



Assessing wastewater and sanitation conditions and management in the Ramotswa transboundary aquifer area between South Africa and Botswana

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MEMOIRE DE FIN D'ETUDES

Assessing wastewater and sanitation conditions and management in the Ramotswa Transboundary Aquifer Area between South Africa and Botswana

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Promotion PARIS

Partenaires:



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Abstract

Since the eighties, the sanitation system has developed a lot in the Ramotswa Transboundary Aquifer Area between South Africa and Botswana. It was essential to protect the groundwater from sanitation in a region of water scarcity. At first, pit latrines were promoted in rural and urban areas. The efficiency of pit latrines depends on the construction quality and the soil characteristics. In the RTBAA, pit latrines can be considered as a direct source of nitrate pollution in groundwater by wastewater infiltration because of the fractured rock soil and the high groundwater table of the Ramotswa Aquifer [1][2]. Then, between 1985 and 2000, wastewater treatment plants were introduced in urban areas such as Gaborone, Lobatse, Ramotswa and Zeerust. But, with population increase and industrial development [3][4][5], wastewater treatment plants such as oxidation ponds are not efficient to treat wastewater. Discharge of wastewater treatment plant and losses from the sewerage network are indirectly affecting the groundwater quality. A vulnerability map of the aquifer to sanitation from the DRASTIC method delimits a priority area where sanitation facilities have to be improved. In fact, more than 50% of the Ramotswa aquifer is highly vulnerable to sanitation pollution during the wet season compare to 2.5% during the dry season. Climate conditions have an impact on sanitation pollution. Moreover, potential challenges of sanitation were assessed such as industrial wastewater pollutants, water balances and transboundary water pollution issues. To improve the current situation, some recommendations are given for on-site sanitation system, wastewater treatment plant management and the development of a sustainable sanitation system.

Depuis les années 1980, le système d'assainissement s'est beaucoup développé dans la région de l'aquifère transfrontalier de Ramotswa, situé entre le Botswana et l'Afrique du Sud. Il était primordial de protéger les eaux souterraines des potentiels contaminants provenant de l'assainissement dans une région où l'eau est si rare. Tout d'abord, les latrines à fosses ont été implémentées dans les zones rurales et urbaines. Or, l'efficacité des latrines à fosses dépend essentiellement des caractéristiques du sol et de leur qualité de construction. Dans la zone d'étude, les latrines à fosses peuvent être considérées comme une source de pollution directe de l'aquifère par les nitrates. En effet, ces structures ne sont pas adaptées pour un sol rocheux fissuré et avec un niveau élevé des eaux souterraines [1][2]. Puis, entre 1985 et 2000, les stations d'épuration ont été introduites en zone urbaine, comme par exemple à Gaborone, Lobatse, Ramotswa et Zeerust. Cependant, en considérant l'augmentation de la population et le développement industriel de la région [3][4][5], les stations d'épuration telles que les bassins de lagunage ne sont pas efficaces en termes de traitement des eaux usées. Ainsi, les eaux usées traitées et rejetées en milieu naturel et les pertes sur le réseau d'assainissement sont impliquées indirectement dans la dégradation de la qualité des eaux souterraines. Une carte de vulnérabilité de l'aquifère par rapport à l'assainissement a été réalisée selon la méthode DRASTIC et permet de délimiter une zone prioritaire en termes d'amélioration de l'assainissement. Selon cette étude, plus de 50% de l'aquifère Ramotswa est hautement vulnérable à la pollution issue des eaux usées pendant l'été, contrairement à 2.5% durant l'hiver. Les conditions climatiques ont donc également une influence sur cette pollution. De plus, d'autres potentiels enjeux en matière d'assainissement sont étudiés tels que la pollution des eaux usées industrielles, le bilan hydrique ou encore les enjeux de pollution d'eau transfrontalière. Afin d'améliorer la situation actuelle, des suggestions en termes d'assainissement sont données, et tout particulièrement pour développer un système d'assainissement durable.

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Acronyms

BMC	Botswana Meat Commission
BOD	Biochemical Oxygen Demand, unit : mg/L
BOBS	Botswana Bureau of Standards
CBD	Central Business District
COD	Chemical Oxygen Demand, unit : mg/L
DO	Dissolved Oxygen
DWA	Department of Water Affairs, Botswana
DWAF	Department of Water Affairs and Forestry, South Africa
E1	Natural estrogen estrone
E2	Natural estrogen estradiol
E3	Natural estrogen estriol
EC	Electrical Conductivity
E. Coli	Escherichia Coli
EE2	Synthetic estrogen ethinylestradiol
EFR	Environmental Flow Requirement
mamsl	Metres Above Mean Sea Level, unit
NAFTEC	National Food Technology Research Centre, Kanye, Botswana
NDP	National Development Plan
NTU	Nephelometric Turbidity Unit
RBC	Rotating Biological Contractor
RMLM	Ramotshere Moiloa Local Municipality, North West Province, South Africa
RTBAA	Ramotswa Transboundary Aquifer Area
SAT	Soil Aquifer Treatment
SBR	Sequential Batch Reactor
SHHA	Self Help Housing Agency
SS	Suspended Solids, unit : mg/L
TBA	Transboundary Aquifer
TCU	True Color Unit
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TON	Threshold Odor Number
US EPA	United States Environmental Protection Agency
WAS	Waste Activated Sludge
WHO	World Health Organization
WUC	Water Utilities Corporation, Botswana
WWTP	Waste Water Treatment Plant
WWTW	Waste Water Treatment Works

I. Introduction

Scarce and seasonal surface water supplies have rendered the population heavily reliant on groundwater resources in the area of the Ramotswa aquifer in the Upper Limpopo. Given the reliance on groundwater, it is critical that the quality of such water be ensured to avoid adverse health impacts. However, evidences sources suggests that conditions in Botswana and South Africa have driven increased adoption of on-site sanitation, conditions which have elsewhere led to pollution [6;7]. It is therefore critical to assess current water quality and pollution risks in the Ramotswa Transboundary Aquifer Area.

Despite some investigations into water quality and pollution in the region, an aquifer-oriented assessment has not been undertaken. Some hydrogeological investigations have been undertaken in the Ramotswa and Lobatse wellfields, respectively by Beger [8] and Staudt [9]. These reports give an identification of the Ramotswa Transboundary Aquifer on the Botswana side and assess the groundwater as polluted by nitrate. Studies were limited on the Botswana side compare to this study which is addressing by giving attention to both sides. Ranganai et al. [1] also reported the extremely vulnerability of groundwater in the Ramotswa wellfield to pollution due to various anthropogenic activities as septic tanks, pit latrines, wastewater discharge and dumpsites. These reports indicate that sources of pollution coexist at practically the same depth as the groundwater table. The characteristic of the aquifer and the soil, such as the depth of the water table and nature of the soil matrix, are the key parameters affecting groundwater pollution.

The present study assesses the impacts of sanitation systems on groundwater quality in the Ramotswa Transboundary Aquifer Area between South Africa and Botswana. Sanitation information is collected by document analysis, interviews and wastewater sampling. A GIS map is established to determine vulnerability areas and sources of pollution. Results from this assessment are used to propose achievable recommendations taking into account of social, climate and economy conditions of the two countries. Wastewater is the “new water” for water scarcity areas, some alternatives for the reuse are proposed for agriculture, groundwater recharge and domestic reuse.

1. Study area

The study is undertaken in the Ramotswa Transboundary Aquifer Area (RTBAA) between Botswana and South Africa. The RTBAA straddles the border between both countries. The delineation of the RTBAA is the Gaborone dam catchment but this study is focused on the Gaborone dam catchment extended on the district's boundaries for both sides. The Botswana side is formed of South East District, south east part of Southern District. This area of Botswana is the most densely populated. The capital Gaborone and Lobatse lie in this district. This part of the study is dominated by urban development with high economic growth. Ramotshere Moiloa Local Municipality in the North West Province composes the South African side of the study area. This local municipality occupies an area of 7193 km² and has a stalling economic growth and a low population density. The main urban area is Zeerust.

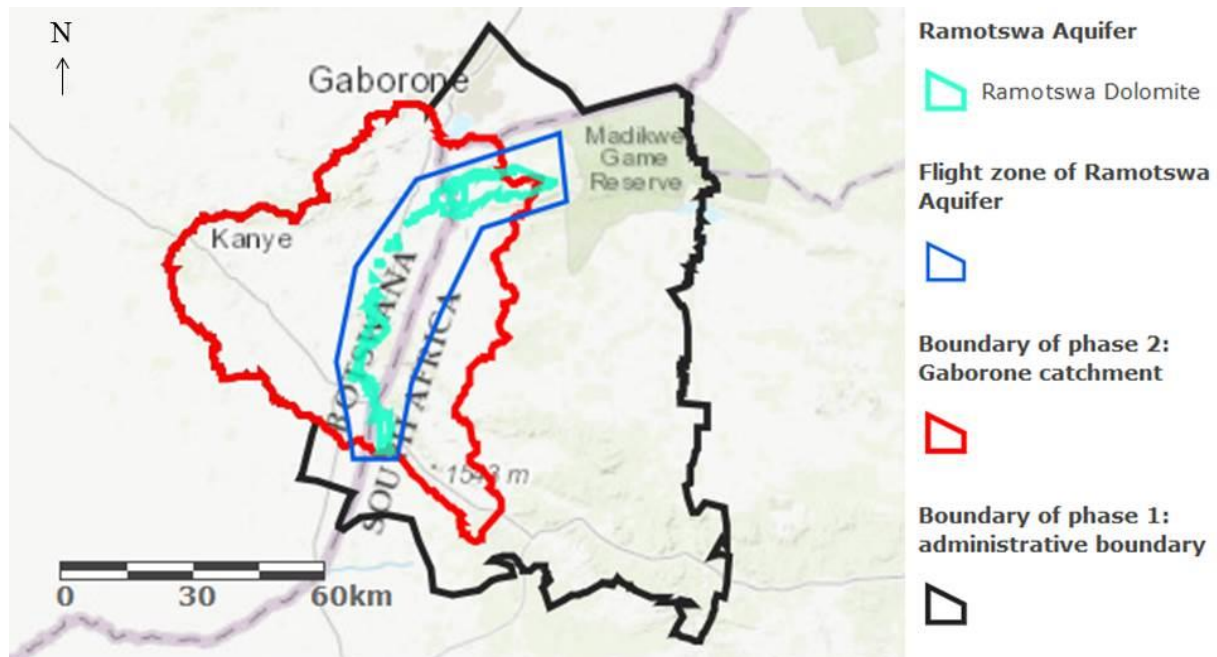


Figure 1: Map of the Ramotswa Transboundary Aquifer Area.

