatment through the soil. Suspended solids that settle in the retention dam will also decrease routine maintenance needed at the infiltration ponds. Good monitoring between the infiltration ponds and abstraction

boreholes will be needed to establish if filtering of contaminants takes place to a satisfactory level. The feasibility of chemical and geochemical interactions in the aquifer will be confirmed in section 3.

#### 2.2.4 Infiltration Ponds

Infiltration ponds are ponds constructed off stream where surface water is diverted to, especially in high run-off events, and allowed to infiltrate into the semi-confined Waterberg aquifer. The volume of run-off determines the size of the infiltration ponds since infiltration is usually slow. Because of high evaporation rates, only very good quality water should be used for these infiltration ponds. (Murray, *et. al.*, 2007)

This is proposed for a linear section along the banks of the Mokolo River channel south and north of the SAT infiltration ponds, where high flows are diverted for infiltration into the Waterberg aquifer (see Figure 2). If practical, some of the water can be diverted to the SAT infiltration ponds to increase the yield and further enhance water quality at these ponds.

##### 2.2.4.1 Feasibility of Infiltration Ponds in Waterberg at Lephhalale

The aquifer conditions for infiltration ponds needs to be the same as that for SAT – i.e. a reasonably thick sand aquifer with relatively high permeability. These conditions appear to be met adjacent to the Mokolo River, but would need to be tested further. From a water availability perspective, infiltration ponds next to the Mokolo River appear highly feasible, since high flow run-off, that would otherwise have been lost to evaporation, can be captured and infiltrated to increase the yield and better the water quality of the groundwater system. Since this water will not be treated it is very important to have a good monitoring system between the ponds and the abstraction boreholes to establish if filtering of contaminants takes place to satisfactory level. The feasibility of chemical and geochemical interactions in the aquifer will be confirmed in section 3.

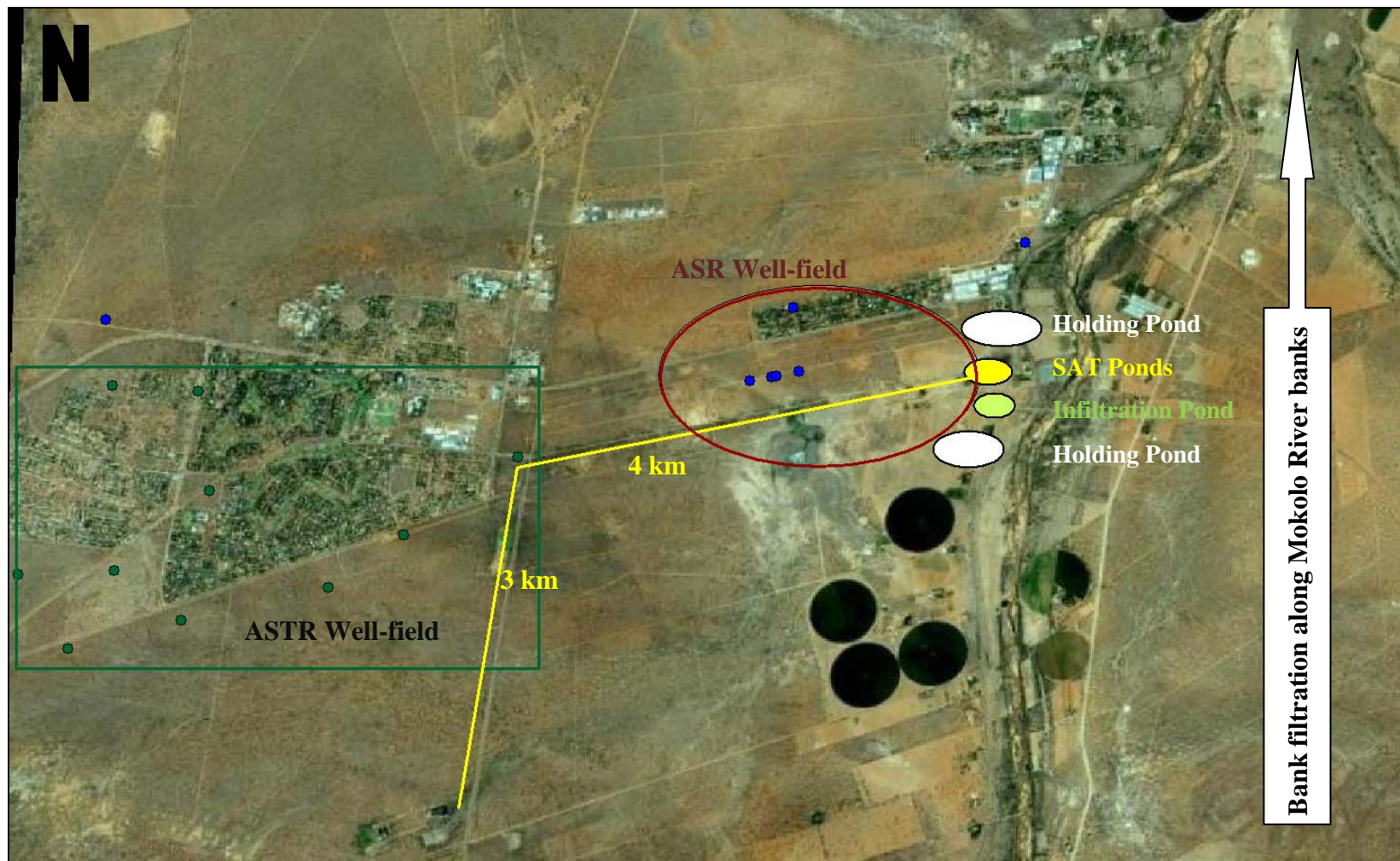


Figure 2: In plan schematic of ASR, ASTR, Bank filtration, SAT and Infiltration ponds

### **2.3 AR Options in the Alluvial Aquifer**

The available information on aquifer hydraulics and groundwater quality of the alluvial aquifer was described in detail in DWA, 2010. Exploration of the alluvial aquifer during this study was only performed through the drilling of 2 boreholes specifically accessing this resource. Drilling logs showed sands of 10 – 18 m thick and this constitutes a major storage space when accessed.

Currently, this aquifer does not have any available storage capacity for excess water. The aquifer also has a direct link to the flow in the Mokolo River and any water pumped from it or recharged to it will either come from or go to the Mokolo River in a fairly rapid manor, unless the level in the river is dropped to below the bottom of the river bed.

Further groundwater exploration needs to focus on the alluvial aquifer in order to find the high yielding areas and to evaluate aquifer characteristics further (e.g. zones where alluvial and Waterberg aquifer is connected). GeoAfrica Consulting is currently busy with a study to define typical aquifer hydraulics of the alluvial material of the Mokolo River.

The AR schemes considered for the alluvial aquifer at Lephale include the following.

#### **2.3.1 Bank Filtration**

Bank filtration occurs when water is extracted through boreholes along the alluvial sands in the river to induce infiltration from the river, thereby improving and making the quality of the water more consistent (Murray, *et. al.*, 2007).

##### **2.3.1.1 Feasibility of Bank Filtration at Lephale**

For bank filtration to be effective, the alluvium adjacent to the river needs to be suitably thick and permeable to allow for the river water to be induced into the aquifer and flow towards the abstraction boreholes. For effective treatment (which is largely a function of travel time) and storage in the aquifer the location of boreholes at suitable distances from the river will need to be established. From the available information, it appears as if bank filtration is feasible both from abstraction boreholes located in the alluvium and in the



Waterberg aquifer. A direct connection exist between the Mokolo River, alluvial aquifer and Waterberg fractured rock aquifer and currently the Waterberg aquifer is discharging under surface level through the alluvial material into the Mokolo River. This will be reversed if the Waterberg aquifer starts to dewater below the water level in the river. The feasibility of chemical and geochemical interactions in the aquifer will be discussed in section 5.

### 2.3.2 Infiltration Ponds

Infiltration ponds are ponds constructed off stream where surface water is diverted to, especially in high run-off events, and allowed to infiltrate into the unconfined alluvial aquifer (Murray, *et. al.*, 2007). These ponds can be constructed in the alluvial material on the banks of the Mokolo River to capture excess water when the river is in flood.

#### 2.3.2.1 Feasibility of Infiltration Ponds in the Alluvial at Lephale

Infiltration ponds on the banks of the Mokolo River is feasible if hydraulic parameters permit fast enough infiltration to minimise evaporation but slow enough flow so that the water can be intercepted before it is lost downstream in the aquifer. The feasibility of chemical and geochemical interactions in the aquifer will be discussed in section 5.

### 3 CHEMICAL AND GEOCHEMICAL INTERACTIONS

Various aspects need to be looked at when considering AR schemes, of which water quality interactions might be the most important before such schemes are implemented. Ideally, *in situ* groundwater quality should be improved during AR. The mixing of two or more sources of water is bound to have chemical and geochemical (water rock interactions where mixing occurs in an aquifer) reactions with a final water quality possibly very different to the two source water qualities. The sustainability of an AR scheme is highly dependent on these interactions and the types of reactions that could undermine the viability include oxidation and reduction reactions (result of blending), acid buffering (result of  $\text{CaCO}_3$  dissolution because of pH changes), cation adsorption (result of availability or lack of stable ions) and clogging (mainly due to suspended solids, microbial growth and chemical precipitation). However, most of these reactions can be prevented with pre-treatment of recharge water. (Murray, *et. al.*, 2007, Stuyfzand, 1998 and Stuyfzand, 2002)

Chemical and geochemical behaviour of water and rock for the different scenarios were simulated with the P<sub>HREEQC</sub>I (interactive) Version 2 geochemical modelling tool, as available from the USGS. P<sub>HREEQC</sub>I Version 2 is used to simulate chemical reactions and transport processes in natural or contaminated water including speciation, batch-reactions, 1D reactive transport and inverse modelling.

#### 3.1 Mixing Scenarios

In order for any AR scheme to be implemented at Lephale the water level in the groundwater “reservoir” needs to be lowered in order to ensure storage space becomes available to recharge additional water in times of excess. This entails abstracting a high volume of groundwater from boreholes and using the abstracted groundwater as part of the available water supply at Lephale. This can either be done by adding the groundwater to one of the reservoirs (balancing dams) at Lephale or to the reservoir at Zeeland. However, it is necessary to determine the final water quality expected and whether mixing the different sources will cause significant precipitation in the reservoirs or pipes.

The mixing of groundwater and water currently distributed from Zeeland is evaluated as a simple box model. Two scenarios were presented: (1) mixing of the current

accessible volume of groundwater (1.4Mm<sup>3</sup>/a) into the Zeeland Reservoir (sample *Zeeland Raw*) water supply and (2) directly into the Lephale reservoir (sample *Zeeland Drink*). The main difference between the two scenarios are the ratio of mixing (groundwater: river water) and chemical composition (river water at Zeeland versus treated water in the Lephale pipe lines). Water quality analyses were obtained for both cases from the Zeeland water treatment works. The expected results for water quality and precipitates are shown in Table 8 - Table 10.

