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RESILIM : Resilience in the Limpopo River Basin Program

RESILIENCE IN THE LIMPOPO BASIN: THE POTENTIAL ROLE OF THE TRANSBOUNDARY RAMOTSWA AQUIFER

Hydrogeology report – Final draft 28th February 2017

Submitted by: IWMI International Water Management Institute and igrac International Groundwater Resources Assessment Centre

Implemented by: IWMI International Water Management Institute; CGIAR Research Program on Water, Land and Ecosystems

In partnership with: igrac International Groundwater Resources Assessment Centre; University of Botswana; Republic of Botswana; XRI BLUE; University of the Free State / Universiteit van die Vrystaat / Yunivesithi ya Freistata UFS UV; University of Pretoria; University of the Witwatersrand, Johannesburg

This report was made possible by the support of the American people through the United States Agency for International Development (USAID). Its contents are the sole responsibility of XRI operating as a subcontractor to Chemonics International, and do not necessarily reflect the views of USAID or the United States Government.

Authors

Yvan Altchenko (IWMI)
Andrew Genco (XRI Blue)
Kristen Pierce (XRI Blue)
Rachel Woolf (XRI Blue)
Geert-Jan Nijsten (IGRAC)
Nienke Ansems (IGRAC)
Manuel Magombeyi (IWMI)
Girma Ebrahim (IWMI)
Jonathan Lautze (IWMI)
Karen G. Villholth (IWMI)
Nicole Lefore (IWMI)
Reshoketswe Caroline Oudi Modisha (MSc student, University of the Witwatersrand)
Simamkele Baqa (MSc student, University of the Witwatersrand)
Bonnie McGill (PhD candidate, Michigan State University)
Piet Kenabatho (University of Botswana)

Preferred citation:

Altchenko Y., Genco A., Pierce K., Woolf R., Nijsten G.J., Ansems N., Magombeyi M., Ebrahim G., Lautze J., Villholth K., Lefore N., Modisha R. C. O., Baqa S., McGill B. and Kenabatho P. (2017) Resilience in the Limpopo basin: The potential role of the Transboundary Ramotswa aquifer, hydrogeology report.

Acknowledgements

The first phase of the *Resilience in the Limpopo Basin: The potential role of the transboundary Ramotswa Aquifer project* (referred to as the RAMOTSWA project) is funded by the Resilience in the Limpopo Basin (RESILIM) program[1] with co-funding from the CGIAR Research Program on Water, Land and Ecosystems (WLE),[2] the International Groundwater Resources Assessment Centre (IGRAC) and XRI. The first phase of the project ran from July 2015 to February 2017.[3]

XRI Blue submitted three reports:

- Hydrogeological Information for the Development of Subsurface Mapping for the Transboundary Ramotswa Aquifer, using Airborne Geophysics
- Conceptual Model, Hydraulic Properties, and Model Dataset Support Progress Report for the Development of Subsurface Mapping for the Transboundary Ramotswa Aquifer, that is part of the Limpopo River Basin, using Airborne Geophysics
- Completion Report for the Development of Subsurface Mapping for the Trans-Boundary Ramotswa Aquifer, that is part of the Limpopo River Basin, using Airborne Geophysics

Reshoketswe Caroline Oudi Modisha submitted her Msc Thesis, Investigation into the Ramotswa Transboundary Aquifer Area, groundwater flow and pollution (2017)

Simamkele Baqa submitted his Msc Thesis, Groundwater Recharge Assessment in the upper Limpopo River Basin: A case study in Ramotswa Dolomitic Aquifer (2017)

The authors would like to acknowledge the contributions, in no specific order, from the Department of Water and Sanitation (DWS) – South Africa, The Department of Water Affairs (DWA) - Botswana, the Council of Geoscience (CGS) – South Africa, the Botswana Geoscience Institute (BGI) – Botswana, the Water Utilities Corporation (WUC) - Botswana, the Ngaka Modiri Molema District Municipality (NMMDM) – South Africa and the Ramotshere Moiloa Local Municipality (RMLM) – South Africa.

[1] Chemonics as the contracting party for RESILIM, funded by USAID.
[2] led by the International Water Management Institute (IWMI)
[3] A proposal for a follow-up project (Ramotsa-2) with a 2 year duration has been submitted for funding under the US Global Development Lab.

Executive summary

As complementary report of the baseline report, this report focus on the hydrogeological assessment of the Ramotswa Transboundary Aquifer and covers only aspects related to the biophysical conditions of the aquifer which is a karstic dolomite aquifer straddling the international border between Botswana and South Africa. The assessment is based on existing data and field data collected (including Airborne Electro-Magnetic survey) during the period September 2015 – November 2016. The technical knowledge developed in the report will be used as based for developing tools for harmonized management and fostering cross-border dialogue in order to help building the joint Strategic Action Programme which will provide, not exclusively, guidelines for better monitoring and future assessment of the aquifer.

While groundwater represents less than 20% of the total domestic water use, rural population relies heavily on groundwater for most uses in the area. The Ramotswa Wellfield was decommissioned in 1996 because of nitrate pollution but in 2014, the Botswana authorities decided to re-open the Ramotswa wellfield again in response to water shortages in periods of prolonged drought.

Groundwater in the Ramotswa Dolomite is located in the part of the dolomite where karstification has occurred. That means that acidic rainfall naturally dissolved the dolomite, creating fracks, cavities and sinkholes. The Ramotswa Dolomite corresponds to five carbonate formations referred to as either “chert-free” or “chert-rich” dolomite, the latter being the most important water-bearing formation. The aquifer is compartmentalized by dikes which act as barriers for groundwater flow between the compartments. Thirteen (13) compartments has been delineated, four of them being identified as transboundary. The eastern extend of the Ramotswa dolomite remains still uncertain. Based on a limited amount of data, it may be tentatively concluded that groundwater flow in the study area follows topographic relief and drainage patterns in a north north-easterly direction. Groundwater flow in the area is also controlled by geological structures such as dikes and fault. However, groundwater interaction across or between the identified compartments is largely unknown and the main sources of uncertainty.

Groundwater recharge seems to occur mainly through direct rainfall infiltration, particularly in the north-eastern part of the study area, and through a mix of direct and diffused rainfall infiltration. That may indicate that recharge is driven by various processes such as localized recharge from surface runoff or direct rainfall recharge depending on the geology and/or the topography. It is also believed that the Ngotwane River could recharge groundwater through the riverbed when the river flows (rainy season). In the North and South of the study area, groundwater is mainly sub-modern water while the central part of study area is recent recharge with a mix of sub-modern and modern water. In fact, recharge is highly influenced by the rainfall pattern in the study area. Extreme weather condition (drought or flood) might occur more regularly in the region but the impact of these changes on groundwater recharge is still unknown. Recharge estimates from field work indicate an average annual recharge value of 76 mm/year but Previous study estimated average recharge value of 18 mm/year. The difference can be explained by high uncertainty on the method used for estimating the recharge.

Groundwater discharge can also occur naturally through springs which seem located closely to the occurrence of the (impermeable) dikes and found on the ‘upstream’ side of the dikes. Groundwater can also probably discharge into the river (baseflow) when the water table starts

to be higher than the river-water surface or the riverbed. Groundwater could work as river flow buffer when rain stops even if the river is non-perennial. Other groundwater discharge is artificial discharge from groundwater abstraction.

Locally, groundwater has been contaminated by human activities with nitrate and coliform. This is due to contamination from pit latrines and agricultural activities (i.e. livestock excreta). Available data are very limited and not available for all settlements. Settlements most severely affected by nitrate pollution are Ramotswa (Botswana) and Supingstad (South Africa). One site with *E. Coli* contamination (Radikkudu village, South Africa) is particularly worrying as water from the borehole is directly used by the community without appropriate disinfection. Rapid action is recommended. While groundwater from the Ramotswa Wellfield is used for domestic purposes, groundwater does not satisfy drinking water standards for nitrate. WUC mixes water from the affected wells with water from other sources to obtain acceptable concentrations.

Based on the knowledge developed in the report, several recommendations are done:

- Developing the monitoring but also harmonising the data across the countries to build and share the database for better groundwater management.
  There is a need to rehabilitate existing boreholes and to install new exploration or monitoring boreholes in order to develop the monitoring network in the aquifer area. Because groundwater quality and water level monitoring depends also on the quality of collected data based on appropriate methodology and regular data collection, it is recommended to somehow harmonise methodology and data through active cooperation and dialogue between the two countries.

- Improving knowledge about the aquifer mechanisms and structure.
  Further surface geophysics data should be collected especially in areas where the airborne survey could not collect the data and where complex geologic structure (collapse features, dikes, and faults) was located. In complement, additional borehole geophysics should be done to better understand the aquifer and to improve the calculation done for the aquifer properties. In addition, the surface geology discrepancies should be examined to determine the need to update the mapped geologic units. Finally, more investigation is necessary to better understand the surface water and groundwater interactions as data did not allow to confirm the probable interactions

- Protecting groundwater from contamination through land use planning
  Protective areas should be identified to prevent groundwater contamination and land-use management policies and specific associated control measures need to be introduced to promote groundwater recharge quality protection at local scale.

- Developing engagement of stakeholders at multi-scale and multi-level.

- Using the aquifer for improving water security by investigating Managed Aquifer Recharge potential of the Ramotswa Transboundary Aquifer.

Contents

ACRONYMS

AEM	Airborne Electro-Magnetic
CGS	Council of Geoscience (South Africa)
CMB	Chloride Mass Balance
DWA	Department of Water Affairs (Botswana)
DWS	Department of Water and Sanitation (South Africa)
BGI	Botswana Geoscience Institute (formerly known as Department of Geological Survey – DGS)
IGRAC	International Groundwater Resources Assessment Centre
IWMI	International Water Management Institute
NMMDM	Ngaka Modiri Molema District Municipality (South Africa)
NGA	National Groundwater Archive (South Africa)
RESILIM	Resilience in the Limpopo Basin program
RIMS	Ramotswa Information Management System
RMLM	Ramotshere Moiloa Local Municipality (South Africa)
RTBAA	Ramotswa Transboundary Aquifer Area
SADC	Southern African Development Community
SAP	Strategic Action Programme
SAWS	South Africa Weather Services
USAID	United States Agency for International Development
WLE	Water, Land and Ecosystems
WUC	Water Utilities Corporation (Botswana)

1. Introduction and background

1.1. Project objectives

The overall objective of the RAMOTSWA project is to support a long-term joint vision and cooperation on the shared groundwater resources of the Upper Limpopo region, where Botswana and South Africa share significant and valuable underground freshwater resources, and an aquifer with the potential for enhanced subsurface water storage. The project facilitates and promotes joint management and better groundwater governance focused on coordination, scientific knowledge, social redress and environmental sustainability, in order to reduce poverty and inequity, increase prosperity, and improve livelihoods and water and food security in the face of climate change and variability.

The specific objectives of phase 1 of the RAMOTSWA project are as follows:

1) Increase awareness of the importance and vulnerability of the transboundary Ramotswa Aquifer.
2) Improve understanding of the socioeconomic importance of the aquifer area, and the inequalities in water access and security across the population.
3) Improve understanding of the extent and hydrogeology of the transboundary aquifer resources under present and future climate and population projections.
4) Establish national and cross-border dialogue and cooperation on the Ramotswa Aquifer, and further encourage international cooperation on transboundary aquifers in the Southern African Development Community (SADC) region.
5) Develop tools for shared and harmonized management and monitoring of groundwater resources, aligned with the national water resources management processes.
6) Develop human and institutional capacity for shared and harmonized management and monitoring of groundwater resources.

Through multilevel diplomacy, the project will contribute to the building of trust and transparency in the development and use of groundwater resources in the border region, and it will encourage the states to enter into agreements on their shared aquifer(s).

1.2. Report objectives

This report presents the hydrogeological assessment of the Ramotswa Transboundary Aquifer which is a karstic dolomite aquifer straddling the international border between Botswana and South Africa (figure 1 and 2). The assessment is based on existing data and field data collected during the period September 2015 – November 2016. The report is complementary to the baseline report (Altchenko et al., 2016) and presents more in depth the hydrogeology of the Ramotswa Transboundary Aquifer. The hydrogeological report covers only aspects related to the biophysical conditions of the Ramotswa Transboundary Aquifer Area (RTBAA). It presents the surface and sub-surface geology and the hydrogeological characteristics of the aquifer including climatic conditions, groundwater flow pattern and groundwater quality. It also gives recommendations on improving knowledge and management of the aquifer.

Ultimately, the technical knowledge developed in the report will be used as based for developing tools for harmonized management and fostering cross-border dialogue in order to help building the joint Strategic Action Programme (SAP) which will be the document delivered to the countries to go forward on the surface and underground water management in RTBAA by providing, not exclusively, guidelines for better monitoring and future assessment of the aquifer.

> Results from the RAMOTSWA project are also available in the on-line Ramotswa Information Management System (RIMS) accessible via: http://ramotswa.un-igrac.org Most maps presented in this report are also available in the RIMS, which also contains additional resources.

1.3. Aquifer background

The dolomite aquifer of the RTBAA covers a small area (outcrop area is approximately 194 km^2) of Botswana and South Africa (Figure 1 and 2). It is located in the Upper Limpopo River Basin, mostly in the Ngotwane sub-catchment and partly in the Marico sub-catchment. The topography is fairly hilly, which is typical for southeast Botswana. The altitude of the plains ranges from 1,000 to 1,050 meters (m) above sea level (masl), whereas the altitude of the surrounding hills can reach 1,676 masl (Figure 3). The climate of RTBAA is semiarid. Rainfall is strongly seasonal, with most of it occurring as thunderstorms during the summer period between October and April. Mean annual rainfall ranges geographically from 450 to 600 mm and decreases from the eastern to the western side of RTBAA. Mean annual temperature ranges between 18 and 20 °C in the area. Maximum and minimum temperatures are experienced in January and July, respectively. Climate projections foresee not only uncertain trends in rainfall volumes in the future, but a likely increase in intensity of rainfall events (Taylor et al. 2009). Floods are recurrent, including flooding of sensitive infrastructure like the Ramotswa wellfield and some water treatment plants. A major flood occurred in South Africa in early 2009.

Groundwater in the Ramotswa Dolomite is located in the part of the dolomite where karstification has occurred. Dolomite formations initially have very poor aquifer characteristics as the primary porosity is low. Karstification, or dissolution of the dolomite rocks by infiltrating acidic rain water, results in cavities in the dolomite which allow storage and flow of groundwater, and subsequently give the dolomite formation its aquifer characteristics. The aquifer is thought to be compartmentalized by intrusive dikes which may create physical barriers which limit groundwater flow between compartments. Currently, there still is uncertainty in the existence and exact location of the compartments, the interactions between the compartments and the exact extent of the aquifer. While groundwater represents less than 20% of the total domestic water use, RTBAA relies heavily on groundwater for most uses, with some irrigation schemes presently using larger shares of the water. Groundwater is mainly used for domestic and agricultural purposes (both crops and livestock). In particular, the rural population is highly depending on groundwater. Inside the RTBAA, 82% of the population on the South African side lives in rural areas while in the Botswana part of the RTBAA only 9% of the population lives in rural villages. In Botswana, there are four wellfields mainly serving domestic and industrial water use: Ramotswa Wellfield, Lobatse Wellfield, Pitsenyane Wellfield and Wooldland Wellfield. Water supply services in RTBAA can be erratic /

discontinuous, even for households and industries connected to the main water distribution systems. This is particularly true during (prolonged) periods of drought. In addition to technical issues such as the lack of maintenance of some boreholes (especially in South Africa), there are periods of water rationing in Botswana because of limited water availability and some instances of borehole failure because of significant water depletion during drought conditions. Despite this precarious situation, there is currently no evidence of conflicts between the two states over the shared groundwater in the RTBAA. To the contrary: There are water transfers from Molatedi dam in South Africa into Botswana to provide additional water for the water supply of the Gaborone area.

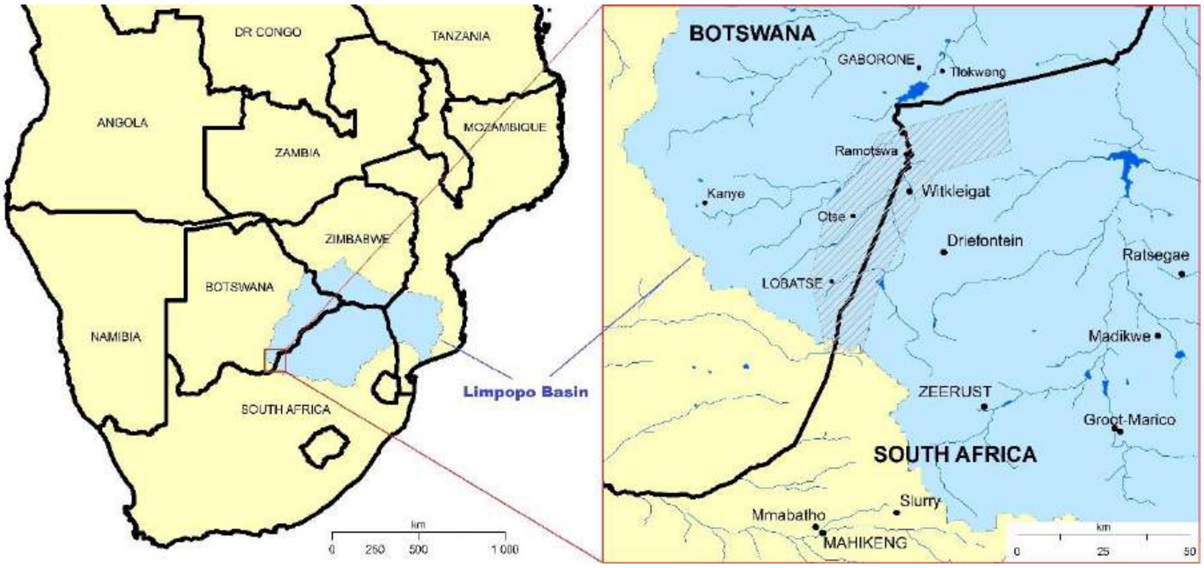

Figure 1: Location of study area within the Limpopo River Basin.

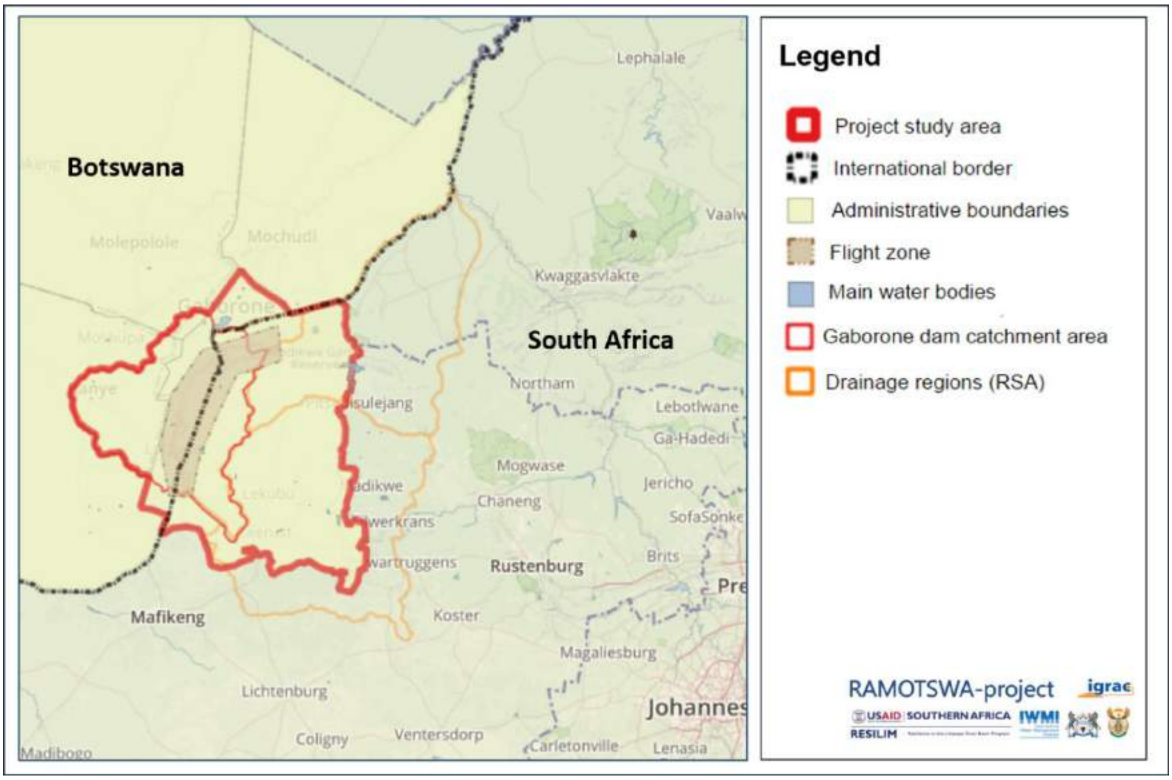

Figure 2: Project study area and flight zone for airborne geophysics. The latter is the focus area for this hydrogeology report. The project study area is defined by the outer boundaries of the Gaborone dam catchment, the administrative boundaries of the South-East district (Botswana) and the Ramotshere Moiloa Municipality (South Africa).

Source: RIMS

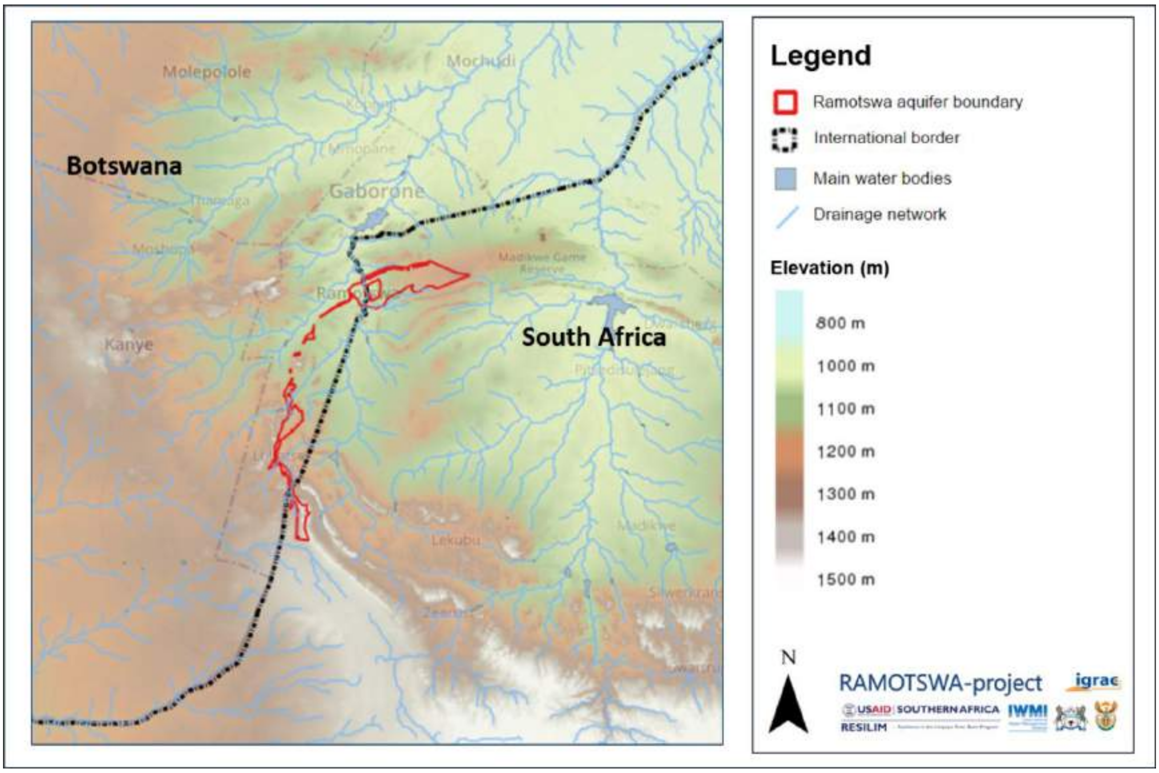

Figure 3: Surface elevation (in meters above sea level).

Source: RIMS

There are instances of contamination of groundwater from by human activities. The most severe groundwater pollution is from high nitrate concentrations in several boreholes, in particular in the Ramotswa wellfield. This pollution is from the continued use of pit latrines, especially at sites where waste may (almost) directly enter the shallow aquifer. Very high nitrate concentration has been found in boreholes in the settlement of Ramotswa. Contamination from pit latrines is less prominent in other settlements in Botswana, for example the town of Lobatse. Groundwater pollution on the South African side in unknown as little or no data is available on groundwater quality.

Despite the groundwater from Ramotswa Wellfield having nitrate concentrations in excess of drinking water standards, it is used for domestic purposes including drinking purposes. Due to this nitrate contamination, the Ramotswa Wellfield was decommissioned in 1996 (Ranganai et al. 2001). Nitrate contamination was expected to decrease after the construction of the Ramotswa wastewater treatment plant in 2001 but recent water quality data from the Ramotswa Wellfield do not show a significant decrease in nitrate concentration. In 2014 the Botswana authorities decided to re-open the Ramotswa wellfield again in response to water shortages in periods of prolonged drought. Groundwater from the wellfield is mixed with water from other surface sources to reduce the nitrate levels to acceptable drinking water standards prior to normal portable water treatment.

2. Methodology

2.1. Aquifer and study area location

In terms of the hydrogeology assessment, the focus is on a buffer zone around the aquifer as delineated on the map of transboundary aquifers of the world (IGRAC, 2012). This delineation is based on the outcrops of the aquifer formation and the international border, using 5 km as the minimum distance from the outcrop or the international border. The buffer zone was used because the exact extent of the aquifer is unknown and 5 km was presumed to accommodate potential lateral extension of the aquifer underground. Figure 2 shows the study area which corresponds to the flying area of the Airborne Electro-Magnetic (AEM) survey. The aquifer formations are dipping to roughly the East which means that the dolomite formations continue eastwards into South Africa. The dolomite aquifers in the area are thought to be compartmentalised by dikes (vertical volcanic structures) that crisscross the dolomite formations and which are thought to act as impermeable / less permeable barriers which limit groundwater flow between compartments. To limit the study area, a natural cut-off of the transboundary part of the system has been chosen based on these dolerite dikes (not shown in Figure 2).