The RTBAA has a semi-arid climate. There are two seasons in the year. Winter is characterized as the dry season with high evaporation level and lasts from April to September. In contrast, from October to March is the wet season which is called summer. Rainfall happens during this season. Average annual temperatures range between 18 and 20°C.

The Ramotswa aquifer is located in the Ngotwane sub-catchment in the Upper Limpopo River Basin. Geologically, the study area is within the western part of the Transvaal Supergroup in Kraapvaal Craton. The main water-bearing unit of the RTBAA is dolomitic. The Ramotswa Dolomite is intruded by three vertical dikes which create compartments. The Ramotswa Dolomite aquifer is fractured and has karst areas with high transmissivity and storativity. Rainfall recharges the aquifer. The median depth to the groundwater table is 9 meters and there are 0 to 12 meters of surface unconsolidated sediment [2]. The quality of groundwater is critical in the Ramotswa Transboundary Aquifer given its use for agriculture (69%), industry (1%) and especially drinking water purposes (30%) [2].

The RTBAA extends on 10533 km² and has a population of 534788 in 2011. Actually, 50% of the population in the RTBAA is connected to a sewage network. But, more than 50% of the population has on-site sanitation because of the climate conditions. During a drought, people are not able to flush toilets, they use on-site sanitation. In urban areas, on-site sanitation is more or less well maintained and dislodged in the inlet of wastewater treatment plant. In rural areas, on-site sanitation is maintained according to funding of households. Human activities are mostly agricultural in this area. Groundwater is also used for irrigating crops or watering cattle.

2. IWMI and Ramotswa project

The International Water Management Institute leads the Ramotswa Transboundary Aquifer Area project in partnership with the Department of Water and Sanitation in South Africa, the Department of Water Affairs of Botswana, Limpopo Watercourse Commission, Southern African Development Community, and the universities of the area. The International Water Management Institute is a non-profit and scientific research organization focusing on the sustainable use of water and land resources

in developing countries of Africa and Asia. The Ramotswa project was developed in 2015 to support management and cooperation on the shared groundwater resources of the upper Limpopo region in order to reduce poverty, inequality and insecurity. Main objectives of the project are to understand the socio-economic importance of the aquifer area, assess the feasibility for managed aquifer recharge, establish cooperation between both countries, and improve management and monitoring of the resource. A stakeholder platform, a strategic action plan for the development and management of the aquifer, a transboundary diagnostic analysis, training material on transboundary diagnostic and an information management system (RIMS – IGRAC) are expected as key outputs by the end of the Ramotswa project.

3. Methods

This research is led by five steps: document analysis, statistics on water balances and population, interviews and visits, modelling map and identification of challenges.

i) Document analysis

Most of the documents analyzed are policy documents and environmental reports from Department of Water Affairs in Botswana, Department of Water and Sanitation in South Africa, institutions in the transboundary area and previous work in the area such as hydrogeology reports from Michael Staudt [9] and Katharina Beger [8]. Document analysis is realized in a chronological order and by categories to update and complete information on each sanitation system. Documents are classified at first by country and then in five subcategories such as wastewater treatment plants, on-site sanitation conditions, hydrogeology assessment, settlement activities and development plan for the environment.

ii) Statistics on water balances and population

Census of South East district [3] and Southern district [4] of Botswana of 2001 and 2011 and census of North West province of 1996 [10], 2001 [11], 2011 [5] and 2016 [12] were collected. They are used to assess population growth rate, consumption of water per household and development of sanitation system over time.

iii) Interviews and visits

Visits in the field permit to collect interviews of workers in wastewater treatment plants of Lobatse, Ramotswa and Gaborone [Appendixes 2, 3, 4, 6] and wastewater samples [Appendixes 5, 7]. Interviews are undertaken to assess the capacity and the treatment of wastewater facilities, to assess the potential impact of wastewater discharge on the environment and to know the trends for on-site sanitation. Interviews correct or confirm information contained in documents contents. No interview is available from the South African side.

iv) Modelling map

Visits and document analysis help to create a GIS map of the area. The aim of this map is to locate the most vulnerable part of the RTBAA for pollution. A DRASTIC (Depth to groundwater, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, Conductivity) method is used for modelling.

v) Identification of challenges

After these four primary steps were achieved, an assessment of sanitation in Botswana and in South Africa is realized. This assessment compiles every information in a chronological order. Five challenges are identified by combining and comparing information from the different steps:

- Priority areas: the modelling map points out priority areas to work on sanitation improvement. These areas are selected according to their vulnerability to pollution depending on climate conditions, settlements, activities and soil characteristics.
- Industrial wastewater: document analysis and visits allow to assess the river quality and the wastewater quality from wastewater treatment plants. High concentration rate of some pollutants (heavy metals, oil and grease, and chemical oxygen demand) does not just come from domestic wastewater. Industrial activities are involved in deteriorated wastewater quality. Biggest industrial activities in the study area and their major pollutants are identified.
- Transboundary pollution: quality assessment and modelling map lead to focus on the transboundary pollution. Surface water and groundwater pollution are linked based on document analysis.
- Water balances: statistics on water balances and population show water consumption and number of sanitation system increasing which mean leakage and losses increasing. Water balances are quantified based on statistics.
- Climate change: interviews and documents report some variation of quality and quantity of wastewater with seasons. Climate change impact on sanitation is studied based on rainfall and evaporation record from the Department of Water and Sanitation of South Africa and the Department of Water Affairs of Botswana.

Once the challenges established, recommendations and opportunities for sanitation improvement are given. Sanitation systems improve with better treatment efficiency or on-site sanitation adapted to the area. Treated wastewater can benefit water bodies by recharge or reuse.

II. Sanitation trends in the RTBAA

Sanitation trends in the RTBAA are studied in the Botswana side and then, in the South African side. In fact, Botswana and South Africa have not developed water acts and development plans at the same time. The installation of sanitation in the last past years is different between the two countries. However, the main challenge is the same for both: protect groundwater from sanitation pollution. The study area has twenty one wastewater treatment works in operation and 91000 on-site sanitation facilities, presented below in Figure 2.

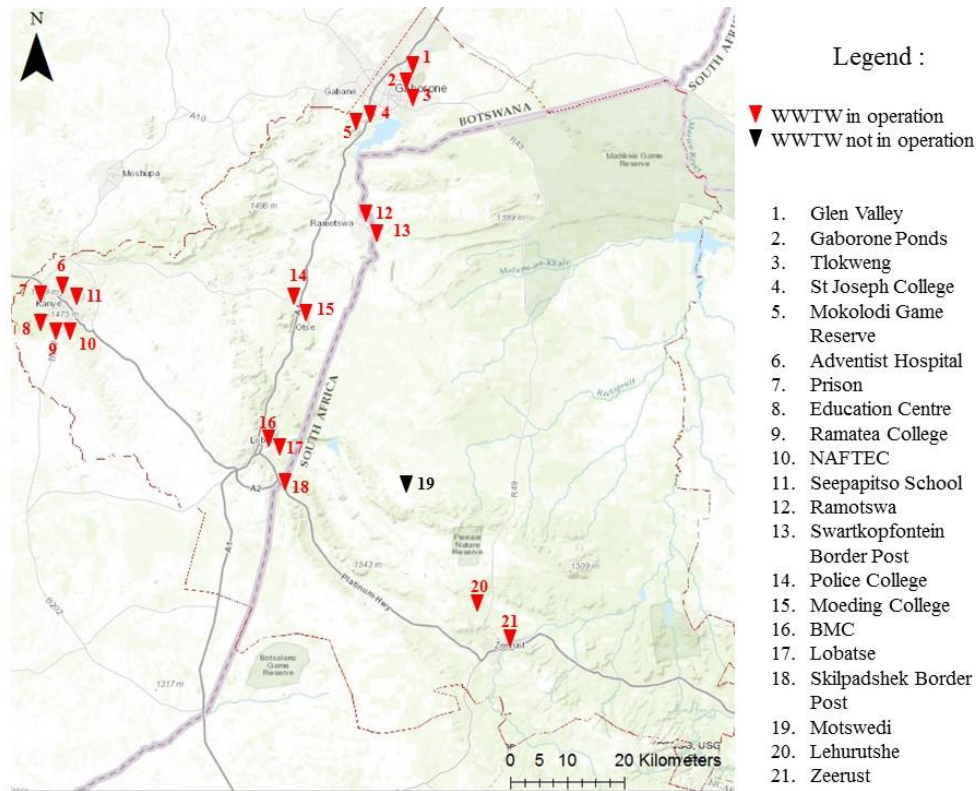


Figure 2 : Localization map of WWTW in the RTBAA.

1. Sanitation development in Botswana side

In Botswana, the Urban Sanitation Research Project promoted the use of pit latrines in urban areas in 1976. This project was extended for rural areas in the eighties with the Environmental Sanitation and Protection Pilot Project. But, the lack of skills in latrine construction and the affordability where, in some cases, the households were not prepared to play their part and complete top structures, caused groundwater pollution in the area.

In fact, in Botswana the construction of pit latrines is controlled as explained below:

- a household wanting to participate in the project would enroll and pay a deposit of P30,
- the household would then excavate a pit to dimensions provided. The project team would assist with a jackhammer if the ground was unpickable,
- the council would then construct the substructure together with the concrete slabs at ground level,
- the householder would then build the superstructure with advice from the project team if necessary,
- the project team then installs the vent pipe, fly screen and seat.

In 1986, major urban centres of Gaborone and Lobatse reported a sewerage coverage of 38% and on-site sanitation coverage of 55%. In the major rural villages sanitation coverage was around 30-40% and minor villages and locations virtually zero coverage. In 1991, a study was commissioned to assist the government in designing a National Rural Sanitation Programme. In 2001, 77% of the households in Botswana had access to adequate sanitation [13]. In the Botswana side of the RTBAA in 2011, 95% of the households had access to adequate sanitation.

	2001	2011
Population	390023	474860
Household	84154	139641
Flush toilet	42776	69892
Pit latrine	29014	56481
VIP	25705	5448
Enviro-loo toilet	454	-
Dry compost	-	444
None	8243	7375
Unknown	50	-

Table 1: Sanitation facilities in the Botswana side of the RTBAA in 2001 and 2011 [3].