### 3.1.1 Adding Groundwater to Zeeland Raw Water

The raw water intake at the Zeeland reservoir is estimated at 5.5 Mm<sup>3</sup>/a and if 1.4 Mm<sup>3</sup>/a groundwater is added into the reservoir the ratio of groundwater to raw intake water would be 1:4 or the mix will be composed of 20% groundwater. This mixing ratio and the two separate water sources quality, Table 2 - Table 5, were used as input into P<sub>HREEQCI</sub>.

### 3.1.2 Adding Groundwater to Lephale Reservoir

The treated water output to Lephale from the Zeeland reservoir is estimated at 1.7 Mm<sup>3</sup>/a and if 1.4 Mm<sup>3</sup>/a groundwater is added into the Lephale balancing dam the ratio of groundwater to treated water would be 1:1.2 or the mix will be composed of 45% groundwater. This mixing ratio and the two separate water sources quality, Table 2 - Table 5, were used as input into P<sub>HREEQCI</sub>.

**Table 8: Water quality results of mixing before precipitation**

	INPUT WATER QUALITY			MIXED WATER QUALITY	
	H21-0671 (Groundwater)	ZEELAND RAW	ZEELAND DRINK	MIX 1 ZEELAND RES / GW	MIX 2 LEPHALE RES / GW
pH	8.52	8.88	9.59	8.72	8.98
EC [mS/m]	150	7	9	40.80	79.40
Alk (mg/l CaCO <sub>3</sub> )	143.24	27.5	34.2	50.69	83.32
Ba [mg/l]	0.08	0.06	0.18	0.06	0.14
Ca [mg/l]	7.68	8.05	12	7.98	10.06
Cl [mg/l]	303.92	5.72	6.99	65.41	140.75
F [mg/l]	10.93	0	0	2.19	4.92
Fe [mg/l]	0.06	0.35	0.14	0.29	0.10
K [mg/l]	2.95	0.88	0.9	1.29	1.82
Mg [mg/l]	0.24	1.74	1.7	1.44	1.04
Mn [mg/l]	0.02	0	0	0.00	0.01
Na [mg/l]	324	6.86	8.63	70.35	150.70
SO <sub>4</sub> [mg/l]	169.78	6.18	5.22	38.93	79.35
Si [mg/l]	8.3	2.24	2.14	3.45	4.92

**Table 9: Potential precipitates as a result of mixing**

	ZEELAND RES	LEPHALALE RES
Precipitate	mg/l	mg/l
Calcite	0.00	6.53
Dolomite	0.00	0.00
Fe(OH) <sub>3</sub> (a)	73.73	73.73
Siderite	0.00	0.00
Witherite	0.00	0.00

**Table 10: Final water quality of mixes after precipitation**

Constituent	MIX 1 ZEELAND RES / GW	MIX 2 LEPHALALE RES / GW
pH	8.74	8.69
EC [mS/m]	40.80	78.40
Alk (mg/l CaCO <sub>3</sub> )	50.39	76.72
Ba [mg/l]	0.06	0.14
Ca [mg/l]	7.98	7.44
Cl [mg/l]	65.41	140.75
F [mg/l]	2.19	4.92
Fe [mg/l]	0.00	0.00
K [mg/l]	1.29	1.82
Mg [mg/l]	1.44	1.04
Mn [mg/l]	0.00	0.01
Na [mg/l]	70.35	150.70
SO <sub>4</sub> [mg/l]	38.93	79.35
Si [mg/l]	3.45	4.92

### 3.1.3 Feasibility of Mixing at Zeeland and Lephale Reservoirs

As discussed in section 2.1.2 the groundwater shows non-compliance in terms of F and only marginal compliance for EC, Na and Cl, while the Zeeland Reservoir (sample *Zeeland Raw*) shows non-compliance in terms of the Coliforms only and the Lephale Reservoir (sample *Zeeland Drink*) shows full compliance for all parameters. In both cases of mixing groundwater with the different reservoirs' water, fluoride values are greatly reduced, although F is still non-compliant in terms of drinking water, and in the case of the Zeeland mix the sodium-chloride are reduced to within ideal water quality standards.

The precipitates listed in Table 9 were identified as a result of saturation indices in the first simulation of both mixes. However, minerals that will precipitate will include mostly carbonates and Fe-hydroxides (Calcite and Fe(OH)<sub>3</sub>). These minerals

precipitate because of the slightly alkaline conditions. Fe-carbonates may eventually also precipitate (e.g. siderite) and may contain small amounts of Mn. F is not removed by precipitation as fluorite precipitation only starts at higher Ca and F concentrations than present in the reservoir mixes.

Mineral precipitation may contribute to blocking of pipes. However, precipitation will not occur indefinitely, but until equilibrium is reached in the reservoir between saturation of elements in solution and the minerals that has precipitated out previously, at which time the water quality will return to the saturated water quality of Table 8. Therefore the water quality of the mixes will vary between that listed in Table 8 and in Table 10.

Figure 3 shows the Piper diagram, illustrating changes in ion dominance in the water, as a result of the mixing scenarios, and the following is deduced from this diagram:

- The groundwater shows NaCl dominance, whereas the Zeeland Reservoir and the Lephale Reservoir are CaCO<sub>3</sub> dominated water.
- Both reservoir waters also show NaCl dominance after mixing.
- No significant difference in ion balance is observed in the reservoir water after precipitation of some saturated minerals.

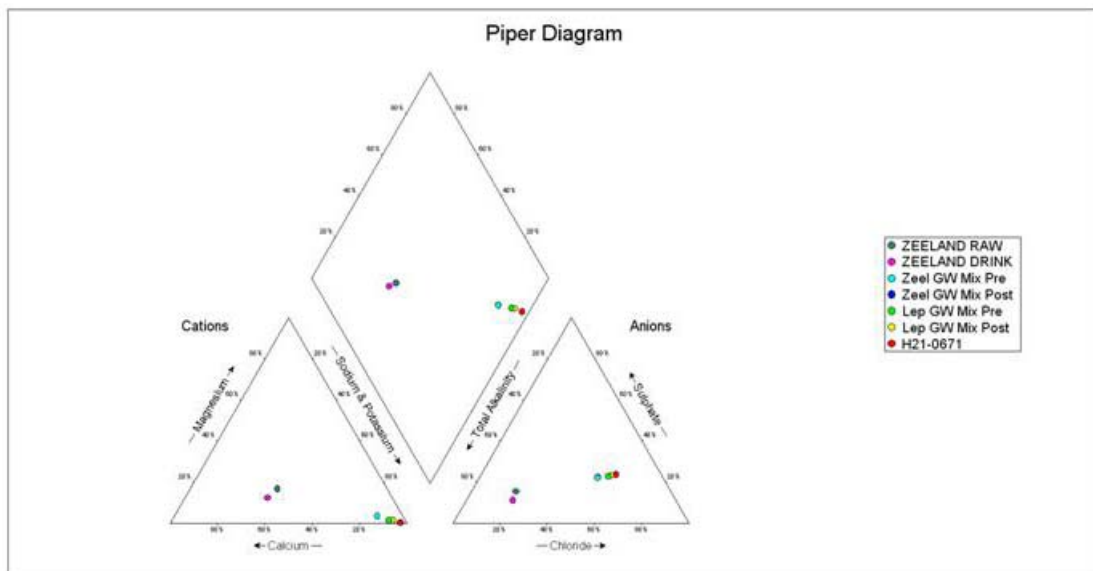


Figure 3: Changes in ion dominance in water sources as result of mixing

Mixing of the groundwater with greater volumes of low fluoride water seems more feasible, but in both cases blending the water does not take the fluoride value within domestic water quality guidelines and removal of the fluoride would be necessary. Removal through Reverse Osmosis is generally more effective with smaller volumes at higher concentrations and in both cases the groundwater will have to be treated (F content lowered) before mixing with the reservoir water is done.

The mixing of both sources of water with the groundwater is considered feasible provided that at least half of the fluoride is removed before mixing occurs.

### 3.2 *In Situ* Groundwater / Rock Equilibrium

Mineralogical analyses of the Waterberg sandstone drilled at Lephale (borehole H21-0671) were done by SGS laboratories in Johannesburg and the report is included in Appendix B. Table 11 shows the mineralogical composition and the calculated moles of mineral potentially available for each mineral at a porosity of 0.05 (Spitz & Moreno, 1996) and a natural groundwater flow rate  $k = 0.037\text{m/d}$  (DWA, 2010). However, not all the minerals in the rock are available to react chemically and calibration of the minerals with the *in situ* groundwater quality is needed to determine how much of these minerals are reacting with the groundwater at equilibrium (natural groundwater system), before simulations are run. Table 12 shows the reaction of each individual mineral with pure water at a pH and temperature similar to the natural groundwater system. This gives an indication of which mineral is most likely to react in those conditions and which to introduce first into the equilibrium phase calculations.

**Table 11: Mineral composition of the Waterberg sandstone at Lephale (H21-0671)**

Mineral	Formula	Composition	Derived %	Composition 1kg rock	Density (kg/dm <sup>3</sup> )	mol/L
Quartz	SiO <sub>2</sub>	> 75 %	85	0.85	2.648	546.4
Hematite	Fe <sub>2</sub> O <sub>3</sub>	3-10 %	6	0.06	5.276	14.5
Muscovite	KAl <sub>2</sub> (Si <sub>3</sub> Al)O <sub>10</sub> (OH,F) <sub>2</sub>	3-10 %	4	0.04	2.831	3.9
Illite	(K, H <sub>3</sub> O) (Al,Mg,Fe) <sub>2</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> [(OH) <sub>2</sub> , (H <sub>2</sub> O)]	3-10 %	3	0.03	2.763	3.0
Chlorite*	(Mg,Fe) <sub>5</sub> Al(Si <sub>3</sub> Al)O <sub>10</sub> (OH) <sup>8</sup>	< 3 %	1	0.01	2.684	0.7
Fluorite	CaF <sub>2</sub>	< 3 %	1	0.01	3.182	4.9

\*Fe-rich variant of chlorite: Chamosite: (Fe<sub>5</sub>Al)(Si<sub>3</sub>Al)O<sub>10</sub>(OH)<sub>8</sub>

**Table 12: Reaction of single specie minerals to pure water at pH and T of *in situ* groundwater**

Amounts single species dissolved in water @ 22.3C and pH 8.52 from 10 mol						
Mineral	Solubility (STP)	mol/L	g/mol	g	mg	Input mg
Quartz	Insoluble	-9.70E-05	60.084	-0.01	-5.83	600840
Hematite	Insoluble	5.00E-11	159.692	0.00	0.00	1596920
Muscovite	Very slightly	-8.64E-07	398.308	0.00	-0.34	3983080
Illite	Slightly	-5.94E-06	383.901	0.00	-2.28	3839010
Chlorite*	Very slightly	-2.24E-06	555.797	0.00	-1.24	5557970
Fluorite	0.0016 g/100 mL (20 °C)	-1.90E-04	78.075	-0.01	-14.87	780750

From the above mineralogical results the following observations could be made:

- The minerals are typical for those of sandstone with quartz as the dominant mineral.
- The hematite identified represents Fe-oxides or hydroxides in the sandstone. Hematite comprises a significant amount of the minor minerals. Hydrated Fe-oxides may significantly contribute to the adsorption of cations in the sandstone aquifer.
- Chlorite, illite and muscovite originate from sedimentary diagenesis or from the original mother rock. Since these minerals do not form at low temperatures they were allowed to dissolve but not to precipitate in the geochemical model. The chlorite is most likely present as the Fe-rich end-member chamosite as very little Mg is present in the rock (relative to Fe).
- Fluorite is the only reactive mineral present in the rock. Fluorite will most likely be in equilibrium with its dissolution products Ca and F.