2.2.Data sources

The report is based on existing data and literature with a focus on Botswana and South Africa, on the study areas and on data collected during the time of the project through AEM survey and field work.

Existing hydrogeological data were provided inter alia by the Department of Water Affairs (DWA) (Botswana), Department of Water and Sanitation (DWS) (South Africa), Council of Geosciences (CGS) (South Africa), Botswana Geoscience Institute (BGI) and the South African Weather Service (SAWS). Data have been extracted from reports and databases, including online self-requests to freely available datasets such as HYDSTRA[4] or the National Groundwater Archive (NGA)[5] both managed by the DWS.

AEM data was collected for the Ramotswa Project Area from February 12, 2016 to February 24, 2016 over the course of 18 production flight resulting in 53 production lines (Figure 4). AEM data were acquired using the SkyTEM 508 airborne electromagnetic system (SkyTem Airborne Surveys Worldwide, 2012). The SkyTEM 508 is a rigid frame, dual-magnetic moment (Low and High) transient airborne electromagnetic ("TEM") system. A total of 1,658.9 kilometres (km) of AEM data were collected during the survey (Figure 4). Open areas in Figure 4 were not covered by the flight as they are built-up areas which are unsuitable to be surveyed using the AEM (i.e. towns or natural reserves).

[4] HYDSTRA is an application containing data on surface water, groundwater and rainfall.
[5] NGA is a web enabled database system that allows capturing, viewing, modifying and extraction (dissemination) of groundwater related data.

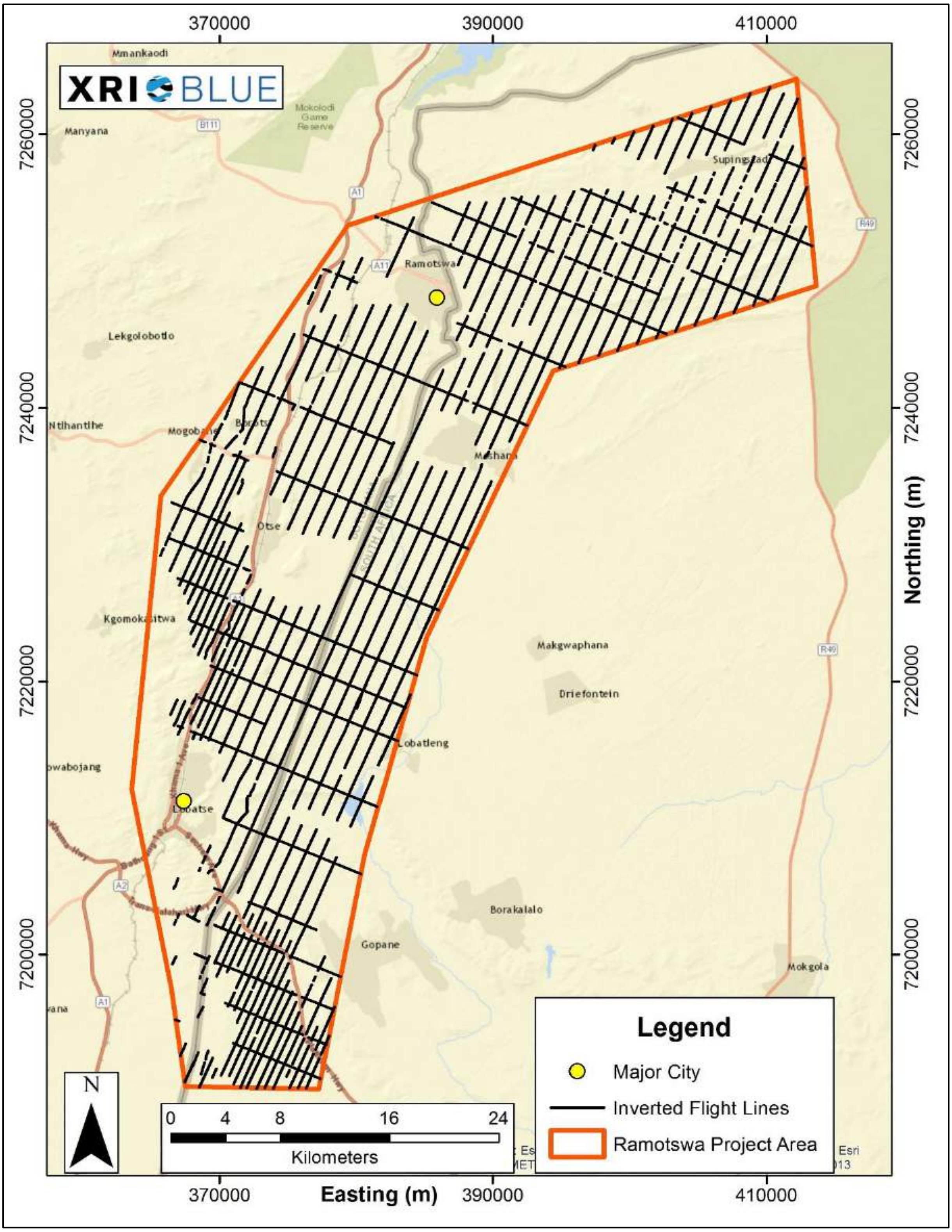

Figure 4 Inverted flight lines within the Ramotswa Project Area.
Source: XRI Blue

Fieldwork was conducted from the 25th – 29th of August 2016 and from the 1st - 5th of September 2016 in both South Africa and Botswana respectively. A total of 36 groundwater levels and samples were collected from municipal wells (both monitoring and water supply wells), private (household) boreholes, dug wells and from springs. Water analysis for chemicals and microbiology have been mainly done by DWS and WUC for the samples collected in each respective country. Aspirata (Centurion, South Africa) did also chemicals and microbiology analysis for one specific day. Isotope analysis (tritium and stable isotopes) were carry out at the University of the Witwatersrand (South Africa). In addition, a total of 65 soil samples from five sampling sites were collected with a hand bucket auger to varying maximum sampling depths depending on the subsurface soil/rock material hardness. Sampling depth varied from 1m to 2.5m depth. These soil samples were collected for chloride profiling, soil grain analysis and for moisture analysis with an objective to develop a conceptual understanding on the factors governing recharge mechanism with the study area. Also, a falling head (infiltration) test was conducted with a double ring infiltrometer in each of the five soil sampling sites to gain insights into the hydrological functioning of the study area.

3. Geology

This section describes the geology and aquifer characteristics in the study area. It is mainly adapted from the report on Hydrogeological Information for the Development of Subsurface Mapping for the Transboundary Ramotswa Aquifer, using Airborne Geophysics (XRI 2016), which is based on a literature review and available data from boreholes at the time of this report.

3.1. General geology of the Limpopo Basin

The Limpopo River Basin is a large and complex geologic area that extends into Botswana, Mozambique, South Africa, and Zimbabwe. Within the Limpopo River Basin, three Archean cratons are present: the Zimbabwe Craton, the Kaapvaal Craton (Figure 5) and the Limpopo Belt in between the two other cratons (not shown on Figure 5).

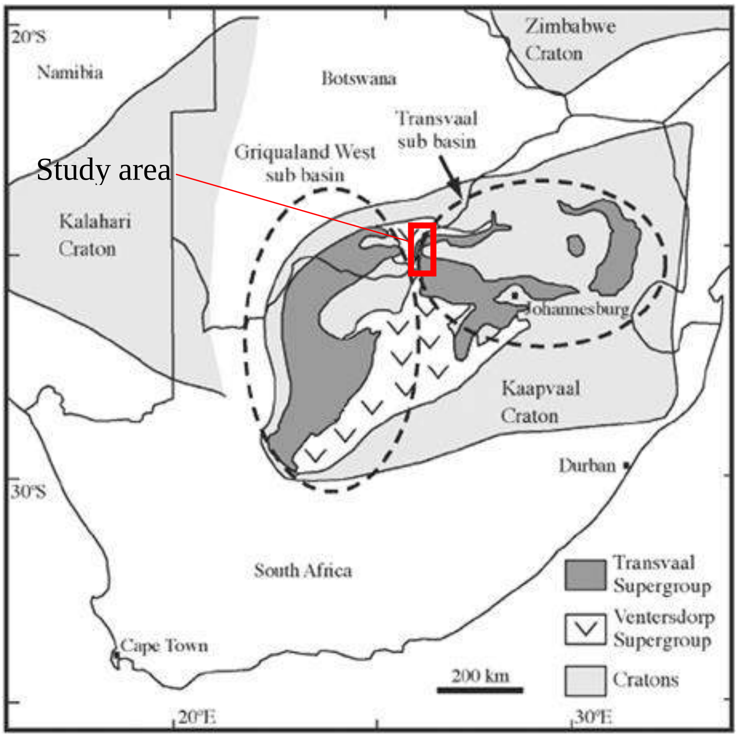

Figure 5. The Transvaal Supergroup inside the Kaapvaal Craton (Schröder et al. 2006).

The entire Limpopo Belt is characterized by a distinctive deformational and metamorphic style which contrasts markedly from that of the adjacent Kaapvaal and Zimbabwe Cratons. This distinctive pattern developed during the Limpopo Orogeny (from ~ 2,700 Ga to ~ 2.65 Ga ago) is probably a consequence of continental collision during the late Archaean between an Atlantic-type margin development on the southern boundary of the Zimbabwe Craton and on an Andean-type boundary on the Kaapvaal Craton (Van Reenen et al 1992; Burke et al. 1985). Thus, the suturing of the Kaapvaal and the Zimbabwe Cratons generated periods of regional compression (Clendenin et al. 1988) characterised by east-northeast trending line of sheared rocks such as amphibolitic and peridotitic gneisses related to riebeckite gneisses and granulitest (Dewey and Burke, 1973). Simple tectonic style (extensional or compressional stress dominates) influenced numerous Early Proterozoic successor basins on the Kaapvaal Craton and is due to stress fields through Transvaal sea time (Clendenin, 1989).

The study area is within the Kaapvaal Craton. The saucer shaped Kaapvaal basin in which the Chuniespoort Group accumulates is a result of thermal subsidence (Clendenin et al. 1988; Clendenin, 1989). The shallower geology is made up of three lithological supergroups deposited onto the Kaapvaal Craton in different sedimentation cycles. The supergroups (Key 1980, 1983; Carney et al. 1994; Thomas et al. 1994) in order of deposition, are:

- The *Ventersdorp Supergroup* (South Africa), also called Lobatse Group (Botswana) is composed of well-preserved and hardly deformed volcano-sedimentary rocks (Van der Westhuizen et al. 1991). This supergroup is expected to underlie the majority of the study area, with possible outcrops in the north and east.
- The *Transvaal Supergroup* contains three sequences (Cheyney 1996). The three sequences are preserved and exposed in two areas, the Transvaal Basin and the Griqualand Basin, which are separated by the Vryburg arc (Moore et al. 2001). The

Transvaal Supergroup is one of the world's earliest carbonate platforms (Beukes 1987), and is made up of carbonates, iron-formations, and minor silica-clastics (Meyer 2014). The Ramotswa aquifer is part of the Transvaal Supergroup.

- The *Waterberg Supergroup* consists of twelve (12) formations of reddish-brown ferruginous sandstones, shales, siltstones, and conglomerates (Chaoka 1988). While evidence pertaining to the Waterberg Supergroup is outside of the study area, its deposits are known to exist in the study.

The Ventersdorp Supergroup sedimentary and volcanic rocks were deposited first in an intricate rift system about 2.64 Ga in the north to northeast trending grabens from the collision of the two Cratons (Burke et al. 1985). The rocks of the Transvaal Supergroup were deposited on the Venterdorp Supergroup in one sedimentary basin that extended into Botswana (Dietvorst, 1988). They are strongly faulted by steep normal faults with bedding planes dipping east towards the basin centre (Crockett, 1972). This 15000 m Transvaal sequence of about 2.55 to 2.05 Ga is relatively undeformed and of low grade metamorphosed clastic, sedimentary and volcanic rocks (Eriksson et al.1993). Faulting followed by regional folding in an easterly to east-northeasterly plunging axes is evident in the villages of Ramotswa and Lobatse and refolding about south-southeasterly axes resulted in basement updoming and block faulting of the underlying supracrustal rocks (Dietvorst, 1988). Tectonic activity had ended before Waterberg sediments were deposited.

3.2.Study area geology

The Ramotswa Aquifer is within the western part of the Transvaal Supergroup which includes one of the world's most well preserved stromatolites, earliest and unique carbonate platform sequences (Beukes, 1987). The three sequences of the Transvaal Supergroup include, in stratigraphic succession from the oldest to the youngest (Moore et al. 2001).

- The *Chuniespoort Group* is typified by basal quartz arenites, thick dolomite, and iron formations. The Ramotswa aquifer is part of the Chuniespoort Group
- The *Pretoria Group* is typified by alternating mudrocks and sandstones, with volcanic horizons, diamictites, and conglomerates.
- The *Rooiberg Group* is composed of volcanics, mudrocks, sandstones, and felsites.

The Black Reef Quartzite (which is the base of the Chuniespoort Group) is ubiquitous at the bottom of these sequences within the Transvaal Supergroup. It represents a combined phase of both tectonic and thermal subsidence (Clendenin, 1988). There are ripple marks in the Black Reef Quartzite indicative of currents moving northeast to southwest (Key, 1983).

The Chuniespoort, Pretoria and Rooiberg Groups were intruded by the Bushveld Complex around 2.06 Ga with several mafic sills and dikes (Walraven, 1990). The carbonates in the Transvaal basin have been affected to a limited extent by the metamorphism as a result of the intrusion of the Bushveld Complex (Button, 1986). The Bushveld Complex intrusion produced classical contact metamorphism lithologies by forming hornfels in fine siliciclastic rocks (Martini et al. 1995).

Within the study area, there are two water bearing formations (aquifers): one within the Pretoria Group and one within the Chuniespoort Group. The Malmani Subgroup within the Chuniespoort Group is the major water-bearing unit for the area (Meyer 2014) and is what we refer to as the Ramotswa aquifer in this study. Table 1 includes a simplified stratigraphic column for the Pretoria and Chuniespoort Groups. The naming convention of the geologic formations of the Pretoria and Chuniespoort Groups used in this report is primarily consistent with names used in existing South African publications. Tables 1 and 2 correlate corresponding geologic formation names used in Botswana when applicable.

Table 1: Simplified stratigraphic column of the Chuniespoort Group which compose the Ramotswa Aquifer and the Pretoria Group.. The naming conventions are consistent with South African geologic mapping and reports with alternate Botswana naming conventions listed in bold, when applicable. The formations with aquifer properties in the study area appear in grey.

<table>
<tr><th>Age (Ga)</th><th>Thickness (m)</th><th>Supergroup</th><th>Group</th><th colspan="2">Formation</th><th>Lithology</th></tr>
<tr><td></td><td>~450-1500</td><td rowspan="10">Transvaal</td><td rowspan="2">Pretoria (Segwagwa)</td><td>Timeball Hill</td><td rowspan="2">(Lephala Formation)</td><td>Mudrock (including shale), quartzite</td></tr>
<tr><td>~2.72-2.05</td><td>10-150</td><td>Rooihoogte</td><td>Quartzite, mudrock, Bevets conglomerate /breccia member</td></tr>
<tr><td></td><td></td><td rowspan="8">Chuniespoort (Taupone)</td><td colspan="2">Duitschland</td><td>Carbonaceous mudrocks, limestone and dolomite</td></tr>
<tr><td>2.5</td><td></td><td colspan="2">Penge (Ramotswa Formation)</td><td>Banded ironstone</td></tr>
<tr><td rowspan="5">2.64 - 2.5</td><td>~400</td><td rowspan="5">Malmani Subgroup (Ramotswa Dolomite)</td><td>Frisco</td><td>Chert-free dolomite</td></tr>
<tr><td>~600</td><td>Eccles</td><td>Dolomite and chert</td></tr>
<tr><td>100-200</td><td>Littleton</td><td>Chert-poor dolomite</td></tr>
<tr><td>300-500</td><td>Monte Christo</td><td>Chert-rich dolomite</td></tr>
<tr><td>10-200</td><td>Oaktree</td><td>Chert-free dolomite</td></tr>
<tr><td></td><td>25-30</td><td colspan="2">Black Reef</td><td>Quartzite, conglomerate and shale</td></tr>
</table>

Table 2: Simplified explanation of the geologic formations composing the Ramotswa Aquifer.

Group	Geologic formations of the Ramotswa Aquifer				
	Lithologic description of formation	South Africa naming convention	Botswana naming convention	Ramotswa aquifer classification	Name of aquifer
Pretoria	Carbonaceous shale and quartzite	Lower Timeball Hill Formation and Upper Rooihoogte Formation	Lephala Formation	Shale portion	Lephala Aquifer
Chuniespoort	Dolomite with varying chert content	Malmani Subgroup	Ramotswa Dolomite	Dolomitic portion	Ramotswa (Dolomite) Aquifer

The main water-bearing unit of the Ramotswa Aquifer corresponds to the Malmani Subgroup (Chuniespoort Group) which is the dolomitic part of the Ramotswa Aquifer, called the Ramotswa Dolomite Aquifer (Tables 1 and 2). The mudrocks, dolomites and interbedded cherts that comprise of the Malmani Subgroup signify epeiric marine deposits deposited over a great portion of the Kaapvaal craton (Eriksson et al. 1993). The sedimentary sequence preserved in the rock record was developed by the north-northeast ward transgressions (Eriksson et al. 1993; Clendenin, 1989). Eriksson and Truswell, (1974) considers the dolomitization of the principal limestone to have taken place quickly after deposition and the dolomitization is related to the pH of meteoric waters. Dolomite is used to describe the sedimentary carbonate rock which is composed, predominantly, of the mineral dolomite, a calcium-magnesium carbonate.

The Malmani subgroup (Ramotswa Dolomite) is a succession of five carbonate formations, which all contain dolomite and are divided based on chert-content, the variety, absence, or presence of stromatolite structures, intercalated shales, and erosional surfaces as described in Table 1 (Button 1973; Eriksson and Truswell 1974; Eriksson et al. 2006; Obbes 2000). Chert refers here to a very hard and resistant microcrystalline variety of quartz while stromatolite structures are carbonate fossil constructions of biological origin (cyanobacteria or blue algae). Both chert and stromatolite structures are extremely resistant to weathering and remain in the soil that forms from the weathering of dolomite. A simplification of the geologic description of the five formations results in being referred to as either "chert-free" or "chert-rich" dolomite.

The Malmani subgroup is up to 2000 m thick and begins above the Black Reef Formation with the chert-poor Oaktree Formation. Overlying the Oaktree Formation is a 300 – 500m Monte Christo Formation which starts with an erosive breccia and continues with chert-rich dolomite platforms with stromatolites (Eriksson et al. 2006). Following the Monte Christo Formation is the 100-200m Lyttelton Formation of dolomites that are chert-poor and followed by about 600m thick Eccles Formation of stromatolitic dolomites that are chert-rich (Eriksson et al. 2006). The Frisco Formation forms the last of the Malmani Subgroup overlying the Eccles Formation which is chert-poor and becomes shale rich towards the top (Eriksson et al. 2006).

The Malmani subgroup has been intruded by three vertical to near vertical dolerite dike swarms, which are large geological structures consisting of a major group of parallel, linear, or radially oriented dikes. The dike swarms correspond to mafic subvolcanic intrusions, with low permeability that may act as barriers to groundwater flow (Meyer, 2014). Dolerite is also called diabase or micro-gabbro. These dike groups were recognized by Day (1980a, b) and strike North-South, North-North-West and East-West, depending on the age of the dike.

Another water-bearing unit of the Transvaal supergroup is the formation called Lephala Formation in Botswana. In this report, this formation refers to the lower part of Timeball Hill Formation and the upper part of the Rooihoogte Formation of the Pretoria Group (Eriksson et al. 1995) but other reference indicates that the Lephala Formation refers only to the Rooihoogte Formation (Carney et al. 1994). This formation is generally mentioned as the shale part of the Ramotswa Aquifer, and it will be called the "Lephala Aquifer" (Tables 1 and 2). In the southern portion of the study area, the Timeball Hill formation (Pretoria Group) overlays the Chuniespoort (Meyer, 2014). The discordantly overlying (and older) Timeball Hill Formation is composed of a coarsening upward carbonaceous shale – hematite oolite-bearing quartzite unit overlain by a second carbonaceous shale, capped by a second glacial diamictite (the well-known Rietfonteindam diamictite) (Coetzee, 2001). The Lephala Aquifer is not the main focus of the study because it is not the main water-bearing unit in the study area.

Figure 6 presents the surface geology within the study area, based on the 1/25000 digitalized map of Botswana and South Africa and the AEM survey. The dolomite outcrops are highlighted in blue on this map. For information, Figure 7 shows some of the discrepancies observed between the digitalized maps and the AEM interpretation in part of the study area. More work is needed to understand these discrepancies in order to develop a harmonized surface geology map of the study area for better understanding of the relationship between surface geology and groundwater.

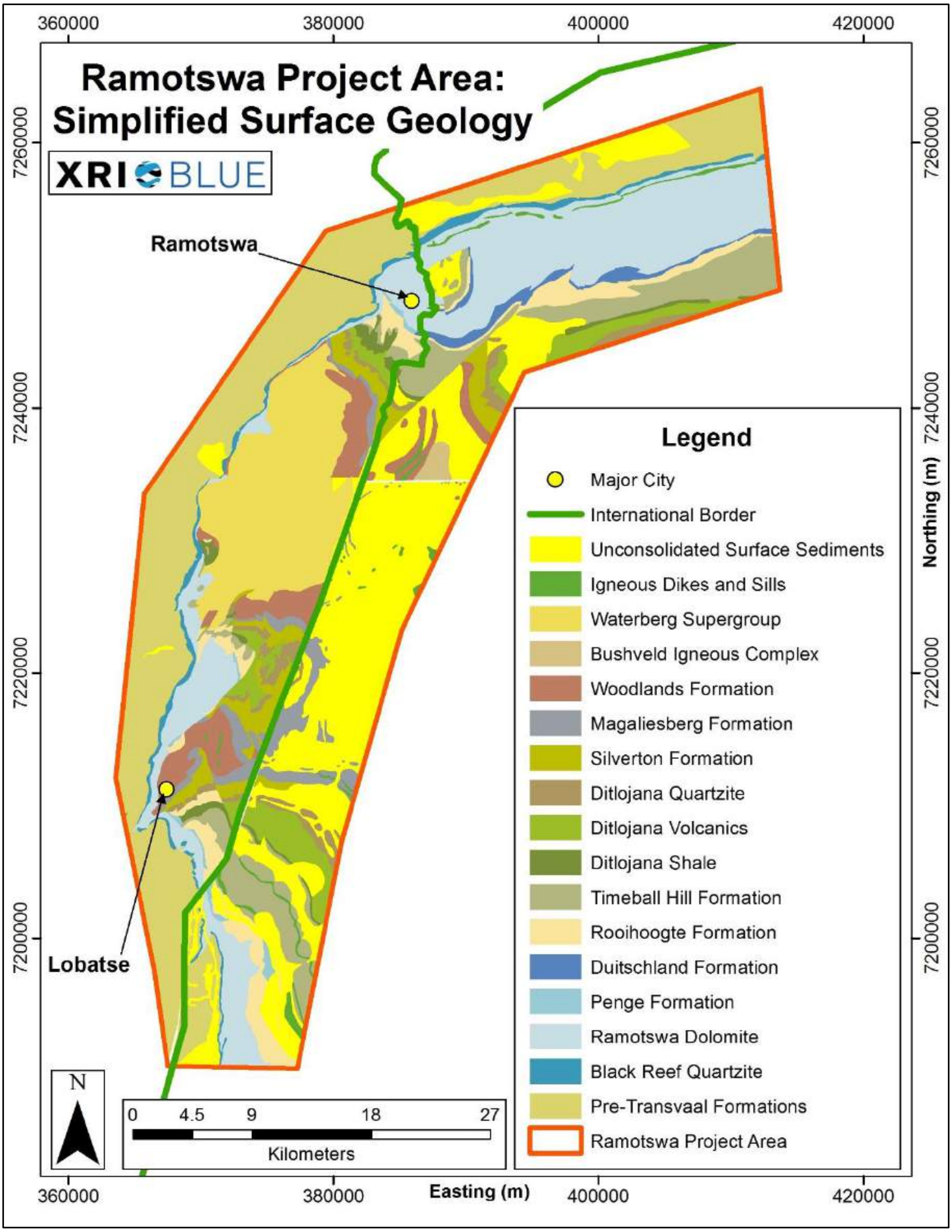

Figure 6: Detailed surface geology of the study area.
Source: XRI Blue

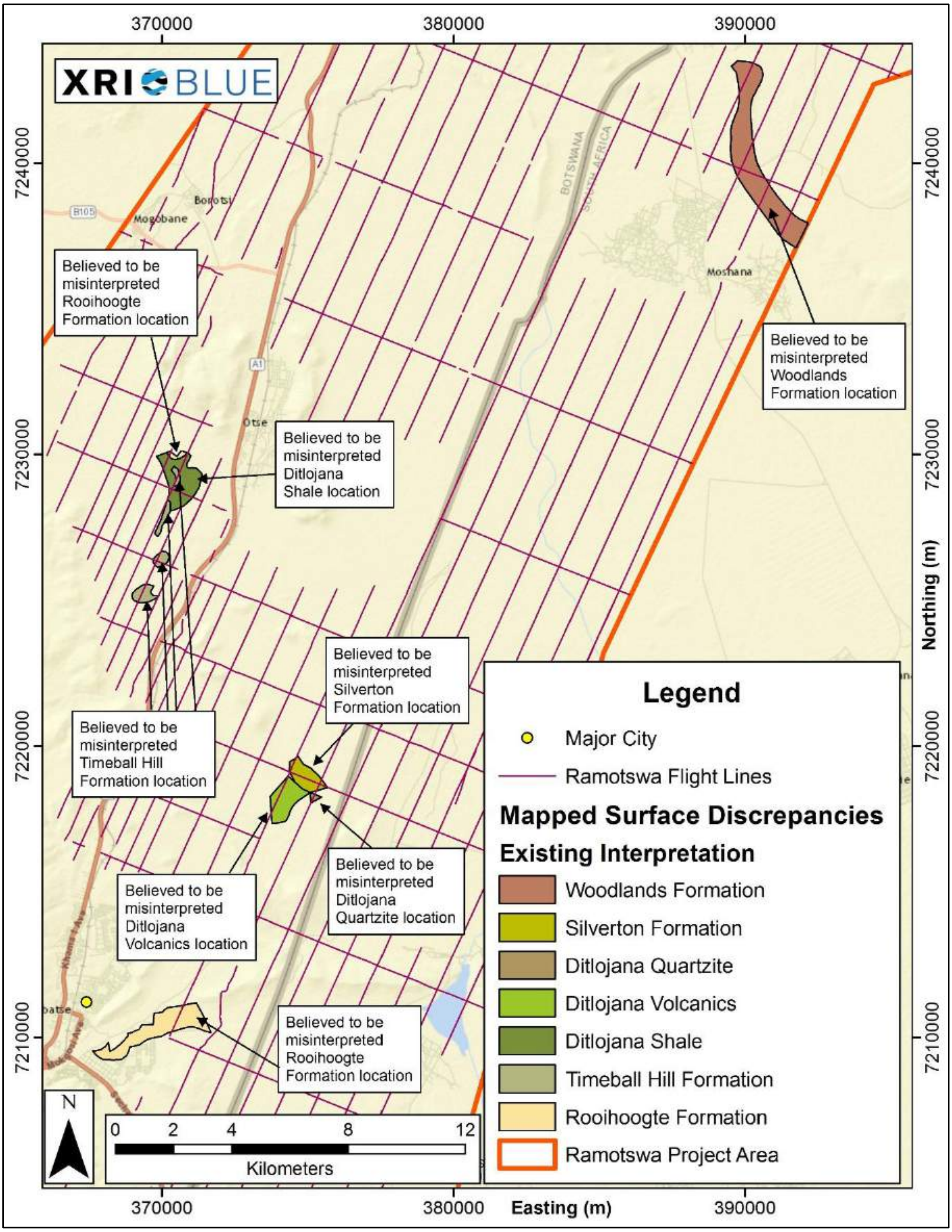

Figure 7: Discrepancies observed between the digitalized maps and the AEM interpretation.
Source: XRI Blue

4. Hydrogeology

4.1. Aquifer description

4.1.1. Aquifers in the RBTAA

The Ramotswa Dolomite forms part of the Malmani subgroup in the Chuniespoort Group of the Transvaal Supergroup. The name Malmani was derived from the Malmani Spring having its origin on the dolomites and giving rise to the Malmani River in the Limpopo province. The Ramotswa Dolomite is the main water-bearing unit of the study area and is the primary focus of this study. This dolomite is characterized by relatively high manganese and iron and structurally forms part of the Transvaal/Bushveld basin (Martini and Kavaliers, 1976). This aquifer has been characterized as an arcuate[6] of shallow to medium depth and being unconfined to semi-confined (Davies et al. 2013). Within the Ramotswa Dolomite formations, it is interpreted that chert content is a primary factor in aquifer productivity. According to Janse van Rensburg (2002), the Frisco, Oaktree and Lyttleton Formations are poor aquifers (chert poor); and the Monte Christo and Eccles Formations are important water-bearing formations (chert-rich).