In the RTBAA, after 1996, most of the water supply came from water surface, such as Gaborone, Molatedi and Nnywane Dams. Ramotswa wellfield was closed because of the high amount of nitrate concentration which came from pit latrines and caused some cases of blue baby syndrome. But, Botswana knows dry seasons and water usage is increasing for livestock watering and irrigation. Moreover, the distribution network is old and experiences frequent pipe failure, which increases the water losses. Dams are not enough to provide water. In 2014, Ramotswa wellfield was re-opened for pumping as an emergency measure. Nowadays, Ramotswa, Otse, Lobatse, Ranaka, Lekgolobotlo, Magotlhwane, and Molapowabojang receive water from Gaborone waterworks blended with water from the wellfields in the area, such as presented in Figure 3. Because of the groundwater pollution, the wellfield water has to be diluted with water from Gaborone, Molatedi and Nnywane Dams. When there is no water from the dam, the water is restricted in the villages. This phenomenon explains why people have pit latrines even if they use toilets connected to the sewage.

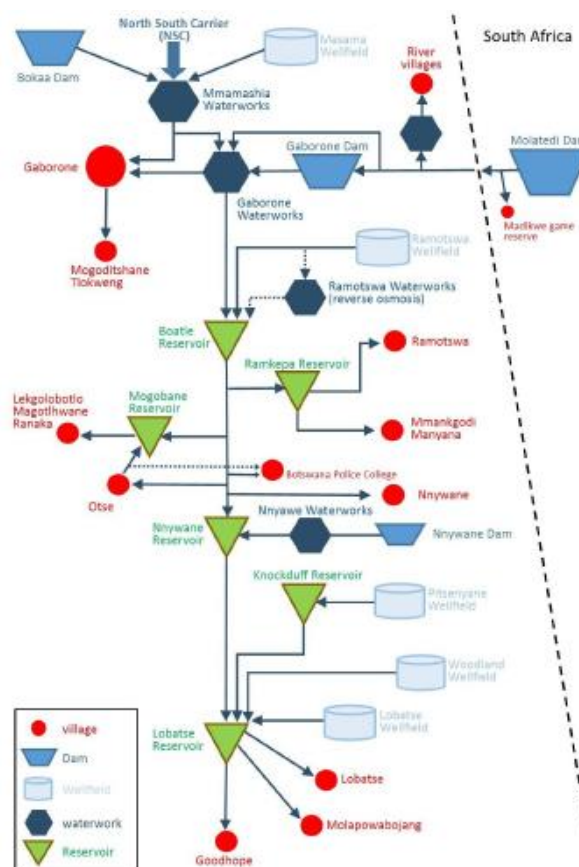


Figure 3: Schematic of the water supply area in Botswana [2].

Between 2008 and 2013, the government of Botswana launched a program Water Sector Reforms. This program was to redefine and change the roles of institution and major stakeholders. From 2011, WUC takes over the operation of wastewater networks in Botswana. Then, from 2013, the operation of the WUC includes vacuum tanker services to pit latrine and septic tanks.

1.1. Gaborone sanitation facilities

Gaborone is the capital of Botswana with a population of 231 592 in 2011 [3] which represents around 10% of the population of Botswana. The sanitation system is quite impressive in Gaborone compare to the other towns in the country. WWTW are located in the Figure 4.

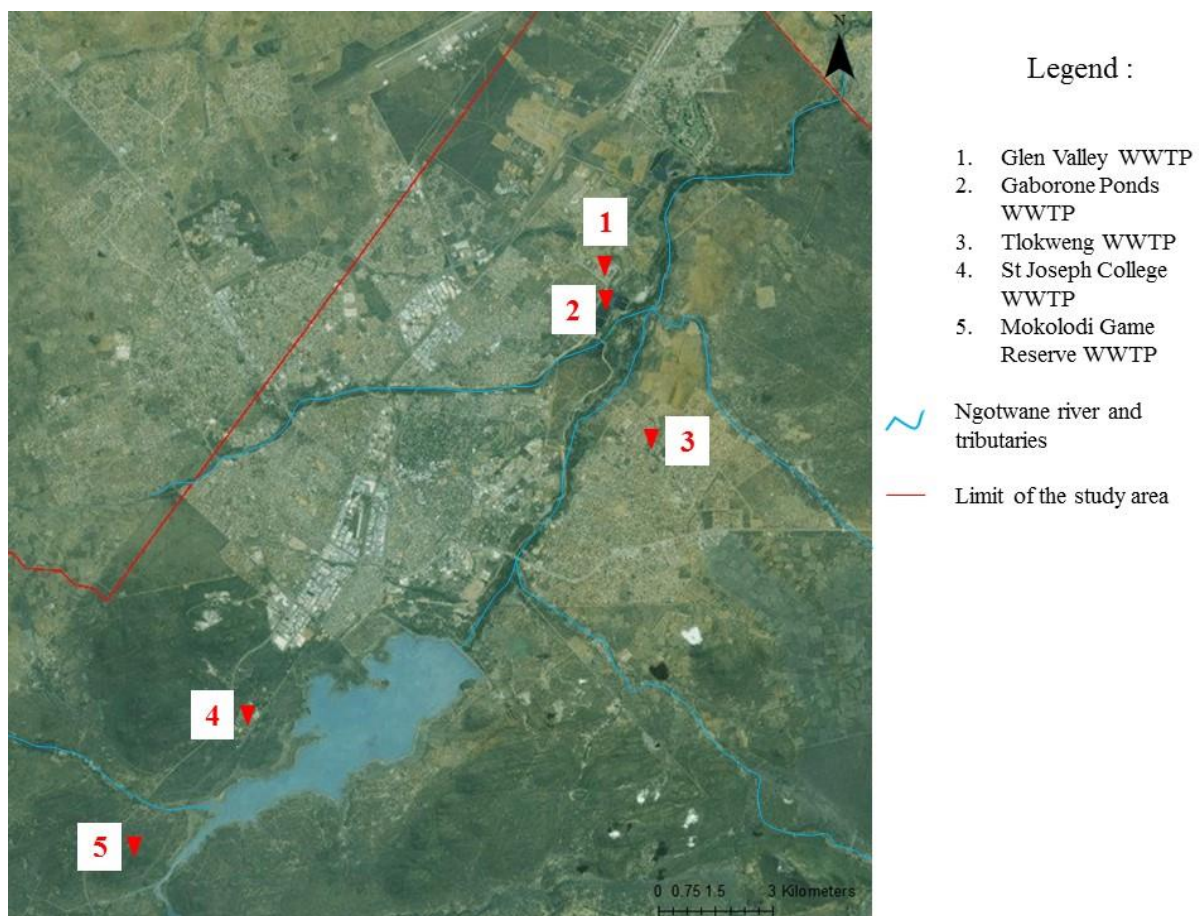


Figure 4: Map of WWTW in Gaborone.

Seven primary trunk mains allow collection of wastewater from all of the defined Gaborone city area, Tlokweng and Mogoditshane, with all the recently low cost areas connected. Unsewered areas are the SHHA areas in Old Naledi, Bontlend and Broadhurst. They were planned to be sewerred in NDP 9, between 2003 and 2009. Problems such as blockages and pipe failures are encountered in the older areas of the city, especially in the Central Gaborone Area [13]. The older areas of the city are still using latrines and tank system.

Glen Valley WWTP treats all wastewater generated in Gaborone and adjacent connected areas. It employs an activated sludge process with polishing of the effluent in the Broadhurst and Phakalane ponds, which are called “Gaborone Ponds” in Figure 5. Effluent discharges into the Ngotwane River

from either these pond systems or are reused for irrigation, it depends on the effluent quantity and the needing for irrigation. Most of the effluent is used for irrigation.

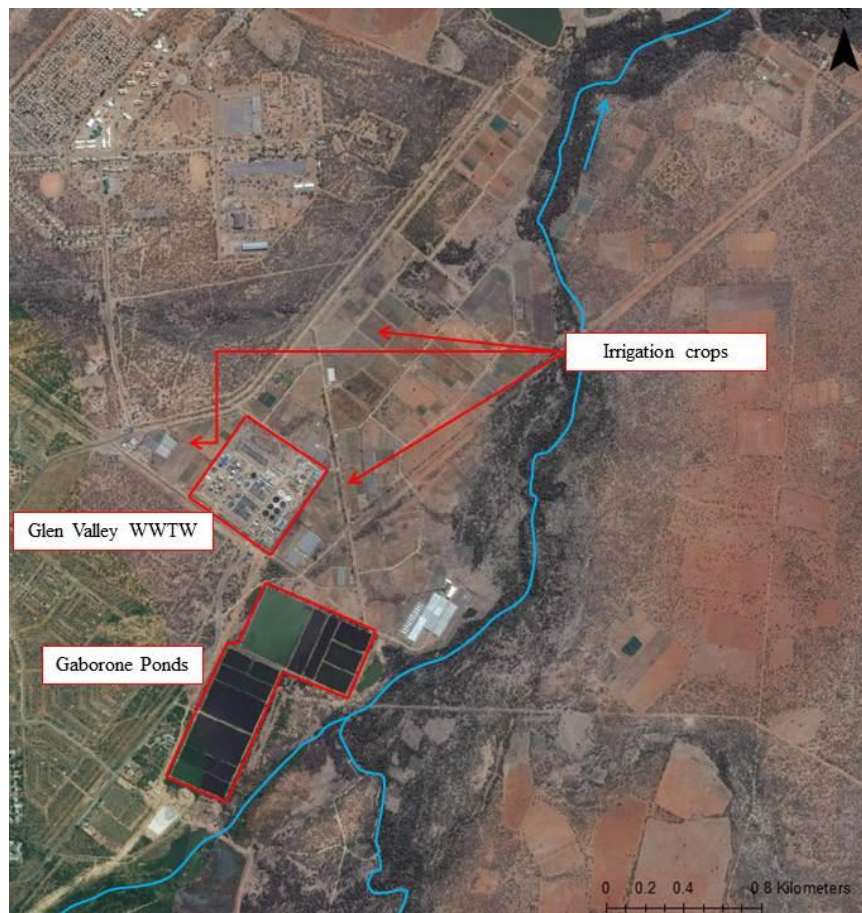


Figure 5: Glen Valley WWTW map.

Influent is largely domestic with industrial component. The WWTP is composed of an inlet work with mechanically raked screens, flow measurement and grit chambers, presented in Appendix 1.1.; a primary settlement; an activated sludge reactor with surface aerators and secondary settling tanks; sludge handling with sludge thickening, anaerobic digestion and drying beds; maturation ponds for polishing and disinfection.