Illite was the only silicate mineral that showed some dissolution and not precipitation. Because it is a slow reacting mineral, illite was included as a mineral that was in disequilibrium with its dissolution products and not in full equilibrium like fluorite. The other silicate minerals as well as hematite were all further omitted from the geochemical model as their precipitation was not allowed (chlorite, hematite and muscovite) or they are just too slow to react (quartz).

**Table 13: Equilibrated mineral phases with resultant groundwater chemistry**

Mineral	Change in mineral (mol)	Density (g/mol)	Change in mineral phase (mg)	Calibrated Saturation Indices
Quartz		60.084	0.00	
Hematite		159.692	0.00	
Muscovite		398.308	0.00	
Illite	-1.47E-07	383.901	-0.06	<b>-2</b>
Chlorite		555.797	0.00	
Fluorite	-1.30E-07	78.075	-0.01	<b>0.03</b>
Groundwater solution	Calibrated mol	Density (g/mol)	Groundwater quality (mg/l)	
Al	3.39E-07	26.982	0.01	
Ba	5.83E-07	137.33	0.08	
C	2.80E-03	12.011	33.63	
Ca	1.92E-04	40.078	7.69	
Cl	8.58E-03	35.453	304.22	
F	5.76E-04	18.998	10.94	
Fe	1.08E-06	55.845	0.06	
K	7.56E-05	39.098	2.96	
Mg	9.92E-06	24.305	0.24	
Mn	3.64E-07	54.938	0.02	
Na	1.41E-02	22.99	324.39	
S	1.77E-03	32.066	56.72	
Si	1.39E-04	28.086	3.90	

Table 13 shows the calibrated information for both the mineral phases and groundwater quality at equilibrium. The following observations could be made from the above modelling results:

- The groundwater is typically NaCl dominated and slightly alkaline. The high Cl values indicate that the groundwater is either stagnant or not recently recharged.
- Not many reactive mineral phases are present in the Waterberg sandstone.
- Fluorite is the most reactive mineral and controls the Ca and F concentrations in the groundwater.
- Ca is more subdued to adsorption and precipitation in the aquifer than F. Therefore, Ca might be at slightly lower and F at slightly higher concentrations than expected. If more Ca was available F would be at concentrations below 10 mg/l.
- Illite is the only silicate mineral that dissolve slightly. This mineral maintains the K content of the groundwater, which is not as high as Ca, but not as low as the Mg concentration.



### 3.3 AR Scenarios

In this section the geochemical reactions of three of the Artificial Recharge Scenarios will be tested for possible dissolution / precipitation of key minerals and resultant groundwater quality after the recharge events have taken place. It must be noted that these results are based on the following assumptions:

- The mineral phases identified as part of the mineralogical study are representative of the whole aquifer;
- The equilibrium of groundwater and minerals, section 3.2, are true for the artificial recharge starting conditions of each option, after groundwater abstraction have created storage in the aquifer;
- No significant changes in equilibrium phases will occur as a result of the introduction of oxygen into the system;
- The results are predictive and no tests have been performed to test the validity of these results.

Each of the scenarios assumes prior creation of storage space in the aquifer through groundwater abstraction for 2 years as was simulated in DWA, 2010. It was assumed that the same volume of water will be recharged than what was abstracted. From water balance information (DWA, 2010) 3974 m<sup>3</sup>/d (1.4 Mm<sup>3</sup>/a) can be abstracted from the current exploration boreholes of which 1669 m<sup>3</sup>/d is from the groundwater system and 2305 m<sup>3</sup>/d is infiltration from the river system.

Each scenario was simulated for 3 different ratios of recharge water to groundwater *in situ* (left behind in the pore spaces) namely (R1) 90:10; (R2) 50:50; and (R3) 10:90. The volume of water left in the pore spaces after abstraction is one of the biggest unknowns in artificial recharge studies and these ratios are used to define two end members and an average to calibrate against any future testing that needs to be done before AR can be implemented. This also defines the range one can expect the results to fall within should the scheme be implemented.

For each simulation 3 consecutive cycles of abstraction and recharge was introduced, with the water quality information as given in Table 2 - Table 5. The first cycle would abstract the *in situ* groundwater, the second cycle the groundwater/recharge water mix and the third cycle the previous mix/third recharged water mix. Each

recharge event would first blend the recharge water with the water *in situ* (dilution with pore space water) before equilibrating with the available minerals in the aquifer.

### 3.3.1 Aquifer Storage Recovery (ASR)

The ASR scenario have been conceptualised as the same boreholes that was used for abstraction will be used for injecting river water into the aquifer. After each period of groundwater abstraction the aquifer was recharged with river water, with the river water mixing with groundwater and the mix equilibrating with the mineral phases from the previous cycle. For this scenario infiltration from the river system was ignored and direct injection assumed as the only water entering the dewatered aquifer.

Table 14 to Table 19 show the results for the 3 consecutive ASR events for each of the Ratios simulated.

**Table 14: Mineral precipitation of ASR events for simulation R1**

Mineral	ASR Event 1	ASR Event 2	ASR Event 3	Precipitation / Dissolution
Calcite	0.00	0.00	0.00	No reaction
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-12.69	-12.52	-12.51	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-19.68	-18.47	-18.47	Dissolved
Kaolinite	15.48	14.54	14.54	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 15: Groundwater quality changes of ASR events for simulation R1**

Constituent	ASR Event 1	ASR Event 2	ASR Event 3	Natural GW Quality
Alk	34.78	23.74	22.63	143.24
Al	0.01	0.01	0.01	0.00
Ba	0.05	0.05	0.05	0.08
Ca	10.36	10.53	10.54	7.68
Cl	37.79	11.14	8.48	303.92
F	7.30	6.85	6.80	10.93
Fe	0.58	0.63	0.64	0.06
K	2.38	2.25	2.24	2.95
Mg	2.32	2.50	2.52	0.24
Mn	0.00	0.00	0.00	0.02
Na	37.73	9.07	6.21	324.00
S	19.05	3.96	2.45	169.78
Si	8.35	8.12	8.10	8.30

The groundwater quality has improved for all but 4 constituents: aluminium, calcium, magnesium and iron, as well as potassium for Ratio 3. The increase of aluminium, magnesium and iron are related to injection water quality and geochemical interaction.

The minerals Illite and Fluorite both dissolved in each recharge event, with Illite responsible for the release of aluminium and silica into the groundwater and Fluorite the main contributor of calcium in the groundwater, see Table 11 for chemical compositions. Kaolinite ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ ) precipitated for each event, consuming released aluminium and silica. For Ratio 2 and 3 calcite ( $\text{CaCO}_3$ ) precipitated in the first event, as result of increase in calcium available, and thereafter some of the originally precipitated mineral dissolved.

Fluoride values decreased regardless of the dissolution of Fluorite and is due to the dilution effect of the river water in the aquifer. Mineral precipitation that might be a concern for clogging of the aquifer include the precipitation of kaolinite and calcite.

**Table 16: Mineral precipitation of ASR events for simulation R2**

Mineral	ASR Event 1	ASR Event 2	ASR Event 3	Precipitation / Dissolution
Calcite	1.81	-1.17	-0.63	Prec / Diss
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-7.63	-6.81	-6.90	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-19.33	-8.13	-8.95	Dissolved
Kaolinite	15.10	6.43	7.06	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 17: Groundwater quality changes of ASR events for simulation R2**

Constituent	ASR Event 1	ASR Event 2	ASR Event 3	Natural GW Quality
Alk	82.47	53.35	38.38	143.24
Al	0.01	0.01	0.01	0.00
Ba	0.07	0.06	0.05	0.08
Ca	8.75	10.04	10.52	7.68
Cl	156.21	82.18	45.20	303.92
F	9.20	7.93	7.34	10.93
Fe	0.35	0.50	0.57	0.06
K	3.15	2.56	2.32	2.95
Mg	1.53	1.99	2.24	0.24
Mn	0.01	0.01	0.00	0.02
Na	165.11	85.50	45.70	324.00
S	86.11	44.20	23.24	169.78
Si	9.91	8.61	8.11	8.30

**Table 18: Mineral precipitation of ASR events for simulation R3**

Mineral	ASR Event 1	ASR Event 2	ASR Event 3	Precipitation / Dissolution
Calcite	3.82	-0.01	-0.02	Prec / Diss
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-2.72	-1.36	-1.38	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-19.73	-1.79	-1.90	Dissolved
Kaolinite	15.31	1.41	1.50	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 19: Groundwater quality changes of ASR events for simulation R3**

Constituent	ASR Event 1	ASR Event 2	ASR Event 3	Natural GW Quality
Alk	130.01	119.25	109.60	143.24
Al	0.00	0.01	0.01	0.00
Ba	0.08	0.07	0.07	0.08
Ca	7.13	7.46	7.77	7.68
Cl	274.62	247.96	223.99	303.92
F	11.18	10.73	10.33	10.93
Fe	0.12	0.17	0.22	0.06
K	3.96	3.77	3.61	2.95
Mg	0.75	0.92	1.08	0.24
Mn	0.02	0.02	0.01	0.02
Na	292.43	263.93	237.95	324.00
S	153.22	138.04	124.50	169.78
Si	11.63	11.22	10.88	8.30

Figure 4 and Figure 5 show the decrease in fluoride, sodium, chloride and iron, the constituents of greatest concern from section 2.1.2, for all three Ratios simulated, from starting groundwater quality through the three recharge events.