Of lesser importance is the Lephala aquifer located within the shales, quartzites and conglomerates of the Lephala Formation (Pretoria Group), which plays a role in local hydrogeology of the urban area of Ramotswa. The Lephala Aquifer is not affected by karstification and has two fissured zones, the upper with a thickness of 30 to 40 meters and the lower, which is approximately 30 meters thick. The fissured zones correspond to the area with potential groundwater abstraction possibility, and yields within the Lephala depend on the location relative to the fissured zones as well as to the river. The Ramotswa dolomites and the Lephala Aquifer are thought to have a local hydraulic connection through the north-south trending fracture zones. This aquifer is also anisotropic due to this fracturing, and has low primary porosity (Staudt 2003). Surface runoff and the river account for the recharge within the Lephala (ibid.) while the discharge area is uncertain.

4.1.2. Groundwater in the Ramotswa Dolomite

Groundwater flow and storage in the Ramotswa Dolomite is characterised by several geological process and structures which define preferential groundwater flow paths or barriers to groundwater flow.

[6] shape of a bowl

Karstification

Groundwater storage occurs in areas where there is karstification and groundwater flow in the dolomites is along the major linear karst feature. Karstification is a natural process of dissolution of soluble rock such as limestone and dolomite by infiltration of rainwater which is generally acidic, allowing such dissolution. It is characterized by underground drainage systems with sinkholes and caves. (Figure 8). The dissolution process during karstification has been noted as being more pronounced in the chert-rich units of the Malmani Subgroup (Holland et al. 2010). In fact, the Eccles and Monte Christo Formations are believed to have undergone significant karstification and therefore have the best aquifer characteristics, hence they may hace good groundwater storage capacity. Thus, the aquifer has two zones of karst development: the upper karstic zone which is 20-50 meters thick and where dissolution occurs along preferential fractures (solution cavities are generally filled with wad which is a complex residual soil mantle with very low density) and the deeper karstic zone which is 25-50 meters thick with open solution cavities (DWAF, 2004). The Malmani dolomitic karst system can be highly fractured because of its lithologies that have been exposed to a variety of geological activities including folding, uplift, tectonization and compaction due to deep burial (Holland et al. 2010).

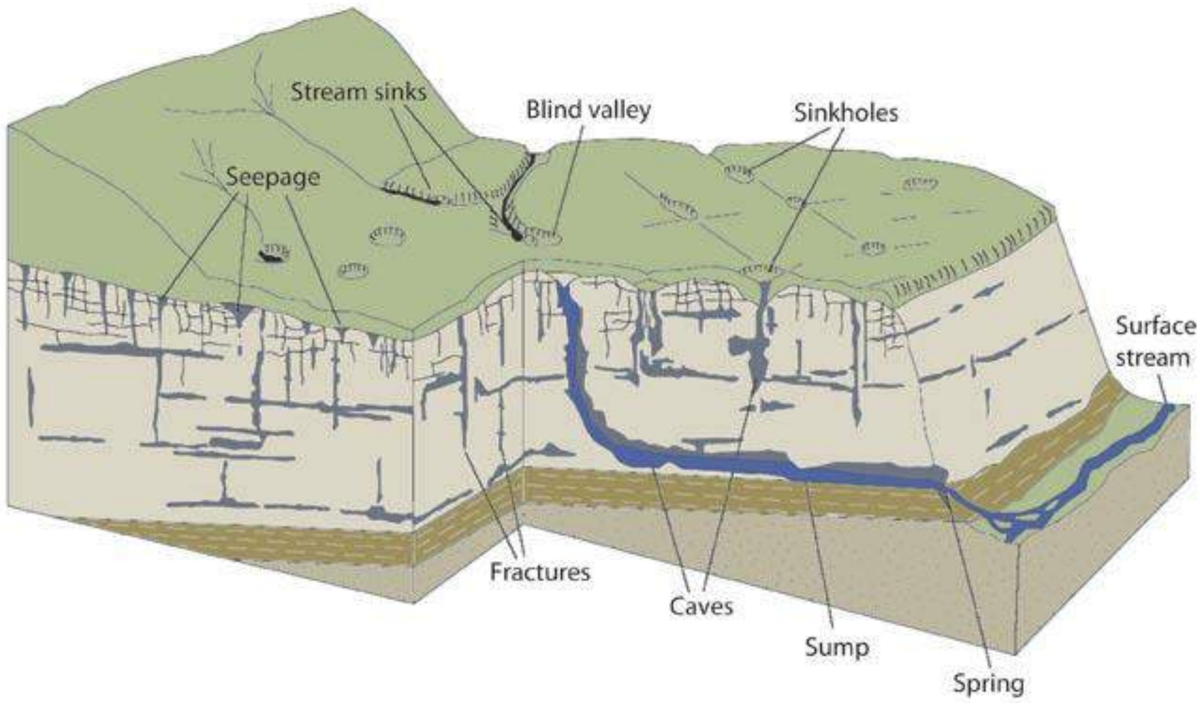

Figure 8: Example of karstification (Runkel et al. 2003).

Collapse features

Associated with the karst area, multiple collapse features have been identified by the AEM survey within the Ramotswa study area (Figure 9). Collapse features can result from the collapse of the cavities created by dissolution of dolomite or from ground or surface water flow change which can flush out existing sediment-filled fissures, sinkholes and caves, leading to subsidence of the land above. This can cause the formation of circular cylindrical or conical depressions at the ground surface known variously as sinkholes, swallow holes, shake holes or dolines. Many of these collapse features occur near a geologic contact, fault or dike, where a change in groundwater flow patterns is expected and could lead to increased porosity through dissolution of geologic materials. Collapse features areas should be targeted for further groundwater investigation, as these are expected to be the more productive zones (high yielding boreholes). Towards the east the Ramotswa dolomite dips underneath younger formations. It is unknown to how far the karstification (and therefore the aquifer properties of the Malmani formation) extends to the East.

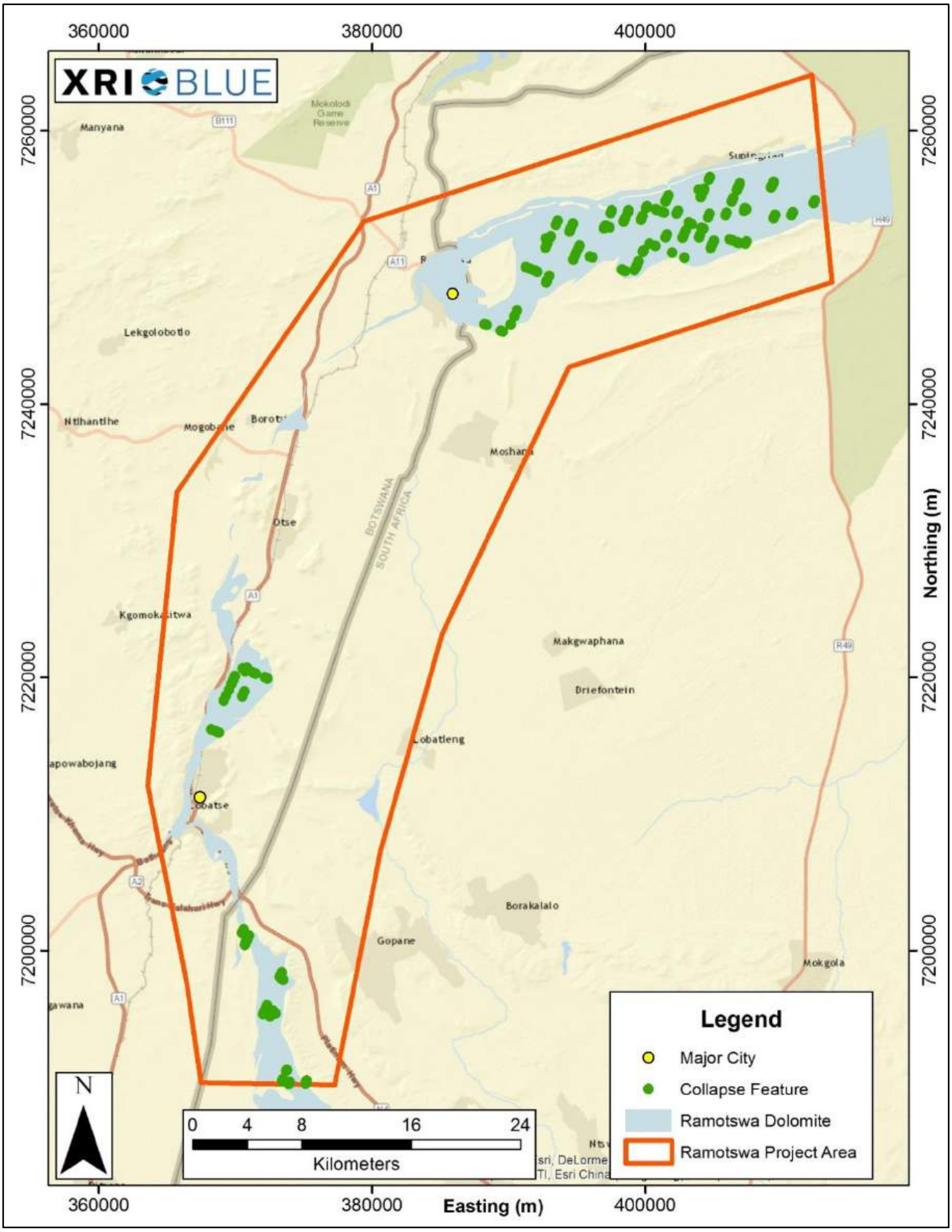

Figure 9: Collapse features identified in the Ramotswa Dolomite.
Source: XRI Blue

Faults

Faults can serve as preferential flow paths or barriers to groundwater flow. Faults were identified from surface faults provided by BGI and CGS and the AEM survey. Figure 10 presents only the surface faults from previous maps and figure 11 presents the interpreted faults. Faults were interpreted as areas where there was a noticeable offset or an abrupt change in the in the resistivity signature. Some faults are present in the subsurface, and did not appear to extend to the surface while other faults did extend to the surface.

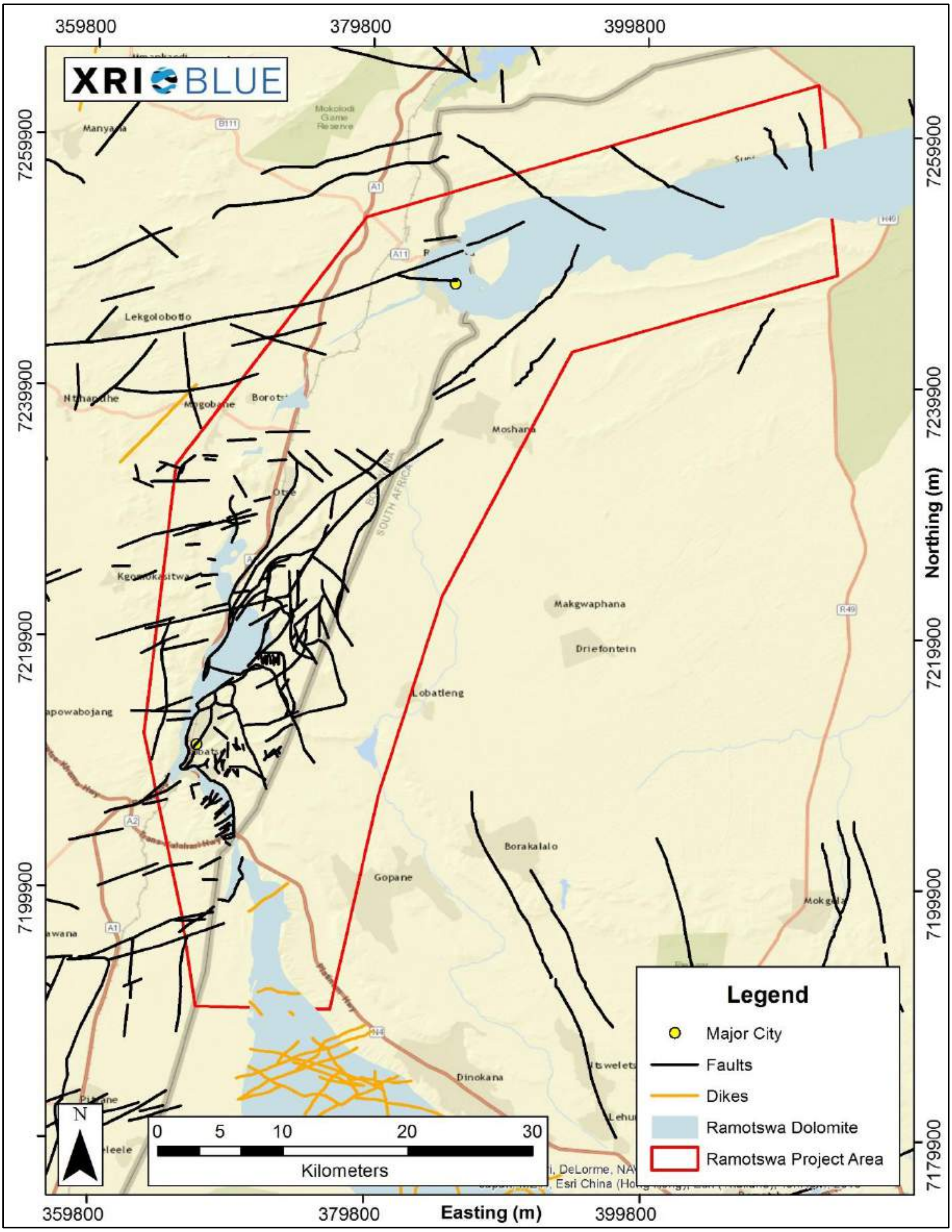

Figure 10: Faults previously mapped by BGI and CGS.
Source: XRI Blue

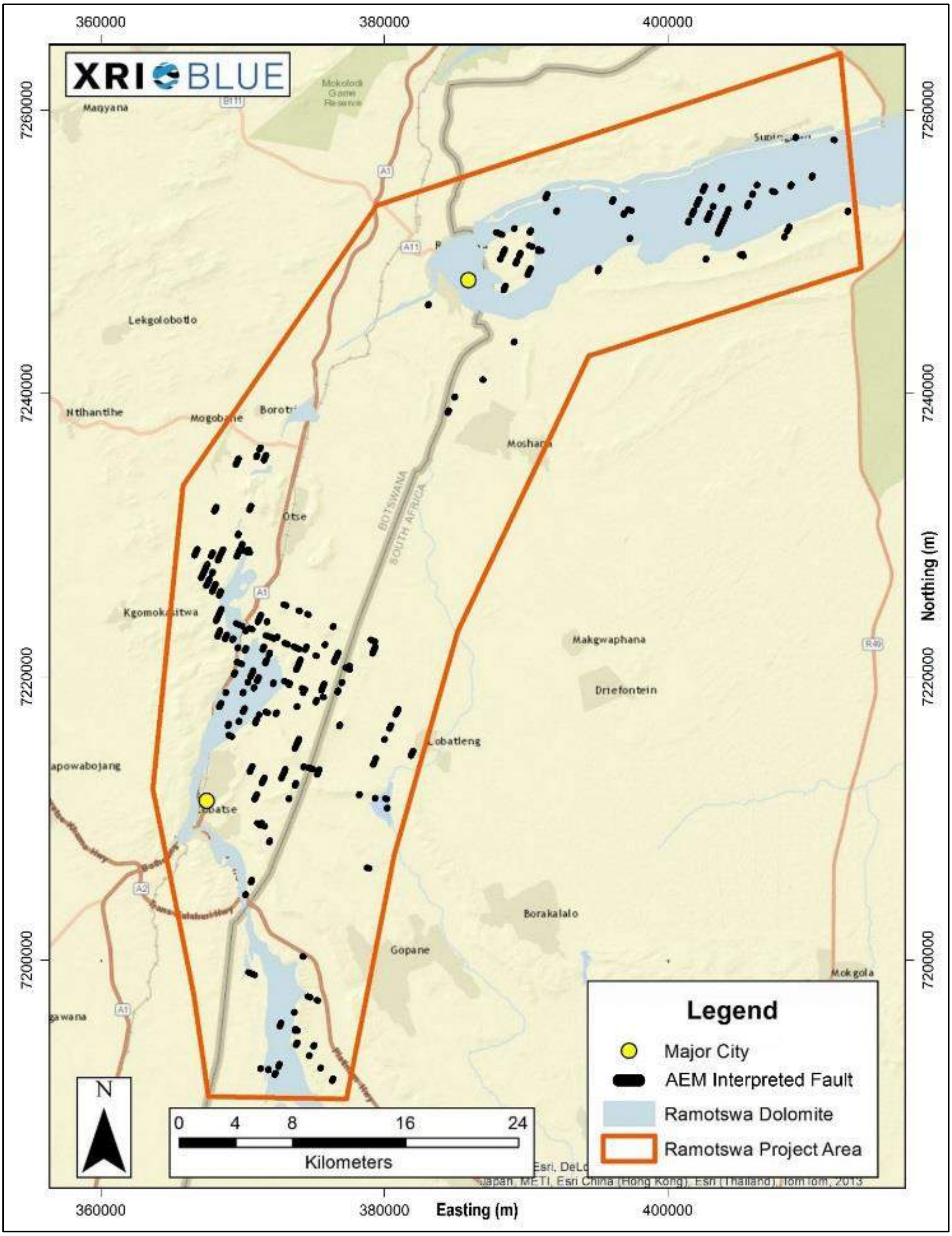

Figure 11: Interpreted faults from airborne AEM (XRI, 2017).
Source: XRI Blue

Dikes and dolomite compartments

Intrusive dikes can serve as either a preferential flow path for groundwater, or as barriers to groundwater flow. A distinguishing component of the dolomite karst aquifers in South Africa is that it is subdivided into compartments because of almost vertical dolerite and syenite dikes (Holland et al. 2010). The dike intrusions are prominent along North-South, North-North-West and East-West direction, depending on the age of the dike and are generally considered impermeable at depth and thus form barriers for horizontal groundwater flow (Meyer, 2014). However, near the surface the dike can be weathered, allowing groundwater to flow across (Meyer, 2014). Additionally, some of the dikes appear to be offset by faulting, which may alter the expected groundwater flow regime near the dike in the faulted area. Another important feature of the dikes is in relation the groundwater levels: in situations where the groundwater levels are high enough to be within the top weathered zone of the dikes, there may be groundwater flow from one compartment into the next (Figure 12). If however the groundwater level drops beneath the weathered zone of the dikes the hydraulic connection between the compartments will become less prominent.

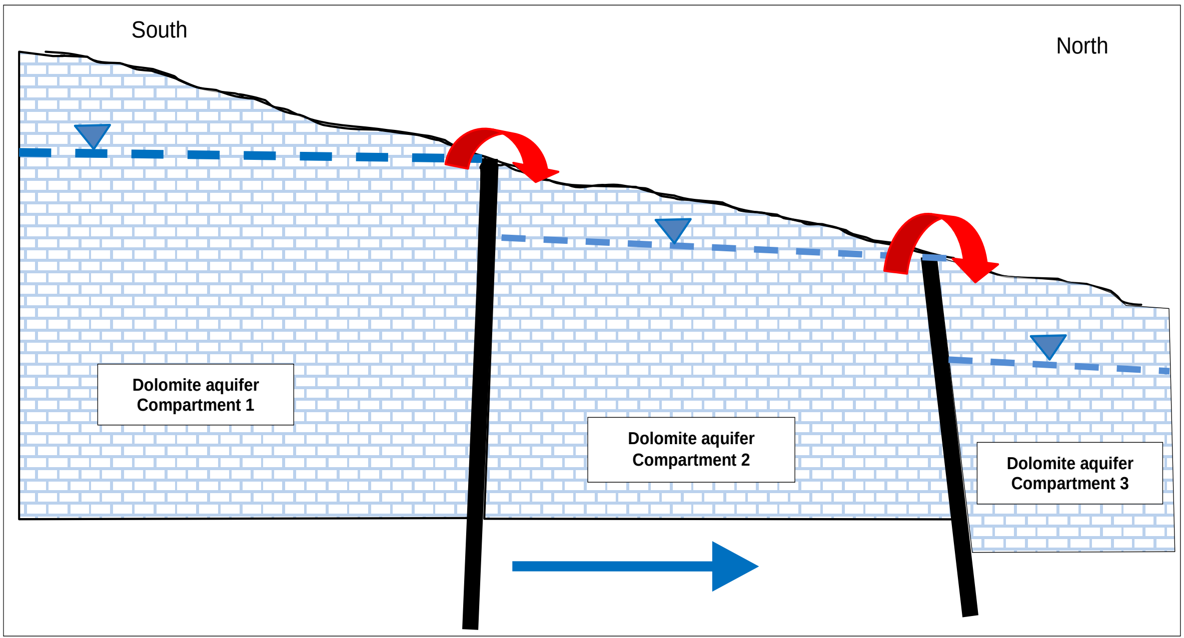

Figure 12: Potential groundwater flow from one compartment to another
Source: Meyer R.

Based on the interpreted locations of dikes (interpretation based on XRI airborne magnetic survey), the Ramotswa Dolomite has been divided into compartments. The boundaries between compartments are delineated in areas where a dike has been interpreted from AEM survey to continuously exist through the Dolomite, resulting in thirteen (13) compartments where groundwater flow may be restricted (Figure 13). The western boundary of the compartments is the western boundary of the dolomite outcrop. The eastern boundary of the compartments is unknown, as it has not been possible to map the eastern extend of the Ramotswa dolomite aquifer underneath the younger formations. The true existence and relevance of these compartments will need to be verified through additional research as the geological structures between AEM flighlines has not been interpreted and thus, there is uncertainty of continuity of the dikes through the dolomites. In addition, the porosity of the dikes through the dolomite layer is also uncertain, particularly at the surface where the dikes can be weathered.