The first phase was built in 1996 and designed to treat an average dry weather flow of $40\,000\text{ m}^3\cdot\text{d}^{-1}$, with current inflow of $34\,000\text{ m}^3\cdot\text{d}^{-1}$. In 2003, inflow represented 52 % of water supplied to the area. The first phase was designed for influent of $1000\text{ mg}\cdot\text{L}^{-1}$ COD, $500\text{ mg}\cdot\text{L}^{-1}$ BOD, $400\text{ mg}\cdot\text{L}^{-1}$ SS. But the raw sewage exceeded the design and impacted on downstream performance. The possible reason of the impact is coming from higher industrial load or malfunctioning of thickeners. The plant is equipped with a laboratory for monitoring COD, BOD, SS, NH_3 , PO_4 .

The second phase in 2001 was designed for a total of $90\,000\text{ m}^3\cdot\text{d}^{-1}$ of inflow. As it can be seen in Appendix 1.2., the second phase is not fully used but the current inflow has improved because of the immigration to the capital. Septic tanks and pit latrines are also dislodged in the current inflow of the WWTP before the screens. The current inflow is around $65\,000\text{ m}^3\cdot\text{d}^{-1}$.

Preliminary daily solid balance of waste activated sludge handling system is maintained by sludge from WAS & digested primary applied to drying beds. The stabilized sludge has in the past been re-

moved to the local sanitary landfill but since the commissioning of the new plant in 2001, sludge has accumulated around the drying beds.

Final polishing provides for die off of bacteria to levels far lower. No bacteriological and limited PO_4 analyses are available for this part of process.

Reuse of treated effluent is for irrigation of golf courses and cultivation of crops. 203 hectares of land are irrigated. The water is pumped by the Department of Agriculture of Botswana. Wastewater are used to irrigate tomatoes, butternut and spinach crops. The discharge has a good compliance for irrigation [Appendix 2]. Glen Valley WWTP is used in this report as an example of reuse.

Gaborone has two other WWTW located off-center which are in Mokolodi Nature Reserve and in Saint Joseph's College. In Mokolodi Nature Reserve, wastewater is treated in a wetland. Wastewater comes from the lodges in the area and treats $10 \text{ m}^3 \cdot \text{d}^{-1}$ with good efficiency. In Saint Joseph's College, the sanitation treatment system is ponds and treats wastewater of 1260 students and 140 teaching staff since 1996. $100 \text{ m}^3 \cdot \text{d}^{-1}$ of wastewater are treated in septic tank, facultative pond and aerobic ponds. $40 \text{ m}^3 \cdot \text{d}^{-1}$ of effluent is discharged into Gaborone dam with good compliance.

Tlokweng is a village adjacent to Gaborone in the South East District of Botswana. The population was 37 340 in 2011 [3]. It is considered as a part of Gaborone for the sanitation system because almost all of Tlokweng is sewered and treated in Glen Valley WWTW. Just Tlokweng Technical Training Centre has its own WWTP which is a wetland system with a nitrification tower built in 2002. Wastewater treated is reused for watering sport fields.

1.2. Kanye sanitation facilities

Kanye is a town located 83 kilometres south west of the capital Gaborone. It is the administrative centre of the Southern District with a population of 52 323 inhabitants [3]. Kanye water supply boreholes are located in Kgwakgwe wellfield lying to the south west of the village. Majority of households have access to water through a yard and standpipe. But, no sewerage facility is available. CBD and Rural Administration Centre are connected to septic tank and soak away systems. Kanye Development Plan envisaged VIP and pit latrines remained as the most appropriate system for sanitation village but there are polluting the groundwater. Six WWTW exist in the town for industrial and education settlements as shown on the map Figure 6.

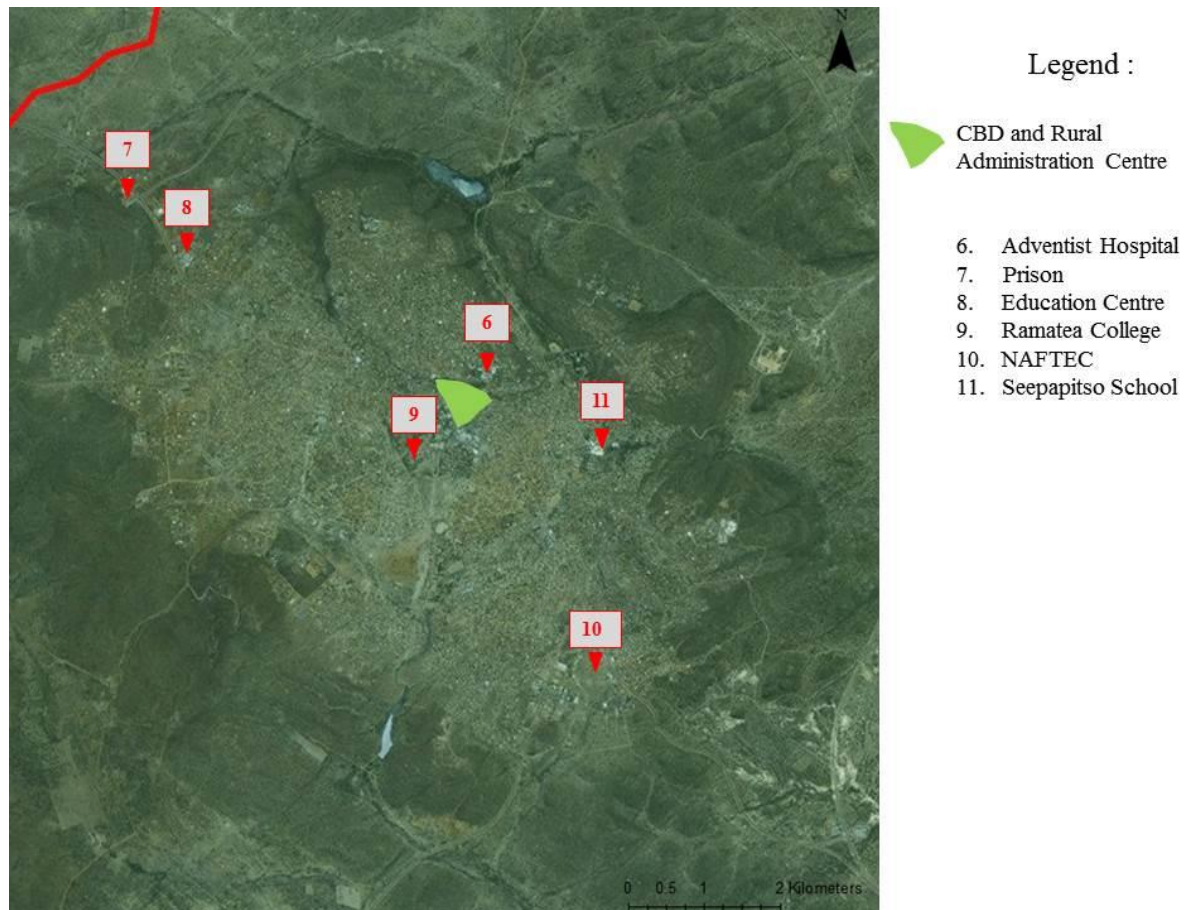


Figure 6: WWTW in Kanye, Southern District, Botswana.

The Seventh – Day Adventist Hospital WWTW are rotating biological contactors treatment. It serves the hospital which hosts 120 patients and 300 staff members. In the plant, there are an inlet structure with bar screen, septic tank, biodiscs in series, humus tank and disinfection. The plant capacity is $20 \text{ m}^3 \cdot \text{d}^{-1}$ and the system is well managed. All effluent is reused for gardens.

Kanye prison and Sejelo police station WWTW is a wetland system with anaerobic rock filter built in 1997. The wetland was designed for $25 \text{ m}^3 \cdot \text{d}^{-1}$, but the current inflow is about $30 \text{ m}^3 \cdot \text{d}^{-1}$. Effluent is used for irrigation of vegetables garden with a good quality.

Kanye Education Centre Ponds were constructed and completed in September 2001. Eight pump stations transfer the sewage. No effluent is produced because of the operation. System is composed of screens, grit chambers, anaerobic ponds, facultative ponds, aerobic ponds. The plant was oversized because the full capacity is $106 \text{ m}^3 \cdot \text{d}^{-1}$, but the current inflow is $50 \text{ m}^3 \cdot \text{d}^{-1}$.

Ramatea Vocational School WWTP was built in 1998 as a wetland system. The current outflow produced is $14 \text{ m}^3 \cdot \text{d}^{-1}$ and presents a good quality.

No quality data was provided from the NAFTEC. Wetlands were built in 2000 and the current inflow is equivalent to the design capacity such as $10 \text{ m}^3 \cdot \text{d}^{-1}$.

Seepapitso Senior Secondary School WWTW are oxidation ponds designed for 400 students. But, the present number of students is around 1500, plus 200 staff members and around 60 staff houses. Sewage overflows into natural water course because the ponds capacity is not enough. The plant is composed of septic tanks, facultative ponds and aerobic ponds. Ponds are cement lined, and there is no maintenance. Raw sewage is spilled from last manhole before entering primary septic tank and flowed

into facultative pond. Spillage results in short circuiting the facultative pond and emanates in very green algae in facultative pond with no flow condition. The treatment is excellent. There is no measure data available, and changes as septic tank being dislodged on a regular basis should be done. Effluent flows eventually into the river when there is not enough evaporation [13].

Kanye pollution is coming from the lack of sewage network in the town. Most of the population is using VIP and pit latrines which are infiltrating the aquifer because of the lack of management and skills in constructing on-site sanitation.

1.3. Ramotswa sanitation facilities

Ramotswa is a town located in South East District of Botswana, southwest of the capital of Gaborone. The population was 30 382 in 2011 census [3] with 6 993 households. Sanitation system in Ramotswa depends on water supply system from Gaborone.

The main sanitation systems in Ramotswa are, first VIP and pit latrines because of water restriction, secondly sewage network. The town is served by 150 km of sewers, two pump stations and a 3000 m³.d⁻¹ WWTW extended on 23 hectares [13]. The sewage network is developed in the new areas of the town, circled in yellow in Figure 7. In the town center, which is the old area, people are gradually connected to sewage network but it depends on the cost. In Ramotswa, every household has latrines system. In brief, 60 % of population use flush toilets connected to the sewage network in the town, 15% use flush toilets connected to septic tank and 20% to 25% use VIP and pit latrines [Appendix 3].