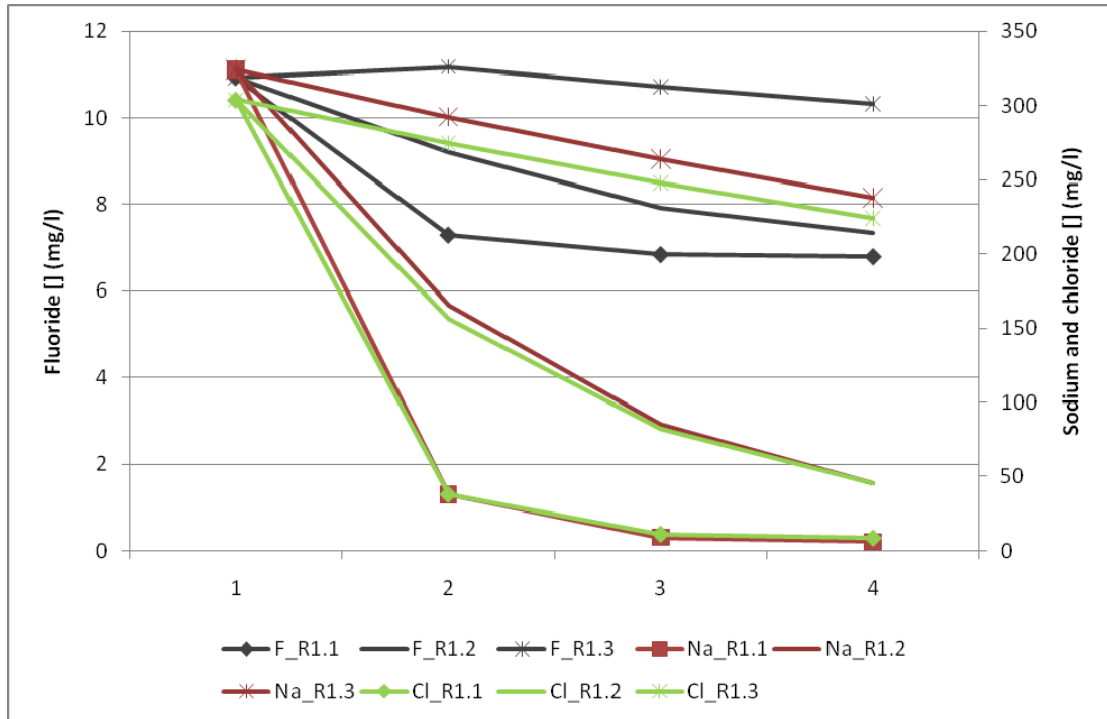


Figure 4: Changes in fluoride, sodium and chloride concentrations as a result of ASR

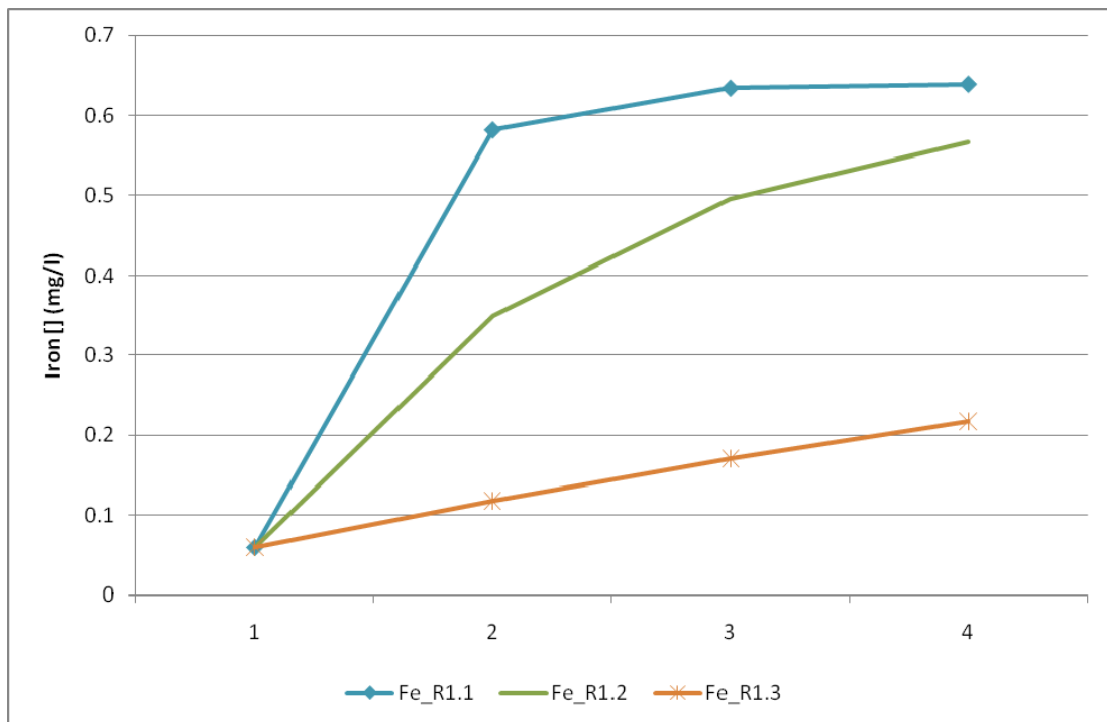
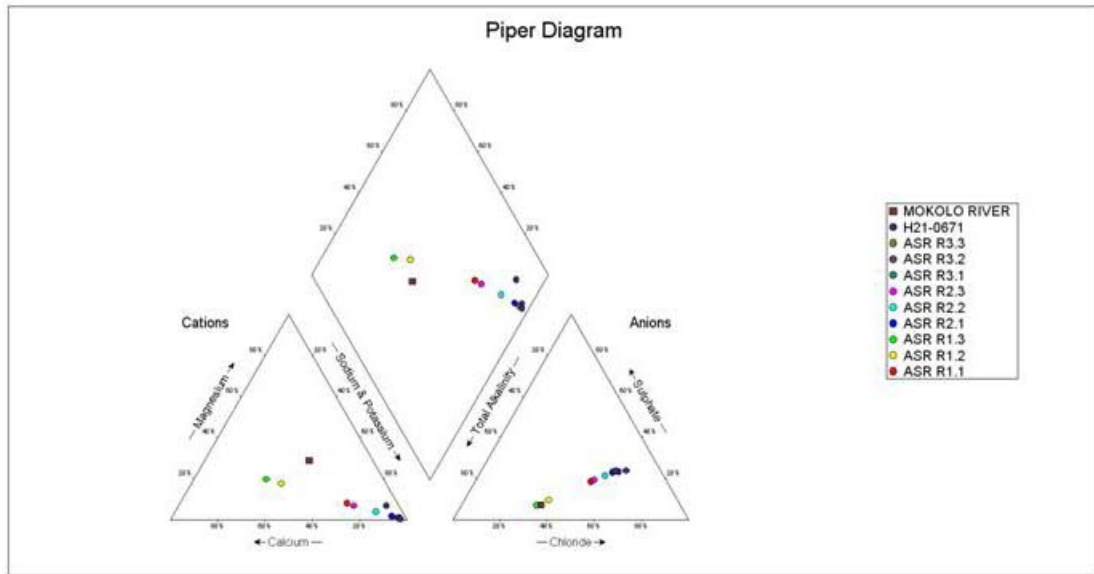


Figure 5: Changes in iron concentrations as a result of ASR

\*R1.1 – Scenario 1, Ratio 1; R1.2 – Scenario 1, Ratio 2; etc.



**Figure 6: Changes in ion dominance in groundwater source as result of ASR**

Figure 6 shows the Piper diagram, illustrating changes in ion dominance in the water, as a result of the ASR events, and the following is deduced from this diagram:

- As expected ASR R1 (90% river water) shows the biggest and ASR R3 (10% river water) the smallest change in groundwater quality respectively.
- The major parameters namely Na, Cl, and  $SO_4$  show a significant decrease in ion balance upon mixing, whereas Mg show a slight increase and Ca and alkalinity show a significant increase in the ion balance upon recharge.
- The groundwater becomes less NaCl and more  $CaCO_3$  dominant with each recharge event.

In all instances precipitation / dissolution and change in concentrations seems to stabilise (become smaller) as the recharge events progress, presumably as a result of the mixed water getting closer to the recharge water quality. The resultant water quality also starts to stabilise for most constituents.

ASR seems like a good option to pursue for testing, since groundwater quality will be improved for the most part, and for the constituents that have increased in concentrations, it will still remain within or close to an ideal drinking water quality.

### 3.3.2 Soil Aquifer Treatment (SAT)

Soil aquifer treatment (SAT) occurs when treated sewage effluent or urban storm water is captured and allowed to infiltrate through constructed infiltration ponds and recovered by boreholes after a certain residence time in the aquifer. For this simulation SAT was simulated for the area south of the storm water dam where ponds can be constructed to capture stormwater and treated effluent from the sewage works return water dam. The existing storm water dam can be utilised as a retention dam where most of the suspended solids can settle before water is channelled to the infiltration ponds.

From water balance information (MCWAP, 2010) 5.5 Mm<sup>3</sup>/a (15 000 m<sup>3</sup>/d) is expected as return flows in the form of either treated effluent or storm water. For this simulation it was assumed that the return flows would either infiltrate along the river alluvium and/or be injected through injection boreholes, effectively recharging the dewatered area with return flows only and river water infiltration is ignored.

Table 20 to Table 25 show the results for the 3 consecutive SAT events for each of the pore volume Ratios simulated.

The groundwater quality has improved for all but 4 constituents: calcium, potassium, magnesium and manganese, as well as silica for Ratio 1. These increases are related to both injection water quality and geochemical interaction.

The minerals Illite and Fluorite both dissolved in each recharge event, with Illite responsible for releasing potassium, magnesium and silica into the groundwater, see Table 11 for chemical composition. Kaolinite (Al<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>) precipitated for each event, consuming aluminium and silica released from illite dissolution. For Ratio 2 and 3 calcite (CaCO<sub>3</sub>) precipitated and then dissolved some of the originally precipitated mineral. For Ratio 2 all of the precipitated calcite was again dissolved.

Fluoride values decreased regardless of the dissolution of Fluorite and is due to the dilution effect of the river water in the aquifer. Mineral precipitation that might be a concern for clogging of the aquifer include the precipitation of kaolinite and calcite.

Figure 7 and Figure 8 show the decrease in fluoride, sodium, chloride and iron, the constituents of greatest concern from section 2.1.2, as well as the increase in

magnesium for all three Ratios simulated, from starting groundwater quality through the three recharge events.