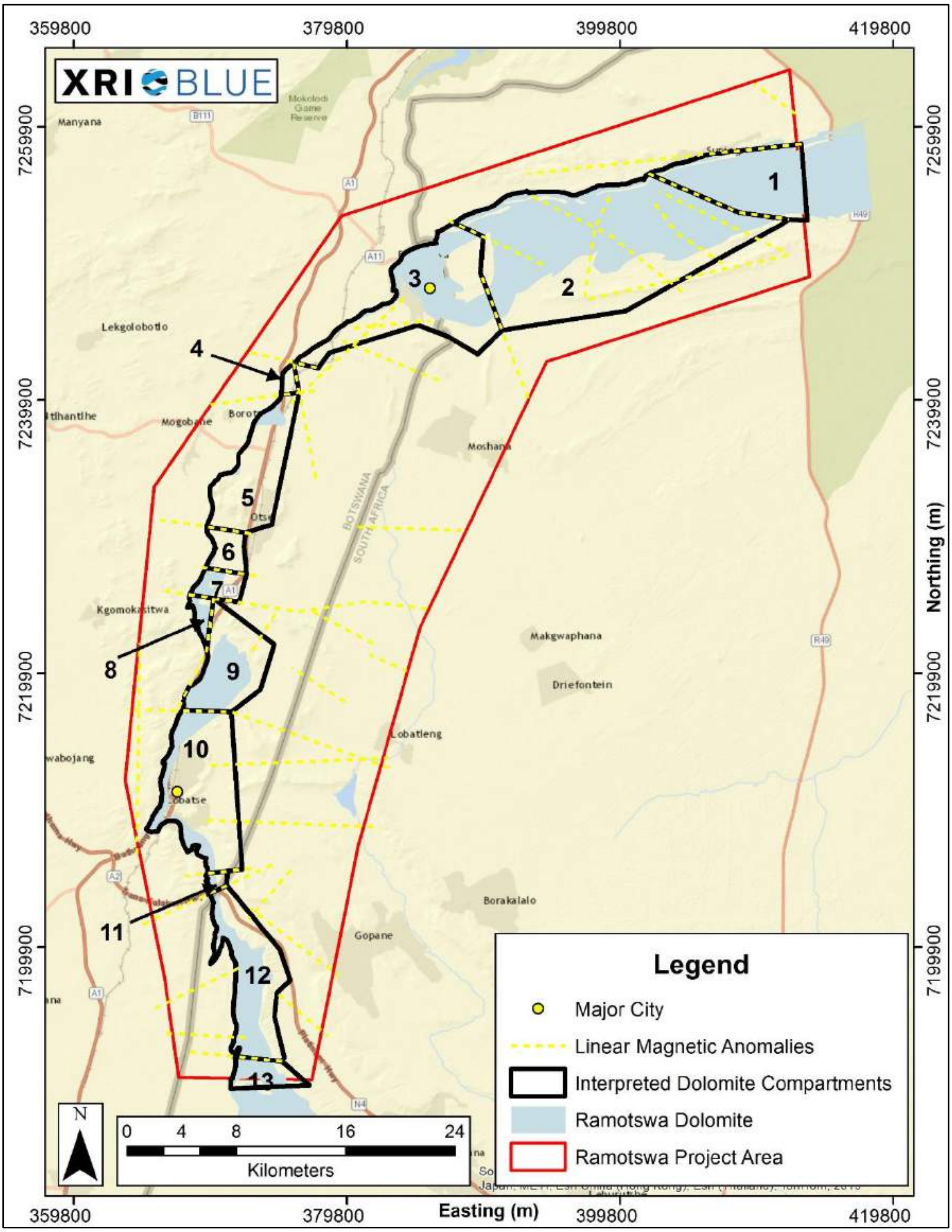

Figure13: Interpreted compartments identified in the Ramotswa Dolomite.
Source: XRI Blue

4.1.3. Aquifer extent and compartments

The extent of the Ramotswa Dolomite (and by association the Ramotswa Aquifer) is based on the interpretations of the geologic contacts between the Dolomite and surrounding geologic formations.

The Black Reef is stratigraphically below the Dolomite, and in contact with the Dolomite throughout the study area. The Black Reef is in contact with the northern edge of the Dolomite in the Northern portion, the western edge of the Dolomite in the Central portion and the southern edge of the Dolomite in the Southern portion. The contact between the Black Reef and the Dolomite is interpreted as the base of the aquifer forming the western and northern boundary of the aquifer. However, there is an unconformity between the Black Reef and the Dolomite, with the base of the Dolomite including a transgressive black shale (Catuneanu & Eriksson, 1999). This shale has been observed in boreholes within the Ramotswa Project Area (Obbes, 2001). As consequence, the base of the aquifer is interpreted by locating a thin shale between the Black Reef and the Dolomite that indicates the shale is present between the two formations and the Black Reef is considered as limit to the aquifer extent.

The top of the Dolomite is interpreted by surrounding geologic formations and on changes in surface expressions, such as a distinct topographic high (i.e. Rooihoogte) transitioning to an area with no distinct surface expression (Dolomite). Thus, the top of the aquifer is the contact between the dolomite and the Duitschland (Northern portion of the Ramotswa Dolomite), the Penge (Southern portion of the Ramotswa Dolomite), the Rooihoogte (Southern portion of the Ramotswa Dolomite), and the Waterberg (Central portion Ramotswa Dolomite).

Figure 14 shows a 3D model of the Ramotswa Dolomite and indicate that the aquifer is dipping eastward in the Southern and Central part and southward in the north forming a half saucer shape. The penetration limit of the AEM doesn’t allow to map the top and bottom of the aquifer over the entire study area as both top and bottom of the dolomite are deeper that the limit of investigation (about 350 m)

Based on the locations of the dikes, the Ramotswa Dolomite might be divided into thirteen (13) unique compartments where groundwater flow may be restricted (Figure 13). Table 3 shows the characteristics of each compartment. The AEM survey interpretation is limited to about 350 m below the surface depending on the geological formation. Calculation for table 3 is conservative and only considers the dolomite part where the dolomite bottom has been fully interpreted. Deeper, the compartments extent is more important. Total area of the dolomite aquifer compartments is about 453 km^2.

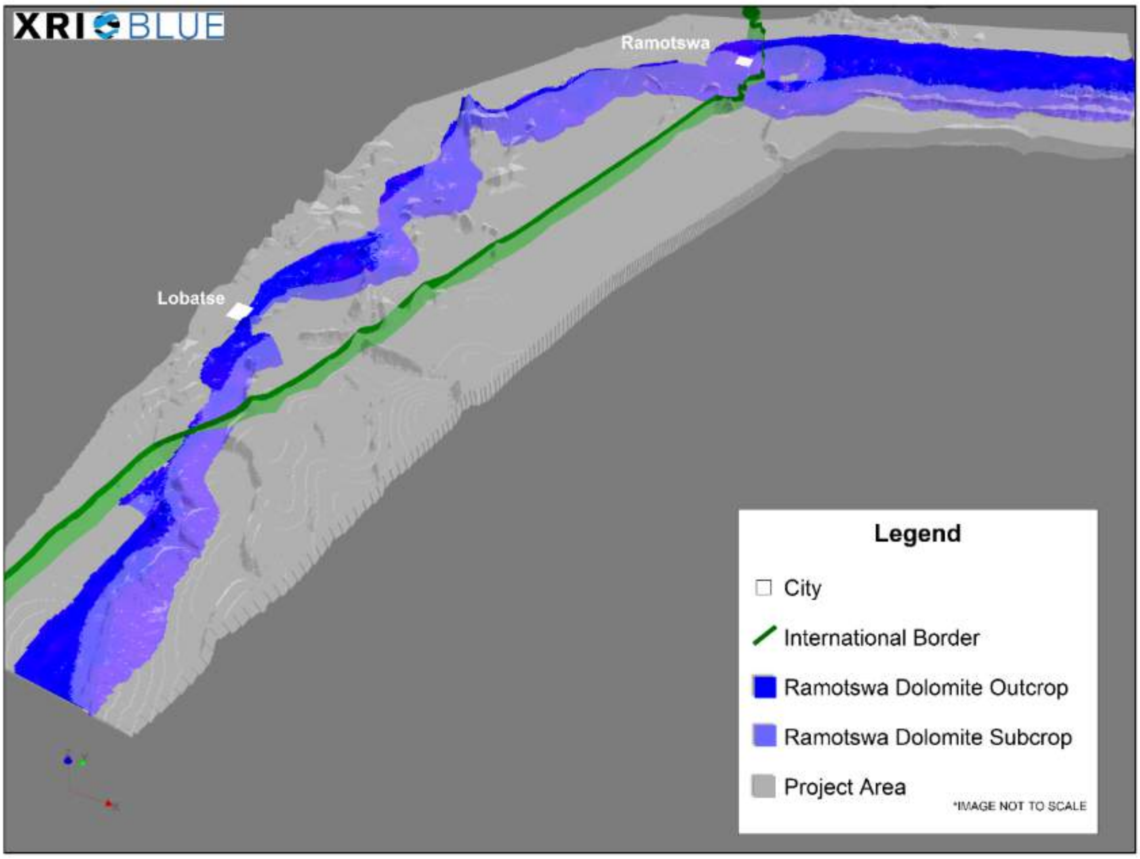

Figure 14: 3D model of the Ramotswa dolomite.
Source: XRI Blue

Table 3: Interpreted compartment characteristics.

Compartment number	Surface Area (km2)	Maximum thickness (m)	Average thickness (m)	Potentially transboundary
1	40.4	335*	232	NO
2	157.1	319*	208	NO
3	61.7	343*	154	YES
4	2.1	29	19	NO
5	35.5	96	43	NO
6	7.7	300*	67	NO
7	7.0	300*	172	NO
8	3.8	300*	121	NO
9	31.0	327*	215	NO
10	54.8	300*	178	YES
11	1.8	212	121	YES
12	40.4	339*	169	YES
13	9.3	325*	194	NO

* the bottom of the dolomite has not been identified as it is lower than the depth of investigation of the AEM survey. As consequence, the dolomite thickness can be higher than the number presented here and this uncertainty affects the calculation of the average thickness of the dolomite layer in the compartment.

4.2. Aquifer properties

The Ramotswa Dolomite aquifer has low primary porosity (Staudt 2003) but it is very heterogeneous due to this fracturing and thus features hydraulically important secondary porosity. The hydraulic conductivity is enhanced by fracturing and karstification (Ranganai et al. 2002). The Ramotswa Dolomite contains two karst zones: the upper (20 to 50 meters thick) and lower (25 to 50 meters thick) karst zones that have high transmissivity and storativity. These two kart zones correspond to potentially good areas for groundwater abstraction. Dolomite and chert have different solubility's and consequently the reason we have more groundwater storage capacity in chert- rich dolomitic sequences than in chert-poor. Dissolution is supported in chert-rich units along bedding planes between dolomite and chert bands (Meyer, 2014).

4.2.1. Transmissivities and borehole yields

The transmissivities of the aquifer are generally high to very high (> 100 m^2/d) with good storage and borehole yields (> 2 l/s). This has been attributed to the chert-rich units of the Malmani subgroup, Eccles and Monte Christo Formations. Data on water yield show that the majority of the boreholes in and around the study area (hydrogeological boundary) have yields of 5 litres per second (l/s) or less. Table 4 provides some information on the boreholes inside the Ramotswa Wellfield (Staudt, 2003).

Table 4: Aquifer statistics based on 32 boreholes in the Ramotswa Wellfield (Staudt 2003).

Aquifer property	
Specific Capacity (l/s/m)	2.7
Average transmissivity (m^2/d)	1,170
Storage Coefficient	5.7×10^{-2}
Borehole property	
Yield (l/s)	2.33

The variations are primarily due to the degree of karstification. Wells that are not within the karst areas are typically low yielding, with a calculated mean transmissivity of 10 m^2/d. Away from the Ngotwane River Valley dry boreholes are common (Staudt, 2003).

4.2.2. Porosity estimates

In the study area, a simplified version of the Archie's equation was used for calculating the porosity of carbonates, where $\mathbf{\Phi^{-m} = \rho_e / \rho_w}$ (Lucia, 1983) where $\mathbf{\Phi}$ is the porosity, **m** is the cementation exponent, ρ_e is the effective resistivity (bulk resistivity of the sample) and ρ_w is the apparent resistivity of the pore fluid. The electrical resistivity data of the Dolomite (from the AEM data), electrical resistivity of the pore fluid, and an “m” value of 2.4, were applied to the Lucia simplification of Archie’s Law to estimate porosity for the Dolomite throughout the Ramotswa Project Area. In fact, Lucia suggests the range of “m” values for carbonates is 1.8 - 3.0. Due to the lack of porosity data available of the Dolomite, and the heterogeneity of the Dolomite in the RAMOTSWA project area, it was decided that a median value of 2.4 would be used for m. Further support for the determined value comes from the Kansas Geological Survey, with recommended “m” value of 2.3 for carbonates (Doveton, 1999).

It was interpreted that due to limitations of Archie’s Law for conductive materials (Worthington, 1993), and the likely presence of shales (conductive material) between the Dolomite Formations, a resistivity threshold needed to be applied for the porosity estimates. After applying multiple resistivity thresholds and examining the resultant porosity estimates, it was interpreted that 40 Ω-m was an appropriate threshold. AEM resistivities lower than 40 Ω-m were excluded from porosity calculations due to these limitations.

In addition, there are anomalous porosity estimates that are greater than 50%. The anomalous porosity estimates may be in areas where significant karstification has occurred, or an area of increased clay content where Archie’s law may not apply. The transitions between the different dolomite formations appear to have higher clay content, leading to a decrease in resistivity, but they are also host to interpreted collapse features. It is possible that transitions between the different dolomite formations may have unrealistic porosity estimates. Figure 15 shows the porosity estimate along the flying line of the AEM survey.

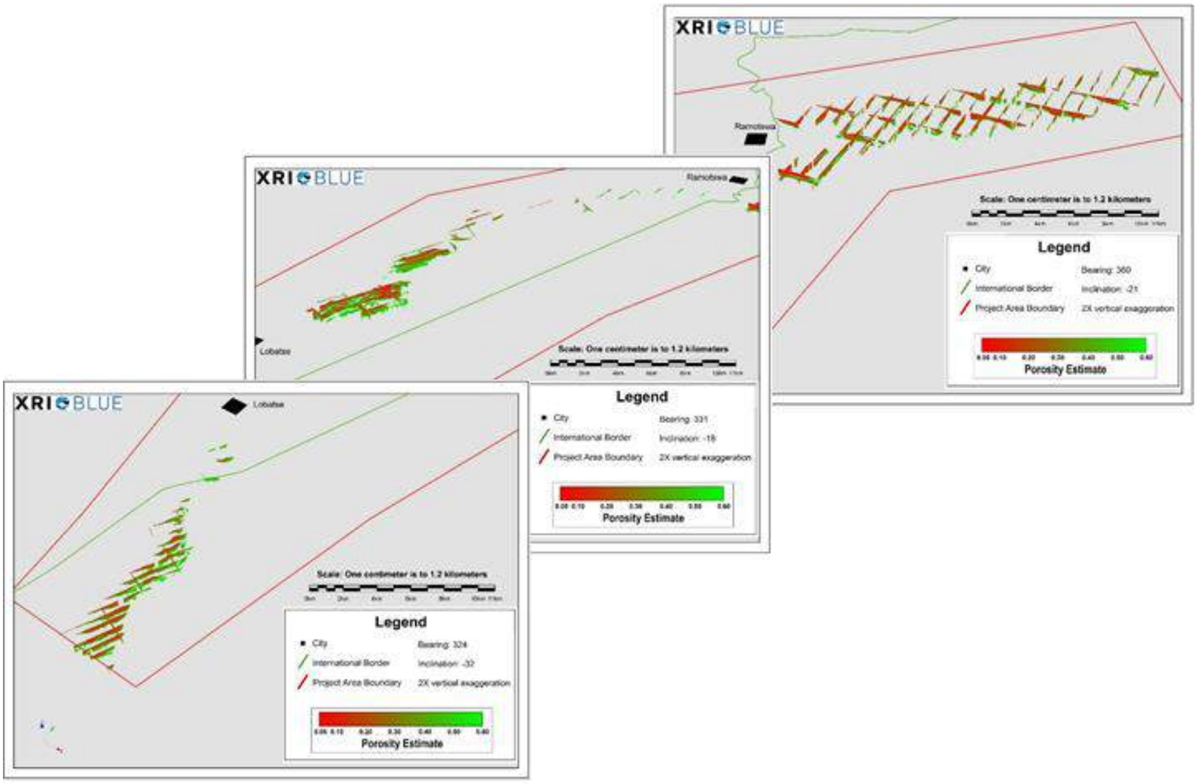

Figure 15: Porosity estimates in the Ramotswa Dolomite.
Source: XRI Blue

4.2.3. Hydraulic conductivity estimates

The distribution of hydraulic conductivity in the dolomite has been geoelectrically estimated by applying a generalized log-log linear electrical-hydraulic correlation function, the slope of which is dependent on the geologic and geochemical environment and is expected to be negative for dolomite (Purvance & Andricevic, 2000). Transmissivity values determined for four production wells in the Ramotswa wellfield, from both constant rate and step pumping tests (Carlsson, 2006), were extrapolated over field and used in conjunction with the AEM resistivity data to calculate the distribution of estimated hydraulic conductivity for the Dolomite Aquifer. Thus, the hydraulic conductivity estimate (figure 16) are given only as indicative value considering the high level of uncertainty.

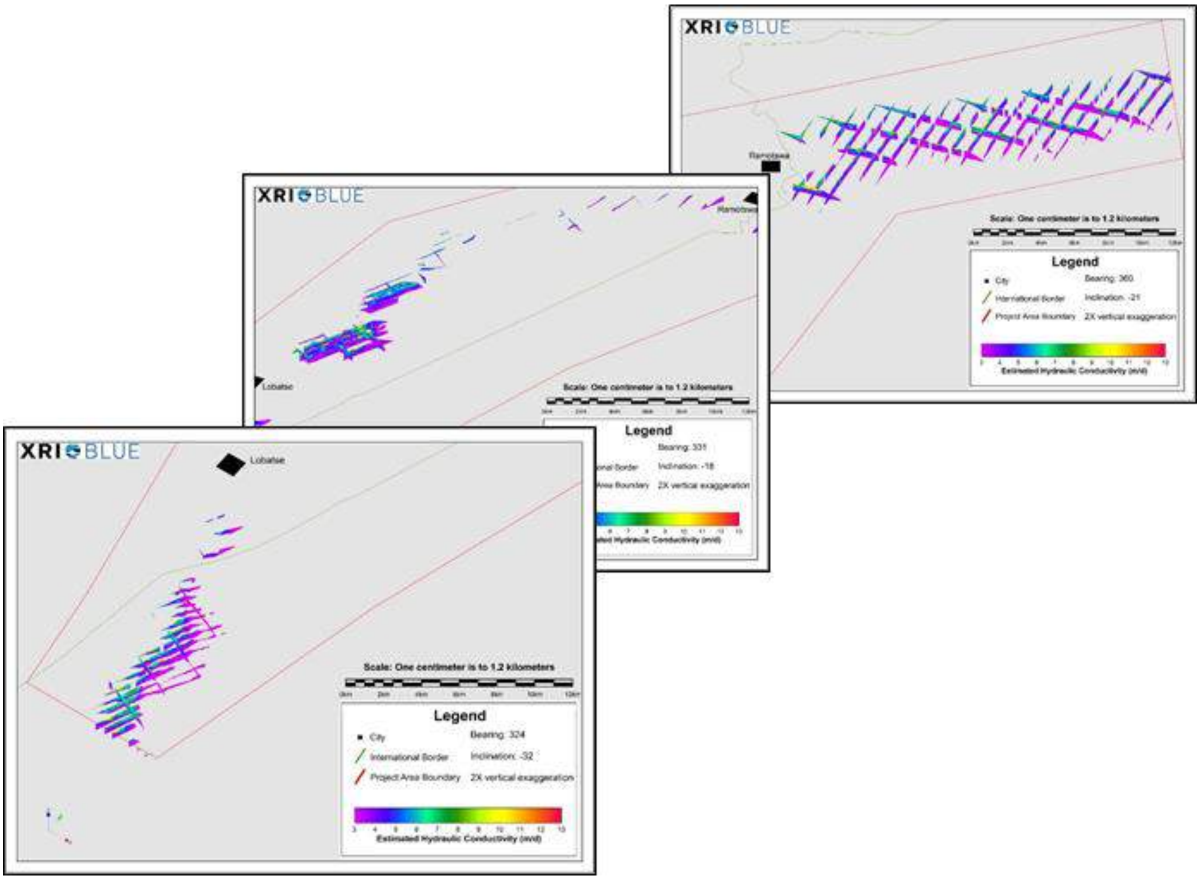

Figure 16: hydraulic conductivity estimates in the Ramotswa Dolomite study area.
Source: XRI Blue

4.3. Groundwater level and groundwater flow direction

Data on groundwater levels and aquifers characteristics are mainly from the Ramotswa Wellfield in Botswana. The Botswana Department of Water Affairs and the Water Utilities Corporate provided long term time series of groundwater level data from 1999 to 2012 in the Ramotswa aquifer. Other data are from the Lobatse area, Botswana, about 50 km south of Ramotswa where an environmental hydrogeology study has been conducted (Beger, 2001), which used data from approximately 180 borehole/well locations in an area of approximately 250 km^2.

4.3.1. Groundwater table fluctuation

The recorded period corresponds to a period when the Ramotswa Wellfield was not used for abstraction. Figure 17 shows the groundwater level variation of some of the monitoring boreholes in the Ramotswa Wellfield.

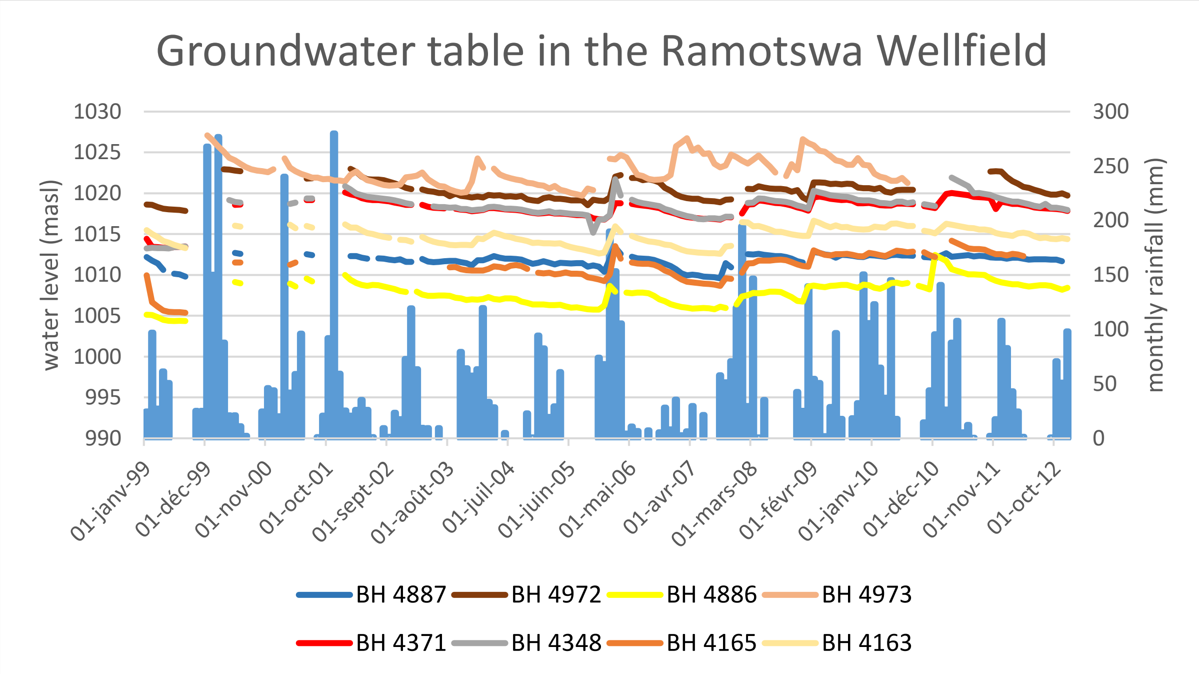

Figure 17: Groundwater level of selected monitoring boreholes in the Ramotswa Wellfield, expressed in masl in correlation with monthly rainfall from the Gaborone rainfall station (mm). *Source: WUC and Kenabatho P.*

Figure 17 indicates possible seasonal variation of the groundwater table with a rising groundwater table during the rainy season from November to March and decline of the groundwater table during the dry season from April to October. This is particularly noticeable in 2008 and 2009 for borehole BH 4371 and BH 4972. In addition to this yearly variation in groundwater levels there appears to be a longer-term fluctuation which seems to correspond to the differences in annual rainfall.

Additional data covering almost the entire study area were provided by the Botswana Department of Water Affairs and the South African Department of Water and Sanitation but they only show one static water level for each borehole in different years. However, analysis of the static water level data in the study area shows that, generally, the depth to water is shallower in the northern portion of the study area, where the average water level is approximately 24 meters below the ground surface, compared to the southern portion where the average water level depth is approximately 41 meters below ground surface. In complement, according to Ranganai et al. (2002) the median depth to groundwater table for the Ramotswa wellfield was 9 meters below ground surface and surface unconsolidated sediment were about 0 to 12 meters thick. Unfortunately, there are few boreholes with available data identified in the South Africa part of the study area.

4.3.2. Groundwater flow direction

A piezometric map has been produced based on data from a water level measurement campaign conducted from the 25th – 29th of August 2016 (in South Africa) and from the 1st - 5th of September 2016 (in Botswana). Unfortunately, no water level data were collected in the north-east part of the study area. The piezometric map (Figure 18) based on this limited data set indicates ground water flow in the southern part of the aquifer to be in a northern direction, gradually changing to a north-easterly direction in the northern part of the aquifer. This groundwater flow direction roughly coincides with the topographic relief and the drainage pattern in the study area which goes from high elevation ridges in the south west to lower topographic relief in the north east. In many karst areas, groundwater flow is expected not to be correlated to the topography. This seems not to be the case here, as both geological structures and topography seem to guide the regional orientation of the groundwater flow. Several authors (Burke et al. 1985; Crockett, 1972 and Clendenin et al. 1988) have mentioned the structural rift sequence with north north-east trending grabens affecting the lithology and probable origin of preferential groundwater flow pathways. This agrees with Staudt (2003), who identified the general groundwater flow around the Ramotswa area to be in a north-north-eastern direction following the course of the Ngotwane River and the finding by Beger (2001), who identified the general groundwater flow around the Lobatse area to be in a northern direction. Subterranean connections following the network of faults must have been established between the high lying areas and the low-lying areas to enable groundwater to flow in this north north-easterly direction.