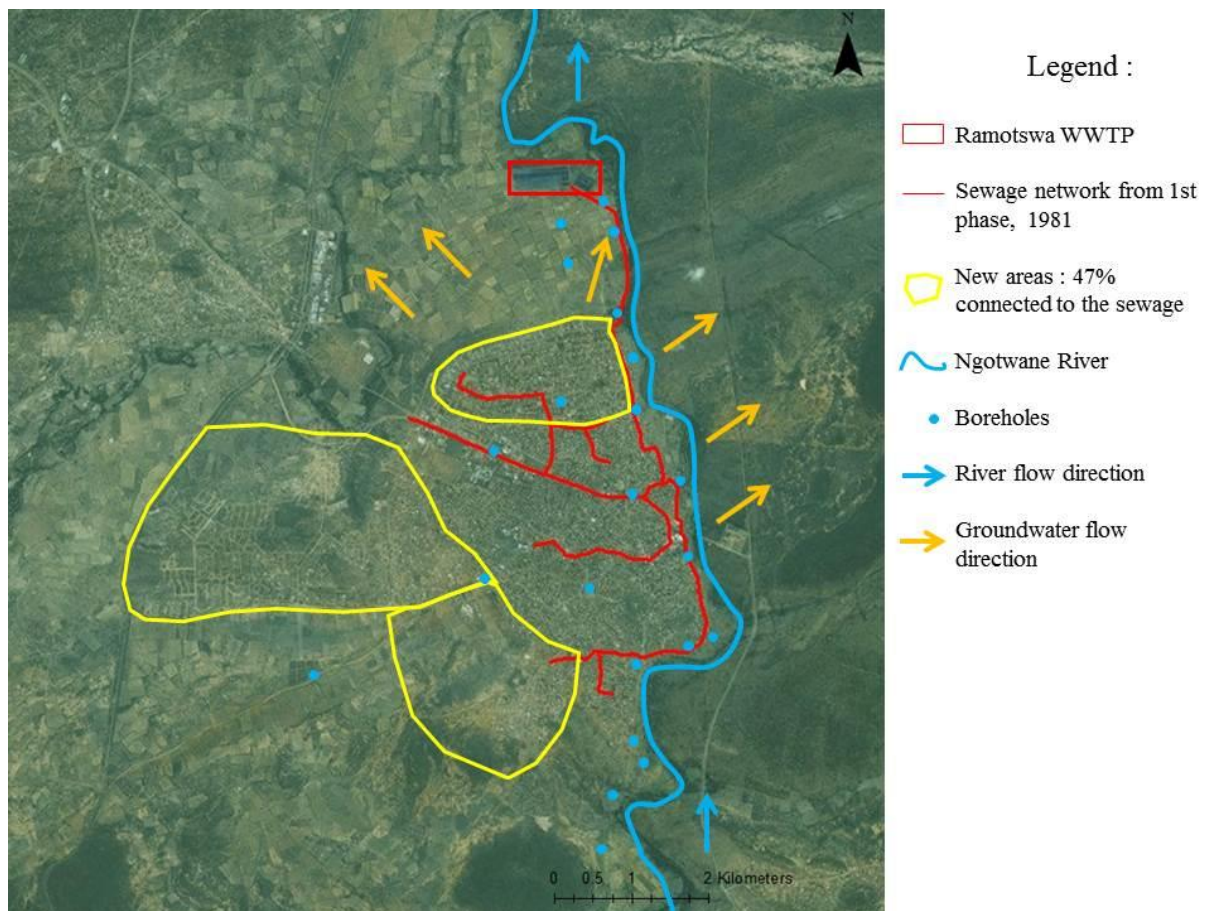


Figure 7: Sanitation system and pollution in Ramotswa.

Figure 7 shows that most of the boreholes are near the sewage network in the east side of the town. Pollution of the groundwater might come from losses in the sewage network which are infiltrating the aquifer and the concentration level of latrines in the area. The groundwater flows to the north-east, so pollution can be detected in the water from the boreholes of Ramotswa.

Ramotswa WWTP was built in 1981; then, it was upgraded in 2001 because of population increasing. The second phase is used when the first phase is full. The capacity design is $3000 \text{ m}^3 \cdot \text{d}^{-1}$, but the current inflow is around $1500 \text{ m}^3 \cdot \text{d}^{-1}$. It is increasing during the rainy season. There is no effluent currently produced during the dry season. The outflow is estimated around $600 \text{ m}^3 \cdot \text{d}^{-1}$. Vacuum tanker discharge bay, manually-raked screens, grit chambers, flume with no flow measurement and ponds form the plant. Flow splits towards the old system from 1981 which is compounded of one anaerobic, two facultative and four maturation ponds, and the new system composed of two primary anaerobic ponds, two secondary anaerobic ponds, one facultative and three maturation ponds. All the ponds are plastic lined. Overflow from final pond is supposed to flow into a woodlot planted with eucalyptus when there is excess, such as presented in Figure 8 [13]. Otherwise, during winter, ponds system is working as an evaporation system [Appendix 4]. Wastewater treated runs off to the Ngotwane River and/or infiltrates the aquifer. Because of this, the quality of the wastewater treated has to be monitored. The quality of wastewater is presented in Appendix 5.

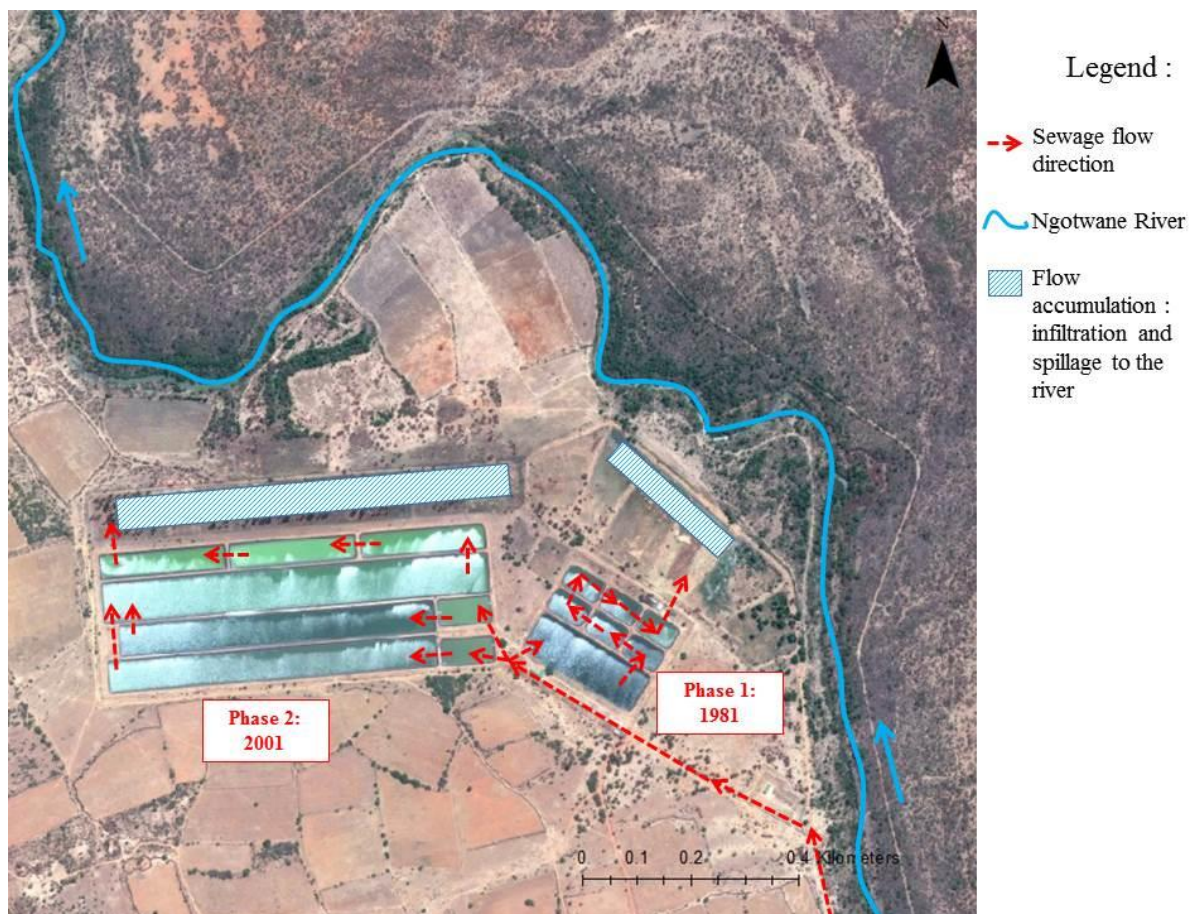


Figure 8: Sewage flow in Ramotswa WWTP.

The inflow of Ramotswa WWTP was tested twice. The inflow from 31st January was grey with an important flow, contrary to the inflow of 2nd February which was dark and sandy with a low flow. Moreover, the second inflow is really concentrated in suspended solids, oil and grease and ammonia. This quantity of oil and grease does not come from domestic wastewater. Fat contributes between 3%

and 8% of the wet weight of feces [14]. The concentration of oil and grease in an untreated domestic wastewater is not higher than a range between 50 to 100 mg.L⁻¹ compare to Ramotswa wastewater which is more than 1000 mg.L⁻¹ [15]. This high amount of concentration comes from industrial wastewater such as Bolux Milling, Higro feeds, and Ramotswa Glass Works. High amount of oil and grease includes physical blockages in sewers, pumps and screens. It reduces oxygen transfer rate, so the degradation of suspended solids and BOD is not totally efficient in facultative ponds. This phenomenon might explain the non-compliance of the outflow to the standards BOBS 93:2012 for COD, BOD and ammonia. Nitrogen is still present under the form of ammonia in the discharge, but with good conditions ammonia is oxidized in nitrate and nitrite, which can contaminate the river and the aquifer. Lastly, these samples were collected during the rainy season when the wastewater is diluted. The quality is considered worst during the dry season.

The main problem of the plant is the evaporation. In fact, the plant was not designed for evaporation but in reality, there is no effluent produced during most of the dry season. The residence time in the ponds is not respected, it is one of the reasons of the poor wastewater quality. Secondly, maintenance is the key to improve the quality such as flow measurement or sludge care mentioned in Appendix 4. Finally, treatment by ponds is not efficient for industrial wastewater. A pre-treatment of the wastewater should be done by the industry.