**Table 20: Mineral precipitation of SAT events for simulation R1**

Mineral	SAT Event 1	SAT Event 2	SAT Event 3	Precipitation / Dissolution
Calcite	0.00	0.00	0.00	No reaction
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-7.64	-8.28	-8.29	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-46.72	-46.99	-46.99	Dissolved
Kaolinite	36.12	36.35	36.35	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 21: Groundwater quality changes of SAT events for simulation R1**

Constituent	SAT Event 1	SAT Event 2	SAT Event 3	Natural GW Quality
Alk	116.90	114.30	114.05	143.24
Al	0.00	0.00	0.00	0.00
Ba	0.07	0.06	0.06	0.08
Ca	27.78	30.12	30.36	7.68
Cl	95.97	75.12	73.03	303.92
F	4.91	4.63	4.60	10.93
Fe	0.01	0.00	0.00	0.06
K	14.31	15.47	15.58	2.95
Mg	4.86	5.33	5.37	0.24
Mn	0.09	0.10	0.10	0.02
Na	91.29	67.98	65.66	324.00
S	43.23	30.56	29.29	169.78
Si	16.75	17.65	17.74	8.30

**Table 22: Mineral precipitation of SAT events for simulation R2**

Mineral	SAT Event 1	SAT Event 2	SAT Event 3	Precipitation / Dissolution
Calcite	1.47	-1.21	-0.26	Prec / Diss
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-2.43	-4.16	-4.53	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-29.08	-22.85	-25.42	Dissolved
Kaolinite	22.50	17.67	19.66	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction



**Table 23: Groundwater quality changes of SAT events for simulation R2**

Constituent	SAT Event 1	SAT Event 2	SAT Event 3	Natural GW Quality
Alk	127.66	121.56	117.95	143.24
Al	0.00	0.00	0.00	0.00
Ba	0.07	0.07	0.07	0.08
Ca	17.33	24.11	27.32	7.68
Cl	188.50	130.68	101.75	303.92
F	6.71	5.44	4.98	10.93
Fe	0.03	0.02	0.01	0.06
K	9.46	12.32	13.92	2.95
Mg	2.86	4.07	4.71	0.24
Mn	0.06	0.08	0.09	0.02
Na	194.86	130.12	97.75	324.00
S	99.52	64.35	46.75	169.78
Si	13.59	15.06	16.27	8.30

**Table 24: Mineral precipitation of SAT events for simulation R3**

Mineral	SAT Event 1	SAT Event 2	SAT Event 3	Precipitation / Dissolution
Calcite	3.76	-0.06	-0.09	Prec / Diss
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-0.88	0.06	-0.22	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-19.59	-3.02	-3.79	Dissolved
Kaolinite	15.17	2.34	2.93	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 25: Groundwater quality changes of SAT events for simulation R3**

Constituent	SAT Event 1	SAT Event 2	SAT Event 3	Natural GW Quality
Alk	138.77	136.02	133.72	143.24
Al	0.00	0.00	0.00	0.00
Ba	0.08	0.08	0.08	0.08
Ca	8.44	10.15	11.85	7.68
Cl	281.07	260.26	241.51	303.92
F	10.29	9.24	8.44	10.93
Fe	0.05	0.05	0.04	0.06
K	5.10	6.01	6.89	2.95
Mg	0.98	1.39	1.76	0.24
Mn	0.03	0.03	0.04	0.02
Na	298.41	275.19	254.04	324.00
S	155.91	143.23	131.80	169.78
Si	11.97	12.13	12.43	8.30

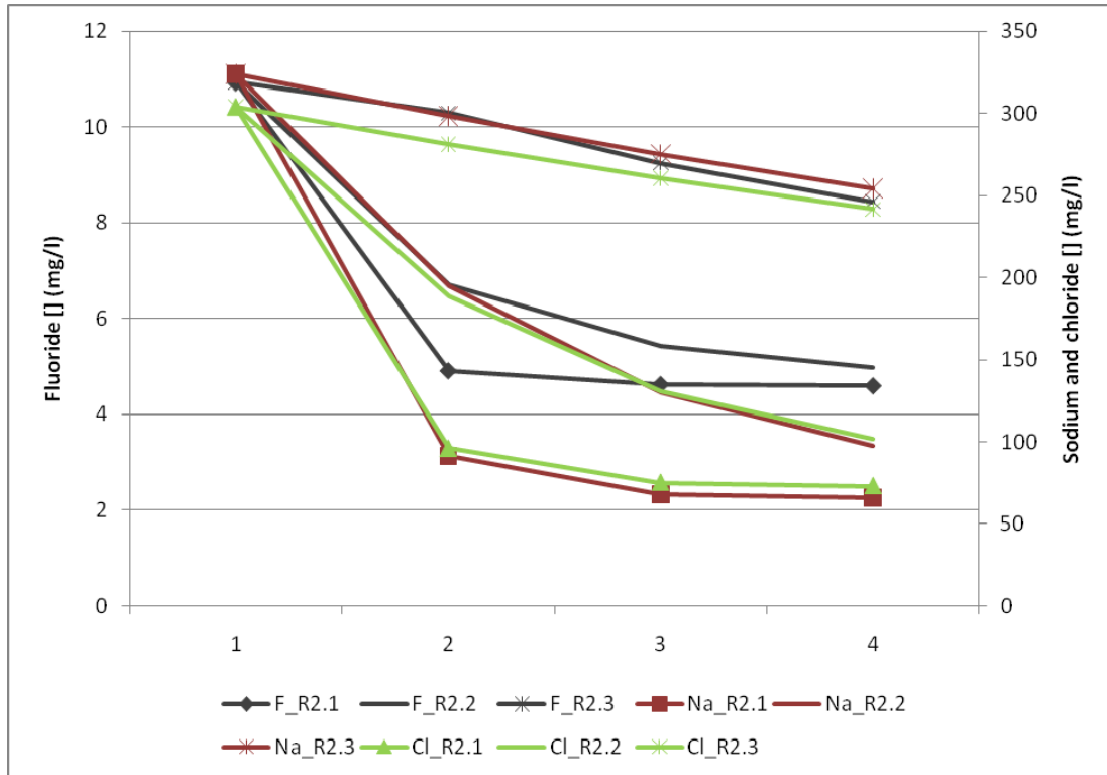


Figure 7: Changes in fluoride, sodium and chloride concentrations as a result of SAT

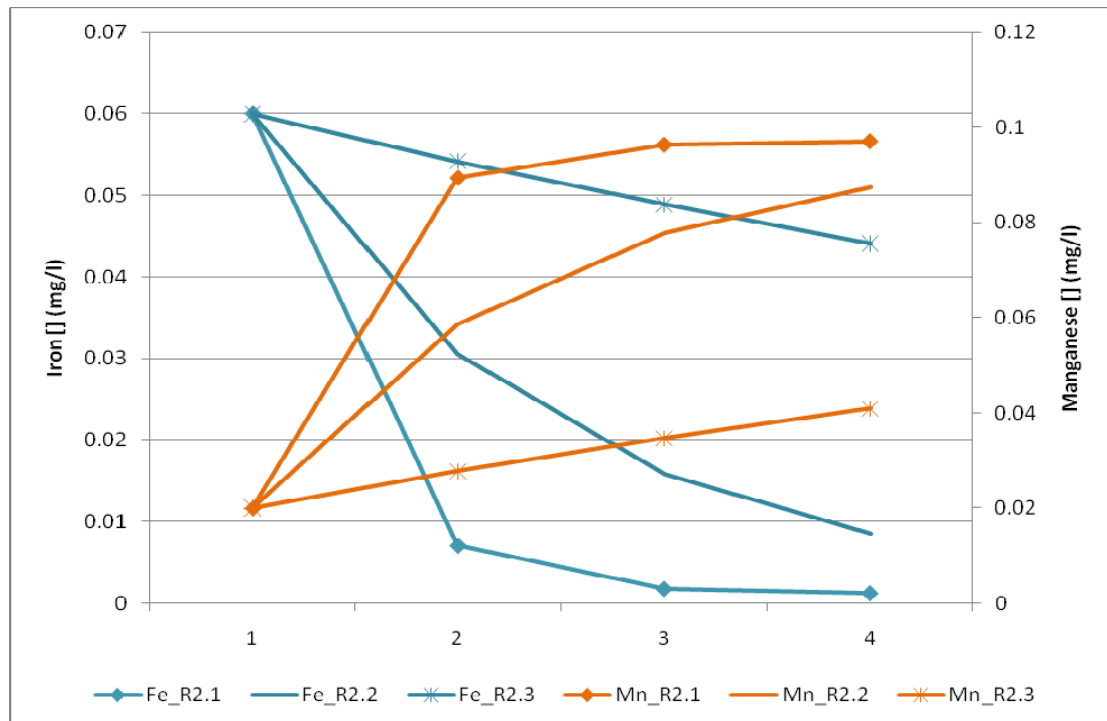
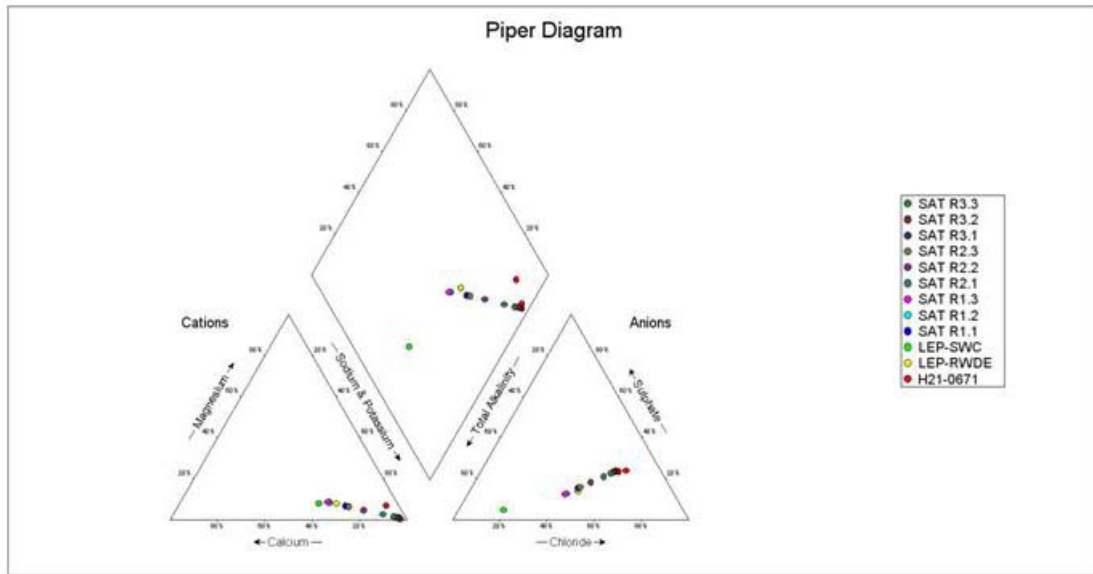


Figure 8: Changes in iron and manganese concentrations as a result of SAT

\*R2.1 – Scenario 2, Ratio 1; R2.2 – Scenario 2, Ratio 2; etc.



**Figure 9: Changes in ion dominance in groundwater source as result of SAT**

Figure 9 shows the Piper diagram, illustrating changes in ion dominance in the water, as a result of the SAT events, and the following is deduced from this diagram:

- As expected SAT R1 (90% effluent) shows the biggest and SAT R3 (10% effluent) the smallest change in groundwater quality respectively.
- The major parameters namely Na, Cl, and  $\text{SO}_4$  show a significant decrease in ion balance upon mixing, whereas Mg show a very slight increase and Ca and alkalinity show a significant increase in the ion balance upon recharge.
- The groundwater becomes less NaCl and more  $\text{CaCO}_3$  dominant with each recharge event.

In all instances precipitation / dissolution seems to stabilise as the recharge events progress, presumably as a result of the mixed water getting closer to the recharge water quality. The resultant water quality also starts to stabilise for most constituents.