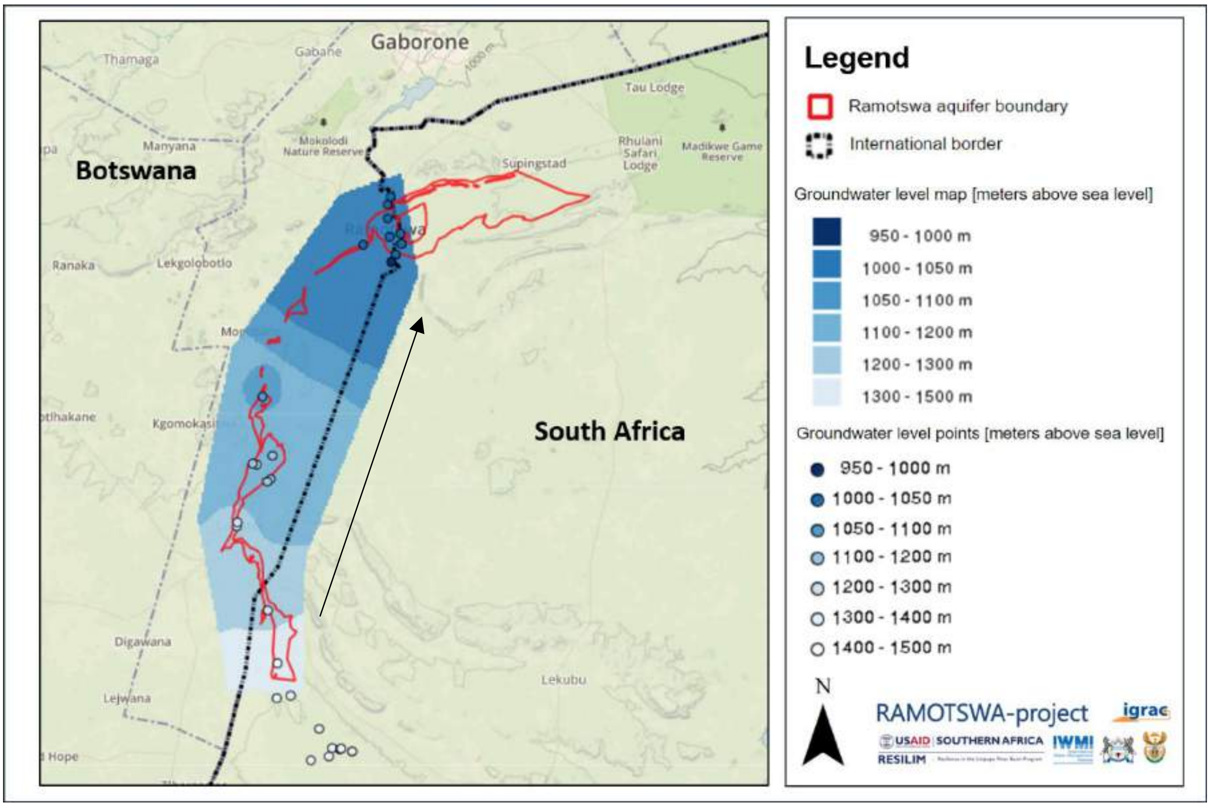

Figure 18: Piezometric map and original point data (data August – September 2016). *Source: RIMS*

4.3.3. Spring flow

Figure 18 presents the flow from the Dinokana eye (South Africa) in correlation with the rainfall record from the Boschrand rainfall station (Figure 19). This perennial spring is not inside the study area but located nearby compartment number 13.

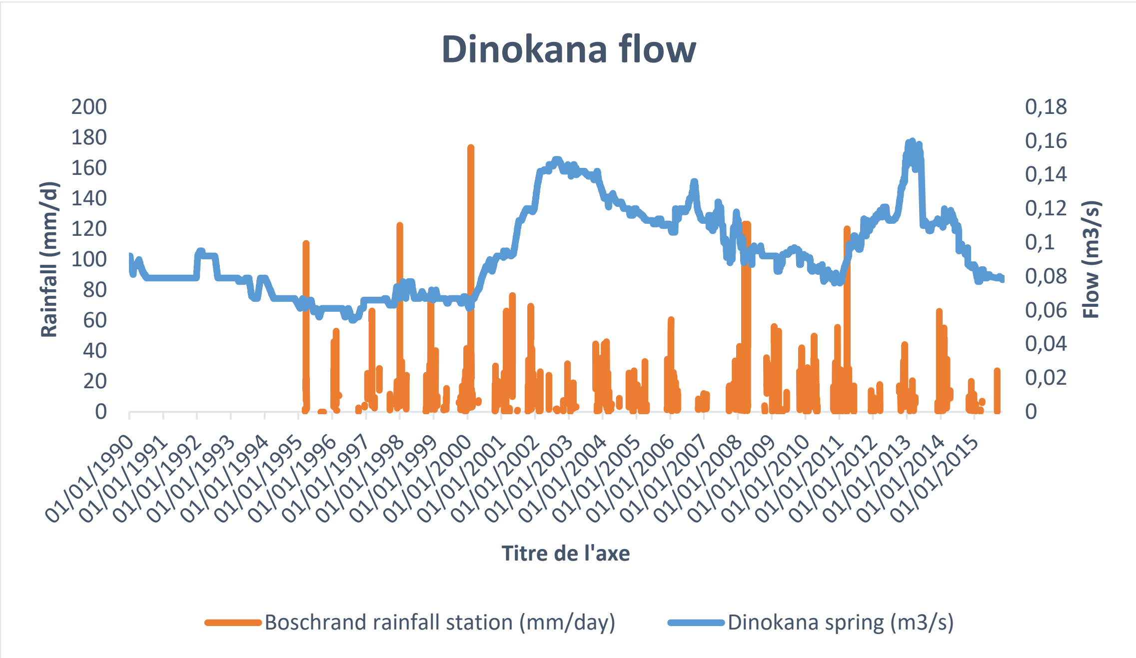

Figure 19. Dinokana eye flow record 1990-2015.
Source: DWS and SAWS

Minimum recorded spring flow is about 0.06 m^3/s during the period 1995-1997 while the maximum value occurs in 2013 with more than 0.15 m^3/s. Simple visual assessment between rainfall data and spring flow, show a delay in the spring's response to the precipitation of about 2 years: while the period 1999-2001 shows an increase in precipitation (Boschrand Rainfall Station), increase in the spring flow is spread over the period was the 2000-2002. The exact mechanism behind this delay is not clear and to better understand the response of the aquifer to precipitation more investigations would be necessary.

4.4. Groundwater dynamics

4.4.1. Recharge mechanisms

The source of recharge to the upper karst zone is thought to be diffuse direct rainfall infiltration and preferential recharge through the Ngotwane riverbed (where it crosses the dolomite outcrops), in times of seasonal flow (Beger, 2001). Factors influencing recharge include rainfall pattern, soil and geology, vegetation and land-use, topography, hydrology (drainage network, lakes/ponds/dams, springs).

Rainfall pattern

Mean annual rainfall ranges from about 450 to about 600 mm in the study area (Figure 20). There is high seasonal variation with rainfall mainly concentrated in the period October – March (Figure 21).

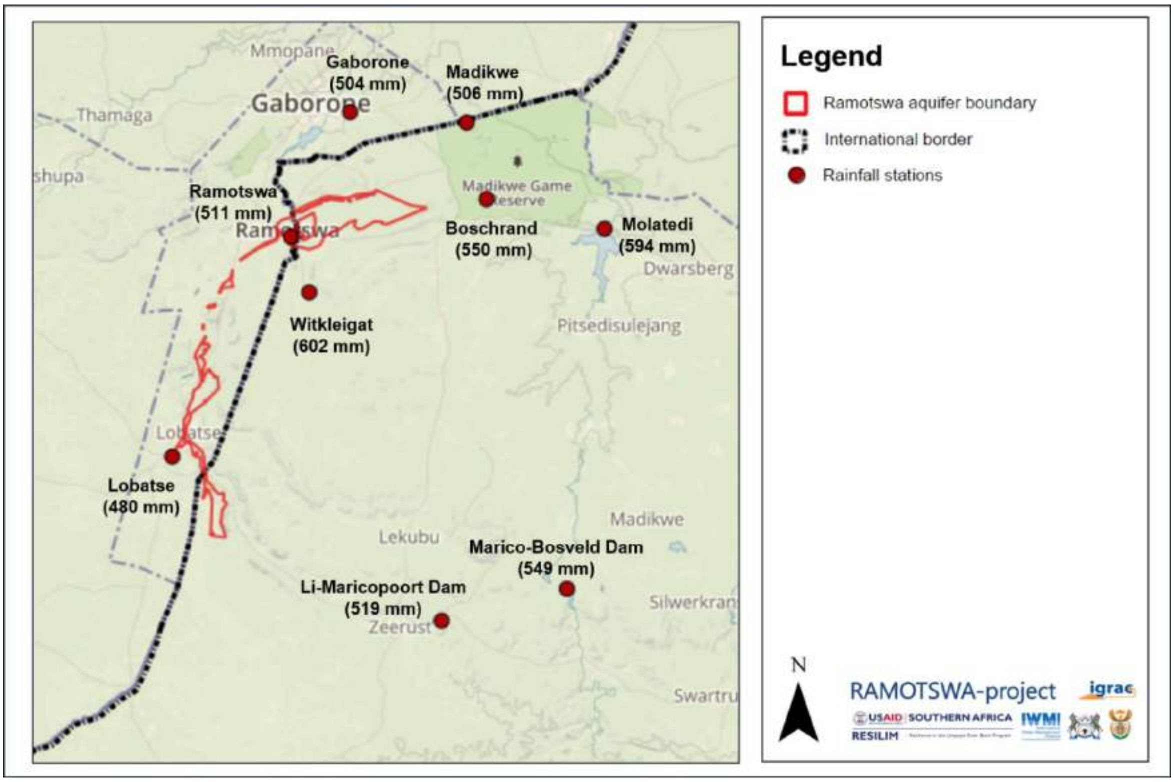

Figure 20. Location of the rainfall stations and their average annual rainfall over the period 1995-2015.
Source: RIMS

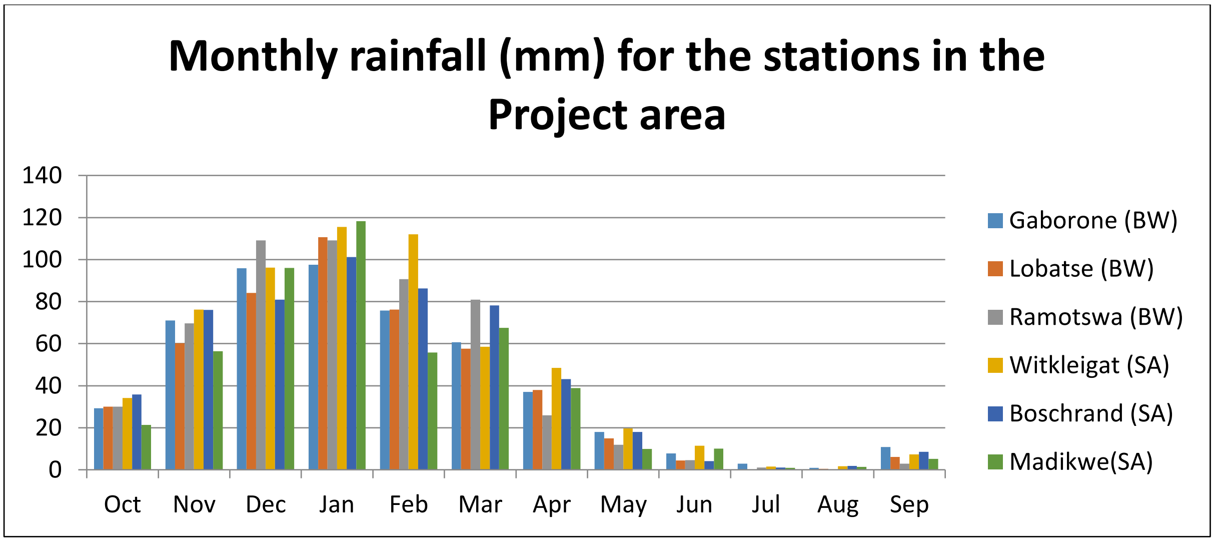

Figure 21. Monthly rainfall values for the stations in the catchment starting from the beginning of the rainy season in October.
Source: SAWS and Kenabatho P.

Annual rainfall values (Figure 22) indicate missing values from some stations in South Africa. However, there is evidence of declining rainfall levels during the observed period (1995-2015). Based on long term data from three rainfall stations the trend in yearly rainfall during the wet season (October – march) has been studied for a rolling 10 year window by calculating the annual wet season minimum (m.min10), maximum (m.max10), and average (m.av10) (Figure 23). Results show that while the average seasonal rainfall stays the same, the wet season maximum has a tendency to have more rain and the wet season minimum tend to have reduction in precipitation. This is an indication that extreme weather condition (drought or flood) might occur more regularly in the region. This trend in precipitation is likely to have a significant impact on annual availability of surface water and on aquifer recharge. With the current limited understanding of the exact recharge mechanisms in the study area it is not possible to say if this impact will be positive or negative on the recharge.

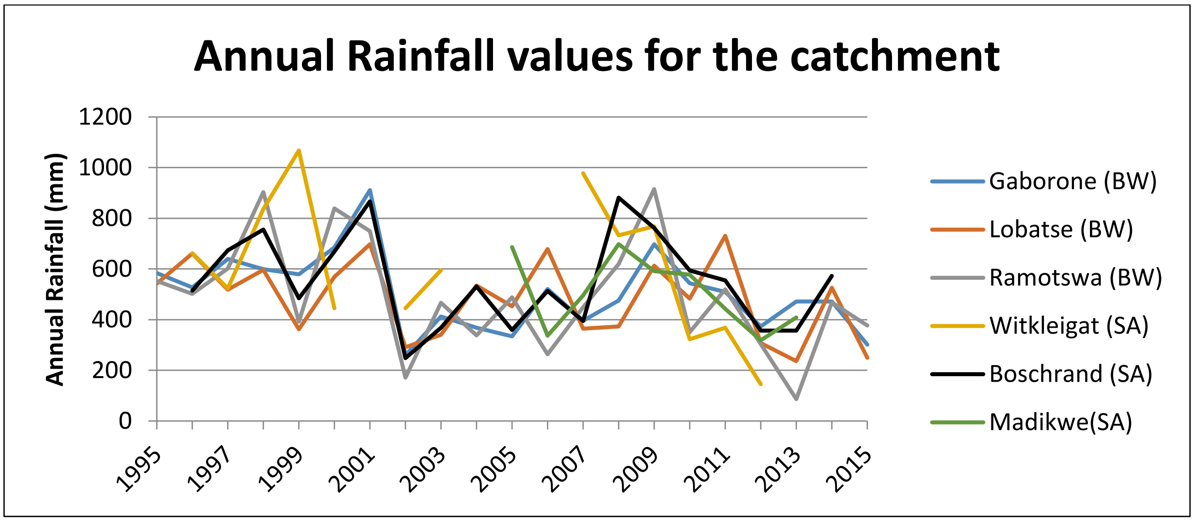

Figure 22. Annual rainfall for the catchment from 1995 to 2015.
Source: SAWS and Kenabatho P.

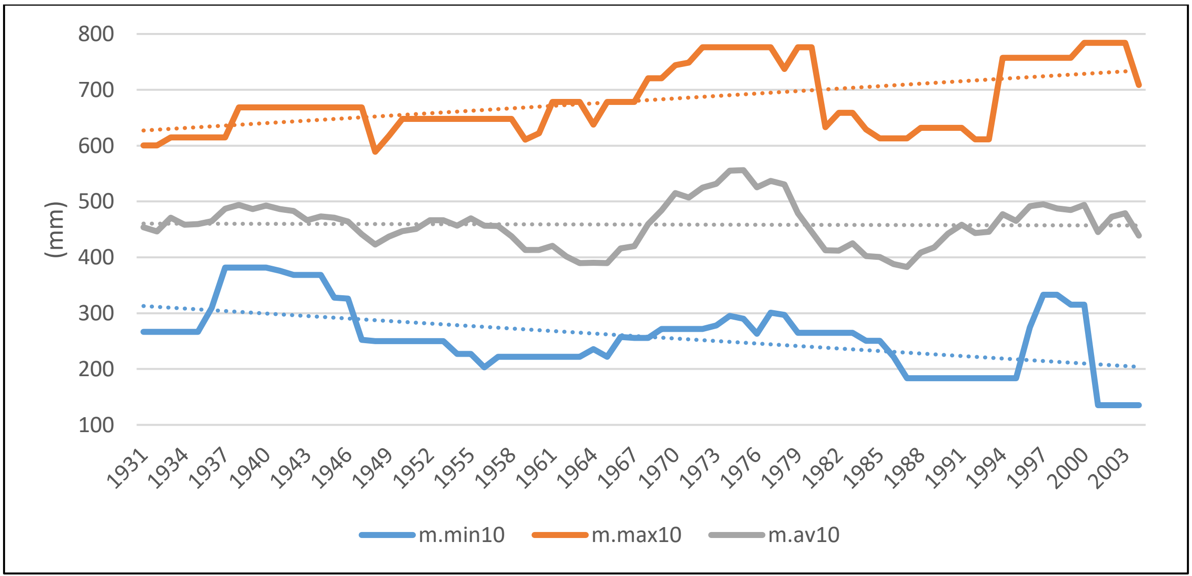

Figure 23: Trend in annual rainfall from Gaborone rainfall station (1925-2014), Ramotswa rainfall station (1980-2014), and Lobatse rainfall station (1922-2012).
Source: McGill B.

Recharge from surface water

The Ngotwane river is flowing northward across the study area and crossing the outcrop in Ramotswa town. Surface water interacts with ground water in all types of landscapes and the interaction takes place in three basic ways (Figure 24) (Winter et al. 1998):

- river gains water from inflow of ground water through the riverbed (groundwater discharge)
- rivers lose water to ground water by outflow through the riverbed (groundwater recharge),
- gaining in some reaches and losing in other reaches.

That means that the groundwater table in the vicinity of the river must be higher than the level of the river for discharge mechanism and lower for recharge mechanism.

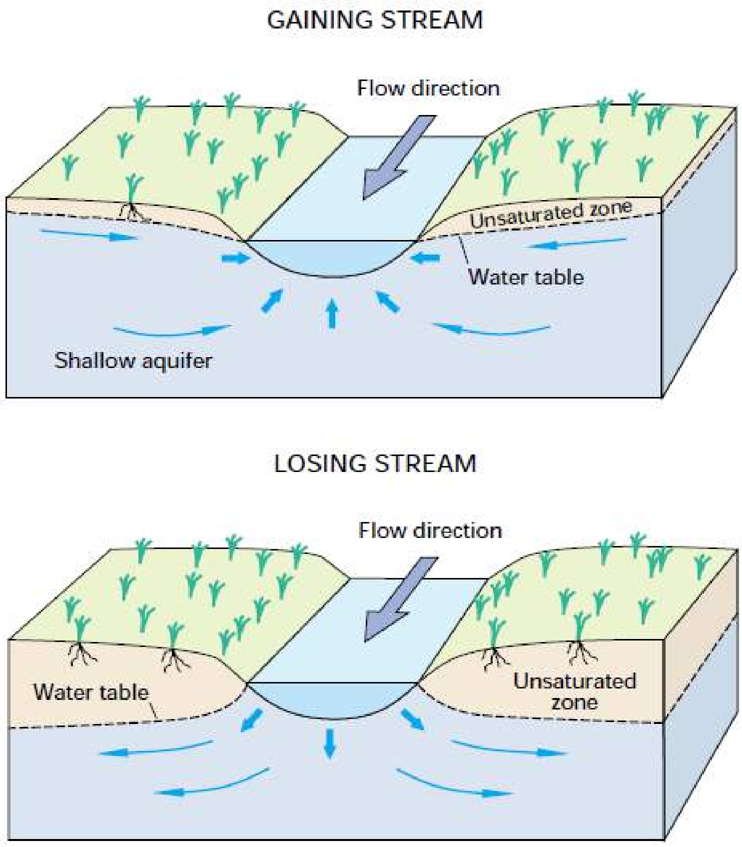

Figure 24: Interactions between river and groundwater (Winter et al. 1998)

The Ngotwane River being non-perennial, it is easy to conclude that the river is not gaining water from the aquifer. However, the flow mechanisms can be more complex. Despite the lack of data, hypothesis can be about surface water – groundwater interactions as following: when the river flows (rainy season), the river could recharge the groundwater but, groundwater can discharge into the river (baseflow) when the water table starts to be higher than the river-water surface or the riverbed. Groundwater could work as river flow buffer when rain stops. Outside the aquifer study area and downstream of the Molatedi Dam, the perennial Marico River is believed to be a source of recharge for the upper karst zone where the river is crossing the dolomite outcrop.

Recharge origin: environmental stable isotope

Environmental isotopes have largely been used by hydrogeologist to characterize and to trace water of different origins. The stable isotopes in rainwater provide unique signatures, which are marked by atmospheric processes, altitude and latitude, and the typical weather pattern during a year. The common practice is to plot groundwater data on stable isotopes of hydrogen-2 and Oxygen-18 diagrams, along with the meteoric water line of local precipitation as reference line. Figure 25 shows the results of the stable isotope analysis. Two main groups were distinguished: direct rainfall infiltration (data above the meteoric water line) and diffused rainfall infiltration (data below the meteoric water line). Diffused rainfall infiltration corresponds to slow accumulation of rainfall and/or recharge from runoff concentrated into depressions either from intense rainfall event and topographical effects. The Supingstad area (north-eastern part of the aquifer) corresponds to areas with direct rainfall infiltration while the rest of the study area correspond to a mix of direct and diffused rainfall infiltration. This may indicate that recharge is driven by various processes such as localized recharge from surface runoff or direct rainfall recharge depending on the geology and/or the topography. In addition, the water samples were highly enriched in heavy isotope, indicating recharge that occurred long time ago.

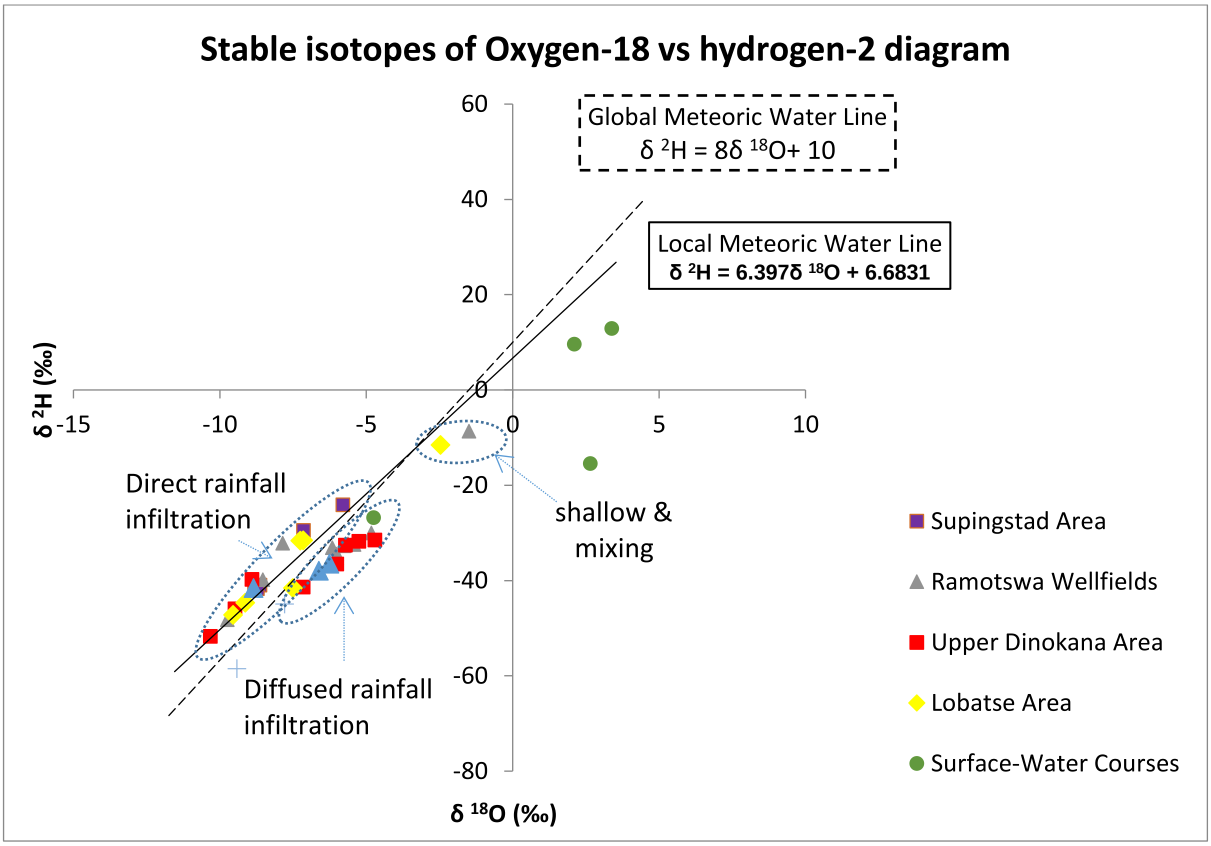

Figure 25: Correlation of stable isotopes of Oxygen-18 versus hydrogen-2 diagram of groundwater samples collected within the greater Ramotswa area. Rainfall isotope data from the upper Dinokana area was collected during field work. Global Meteoric Water Line and Local Meteoric Water Line (Lobatse) are plotted for comparison.
Source: Baqa S.

Age of groundwater

The method of tritium aging is based on the premise that precipitation contains a small amount of radioactive tritium and therefore, the rainfall-infiltrating through the subsurface consists of tritiated water in which its concentration decreases with a half-life of 12.43 years (Vogel et al. 1974). From the analysis, the time that elapsed since the tritiated water moved across the water table and became isolated from its source is determined. The age determined would be calculated from the tracer concentrations and equated to the relative/apparent age of groundwater. The results of the tritium aging analysis are shown in Figure 26. In the north and South of the study area, groundwater is mainly sub-modern water which means that it has been recharged prior to 1950s. The central part of study area is a mix of sub-modern and modern water which correspond to more recent recharge (Clark and Fritz, 1997).