1.4. Otse sanitation facilities

Otse is located 60 km south of Gaborone in the South East District. The population was 7976 in 2011 census [3]. The main sanitation system in the area is on-site sanitation. But, two wastewater treatment plants in the village are used for the Police College and Moeding College. The sanitation system of the area is presented in Figure 9.

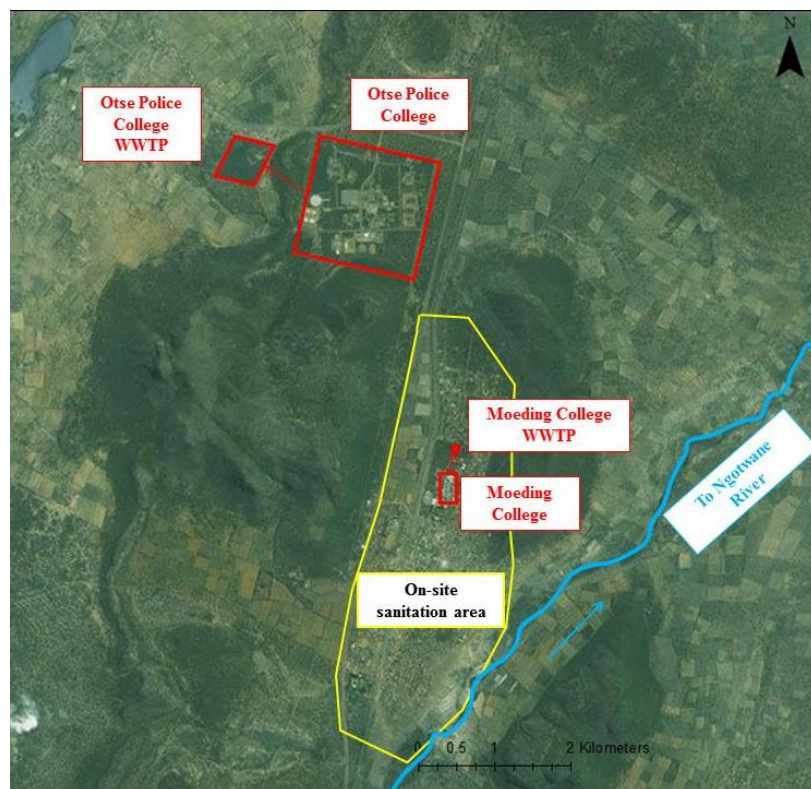


Figure 9: Map of Otse sanitation facilities.

Otse Police College WWTP was commissioned in 2001. It is the biggest WWTP using rotating biological contactors in Botswana and is operating under design capacity, such as $200 \text{ m}^3 \cdot \text{d}^{-1}$ instead of $260 \text{ m}^3 \cdot \text{d}^{-1}$. The primary treatment sewage is achieved by means of septic tank and followed by biological treatment in rotating biodiscs units. Humus tanks downstream of the biodiscs are provided for effluent clarification. The effluent is disinfected before storage in a holding pond. $200 \text{ m}^3 \cdot \text{d}^{-1}$ of effluent produced are reused for college gardens and sport complex. The excess of effluent overflows to an infiltration field [13].

Moeding College WWTP is similar to the police college WWTP and was built in 1998. Differences between the two WWTP are biodiscs: there are smaller in Moeding College WWTP. This plant serves 1800 students and staffs members, which represents a full inflow capacity of $50 \text{ m}^3 \cdot \text{d}^{-1}$. The pre-treatment operates in septic tank, followed by organic removal in rotating discs. Effluent is clarified in humus tanks followed by disinfection. The excess overflows from the pond to nearby environment where cattle drink from [13].

Lastly, the first concern of the area is the use of on-site sanitation because of the population density and the proximity of tributaries of Ngotwane River. In fact, the poor design of latrines and septic tank, and the lack of maintenance, impact on the water quality. Raw sewage infiltrates the aquifer or is spilled to the tributaries.

1.5. Lobatse sanitation facilities

Lobatse is an administrative town in South East District of Botswana, 70 kilometres south of the capital Gaborone. According to the 2011 census [3], the population of Lobatse is around 29 007 inhabitants. Few industries are located in this town such as BMC, Lobatse Tiles, Lobatse Clay Works, sugar packaging industries, brewery and milling.

62% of Lobatse are sewered inclusive of all institutions, government facilities and the town centre. In Peleng, Tsopeng and Woodhall areas, presented in Figure 10A, on-site sanitation technologies are being used. These pits and septic tanks have been sealed to prevent contamination of the aquifers and are emptied by vacuum tanker. All new development is connected to the sewer system, including low cost housing areas. In March 2017, 3642 households connected to the sewage network, 1700 pit latrines, and 800 septic tanks were identified. To summarize pit latrines are used by 25% of population; flush toilets are used by 75%, but 25% are evacuated in septic tanks and 50% are evacuated in the sewage network.

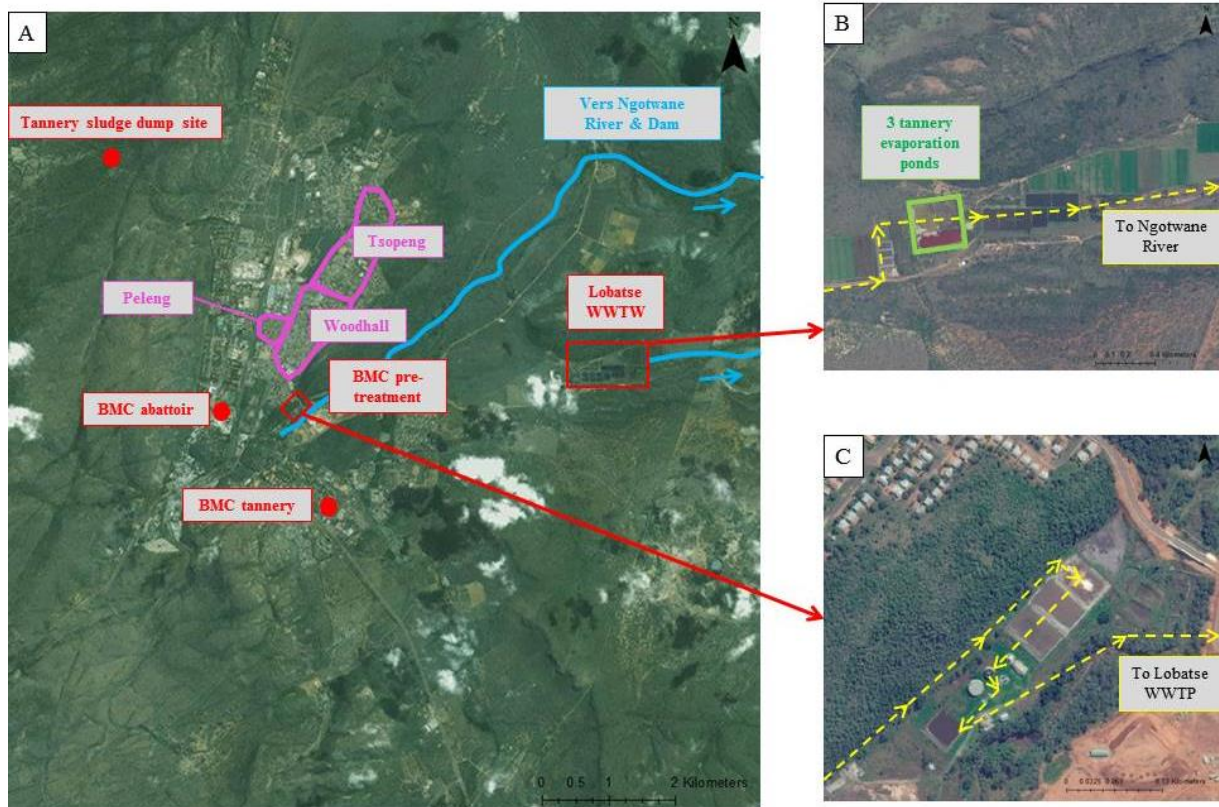


Figure 10: A) Map of Lobatse; B) Zoom on Lobatse WWTP; C) Zoom on BMC pre-treatment.

The plant, presented in Figure 10B, was built in 1989, upgrading in 1995 because of the population increasing. There will be no need to increase the capacity because Lobatse has a slow population decreasing with the emigration to other economic centres. The plant is composed of 14 ponds which are divided in 3 primary anaerobic ponds, 2 secondary anaerobic ponds, 6 facultative ponds and 3 maturation ponds [Appendix 6]. The plant was designed for treating $6200 \text{ m}^3 \cdot \text{d}^{-1}$ domestic and industrial wastewater with provision for future flows allowed $9500 \text{ m}^3 \cdot \text{d}^{-1}$. Effluent from ponds were reused on 40 ha Lucerne production by private contractor.

The efficiency of the treatment was tested. Samples of the inflow and outflow of Lobatse WWTP have been collected, as well as samples of upstream and downstream of the river. The place where each sample was collected is presented in Figure 11. Wastewater quality is available in Appendix 7.



Figure 11: Map of the place where samples were collected in Lobatse WWTP.

The inflow is high in BOD, COD, SS and ammonia. The treatment removed most of the pollutants but the outflow is not compliant to BOBS 93:2012 for ammonia and COD. Nitrogen is present in the form of organic nitrogen and ammonia because the wastewater is freshly polluted. But, natural biochemical process converts ammonia into nitrite then nitrate, which are flowing to Ngotwane Dam. Moreover, the concentration level of coliforms is quite high (1280/100 mL) even if it is compliant to the standards of BOBS 93:2012. Stricter rules were applied in the standards BOBS 93:2004. It has to be noticed that these samples have been collected during the rainy season. The quality is normally better during this season because the effluent is diluted. Discharge, upstream and downstream river can be also compared to prove if cattle may have an impact on the water quality. In fact, COD, SS and coliforms are increasing downstream, so cattle defecating and the cemetery near the river are involved in the pollution of Ngotwane Dam, such as mentioned during the interview with the manager of Lobatse WWTP [Appendix 6].

In any case, effluent water quality is in accordance with application criteria BOBS 463:2011 as stipulated by DWA for irrigation purposes on fodder crops, nuts and citrus fruit trees [Appendix 8C].