SAT seems like a good option to pursue for testing, since groundwater quality will be improved for the most part and for the constituents that have increased in concentrations, it will still remain within or close to an ideal drinking water quality.

### 3.3.3 Infiltration Ponds

Infiltration ponds are ponds constructed off stream where surface water is diverted to, especially in high run-off events. The volume of run-off determines the size of the infiltration ponds since infiltration is usually slow. This is proposed for a linear section along the banks of the Mokolo River channel south and north of the SAT infiltration ponds, where high flows are diverted for infiltration into the semi-confined Waterberg aquifer. If practical, some of the water can be diverted to the SAT infiltration ponds to increase the yield and further enhance water quality at these ponds.

From water balance information (DWA, 2010) 2305 m<sup>3</sup>/d of the groundwater abstracted over the 2 year simulation period, is infiltration from the river system. This infiltration takes place along a stretch where the cone of depression intersects the river alluvium. The water balance across the section where the infiltration ponds would be situated indicates that 790 m<sup>3</sup>/d would infiltrate from the river and 27 m<sup>3</sup>/d is lost to evapotranspiration.

Since simulating river infiltration is expected to produce results similar to the ASR scenario, for this scenario it was conceptualised that the return flows (SAT) and river water infiltration ponds would function as one infiltration system. The return flows would still go to the existing storm water dam for settling of sediment and the river water would be diverted to holding ponds or balancing dams where river water sediment can settle out. During this time supersaturated elements would likely precipitate as in the dams. The settling pond and holding ponds would have an overflow to the infiltration pond and mixing ratios would be 50:50 of river water to return flow. This was simulated through the following steps:

- Groundwater and minerals in the Waterberg were brought into equilibrium to define the in situ water quality of the water in the pore spaces;
- Return flow water was mixed as 10:90 stormwater: treated effluent and equilibrium phases (minerals) were precipitated out of solution, Table 26. The return flow solution was saved as the mix available in the existing storm water dam;

- River water equilibrium phases (minerals) were precipitated out of solution, Table 26, and the solution saved as the water in the river water balancing dam;
- The return water solution and river water solution were mixed 50:50 and a minor amount of equilibrium phases (minerals) still precipitated out of solution;
- This final equilibrated solution was used as the recharge solution for the 3 consecutive recharge events;
- The recharge events were again simulated as in the previous two scenarios.

**Table 26: Mineral precipitation expected at the storm water dam and balancing dam**

Mineral precipitation (mg/l)		
Mineral	Storm water dam - effluent mix	Balancing dam - river water
Calcite	0.00	0.00
Dolomite	0.00	0.00
Fe(OH) <sub>3</sub> (a)	1.32	1.22
Gibbsite	0.00	0.00
Illite	0.00	0.00
Kaolinite	0.96	0.33

Iron-hydroxides (Fe(OH)<sub>3</sub>) and kaolinite is expected to precipitate at different ratios at the two recharge water sources storage dams. Table 27 to Table 32 show the results for the 3 consecutive infiltration events for each of the pore volume Ratios simulated.

The groundwater quality has improved for all but 5 constituents: calcium, potassium, magnesium, manganese and silica. These increases are related to both injection water quality and geochemical interaction.

The minerals Illite and Fluorite both dissolved in each recharge event, with Illite responsible for releasing potassium, magnesium and silica into the groundwater, see Table 11 for chemical composition. Kaolinite (Al<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>) precipitated for each event, consuming aluminium and silica released from illite dissolution. For Ratio 2 calcite (CaCO<sub>3</sub>) precipitated in infiltration event 1 only to dissolve all of it in the second infiltration event. For Ratio 3 calcite (CaCO<sub>3</sub>) precipitated and then dissolved some of the originally precipitated mineral.

Fluoride values decreased regardless of the dissolution of Fluorite and is due to the dilution effect of the river water in the aquifer. Mineral precipitation that might be a concern for clogging of the aquifer include the precipitation of kaolinite and calcite.

Figure 10 and Figure 11 show the decrease in fluoride, sodium, chloride and iron, the constituents of greatest concern from section 2.1.2, as well as the increase in magnesium for all three Ratios simulated, from starting groundwater quality through the three recharge events.

**Table 27: Mineral precipitation of infiltration events for simulation R1**

Mineral	Infil Event 1	Infil Event 2	Infil Event 3	Precipitation / Dissolution
Calcite	0.00	0.00	0.00	No reaction
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-9.41	-9.74	-9.75	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-34.82	-35.51	-35.52	Dissolved
Kaolinite	26.93	27.44	27.47	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 28: Groundwater quality changes of infiltration events for simulation R1**

Constituent	Infil Event 1	Infil Event 2	Infil Event 3	Natural GW Quality
Alk	75.82	69.16	68.46	143.24
Al	0.00	0.00	0.00	0.00
Ba	0.06	0.06	0.06	0.08
Ca	18.68	19.95	20.08	7.68
Cl	66.86	43.15	40.77	303.92
F	5.74	5.38	5.35	10.93
Fe	0.01	0.00	0.00	0.06
K	8.45	9.04	9.10	2.95
Mg	3.61	3.96	4.00	0.24
Mn	0.05	0.05	0.05	0.02
Na	64.51	38.53	35.93	324.00
S	31.13	17.25	15.87	169.78
Si	12.85	13.43	13.49	8.30

**Table 29: Mineral precipitation of infiltration events for simulation R2**

Mineral	Infil Event 1	Infil Event 2	Infil Event 3	Precipitation / Dissolution
Calcite	1.38	-1.38	0.00	Prec / Diss
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-4.47	-5.02	-5.39	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-22.84	-15.34	-19.43	Dissolved
Kaolinite	17.67	11.86	15.03	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 30: Groundwater quality changes of infiltration events for simulation R2**

Constituent	Infil Event 1	Infil Event 2	Infil Event 3	Natural GW Quality
Alk	104.99	87.43	77.87	143.24
Al	0.00	0.00	0.00	0.00
Ba	0.07	0.06	0.06	0.08
Ca	12.86	16.82	18.44	7.68
Cl	172.37	106.43	73.46	303.92
F	7.68	6.32	5.82	10.93
Fe	0.03	0.02	0.01	0.06
K	6.22	7.39	8.23	2.95
Mg	2.17	3.02	3.50	0.24
Mn	0.03	0.04	0.04	0.02
Na	179.99	107.80	71.73	324.00
S	92.83	54.28	35.00	169.78
Si	11.49	11.67	12.53	8.30

**Table 31: Mineral precipitation of infiltration events for simulation R3**

Mineral	Infil Event 1	Infil Event 2	Infil Event 3	Precipitation / Dissolution
Calcite	3.78	-0.06	-0.09	Prec / Diss
Dolomite	0.00	0.00	0.00	No reaction
Fluorite	-1.77	-0.56	-0.68	Dissolved
Gibbsite	0.00	0.00	0.00	No reaction
Illite	-19.51	-2.11	-2.53	Dissolved
Kaolinite	15.10	1.64	1.95	Precipitated
Siderite	0.00	0.00	0.00	No reaction
Witherite	0.00	0.00	0.00	No reaction

**Table 32: Groundwater quality changes of infiltration events for simulation R3**

Constituent	Infil Event 1	Infil Event 2	Infil Event 3	Natural GW Quality
Alk	134.37	127.56	121.51	143.24
Al	0.00	0.00	0.00	0.00
Ba	0.08	0.08	0.07	0.08
Ca	7.77	8.75	9.72	7.68
Cl	277.85	254.13	232.75	303.92
F	10.72	9.92	9.27	10.93
Fe	0.05	0.05	0.04	0.06
K	4.52	4.87	5.20	2.95
Mg	0.86	1.15	1.41	0.24
Mn	0.02	0.03	0.03	0.02
Na	295.42	269.44	245.99	324.00
S	154.57	140.64	128.15	169.78
Si	11.77	11.60	11.52	8.30

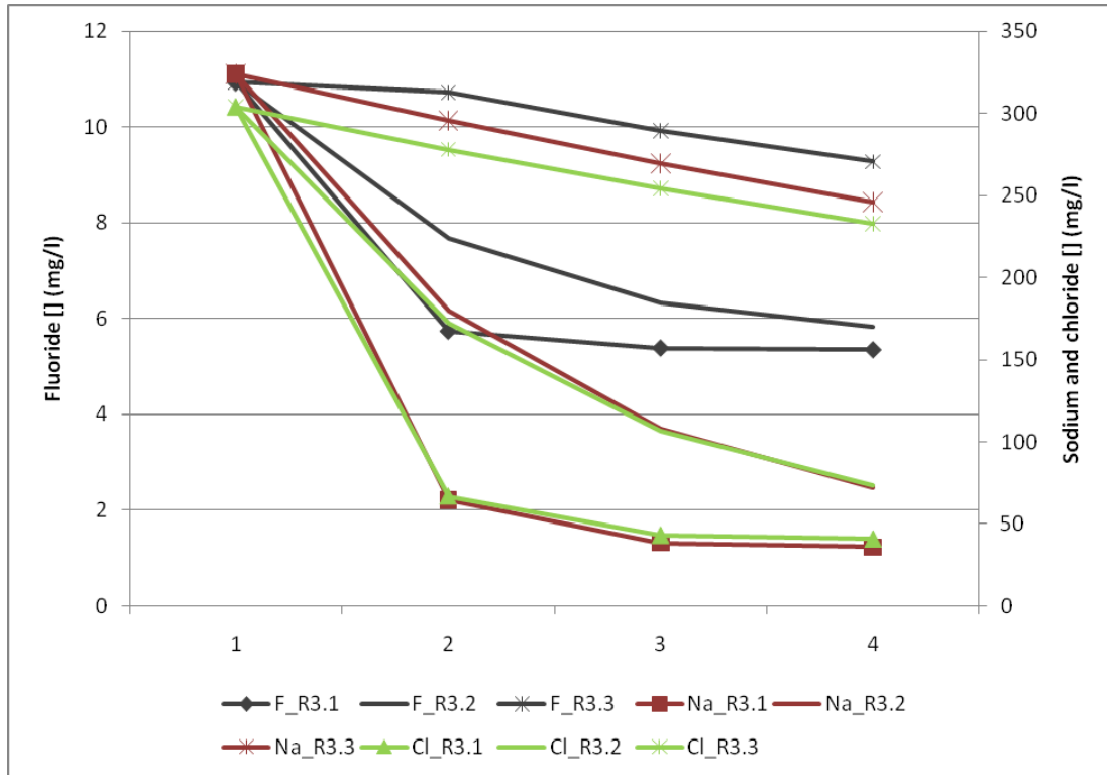


Figure 10: Changes in fluoride, sodium and chloride concentrations as a result of infiltration