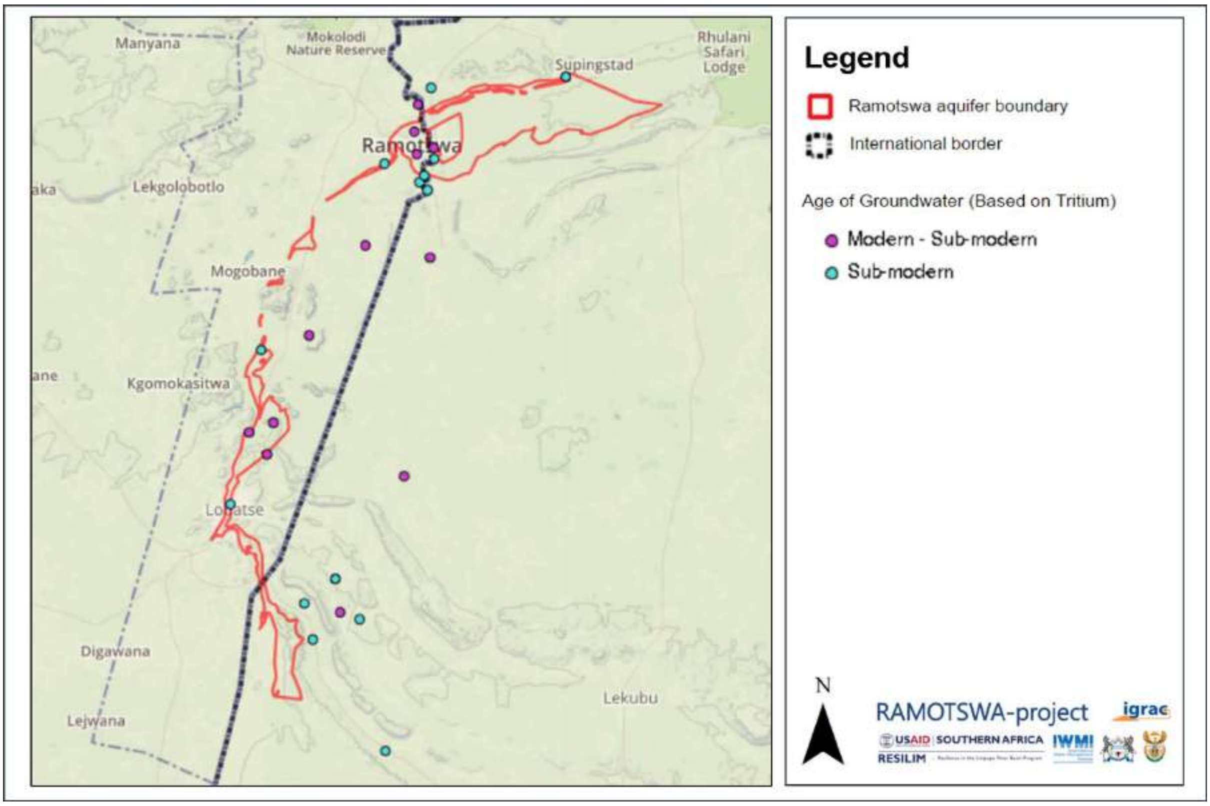

Figure 26: Groundwater aging distribution based on tritium isotope
Source: RIMS

Recharge estimation

During the fieldwork, 36 water samples were collected and analysed for chloride profiling. Assuming that there is no chloride from halite minerals, the Chloride Mass Balance (CMB) method is based on the high solubility and chemically conservative behaviour of chloride, and that most plant species do not take significant quantities of chloride in soil water. As a consequence, the chloride concentration in subsurface zone is mainly concentrated as a result of evapotranspiration in the root zone. In general, low chloride concentration is correlated to high recharge rates, while high chloride concentration is correlated to low recharges rates. Figure 27 presents the results of the CMB. Generally, there is higher recharge in the southern part of the aquifer at the bottom of hills (sometimes outside the dolomite outcrop) than in the northern part while rainfall is slightly lower in this southern part. The average recharge value in the study area is about 76 mm/year. However, recharge estimates seem very high for some samples with recharge estimates higher than 40% of the mean annual rainfall. High uncertainty on the method comes from the lack of knowledge of the chloride concentration in rainfall as only one rainfall sample has been collected and analysed for chloride concentration. According to Gieske (1992), recharge values vary from 10 mm/year to 70 mm/year in in an area between Lobatse and Otse, with an average value of 18 mm/year.

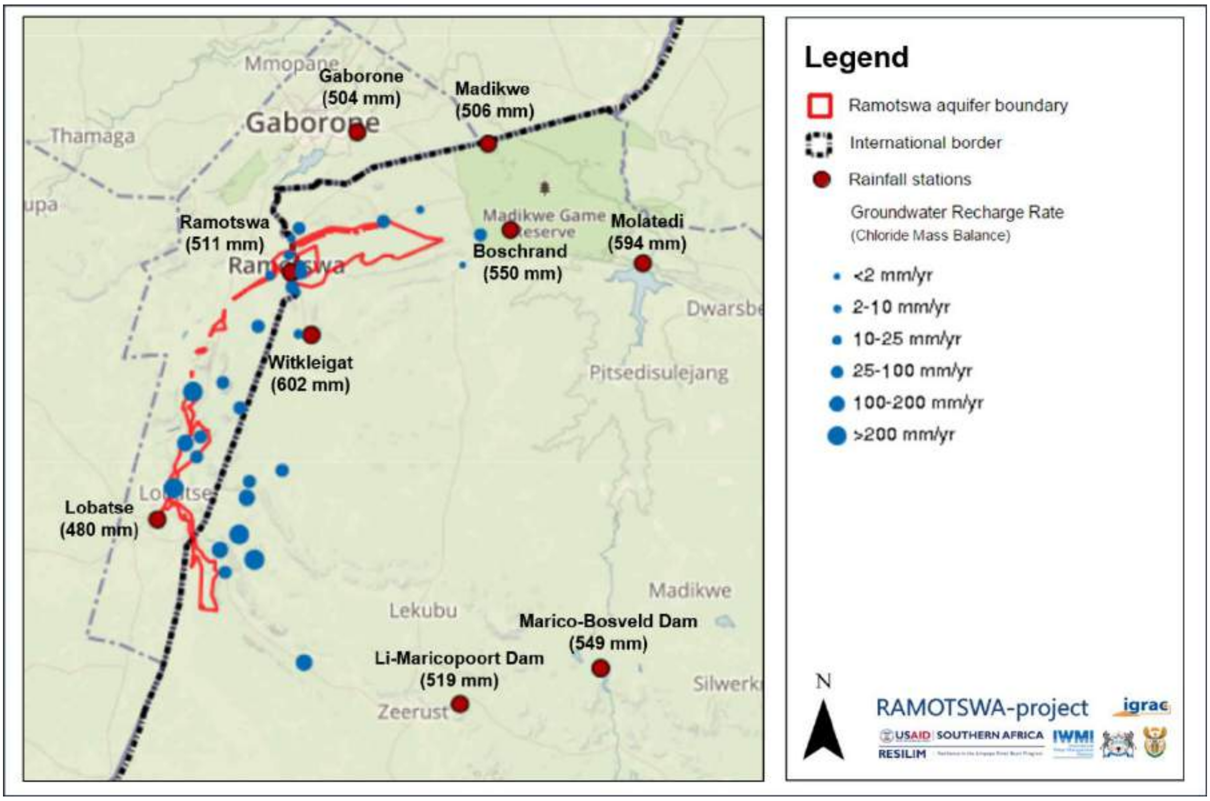

Figure 27: Recharge distribution in mm/year based on CMB
Source: RIMS

4.4.2. Discharge mechanisms

Natural discharge: rivers, springs and depression

There is no apparent baseflow from groundwater for the Ngotwane River as the river is non-perennial. The river seems to flow only during rainy season. However, it is believed that groundwater discharge to the river could occur. In fact, groundwater could work as river flow buffer when rain stops as explained previously in the recharge from surface water section. Better understanding of baseflow at the end of rainy season need to be investigated but there is no record of the natural flow of the river.

Groundwater discharge occurs mainly in South Africa as springs and eyes, eyes being larger springs from circular or oval bowl-shaped surface depression sinkholes. There is no record of eyes in the study area but discharge through springs exist in the southern part of the study area. Spring locations seem to be closely related to the occurrence of the (impermeable) dikes and are found on the 'upstream' side of the dikes. Large springs such as the Dinokana spring (not inside the study area), are not related to cave systems as is often the case with large springs in karst areas studied elsewhere in the world (Martini and Kavalieris, 1976). The Dinokana spring is the result of groundwater outflow against an impervious contact such as a fault or dolerite dike and due to the thinning of the dolomite lithologies along the western outcrop on the South African side of the study area (Pietersen et al. 2011). Figure 28 shows the potential locations of springs/depressions based on interpretation of satellite images. Improved fieldwork is necessary to check the accuracy of the identified springs/depressions and to determine the aquifer origin of the groundwater (i.e. there is two water bearing in the study area: dolomites or shales). This will allow to identify potential source of water to small communities for domestic small garden water uses.

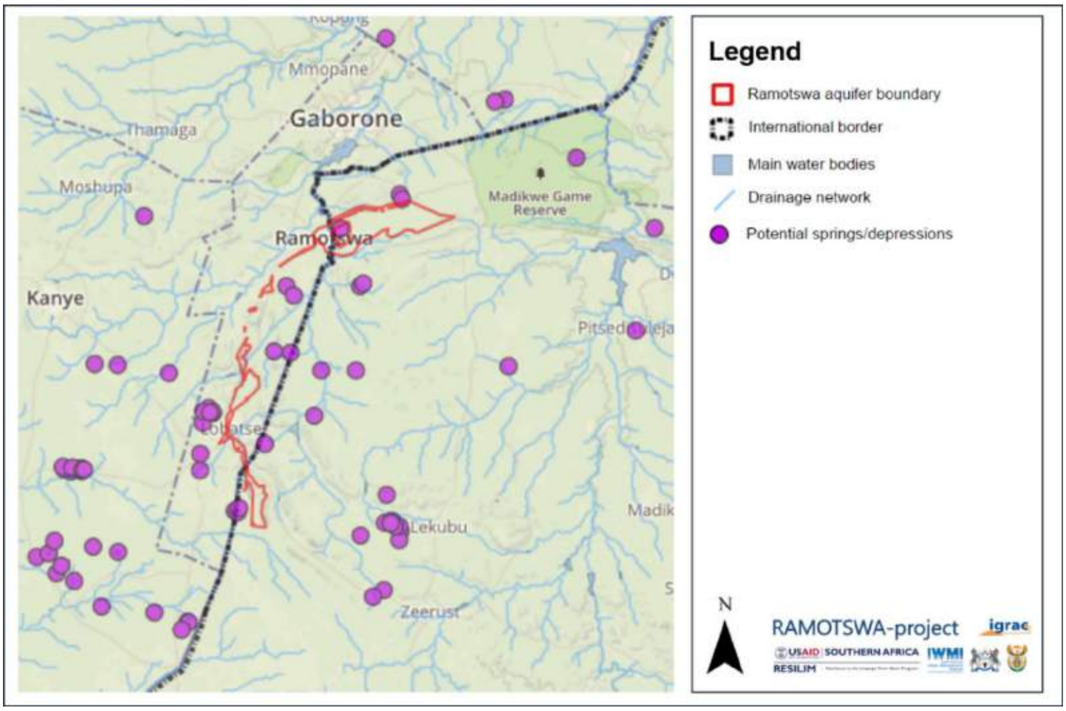

Figure 28. Locations of existing and potential springs and depressions, based on analysed from satellite image (google earth)
Source: RIMS

Other discharge: wells and wellfields

Discharge occurs also artificially by abstraction groundwater. In the study area, there are 4 wellfields for public water supply in Botswana (Ramotswa Wellfield, Pitsenyane Wellfield, Woodland Wellfield and Lobatse Wellfield) and numerous other boreholes but no exhaustive borehole inventory has been done yet.

5. Groundwater quality

5.1.General groundwater quality

During the fieldwork conducted from the 25th of August 2016 to 5th of September 2016 , a total of 36 groundwater samples was taken from the municipal boreholes (both monitoring and water supply boreholes), private (household) boreholes, dug well and from the springs (Figure 29). Water analysis was done by WUC, Aspirata and DWS for both chemical and microbiological parameters.

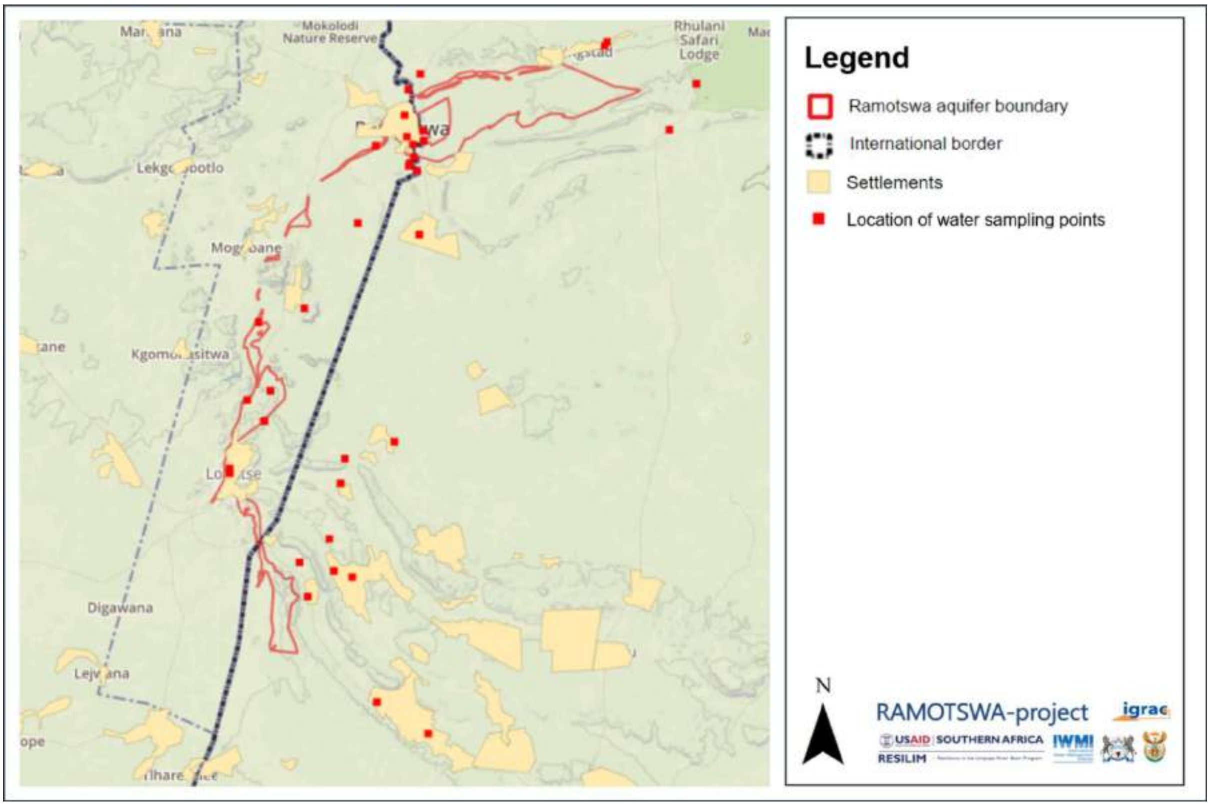

Figure 29: Location of the water sample points.
Source: RIMS

5.1.1. Groundwater chemistry

The bicarbonate has not been tested by WUC and thus, only the results from South Africa have been plotted into the Piper diagram (Figure 30). Almost all the samples are clustered in the calcium – magnesium – bicarbonate (Ca-Mg-HCO_3) facies of the Piper diagram. That reflects the chemistry of the dolomite, indicating that the dissolution of dolomite is the dominant process controlling the chemistry of the groundwater.

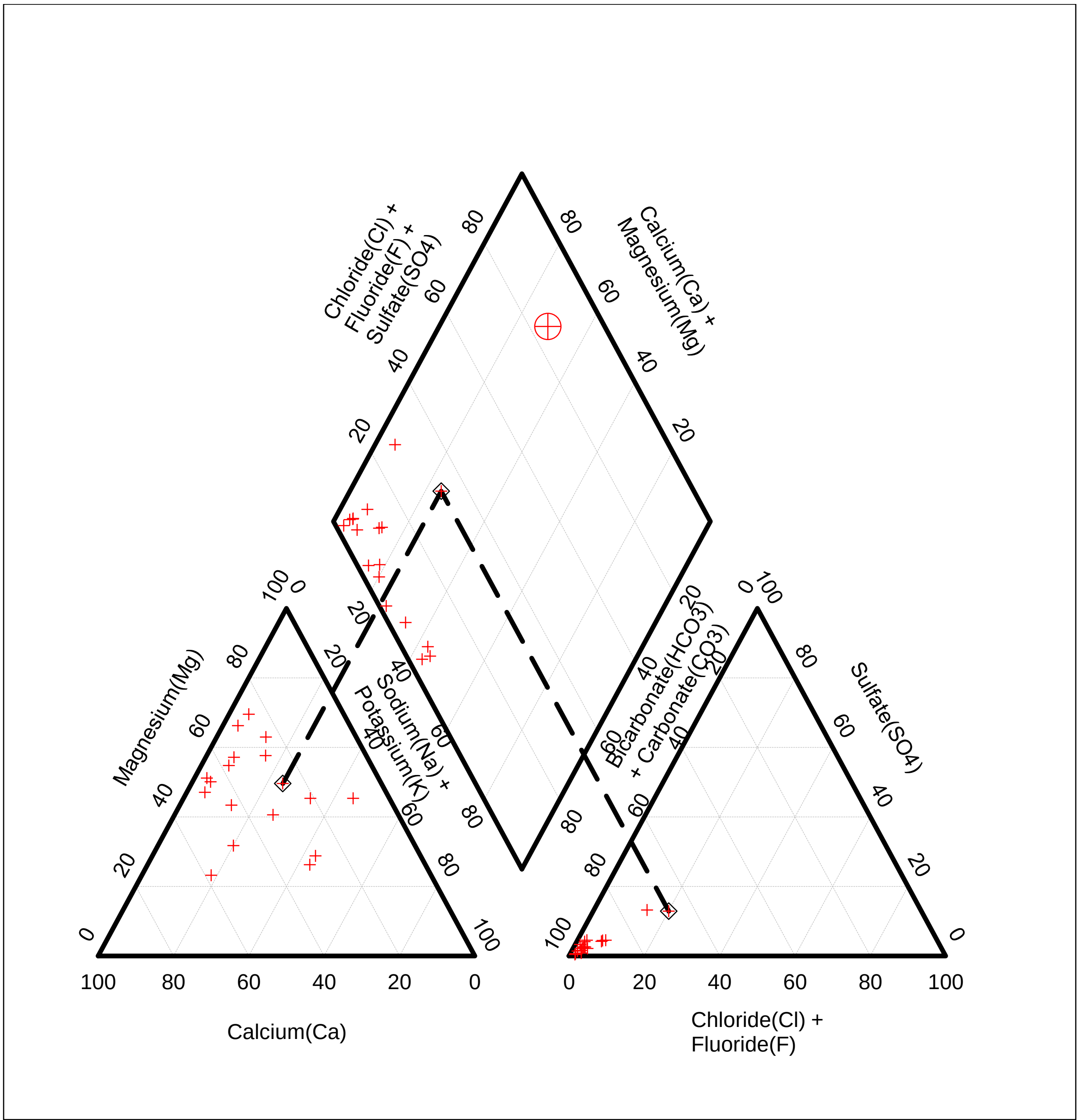

Figure 30: Piper Diagram for water samples from South Africa.
Source: Modisha O.

Table 5 shows the water analysis results, including both chemical and microbiological results. Chemistry results indicate that the water generally satisfies the water drinking standard of the country except for three samples in Botswana and five samples in South Africa. Drinking water standards are mainly a problem for magnesium and nitrate parameters. Water samples in Botswana has been also tested for a large range of cations. Results show that eleven samples are above drinking water standards for iron and nine of them are also above water standards for manganese. As one sample show that iron concentration is 200 time more than the drinking water standard limit, these results need to be taken with caution and probably re-checked.

Magnesium is of natural origin resulting from dissolution of the dolomite $CaMg(CO_3)_2$. It is possible that above average magnesium concentrations are associated with high nitrate concentrations (oxidation of organic material by nitrate would result in a lowering of the pH which can result in additional dolomite dissolution). High magnesium concentration in water results in an increased risk of cardiovascular disease (WHO, 2009).

Nitrate found in the groundwater the direct result of human activities (leakage from pit latrines and in more rural areas leakage from cattle excrements). High nitrate levels may present a serious health concern for infants and pregnant or nursing women. Nitrate can interfere with the ability of the blood to carry oxygen to vital tissues of the body in infants of six months old or younger. The resulting illness is called methemoglobinemia, or "blue baby syndrome" (WHO, 2016).

The most common sources of iron and manganese in groundwater are naturally occurring, for example from weathering of iron and manganese bearing minerals and rocks. Table 1 shows that the Ramotswa Dolomite is associated with the Penge/Ramotswa formation which is a banded iron formation. That could explain the natural source of iron and manganese in the groundwater. However, industrial effluent, acid-mine drainage, sewage and landfill leachate may also contribute iron and manganese to local groundwater. While manganese and iron are not a health concern at levels causing acceptability problems in drinking-water (WHO, 2003 and 2011), more investigation is needed to understand the contamination source of both elements.

Table 5: Chemical analysis of groundwater samples (36 sample points) collected during the period from 25th August 2016 to 5th of September 2016

Parameters	Unit	Botswana Drinking Water Standard-BOS32 (2009) – Class II	South Africa National Standard (SANS 241 - (2015)	Number of sample over the standards				
				In Botswana		In South Africa		More restrictive limit
				BOS32	SANS 241	BOS32	SANS 241	
pH	-	*5.0 – 10.0*	5 – 9.7	0	0	0	0	0
Electrical conductivity EC at 25 °C	µS/cm	*3100*	1700	0	0	0	1	1
TDS	mg/l	*2000*	< 1200	0	0	0	0	0
Sodium, Na	mg/l	*400*	200				0	0
Potassium, K	mg/l	*100*	50	0	0	0	0	0
Magnesium, Mg	mg/l	*100*	70	1	6	2	4	10
Calcium, Ca	mg/l	*200*	150	0	0	0	0	0
Chloride, Cl	mg/l	*600*	300	0	0	0	0	0
Sulphate, SO4	mg/l	*400*	500	0	0	0	0	0
Ammonia N	mg/l	*2*	1.5	0	0	0	0	0
Fluoride F	mg/l	*1.5*	1.5	1		1	1	2
Nitrate, NO3	mg/l	*50*	48.7	1	1	0	0	1
Nitrite NO2	mg/l	3	0.9	0	0	0	0	0
Iron, Fe	µg/l	300	300	11	11	Not Tested		11
Manganese, Mn	µg/l	100	100	9	9	Not Tested		9
E. Coli.	unit	Not detected	Not detected	3	3	3	3	6
Total coliform	unit	Not detected	< 10	9	7	13	9	22

5.1.2. Water microbiology

The only microbiological parameters which have been tested are the Escherichia coli (abbreviated as *E. coli*) and total Coliforms. *E. coli* are bacteria found in the environment, foods, and intestines of people and animals. *E. coli* is part of the faecal coliform group. Some kinds of *E. coli* can cause diarrhea, while others cause urinary tract infections, respiratory illness and pneumonia, and other illnesses. If *E.coli* is present in the water, it means that there has been recent faecal contamination and other pathogens may be present too. Coliform bacteria are unlikely to cause illness but their presence in drinking water indicates that disease-causing organisms (pathogens) could be present too. If *E.coli* is absent, but only total coliforms are present, there is a risk of contamination from other pathogens too. Appropriate disinfection before using the groundwater for drinking purposes could eliminate the bacteria.

Results indicate that three samples in South Africa and three samples in Botswana are contaminated with *E. Coli* and that almost half of the samples are contaminated by coliforms. Unfortunately, water from some boreholes is used without a disinfection system. That is the case in Radikkudu village for one community water supply tap where high number of *E coli* count where found. This is concerning. This could be due to the nearby livestock excreta from a kraal situated less than 100 m from where the borehole is located. While one borehole with *E,Coli* is near a pit latrine, it is not immediately clear what may be the source of pollution for most of boreholes with *E. Coli* in the water samples. Surroundings environment of the borehole include an abandoned dumpsite or old farm land. The spatial delineation of the *E. coli* and total coliform are shown in Figure 31 and Figure 32, respectively.

Total coliform counts across sample sites seems to follow a similar trend to that of *E. Coli* with additional sample sites identified with total coliform indicator where *E coli* counts were not picked up. In fact, more that 60% of the sample are contaminated with total coliforms. The sources of pollution at the additional sites identified by total coliform indicator coupled with the study of surrounding environment are as follows. One site has prevalent pit latrines in this village with the potential pollution source less than 500 metres from private borehole. Another site is a private borehole located on the highly karstified region of the aquifer with the borehole situated in a goat kraal with abundant livestock excrement. And finally, one site is a community tap located not far from the Ngotwane dam with potential pollutant sources being either pit latrines or huge irrigation activities nearby the village with probable use of fertilisers.