Pollution might come from the BMC pre-treatment, presented in Figure 10C, established in 1978. The BMC plant capacity is 170000 cattles per year, including water used to wash down equipment and 2.3 m³ of water per head of cattle per day. The design capacity is 1700 m³.d⁻¹. The main waste from an abattoir is blood, fats and rumen contents. The BMC WWTP is a wastewater pre-treatment system with anaerobic ponds followed by trickling filter but it is not enough to treat the raw wastewater. After the pre-treatment, wastewater is flowing to Lobatse WWTP. Pollution occurred in Peleng River due to three reasons:

- Pumping of wastewater, sludge and disposal of fats, oil and grease into the sludge pits which are unlined pits in river alluvium,

- Spillage from BMC WWTP,
- Surface wash and percolation of rainfall through the screening waste materials [16].

Moreover, the BMC Tanning has an evaporation pond system consists of three ponds totalling an area of 56 740 m². A stench is emitted from the ponds. Wastewater seepage is going into the ground. An agreement in the end of 2016 has been signed between BMC and WUC, it will be effective by the end of 2017. The BMC will have its own WWTP.

The main problem in this area is the pollution from industrial activities which is polluting Ngotwane River and Ngotwane dam in the North of South Africa. This pollution leads to a transboundary impact between South Africa and Botswana.

2. Sanitation development in South African side

In South Africa, three distinct periods exist to describe the establishment of sanitation facilities.

In pre – 1994, South Africa was built in ten homelands managed by tribal authorities. There was no cohesive strategy, guidelines or support structure between homelands. At first, the sanitation service provision was focused on toilet building, sewer system and maintenance. People who had inadequate sanitation were using the bucket system, rudimentary pit toilets or veld. The major concern for the government was the groundwater pollution associated with on-site sanitation.

Between 1994 and 2001, the Department of Water Affairs and Forestry was created and the Community Water Supply and Sanitation was formed. The objective was to extend the access of basic water supply and sanitation services to all people resident in South Africa. In 1996, the Constitution of Republic of South Africa has indicated the government has the responsibility of providing water and sanitation services access to all. At first, people were provided with 25 liters of water per day per people within 200 meters of their home. Moreover, each household was provided with basic sanitation in the form of at least VIP.

In 2001, South Africa census estimated that up 26 % of urban household and 76 % of rural household had inadequate sanitation. Compare to this national estimation, in the Ramotshere Moiloa Local Municipality, 8.5 % of household had no sanitation facilities. Moreover, in 2001, a cholera outbreak happened in South Africa which showed how important sanitation is. Then, the Department of Water Affairs and Forestry launched the National Sanitation Program. The progress of sanitation implementation was monitored and evaluated with performance indicators, such as:

- Programs to clear the backlog,
- Promotion of health and hygiene education,
- Impact of sanitation improvement programs on the health of communities,
- Allocation application and management of funds,
- Involvement of communities,
- Development of common norms, standards guideline, and other tool [17].

Nowadays, the Department of Water Affairs and Sanitation is in charge of sanitation. The main challenge in the North West Province is to replace unimproved pit latrines with VIP [18].

Three policies have been launched recently about sanitation in South Africa:

- 2009: Free Basic Sanitation Implementation Strategy [19], which gives the specific steps that can be taken at a local level to implement the free basic water policy.

- 2013: National Water Resource Strategy.
- 2016: National Sanitation Policy [20], which is a review of any previous draft sanitation policy. The entire sanitation value chain such as collection, removal, disposal or treatment of human excreta, domestic and industrial wastewater, is considered in this policy.

In the Ramotshere Moiloa Local Municipality, the sanitation facilities are improved since 1996. The sanitation facilities of the RMLM are presented in the Table 2.

	1996	2001	2011	2016
Population	15176	137443	150315	157691
Household	3290	31977	16634	47235
Flush toilet to sewerage system		6052	9310	12428
Flush toilet to septic tank	2967	1124	1730	1673
Chemical toilet		332	218	2404
VIP		6360	2637	5002
Pit latrine	45	15415	24261	22536
Bucket latrine	290	335	92	202
Ecological toilet	-	-	-	1115
None	-	2740	2387	-

Table 2: Sanitation facilities in Ramotshere Moiloa Local Municipality in the last past 20 years [5, 10, 11, 12].

It can be noticed that the number of flush toilet connected to septic tanks is stable. Every five years, household connected to sewage network is increasing. Moreover, the number of pit latrines is decreasing contrary to the number of VIP. It means on-site sanitation is followed and improved. In the South African side of the study area, the majority of sanitation facilities used is VIP and pit latrines. But, four wastewater treatment works are operating in Zeerust, Lehurutshe and in the border posts of Skilpadshek and Swartkopfontein.

2.1. Motswedi sanitation facilities

The Motswedi WWTP is located approximately 2 km from the village of Motswedi, around 71 km north east of Mafikeng. The plant in Motswedi is currently not in operation. The inflow has been cut off for many years. But, the facilities which the plant serves, such as a school, a police station and a number of private houses, are still functioning. Because of this, the wastewater from these buildings is going into the environment. The sanitation facilities of the town are presented in Table 3. It has to be noticed that Motswedi is far from 4.5 km of the Ngotwane river which is flowing in the Ngotwane Dam.

	Population	Household	Flush toilet to sewerage network	Flush toilet to septic tank	Chemical toilet	VIP	Pit latrine	Bucket latrine	None
Motswedi Consensus 2011	2794	558	80	27	4	66	701	0	15

Table 3 : Sanitation facilities in Motswedi, 2011 [5].

In South Africa, a typical household, with three children and two parents, uses about 250 litres of water a day [21]. Considering that households with flush toilet connected to the sewerage network are

discharging their wastewater in the sewerage system, at least 20 m³ of wastewater per day are discharged into the environment in Motswedi.

The only way to know the impact of the lack of sanitation in Motswedi is to assess the quality of water supply in Motswedi. The quality of the boreholes in Motswedi was assessed in the Blue Drop Report [22]. In average, 50 L.person⁻¹.d⁻¹ are consumed from Motswedi water supply. The microbiological compliance is 74.4% and the chemical compliance is 93.7%. So, groundwater is not compliant for nitrate, nitrogen and faecal coliforms. Lack of sanitation in Motswedi has an impact on the aquifer.

2.2. Lehurutshe sanitation facilities

The Lehurutshe WWTP is located approximately 6.4 km north west of Lehurutshe as mentioned in Figure 12, around 54 km north east of Mafikeng. This plant has been built in 1980 and is operated and maintained by the Ramotshere Moiloa Local Municipality.

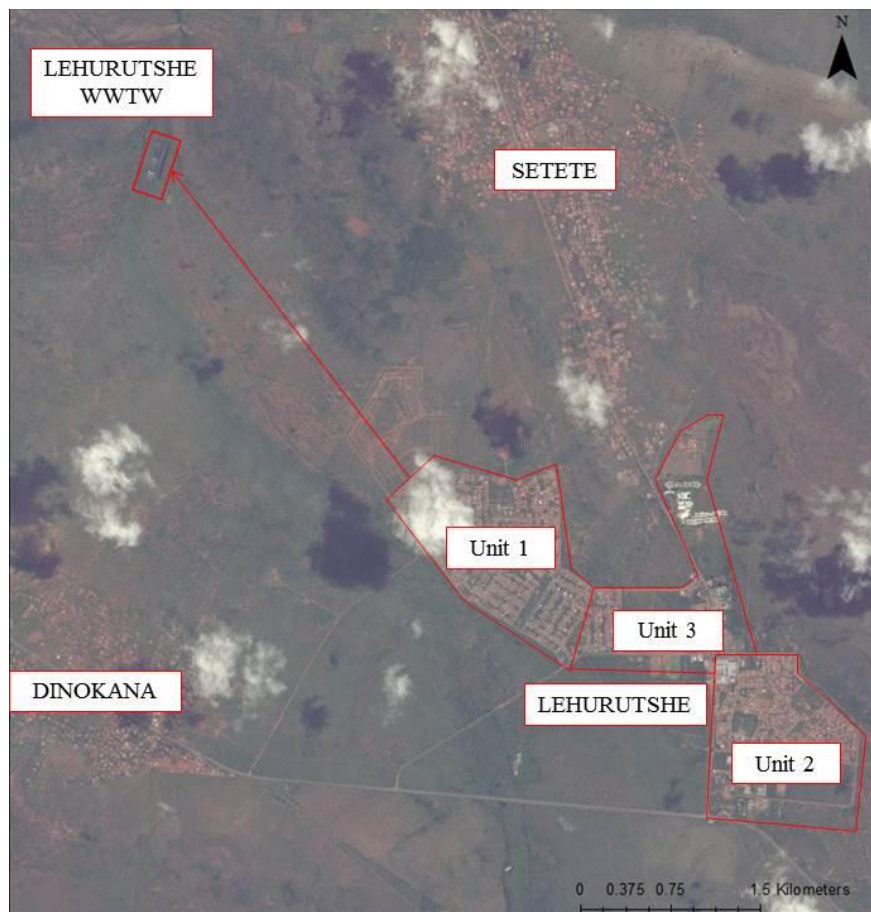


Figure 12: Map of Lehurutshe.

Lehurutshe is divided in three units for the census of sanitation facilities. The three units of the town are entirely connected to the sewerage system, as presented in Table 4 for the consensus of 2011. There still are septic tanks and latrines for old houses.

Lehurutshe	Population	Household	Flush toilet to sewerage network	Flush toilet to septic tank	Chemical toilet	VIP	Pit latrine	Bucket latrine	None
Unit 1	4559	626	1495	39	0	18	14	0	34
Unit 2	1809	190	641	2	0	2	33	0	2
Unit 3	105	1	28	0	0	0	0	0	0

Table 4: Sanitation facilities in Lehurutshe [5].

The WWTP is designed to receive $1\,500\text{ m}^3\cdot\text{d}^{-1}$ of wastewater but it is actually operating for $900\text{ m}^3\cdot\text{d}^{-1}$ from 5993 inhabitants, which means about 60% of its full capacity. The plant comprises an inlet work, three anaerobic and one aerobic oxidation ponds, three maturation ponds, and a set of recycle pumps from the maturation ponds to the anaerobic ponds. The system is presented in Figure 13. The recycle pumps are unserviceable. A chlorination tank was removed. Some maintenance should be done for anaerobic and aerobic oxidation ponds which are overgrown.