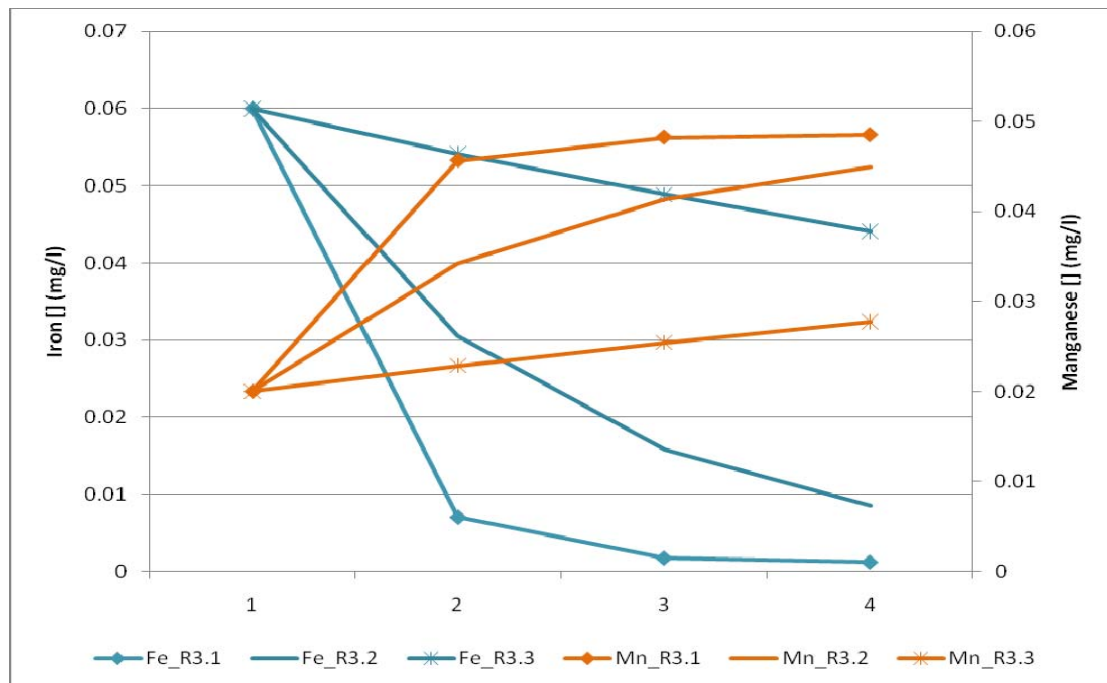
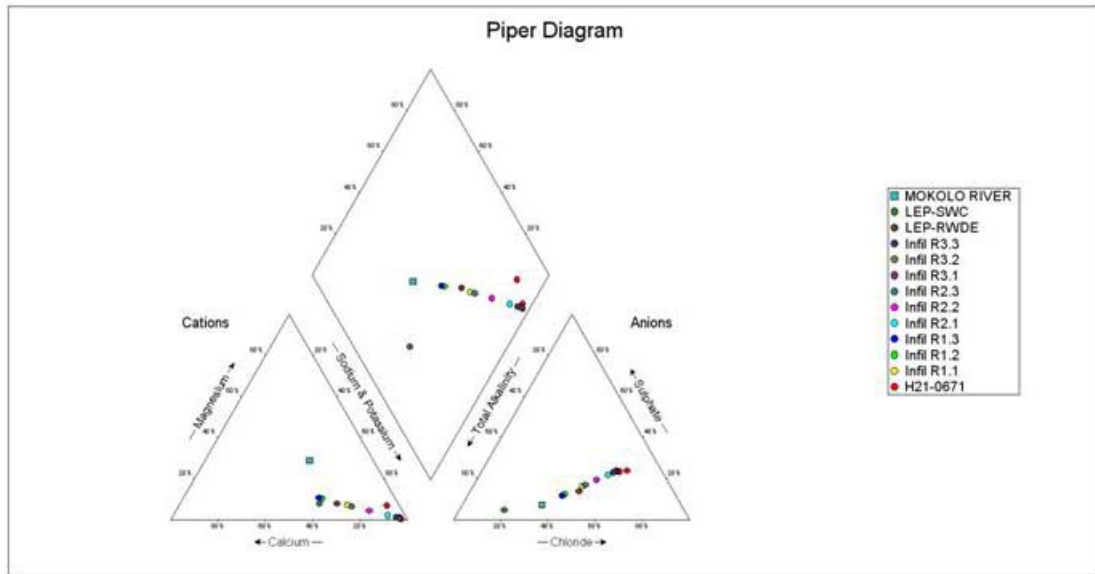


Figure 11: Changes in iron and manganese concentrations as a result of infiltration

\*R3.1 – Scenario 3, Ratio 1; R3.2 – Scenario 3, Ratio 2; etc.





**Figure 12: Changes in ion dominance in groundwater source as result of Infiltration**

Figure 12 shows the Piper diagram, illustrating changes in ion dominance in the water, as a result of the Infiltration events, and the following is deduced from this diagram:

- As expected Infiltration R1 (90% river-effluent-mix) shows the biggest and Infiltration R3 (10% river-effluent-mix) the smallest change in groundwater quality respectively.
- The major parameters namely Na, Cl, and SO<sub>4</sub> show a significant decrease in ion balance upon mixing, whereas Mg show a very slight increase and Ca and alkalinity show a significant increase in the ion balance upon recharge.
- The groundwater becomes less NaCl and more CaCO<sub>3</sub> dominant with each recharge event.

Precipitation / dissolution changes as each recharge event progress, however the resultant water quality seems to stabilise for most constituents.

Infiltration of the combined scenario is a good option to pursue for testing, since groundwater quality will be improved for the most part and for the constituents that have increased in concentrations, it will still remain within ideal drinking water quality.

## **4 TECHNICAL & INSTITUTIONAL REQUIREMENTS**

The technical and institutional requirements listed below will not be dealt with in detail, but need to be dealt with as soon as the AR options at Lephale is viewed as an option to pursue at feasibility level.

### **4.1 Technical Controls**

The AR schemes will have to be designed to ensure efficient use (abstraction, injection and infiltration) of excess water. Various engineering issues exist with each of the options and will be evaluated when feasibility continues. Environmental benefits, risks and constraints also need to be clear and ways to manage it defined.

Costing of the AR schemes is highly dependant on the type of scheme and since no decision has been made to implement either one of these schemes, costing at this stage is considered to be premature.

If the water managers at Lephale deems AR a feasible option based on current information, it would be necessary to do injection tests after a period of high volume abstraction from the aquifer (creating storage for injection), infiltration tests at infiltration ponds or basins, monitoring and evaluating of water quality during both these sets of tests and infrastructure design and costing based on the outcomes of the tests to prove feasibility of each of the schemes. During this costing the implementation phases needs to be defined and where funding will be sourced for the implementation of these projects. This needs to be weighed to the cost per 1 m<sup>3</sup> water in relation to other options of water.

### **4.2 IWULA Conditions and Authorisation Requirements**

An Integrated Water Use License Application (IWULA) needs to be submitted at the DWA for the developing, testing and operation for each AR scheme prior to implementing the scheme. This type of activity will also be regulated by the National Environmental Management Act (NEMA) and therefore the IWULA will have to be supported by an EIA/EMP document. The specific requirements for the IWULA process will differ between regional offices and the requirements from the DWA Limpopo will need to be finalised before the process is started. Questions that will need to be answered include legal constraints to the water use, existing water users

and how they will be affected, the environment and the conditions of the water use applied for.

### **4.3 Institutional Arrangements**

Specific skills are required to operate and maintain an AR scheme e.g. managing abstraction and injection of water from and to the aquifer at set rates and set times, ensuring the quality of the injection water complies to set objectives and maintaining AR infrastructure to a high level. If these functions are not performed correctly an AR scheme becomes a very costly exercise with limited benefit.

Currently the Lephale Municipality do not have personnel trained to do this and might not have the personnel to spare for operating schemes like this in future. It is more likely that some of the relevant skills are already available at the water treatment works of Zeeland and that the minimum effort will be needed to bring the personnel at Zeeland to a level needed for an AR scheme to function optimally. The waterworks is the current single entry point of raw water and exit point of treated water to the area. If this is considered feasible, Zeeland is also most likely the water service provider that can benefit most by increasing water availability or assurance of supply to the rest of the region.

## **5 CONCLUSIONS**

### ***Available water sources***

The sources of water available for artificial recharge in the Lephalale area include:

- Run of river excess in the form of high flows during the rainy season to the volume of 1.3 Mm<sup>3</sup>/a from the year 2010 and >4.5 Mm<sup>3</sup>/a from 2015.
- Return flows in the form of treated effluent and storm water to the volume of 5.5 Mm<sup>3</sup>/a from the year 2015.

### ***Creating storage space in the Waterberg aquifer***

Storage space needs to be created for artificial recharge and depending on the demand and preferred options 0.6 – 5.4 Mm<sup>3</sup>/a can be abstracted and therefore, similar storage space be created. However, this report's focus was on the potential chemical and geochemical interactions and used the sustainable abstraction rate (1.4 Mm<sup>3</sup>/a) of the existing boreholes for the simulations. Therefore, the aquifer has not been stressed above sustainable capacity and the maximum volume/benefit that can be gained through Artificial Recharge (AR) has not been estimated. However, AR will ensure that evaporation and evapo-transpiration is minimised from surface water sources and that the abstraction rate can be maintained even in rainfall events where recharge might not occur, thereby increasing assurance of supply.

Utilising the abstracted groundwater include mixing the water with (1) the Zeeland Raw water supply and (2) directly into one of the Lephalale reservoirs. Both options seems feasible, however for both options fluoride concentrations will not decreased to drinking water standards as a result of mixing and would have to be removed before blended with the existing water supplies.

Iron-hydroxide and calcite precipitation is expected, however this will not occur indefinitely, but only until the precipitate and elements in solution is in equilibrium.

### ***AR in the Waterberg aquifer***

The Waterberg fractured aquifer groundwater quality has elevated NaCl (sodium-chloride) and very high levels of F (fluoride), with very low levels of heavy metals and microbiological constituents. The sources of artificial recharge water have elevated heavy metals (aluminium, iron and manganese) and very high concentrations of micro-organisms. Blending the different water sources in a reservoir or in the aquifer can better overall water quality of the available water supply.

However, since artificial recharge should never worsen an aquifer's water quality the source water will have to be cleaned of microbiological contaminants before it is used for either injection or infiltration.

For the geochemical evaluation of the simulations Ratio 1 (10% *in situ* pore water to 90% source water) was considered most likely for a dewatered fractured rock aquifer.