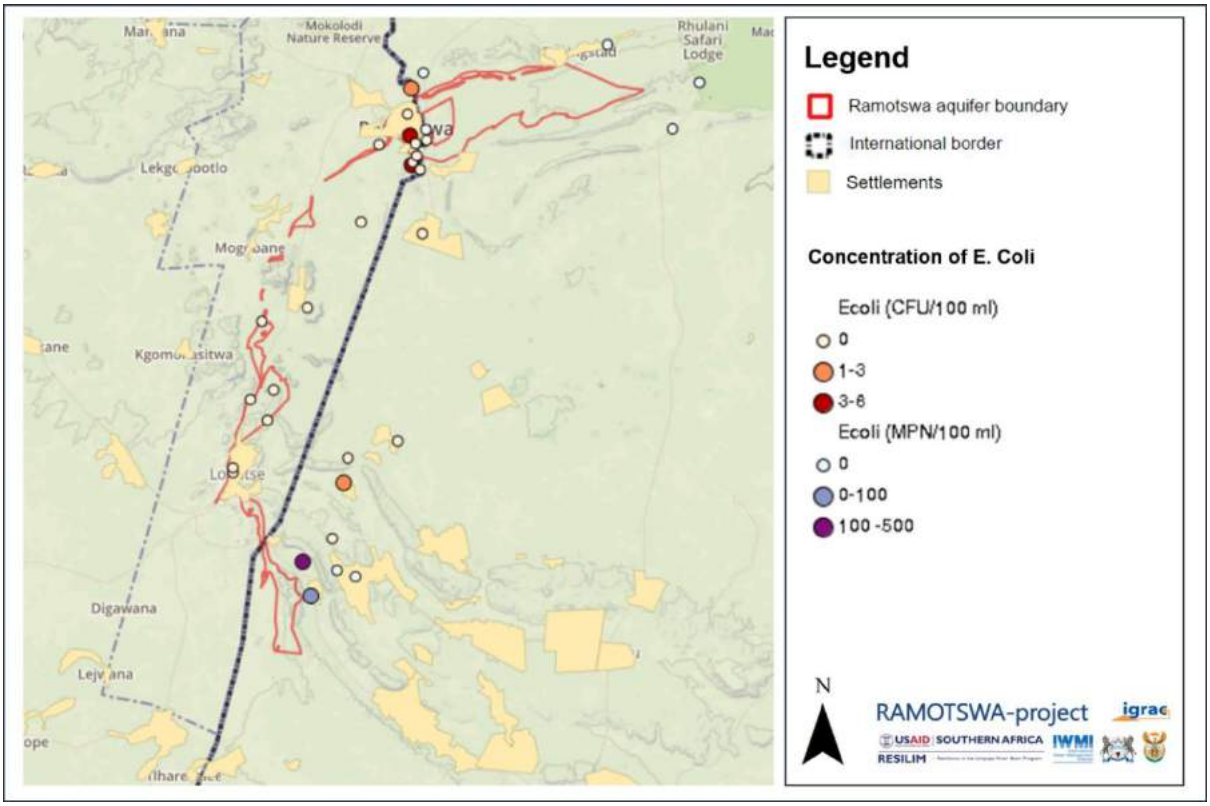

Figure 31: Concentrations of *E. Coli* (note that 2 different techniques were used to analyse *E. Coli* in the set of samples).
Source: RIMS

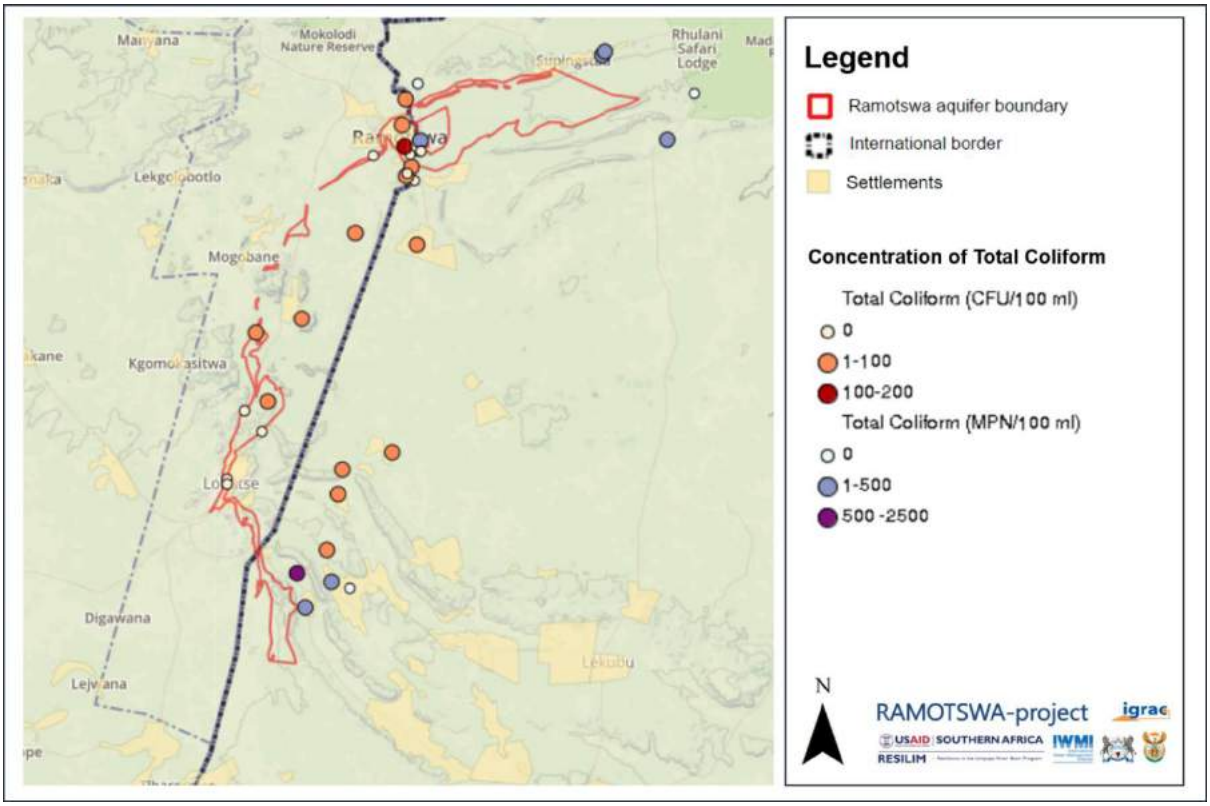

Figure 32: Concentrations of Total Coliform.
Source: RIMS

5.2.Nitrate contamination

The sum of nitrate and nitrite will be used across the entire study area to understand the nitrate contamination in the study area. Generally, nitrate and nitrite concentrations are below the WHO nitrate guideline limit of 50mg/l (WHO, 2017). For one site inside Ramotswa town (Botswana), the concentration is nearly twice the permissible concentration and one site is just below the limit (Supingstad, South Africa). Table 7 shows the chemical analysis results of groundwater sample in comparison with the Botswana (Botswana Bureau of Standards, 2009) and South African (South African National Standard, 2015) national drinking standards. Figure 33 presents the spatial distribution of the nitrate and nitrite concentration. An assessment of increased nitrate and nitrite concentrations would have to take into account karst maturity, population density, rainfall amounts and a study of the surrounding environment. It is interesting to note that both sample sites with elevated nitrate and nitrite concentrations are found inside villages (i.e Ramotswa and Supingstad), in the north-easterly region of the study. That corresponds to areas where groundwater levels are shallow, meaning natural retardation processes are not effective in removing nitrate from the polluted water and rainfall increases the concentrations. These points are also located where the aquifer is shallow and has more karstification, therefore allowing pollutants to pass rapidly to the water table. The highly karstified and shallow water levels have also been identified by Ranganai et al. (2001) as contributing factors to groundwater pollution around Ramotswa village.

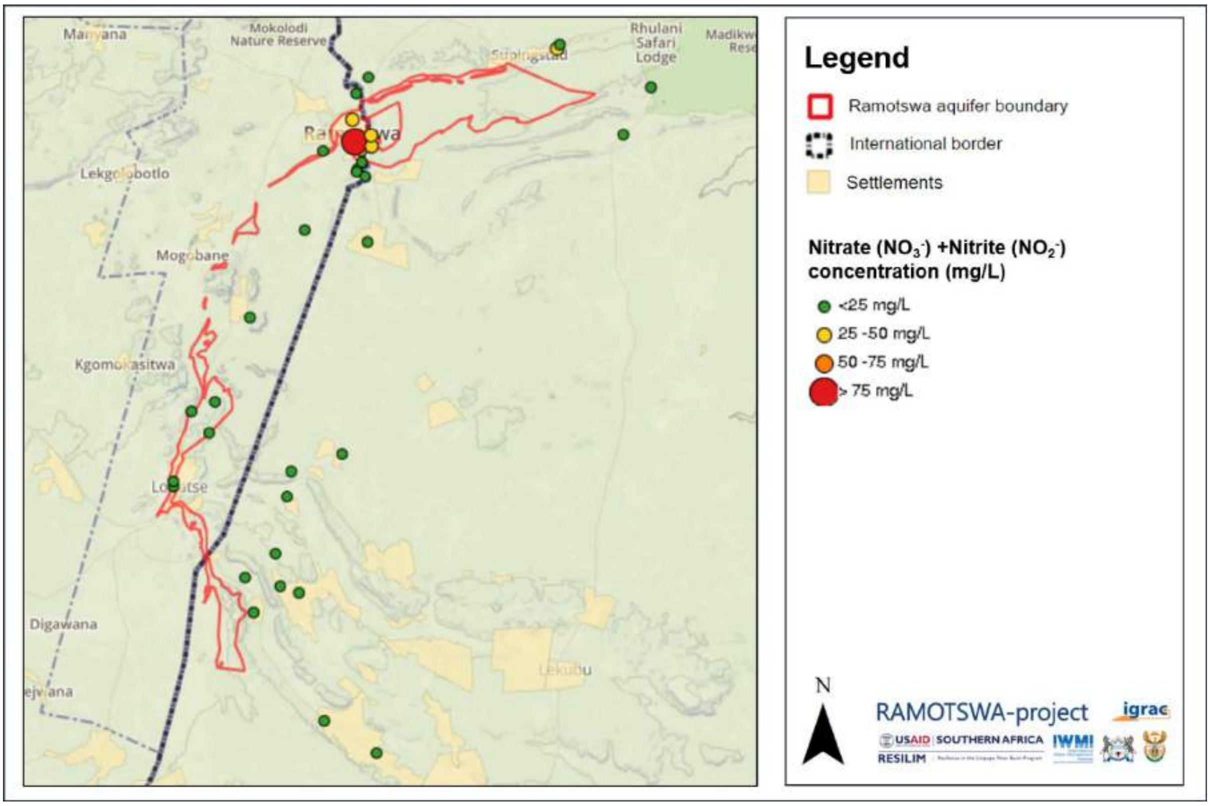

Figure 33: Nitrate and nitrite concentration in the study area
Source: RIMS

Generally, pollution is from human activities. Pollution is probably from the continued use of pit latrines, especially at sites where waste may directly enter the aquifer. This is particularly true in the case of Ramotswa. Contamination from pit latrines is less significant in Lobatse. In fact, in parallel to the development of pit latrines, the increase in nitrate concentration in the Ramotswa Wellfield seems to be observed during the period 1983 – 1995 (Figure 34).

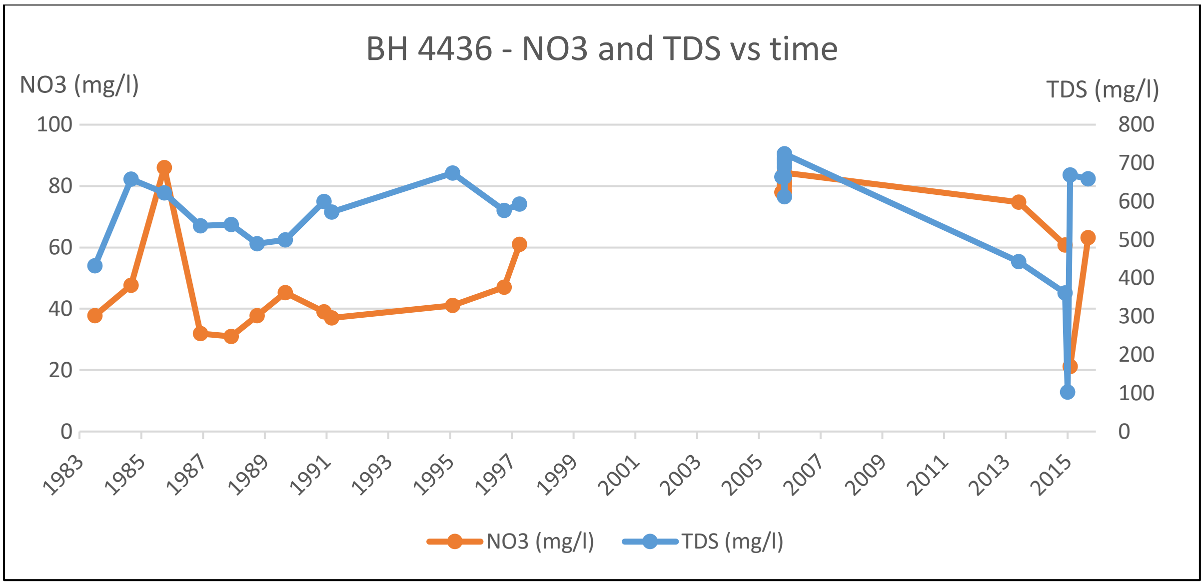

Figure 34: Trend of nitrate concentration for BH 4436 in the Ramotswa Wellfield
Source: WUC

After the building of the Ramotswa wastewater plant in 2001, there is no significant decrease in nitrate concentration. This may partly be because not all households have been connected to the waste water plant. Also in times of drought people revert to using their old pit latrines when they cannot or do not want to use water for flushing toilets in times of water use restrictions / rationing.

5.3. Groundwater contamination risk

During the February 2016 Ramotswa training workshop in Mahikeng, South Africa, participants mapped out their perceptions on ecosystem- and groundwater-dependent livelihoods in the study area in both Botswana and South Africa. The results of the exercise are based on expert opinion from both countries in the study, as opposed to observed data, but suggest important economic activities that relate to the ecosystem context. This is represented in Figure 35.

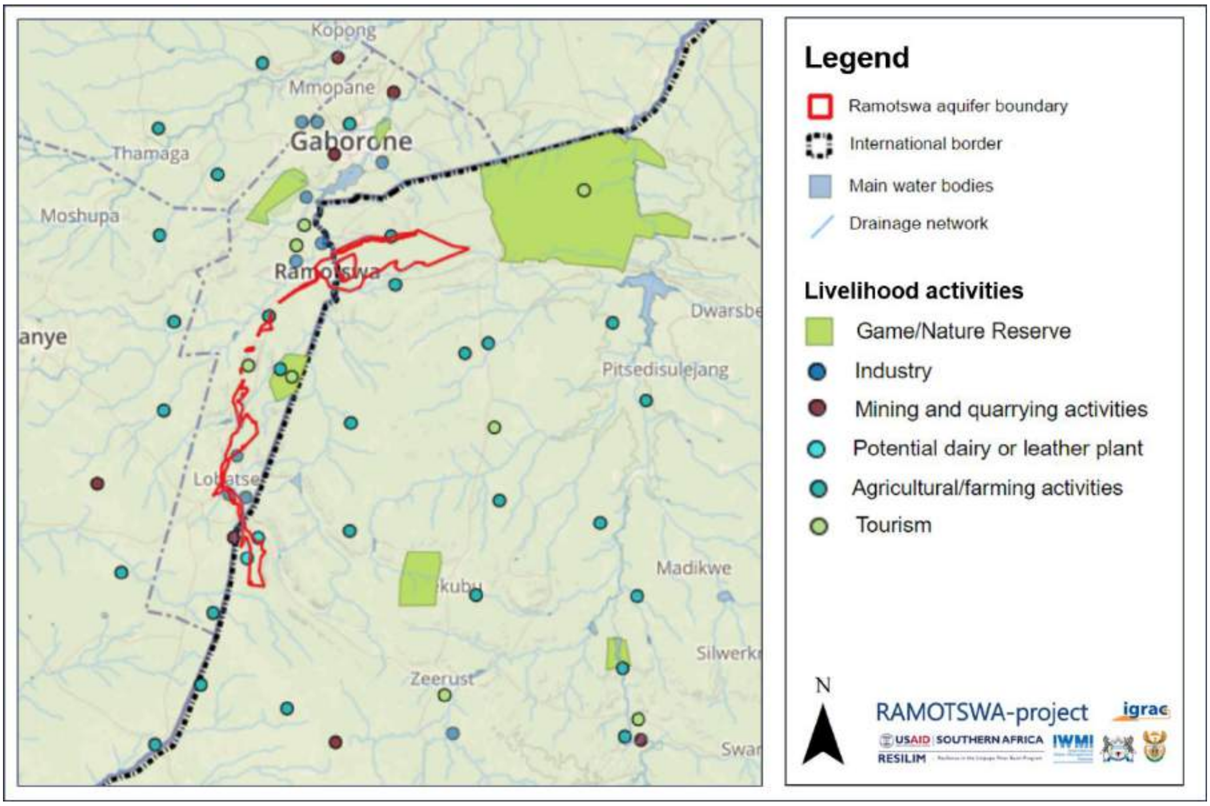

Figure 35. Map of perceived livelihood activities and vulnerability related to ecosystems and groundwater.
Source: RIMS

6. Conclusion

There are two aquifers in RTBAA: the Lephala Aquifer and the Ramotswa Dolomite, the latter being the major water-bearing unit and the focus of the project. Groundwater in the Ramotswa Dolomite is in the part of the dolomite where karstification has occurred. That means that acidic rainfall naturally dissolved the dolomite, creating fracks, cavities and sinkholes. The Ramotswa Dolomite corresponds to five carbonate formations referred to as either “chert-free” or “chert-rich” dolomite, the latter being the most important water-bearing formation. The aquifer is compartmentalized by dikes which act as barriers for groundwater flow between the compartments. The AEM survey allowed to identify the top and bottom of the Ramotswa Dolomite in the zone where the dolomite is on the surface in the limit of the depth of investigation of the AEM survey as well as the faults, dikes and collapses features in the dolomite. Interpretation of thirteen (13) compartments has been delineated, four of them being identified as transboundary. The eastern extend of the Ramotswa dolomite remains uncertain as east of the outcrop area the dolomite are dipping below the maximum depth of investigation of the AEM.

Based on a limited amount of data, it may be tentatively concluded that groundwater flow in the study area follows topographic relief and drainage patterns in a north north-easterly direction. Groundwater flow in the area is also controlled by geological structures such as dikes and fault. However, groundwater interaction across or between the identified compartments is largely unknown.

Groundwater recharge seems to occur mainly through direct rainfall infiltration, particularly in the north-eastern part of the study area, and through a mix of direct and diffused rainfall infiltration. That may indicate that recharge is driven by various processes such as localized recharge from surface runoff or direct rainfall recharge depending on the geology and/or the topography. It is also believed that the Ngotwane River could recharge groundwater through the riverbed when the river flows (rainy season). In the North and South of the study area, groundwater is mainly sub-modern water while the central part of study area is recent recharge with a mix of sub-modern and modern water. In fact, recharge is highly influenced by the rainfall pattern in the study area. Extreme weather condition (drought or flood) might occur more regularly in the region but the impact of these changes on groundwater recharge is still unknown. Average annual recharge estimates from CMB is 76 mm/year but some estimates seem very high for some samples with recharge estimate higher than 40% of the mean annual rainfall. Previous study estimated average recharge value vary of 18 mm/year (less than 4% of the mean annual rainfall). That can explained by high uncertainty on the method comes from the lack of knowledge of the chloride concentration in rainfall as only one rainfall sample has been collected and analysed for chloride concentration.

Groundwater discharge can occur naturally through springs which seem located closely to the occurrence of the (impermeable) dikes and found on the ‘upstream’ side of the dikes. Groundwater can also probably discharge into the river (baseflow) when the water table starts to be higher than the river-water surface or the riverbed. Groundwater could work as river flow buffer when rain stops even if the river is non-perennial. Other groundwater discharge is artificial discharge from groundwater abstraction.

Locally, groundwater has been contaminated by human activities with nitrate and coliform. This is due to contamination from pit latrines and agricultural activities (i.e. livestock excreta). Available data are very limited and not available for all settlements. Settlements most severely affected by nitrate pollution are Ramotswa (Botswana) and Supingstad (South Africa). One site with *E. Coli* contamination (Radikkudu village, South Africa) is particularly worrying as water from the borehole is directly used by the community without appropriate disinfection. Rapid action is recommended. While groundwater from the Ramotswa Wellfield is used for domestic purposes, groundwater does not satisfy drinking water standards for nitrate. WUC mixes water from the affected wells with water from other sources to obtain acceptable concentrations.

7. Recommendations for improving monitoring, other aquifer investigations, and groundwater use, protection and management

7.1. Building and sharing a common database for better management

In the RAMOTSWA project a shared RIMS has been set up (http://ramotswa.un-igrac.org) which currently contains all mapable results from this project. The aim of building such a database and international sharing of data is to understand and follow the transboundary aquifer system, so that it becomes possible to take informed decisions on the control of groundwater abstraction and contamination. This aligns with the improvement of the monitoring borehole network. Monitoring aquifer response and groundwater quality trends are key inputs for both qualitative and quantitative groundwater protection/management. In fact, changes in groundwater quantity and quality are often slow processes and these changes cannot be observed through simple one-off snapshot surveys alone. It requires more elaborate and long-term monitoring networks, as well as data interpretation to identify the changes. Table 6 presents some of the data necessary to support improved groundwater management.

Table 6: Type of data required for groundwater management adapted from Tuinhof et al. (2004)

Type of data	Baseline data	Time-variant data from field stations
Groundwater occurrence and aquifer properties	• water well records (hydrogeological logs, instantaneous groundwater levels and quality) • well and aquifer pumping tests	• groundwater level monitoring • groundwater quality monitoring
groundwater use	• water well pump installations • water-use inventories • population registers and forecasts • energy consumption for irrigation	• water well abstraction monitoring (direct or indirect) including recording of water use category
supporting information	• climatic data • land-use and groundwater contamination risk inventories • geological maps/sections and/or aquifer 3D model	• river flow gauging • meteorological observations • satellite land-use surveys

In the Ramotswa aquifer context, it is not only necessary to develop monitoring but also harmonising the data across the countries is important in order to build and share the database for better groundwater management.

7.1.1. Optimising the network of observation boreholes

There are two recommendations about how to optimise the network of observation boreholes in the study area:

- there is a need to **rehabilitate existing boreholes**. This necessitates an exhaustive and intense borehole survey of the study which will allow to identify unused borehole in strategic areas where data are needed. The borehole survey which should include the borehole use and groundwater abstraction volumes will also facilitate water balance calculation in the study area
- it is recommended that **new exploration or monitoring boreholes** should be installed in specific areas within the Ramotswa Project Area to better understand water levels, hydraulic conditions, and groundwater flow. The new boreholes should be installed in areas where there is a lack of existing boreholes, as well as areas where the Dolomite is present (Figure 36). The highest priority areas, are on the South African side of the international border, as this is where there is a significant lack of well data. Additionally, the largest extent of the Dolomite (and aquifer) is in South Africa. By adding additional wells to these areas in South Africa, an improved understanding of the variations in the aquifer across the international boundary can be obtained. These areas correspond also to place with already observed groundwater contamination. Other locations that are recommended for additional well installation are on the Botswana side of the international boundary, where there is a lack of existing wells.

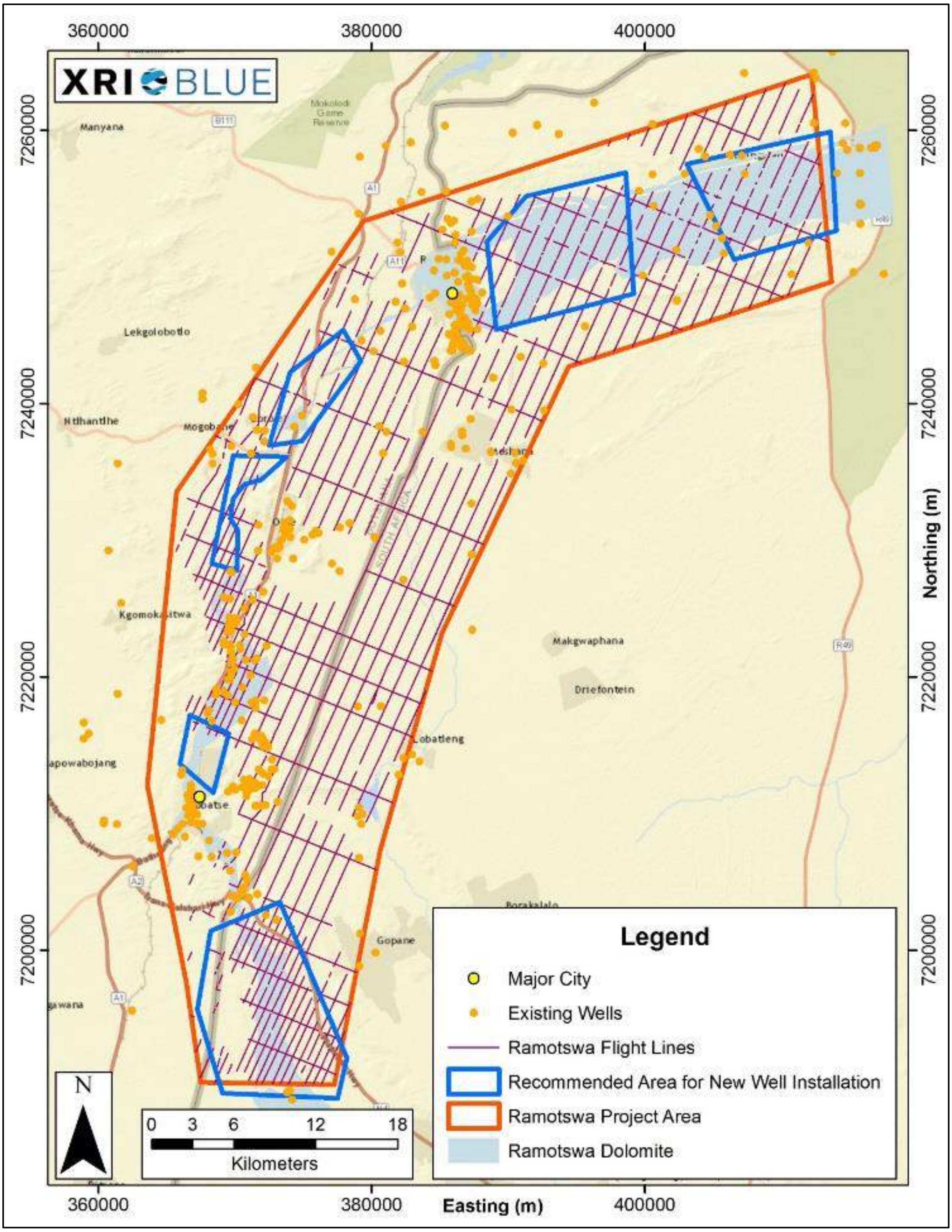

Figure 36: Proposed areas recommended for additional exploration / observation boreholes.
Source: RIMS

7.1.2. Developing water level and water quality monitoring

Groundwater quality and water level monitoring depends not only on an adequate network of monitoring boreholes but also on good quality of collected data based on appropriate methodology and regular data collection. It is recommended that each interpreted compartment should have adequate spatially boreholes distributed inside the compartments in order to follow the water level and water quality of each compartment. For small compartments (i.e. compartment number 11) installing one monitoring borehole could be sufficient. To obtain water level, water quality, and hydraulic conditions data, it is recommended that pressure transducers and chemical sensors are installed at key well locations to measure change in water level water level over time. This should be done in conformity with a maintenance and data collection plan.