Various options of artificial recharge exist that can be implemented for the Waterberg aquifer and include the following:

- Aquifer Storage Recovery – with the existing boreholes and new boreholes used as both abstraction and injection boreholes. Only treated river water should be used for injection into the aquifer. From the geochemical simulation some elements show an increase in concentration in the aquifer, but iron is the only one of real concern. However, after the 2<sup>nd</sup> ASR event iron concentrations flatten of to 0.6 mg/l, which is still within the good water quality range.
- Aquifer Storage Transfer & Recovery – with new boreholes at the outer rim of the cone of depression to increase yield of the aquifer, better water quality in the aquifer and mitigate the abstraction impact on other users. Water quality was not simulated for this scenario, since this scenario is similar to ASR and water quality changes are expected to be the same.
- Soil Aquifer Treatment – with settling and infiltration ponds for the treated effluent and storm water in the area of the existing storm water dam. Settling of suspended solids and most mineral precipitation will occur in the existing storm water dam and “clean” water will decant into an infiltration pond specifically designed for this purpose. Assuming that microbiological

contaminants is removed before infiltration occur into the Waterberg aquifer, elements that show an increase in concentration all stabilise and are within the ideal water quality range from the 2<sup>nd</sup> SAT event.

- Infiltration ponds – with holding dams and infiltration ponds for excess run of river in times of high rainfall. If only river water is used then similar water quality changes to that of the ASR scenario is expected. If the run of river infiltration ponds are combined with the SAT ponds in a 50:50 ratio the same elements show an increase in concentration when compared with the separate scenarios, however to lower levels of concentration and all are within the ideal water quality range for drinking water.

All the simulations show an *in situ* lowering of fluoride concentrations to below 6 mg/l and sodium/chloride to within ideal drinking water standards. Mixing this lower fluoride concentration into the reservoirs at Zeeland or Lephale now becomes a much more feasible option.

All the simulations of the different sources of water entering the Waterberg aquifer show kaolinite and calcite precipitation to be the main concern for clogging in the aquifer.

Iron-hydroxides ( $\text{Fe}(\text{OH})_3$ ) and kaolinite will precipitate in the surface storage dams for the treated effluent, storm water and excess run of river. For the combined scenario very little precipitation is expected after the initial precipitation of minerals in the storm water dam and holding pond.

### ***AR in the alluvial aquifer***

Various options of artificial recharge exist that can be implemented for the alluvial aquifer and include the following:

- Bank filtration – in the form of abstraction boreholes in the river alluvium to induce flow towards the alluvial aquifer.
- Infiltration ponds – as off-channel ponds to divert surface water to in times off excess. This facilitates the slower infiltration of water into the river alluvial and increase lag time of losses to the downstream river environment.

A direct link exists between the Mokolo River and the river alluvium, therefore the water quality is very similar. Apart from increased suspended solids that might clog infiltration ponds, no other water quality issues are expected for artificial recharge of the river alluvium.

The benefit in both these options is to increase retention time of excess river run off closer to Lephale, minimise losses of surface water to the downstream river environment and increase infiltration to the Waterberg aquifer, if the fractured rock aquifer is utilised and dewatered.

### ***Other***

The alluvial groundwater users north of the Eenzaamheid Fault will be impacted upon through abstraction from the Waterberg with reduction in surface water flow if this reduction cannot be supplemented by upstream releases from the Mokolo dam storage.

Fluoride remains a water quality constraint for the initial groundwater abstraction from the Waterberg aquifer. Treatment might not be required for industrial use; however, treatment is required for domestic use and would typically involve reverse osmosis.

All the sources of water have water quality constituents that remain a concern if AR is not implemented in the Lephale area. With AR, only one constituent (fluoride in the groundwater) is still considered problematic; however, fluoride levels will decrease with each AR event, regardless of the option implemented.

Based on the available source water volumes and water quality artificial recharge is a feasible option to explore further for water storage and conservation and demand management in the greater Lephale area.

## **6 IMPLEMENTATION RECOMMENDATIONS**

It is recommended that the Waterberg fractured rock aquifer be developed as part of an artificial recharge scheme, since geochemical changes due to mixing of aquifer and source water is expected to be minimal. AR will enhance water use efficiency in the Lephale area through re-use of water, bettering groundwater quality *in situ* or minimising evaporation from the available water sources. In this semi-arid region and with climate change becoming more apparent this is considered a non-negotiable option for long-term planning and optimisation of water use. For this area planning and implementing AR can be done in advance for the different phases to the greatest benefit for all.

All of the AR options listed are considered useful and feasibility and/or time of implementation would depend on the cost-benefit to the area. Further work needs to take place before AR can be implemented. The various phases for implementation is listed as follows:

### ***Phase 1 – creating storage in the aquifer***

It is of utmost importance that the various AR options are tested in the field before large scale implementation starts. For testing to occur, storage space will have to be created and the only way to do this is to develop the exploration boreholes as production boreholes and start utilising the Waterberg aquifer. However, some constraints to the use of this water exist and the following is recommended:

- Obtain a Water Use License for the large scale abstraction from the Department of Water Affairs;
- Blend the different sources of water, sample and test to verify the final water quality;
- Continue monitoring the Waterberg and alluvial aquifer for water quality and water level changes, with the data loggers currently in place, since available storage will need to be calculated before testing starts; and
- Distribute the pumped water as part of the industrial water use if water quality is suitable; or



- Construct a reverse osmosis (RO) plant specifically designed to filter out fluoride, after which it can be pumped to either the Zeeland reservoir or one of the Lephale reservoirs, depending on the level of fluoride in the discharge from the RO plant.

### ***Phase 2 – testing ASR scenario***

As soon as storage is sufficient start with small scale ASR testing to determine whether geochemical reactions are in the order of what was predicted with this study. If not, re-calibration of equilibrium phases and possibly testing of more Waterberg aquifer material is needed to refine the reactions occurring. The testing phase will have to consist of the following tasks:

- Treating source water to acceptable standards, especially with regard to suspended solids and microbiological constituents to reduce chances of clogging the aquifer;
- Injection tests at abstraction boreholes to determine hydraulic viability of injecting source water, as well as water quality of *in situ* mixed water;
- Monitoring water quality close to the infiltration areas of the Mokolo river;
- Re-do geochemical modelling for other options based on the injection test results;
- Testing of the other options is only feasible as soon as the water sources becomes available;
- Define treatment, engineering designs and environmental health risks based on the test results;
- Detailed costing of ASR and preliminary costing of the other AR options;
- Prioritise AR options based on cost-benefit.

### ***Phase 3 – implementing AR options***

If found feasible, the only option for implementation at this stage will be the Aquifer Storage Recovery (ASR) well-field. It is expected to be the most cost effective phase

to implement since some of the boreholes already exist and the testing phase would have defined all other issues. The other AR options are expected to follow in the following order:

1. Testing and implementation of the combined Soil Aquifer Treatment (SAT) and Infiltration ponds;
2. Testing the option of Bank filtration with drilling exploration boreholes based on the information from the GeoAfrica study;
3. Testing and implementing the Aquifer Storage Transport & Recovery (ASTR) option. This is expected to be one of the last options to be implemented since dedicated boreholes will have to be drilled for injection to the western and southern outer extent of the cone of depression;
4. Testing the option of Infiltration ponds in the alluvium along the Mokolo River to increase retention time of high flows at high rainfall periods. This option will only be deemed viable if environmental risks are proven to be acceptable to the river health and downstream environment. It can only be implemented after the information from the GeoAfrica study becomes available.

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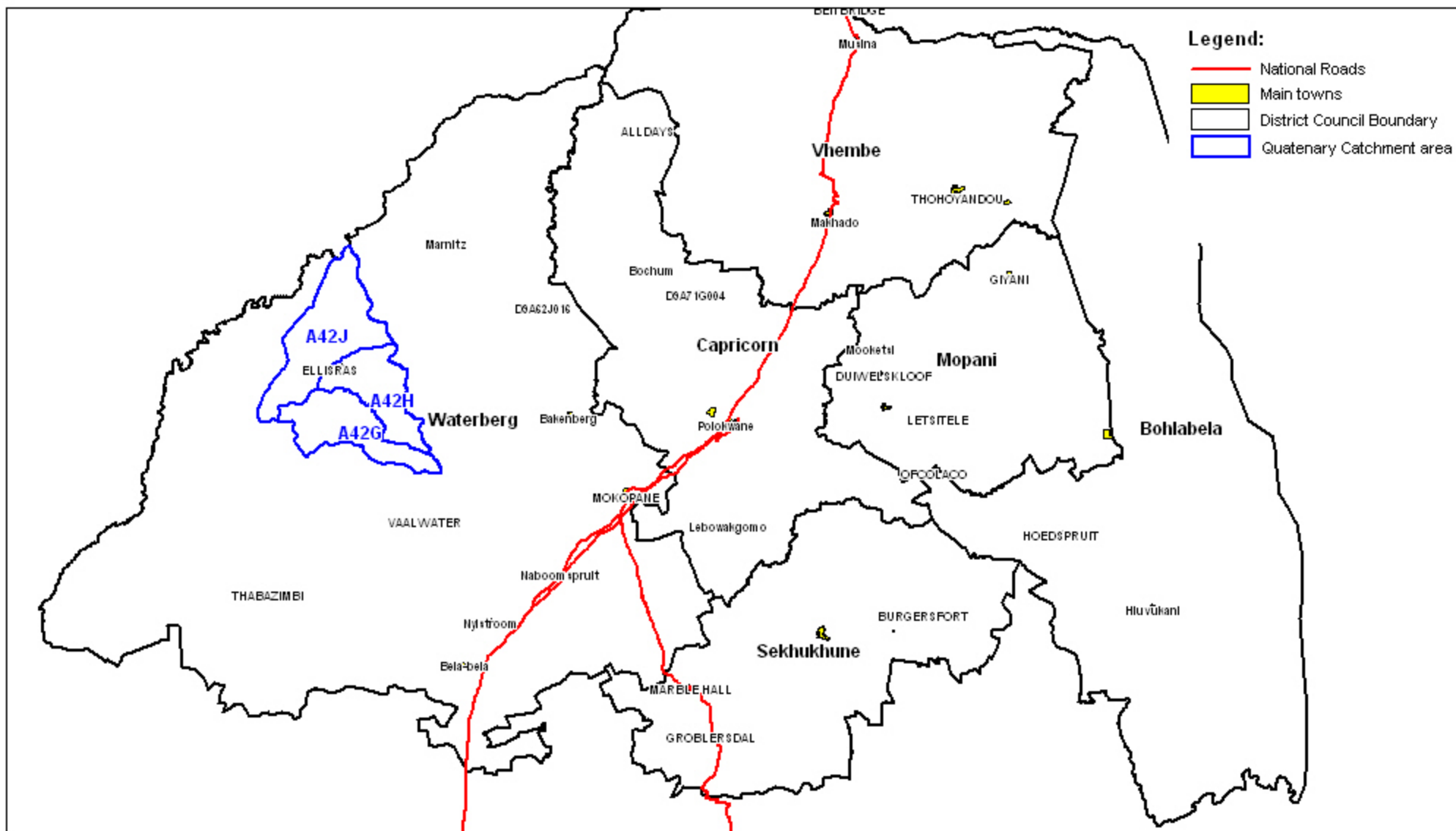
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## **Appendix A: Lephale Project Maps**

# Plan 1 : Locality Map



Scale 1 : 2,500,500  
Scanned Maps



## **Appendix B: Waterberg Sandstone Mineralogy**



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