In fact, availability of water quality data in communities in South Africa is lacking, despite these communities relying directly on groundwater. This exposes these communities to the risk of contamination from bacteria and chemicals, thereby affecting their health and well-being. Water quality data is still lacking across the whole study area. This is concerning given the fact that most villages are not connected to regional water scheme pipelines (for which the water quality is monitored). In those villages people have to rely on either community boreholes or private boreholes, and often the water quality is unknown to the people who make use of these facilities. In Botswana, the water quality monitoring takes place predominately at production boreholes and less so at observation boreholes. Considering that it is a karst aquifer, pollutants and contaminants could make their way to production boreholes and even affect communities relying on private borehole, where such boreholes are located. In the karst conduit systems. There is also a decline in groundwater level monitoring at points furthest away from communities and at observation wells furthest from production wells. Should populations growth increase or the village grow in the direction of these areas, historic water level monitoring would be helpful in coming up with solutions and plans of managing the aquifer.

7.1.3. Database harmonisation and data sharing

One of the challenges in the management of a transboundary aquifer is the discrepancies existing between country's databases, terminology and methods. Discrepancies can appear because of the legal framework of the country (e.g. different water quality standards and licensing standards), data collection methods and current usual practise in the country. Discrepancies can also exist within a country when data are kept at different institutes or departments with different (storage) systems. Hence, it is recommended to somehow harmonise data through active cooperation and dialogue between the two countries' authorities in charge of the collection and management of groundwater relevant data. The harmonisation must particularly concern the following bullet points:

- Data units must be identical in the countries. Particular attention must be given for the unit used for microbiological parameters and for the aquifer characteristics.
- Geo-referenced database must use the same coordinate system. It might also be necessary to internally harmonised the coordinate system in the case that several

coordinate systems exist in one country or if the usual coordinate system changed over time.

- Methodology for water sampling, collecting and measuring the data like chemicals or microbiology need to be identical in the two countries. The way that groundwater sampling is done can have a high impact on the groundwater quality results. In addition, the calendar recurrence of the monitoring should match on both side of the border.
- Software for the storage of the database must be easily compatible with the national database storage systems in order to facilitate data sharing.

Data sharing is key to increasing country cooperation and transparency for better groundwater management. The RIMS developed by IGRAC in the framework of this project already includes a harmonised geo-referenced database. This tool specifically designed for transboundary groundwater data is a basis for the countries to be further expanded as their own data sharing and groundwater management tool.

7.2. Improving knowledge about the aquifer mechanisms and structure

While the AEM survey improve the understanding of the geological aquifer structure, there is still a score to increase knowledge of the aquifer geology and hydrogeology. This can be done by developing the bio-physical and geophysics.

7.2.1. Understanding surface water and groundwater link

Based on existing data, it is very difficult to understand the exact relationship between the surface water and the groundwater. Only hypothesis have been developed in this report. Thus, more investigation is necessary to better understand this surface water and groundwater interactions. For example, river flow measurements at several points along the river should be checked whether the river is gaining or losing. This should be done in conjunction with groundwater level measurements at the vicinity of the river and regular flow measurements when the river flows. The impact of the Ngotwane Dam in South Africa and other small dams should be also taken in consideration. Installation of several river gauging stations, preferably automatic ones, might be necessary.

7.2.2. Improving surface geophysics data

In regards to future geophysical work in the study area, it is recommended that ground geophysical surveys should be carried out in areas where AEM data were not collected, including but not limited to the areas between flight lines, around Lobatse, the Manyelanong Game Reserve, other populated areas that the AEM system could not fly over (Figure 37). Three of the areas recommended for future geophysical surveys extend across the international boundary as it is critical to understand geology, hydrology, and the role that the international boundary may play. By filling in the gaps where AEM data was not collected, it will help to further refine the interpretations of the surface extent and subsurface characteristics of the geologic formations. It is recommended that the primary geophysical method of investigation should be electrical resistivity, as that would be easiest to incorporate into the AEM dataset for further refinement or extension of hydraulic property estimates by also taking in consideration the resistivity signature of the geologic units found by the AEM survey. Secondly, seismic, gravity, or magnetic data could also be helpful in interpreting the subsurface geology in these areas.

In addition, further investigation is required in some area where complex geologic structure (collapse features, dikes, and faults) was located (figure 38). Collapse features can be areas where substantial water may collect in the subsurface, therefore further investigating the extent of the identified collapse features are critical. This may be done through additional ground geophysics and/or exploratory drilling which is however very costly. Dikes and faults also can influence groundwater flow, and understanding their effects on groundwater is critical. The area extending across the international boundary is critical to understand geology, hydrology, and the role that the international boundary may play. Other geophysical surveys utilizing the gravity method are recommended for their ability to delineate and characterize the extent of both collapse features and dikes, though other geophysical methods can also be used to constrain the interpreted extent and characteristics of the geologic and structural features of the Dolomite. Therefore, ground gravity surveys with a dense data coverage combined with an additional geophysical method (seismic, resistivity, magnetics, etc.) designed in the highlighted areas are recommended. These recommended surveys would be an ideal opportunity for students in the geology or geophysics program at either The University of Botswana or The University of Free State to participate in the Project moving forward.

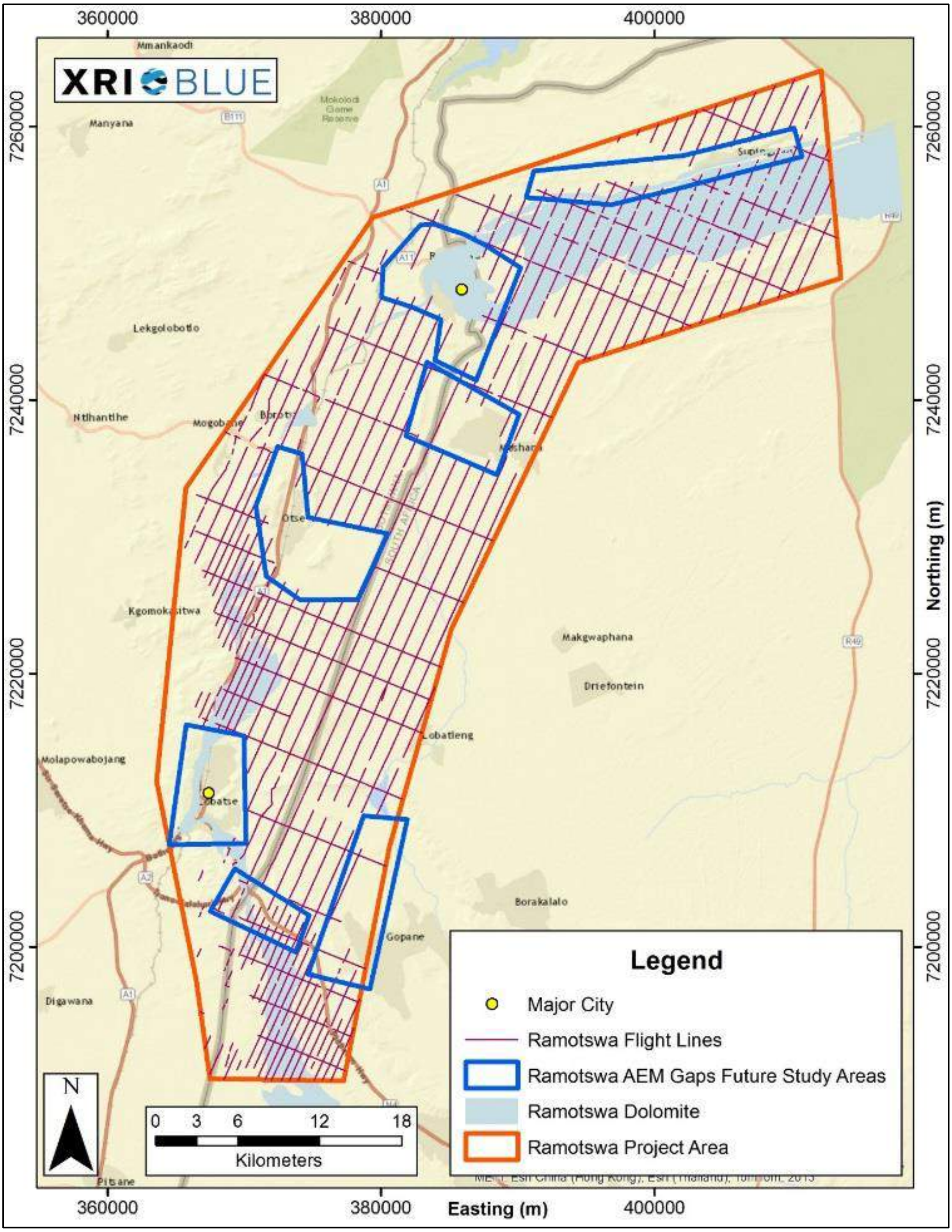

Figure 37: Proposed future further investigation areas.
Source: RIMS

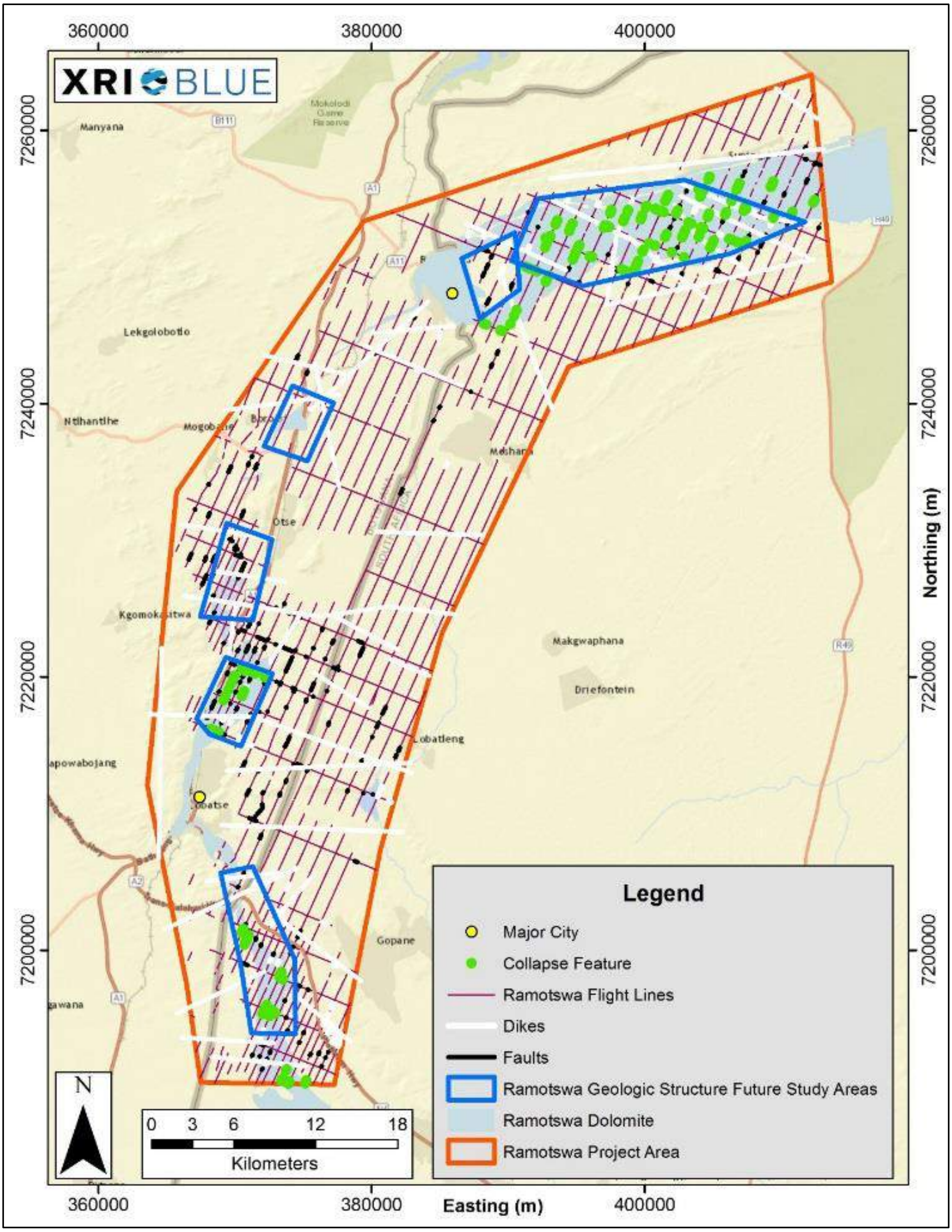

Figure 38: Areas where better understanding of the geological structure is needed.
Source: RIMS

7.2.3. Improving borehole geophysics data

Improving the knowledge of the borehole/well geophysics is key to better understand the aquifer and the other water-bearing formation of the study area. Because of the lack of data, some estimates have high uncertainty. If additional borehole data (i.e. water level, transmissivity, specific yield, hydraulic conductivity, pumping rates) is collected in the future within the study area, specifically resistivity of the pore fluid in the Dolomite, the porosity estimates can be recalculated. The new pore fluid resistivity data would need to be incorporated into the existing pore fluid resistivity dataset. The pore fluid resistivity grid would be recreated and the porosity estimates could be recalculated using the Lucia equation. This recommendation applies to the hydraulic conductivity estimate too. In complement, this data can be used to further understand the subsurface flow rates, geohydraulic connectivity of the system, whether or not dikes are serving as aquitards or aquicludes, and how faults are interacting with the system.

7.2.4. Improving surface geology

A coordinated effort should be made by DGS and CGS to construct an international geologic map. This involves creating a unified stratigraphy and working to remove all data gaps and discrepancies that currently exist in the simplified surface geology map. In particular, effort should be made at the multiple locations which were interpreted as having an incorrect geologic unit mapped at the surface (Figure 7). It is recommended that the surface geology in these areas is examined to determine the need to update the mapped geologic units. In addition, the interpreted surface geology of the AEM lines should be critically compared with the surface geology map in order to identify other discrepancies and facilitated the surface geology harmonisation. Finally, the Lephala Formation need to be clarify as there is discrepancy in the references, particularly with the idea of increasing water security in the area as explained below in section 7.5.

7.3. Land use planning

While there are number of ways of preventing groundwater contamination, such as appropriate well design / construction and management of potential contamination sources, land- use planning is one of the most effective ways to protect groundwater from contamination. Land-use planning is a dynamic process with social, economic and environmental interests which can influence to varying degrees the use of land and water. In addition, groundwater response to land-use impacts is often gradual and/or delayed and groundwater quality degradation, once it has occurred, is likely to be long-lived and costly to remediate. Figure 39 presents some potential sources of groundwater contamination based on different land-uses. Land-use planning focusing on groundwater protection should take into consideration both the geology and the hydrogeology factors.

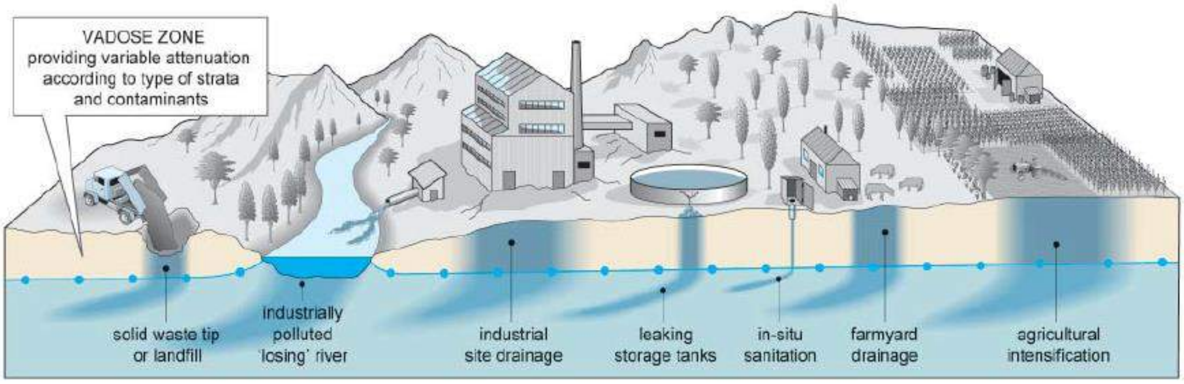

Figure 39: The link between land use and groundwater (Foster and Cherlet, 2014).

The Ramotswa Aquifer is a semi-confined aquifer and highly vulnerable to pollution. In fact, karstic aquifer with shallow groundwater tables are vulnerable by nature because of human activities that often occurs in the zone highly affected by karstification where productive borehole are found. This report clearly shows that the aquifer is contaminated by pit latrine and livestock. In the latest case, simple land-use management action like fencing a protective area around the borehole to avoid livestock presence in the surrounding of the abstraction borehole can be done. The determination of the protective area should be done by taking into consideration the hydrogeology conditions like surface geology, transmissivity and groundwater flow direction. Generally, in order to avoid groundwater pollution problems, selective land-use management policies and specific associated control measures need to be introduced to promote groundwater recharge quality protection at local scale. Such policies and measures can provide major economic and ecological returns in the long run by preserving groundwater quality (Foster, 1987).

7.4. Developing engagement of stakeholders

Stakeholder engagement should be seen as an on-going, long-term process that adapts to the contextual conditions and needs, and changes therein and its benefits are (AGW-Net el al., 2015):

- more informed and transparent decision-making;
- conflict prevention by development of consensus and information sharing;
- social benefits, because it tends to promote equity among users;
- economic benefits, because it tends to optimize pumping and reduce energy costs;
- technical benefits, because it usually involves stakeholders in maintenance and leads to better estimates of water abstraction;
- environmental benefits, because specific local concerns are addressed and incorporated into the management
- management benefits, because they trigger local stakeholder initiatives to implement demand and supply measures and reduce the cost of regulation.

In the case of the Ramotswa transboundary aquifer, stakeholder engagement should occur at multi-scale and multi-level. The multi-scale engagement refers mainly to the transboundary aspect of the aquifer which necessitates stakeholder engagement inside each country but it also includes local stakeholders with specific and localised interest for the underground resource. The multi-level engagement refers to the range of stakeholder from water users to policy maker but it ultimately includes international cooperation. Figure 40 propose a synoptic for the stakeholder engagement for participatory groundwater resource management of the Ramotswa aquifer

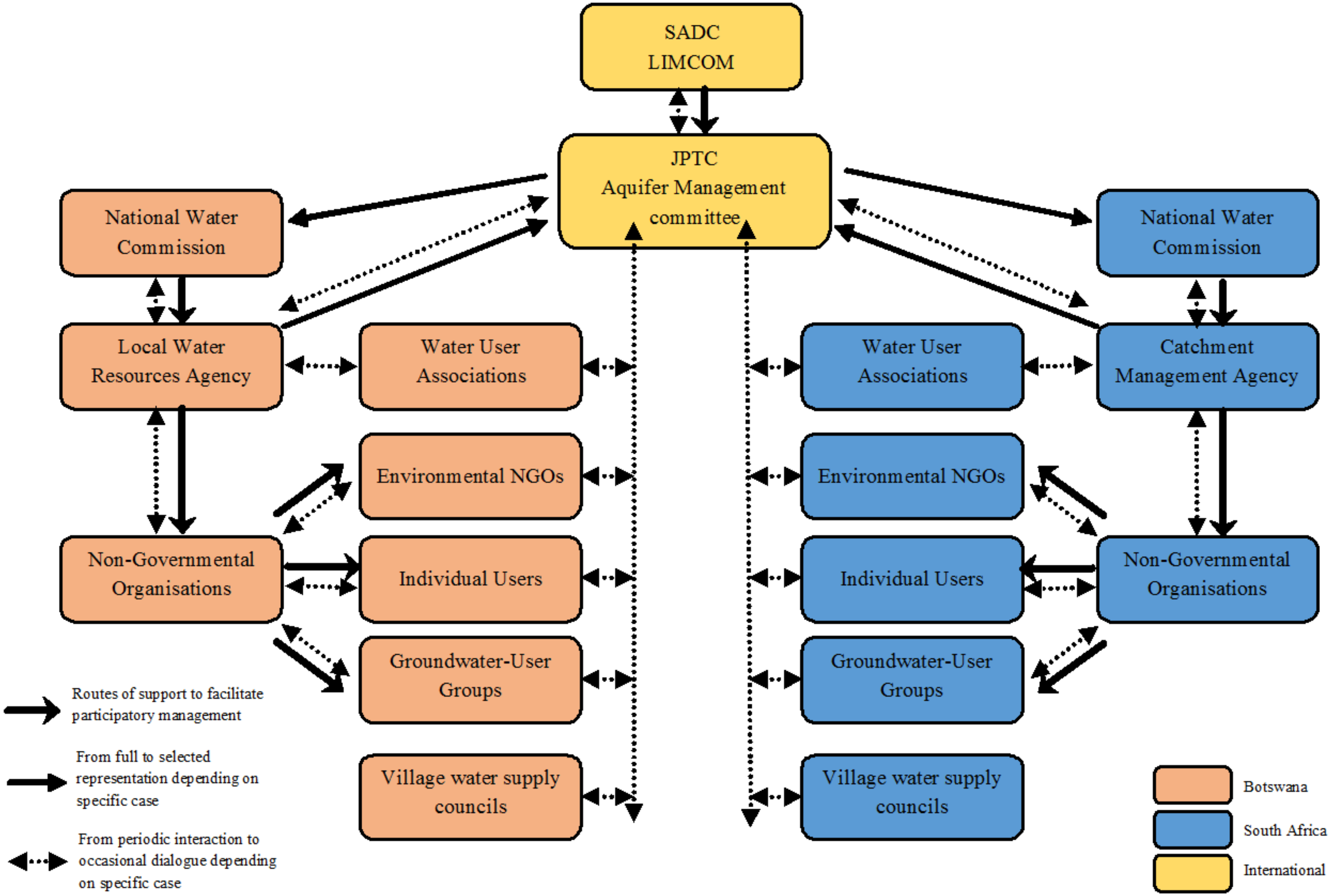

Figure 40: Proposed stakeholder interaction in participatory groundwater resource management, adapted from Garduño et al. (2011).

7.5.Using the aquifer for improving water security

Water demand in the area is planned to increase, especially because of the population increase in the Greater Gaborone area. While water demand management stays the cheapest option, the aquifer may help improving the water security in the area, especially in this context of limited water resource availability. The aquifer has a good storage capacity and it is thought that the aquifer can be used as water storage in the limits of its capacity. In the context of drought, the extra-water stored in the aquifer could increase water security in the area. Moreover, water from underground storage is much less affected by evaporation than surface water storage. Thus it is recommended to explore the Managed Aquifer Recharge (MAR) potential in the area in complement to water demand management.

MAR is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit (Dillon et al. 2009). Recharged water may be sourced from rainwater, storm water, re-used waste water or other water source like surface water (i.e. rivers and dams). According to Gale et al. (2006), MAR can be used to address a wide range of water management issues such as (i) temporary storage of water in the aquifer for future use, (ii) balance the variations in supply and demand, (iii) to raise the groundwater levels in over exploited aquifer, (iv) in areas where no suitable surface storages sites available, and (v) for securing and enhancing water supplies. In the Ramotswa project, the MAR options will be mainly to investigate the potential for increasing water storage for future use, while all different MAR uses are relevant here. For the Ramotswa project area it is also interesting to investigate to what extend MAR could contribute to reduce the risk of flooding of sensitive infrastructure like the Ramotswa wellfield and waste water treatment plants in the area.

Common types of MAR systems include: surface infiltration, subsurface infiltration using vadose zone wells or trenches, and direct injection, which uses wells to inject directly into an aquifer (Bouwer, 2002). Surface infiltration systems offer the best opportunity for controlling clogging problems and provide soil-aquifer treatment if quality improvement of the water is important.. However, in areas where evaporation is high, soils are impermeable, the aquifer is confined or impermeable strata existence between the surface and aquifers and sufficient land for surface infiltration is not available, surface infiltration systems are not suitable. In these cases depending on the depth of the impermeable layer, vadose zone wells, trenches or direct injection wells can be used. If the bottom restricting layer is not too deep (less than 3m) trenches can be used to drain the perched water. For deeper restricting layers (up to about 40 m) Vadose –zone wells can be used (Bouwer, 2002). Where the restricting layer is very deep injection wells are preferred. The disadvantage of surface infiltration and injection wells method is clogging problem. To minimize clogging the water should be pre-treated to remove suspended solids. In addition, the treatment of the water used for MAR must align with the final water quality needed for the abstracted groundwater. Ramotswa aquifer is mainly used for domestic and agricultural purposes. Hence, the water quality of the water used for MAR should reach quality standards close to potable standards, the latter being more restrictive than the agriculture quality standard.

Aquifer properties such as hydraulic conductivity (transmissivity) and storage coefficients affect MAR. Low aquifer storage, thin unsaturated zone, low hydraulic conductivity, high probability of clogging during recharge, loss of recharge water, degradation of water quality due to physical, chemical or biological processes are some of the factors that precludes the development of MAR.

MAR must be approached in an appropriate and rational manner to ensure the success of MAR in karst aquifers. Karst aquifers have complex characteristics that make them different from other aquifers (Bakalowicz, 2005). For MAR operations in karst aquifer it must be prevented that water flows through concentrated fast infiltration flow paths because of potential contamination risks and of rapid transfer to springs or abstraction borehole through conduits. Conduits are underground flow preference formed by dissolution of carbonate rocks that carry water from the recharge area to the discharge. According to Daher et al. (2011), MAR operations should be designed to avoid direct injection into the phreatic zone by making use of slow and delayed epikarst infiltration, epikarst being the upper part of the kasrt and considered as recharge regulator. MAR may not be feasible in extremely developed karst drainage systems. In such cases, injected water may not be stored for a sufficient period of time. Thus, while collapses features have been identified for better groundwater abstraction potential, these areas should be avoided for MAR which should be preferably done through surface or sub-surface infiltration when possible.

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