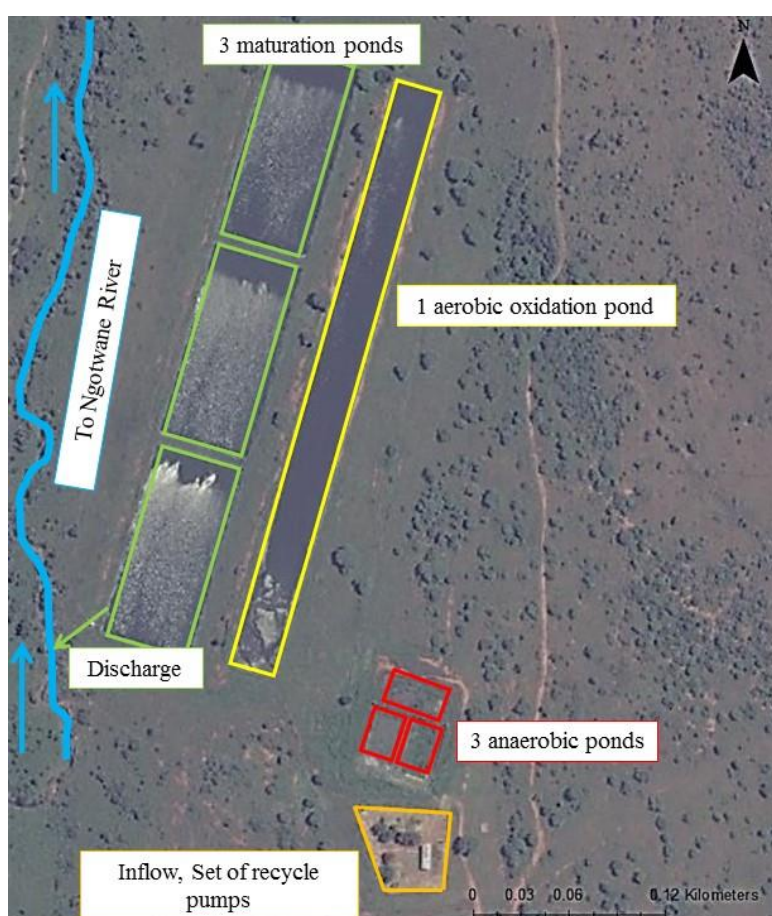


Figure 13: Map of the Lehurutshe Wastewater Treatment Plant.

Wastewater treated is discharged in a tributary of the Ngotwane river, flowing until the Ngotwane Dam. The average evaporation for wastewater treatment ponds is around 60%. At least, the WWTP discharges $360\text{ m}^3\cdot\text{d}^{-1}$ in the river. According to the Green Drop Report of 2014 [23], the discharge is not compliant to the South African standards. The microbiological determinands, which are *Escherichia Coli* and Faecal Coliforms, are 16.7% compliant to the standards. Moreover, chemical determinands as COD, Ammonia and Nitrate, Nitrogen, Ortho – Phosphate, are 5.6% compliant. At last, physical determinands such as pH, Suspended Solids, Electrical Conductivity are 10.4% compliant. The dis-

charge represents a real risk for the environment and contaminates irrigation water of the Ngotwane Dam.

The compliance of the WWTW could be improved by cleaning the ponds and installing a new chlorination plant. The pollution is discharged in the Ngotwane river which infiltrates the aquifer and flows to the Ngotwane Dam [24].

2.3. Zeerust sanitation facilities

Zeerust WWTP is located approximately 1.5 km east of Zeerust, around 58 km east and north of Mafikeng. This plant has been built in the sixties and was upgraded in 1993. Zeerust WWTP serves the town of Zeerust, Ikageleng township, an abattoir and a few other light industries, presented in Figure 14. It has been designed for a capacity of $3500 \text{ m}^3.\text{d}^{-1}$ but the WWTP operates for $4000 \text{ m}^3.\text{d}^{-1}$ of inflow from 17 708 inhabitants. In this area, wastewater pollution does not come from on-site sanitation. All the population is connected to the sewage network.

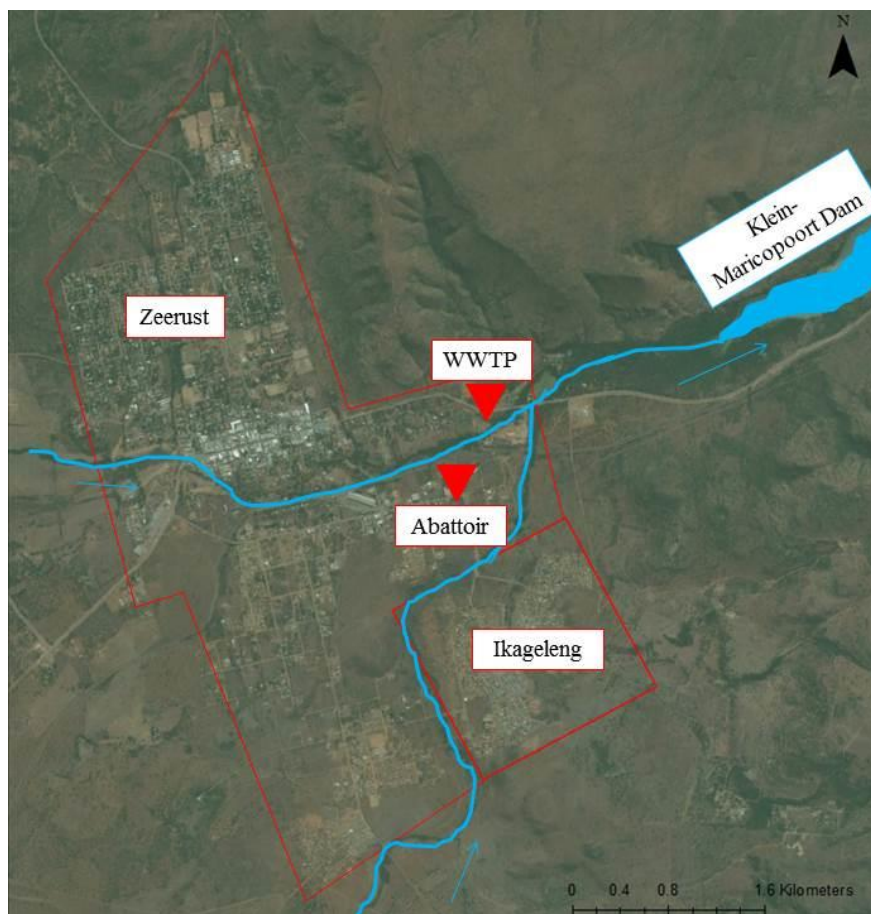


Figure 14: Location map of Zeerust WWTP.

The composition of the plant is described in Figure 15. Evaporation losses can be estimated around 45% in an activated sludge treatment. Indeed, around $2200 \text{ m}^3.\text{d}^{-1}$ of wastewater treated are produced. Moreover, Zeerust plant produces $3.7 \text{ tons}.\text{d}^{-1}$ of sludge.

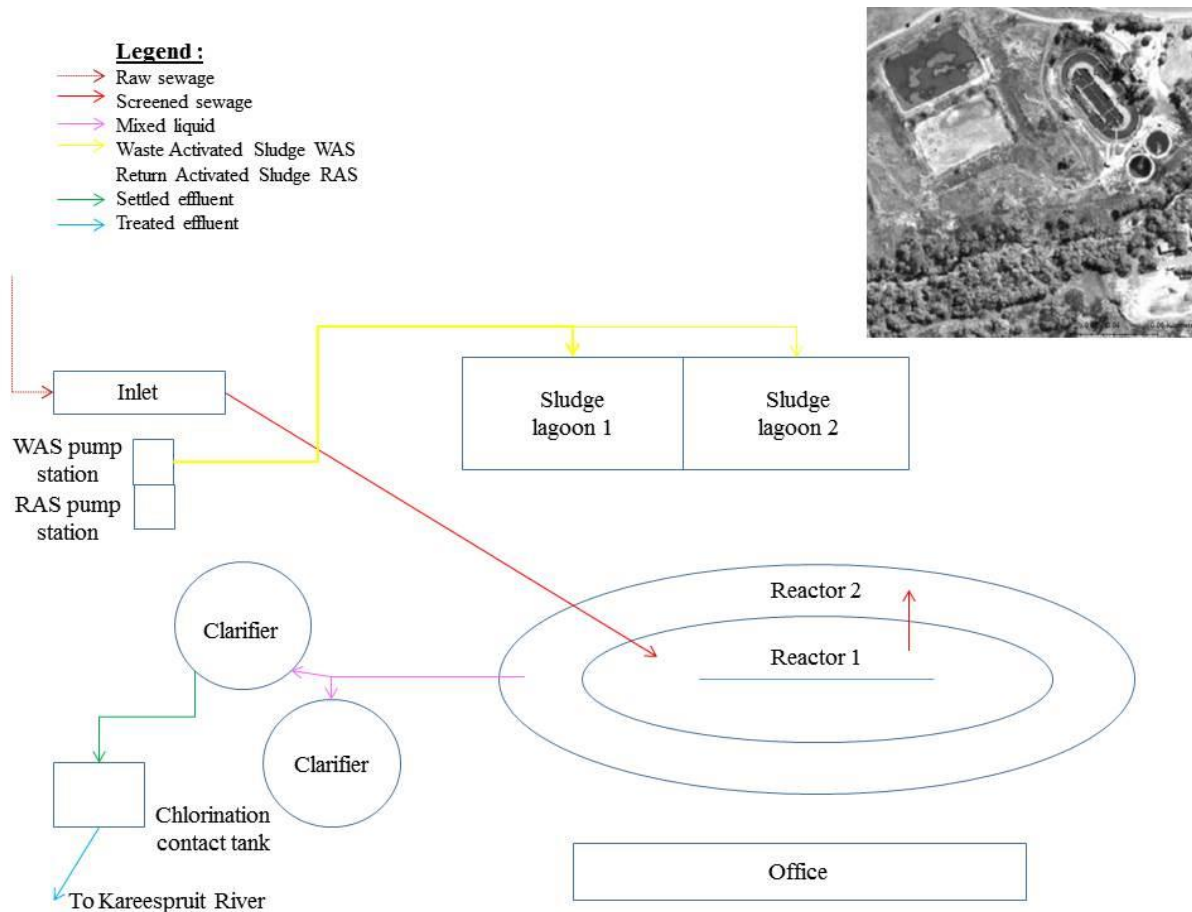


Figure 15: Design of Zeerust WWTW.

In 2013, an investigation was led on the quality of the Groot Marico River and Kareespruit River due to the mismanagement of the wastewater plants in Groot Marico and Zeerust [25]. Rivers of the area of Zeerust are highly polluted by *E. Coli* (1000 unit/100 mL) because of the wastewater management. The pollution comes from Zeerust and Marico WWTW. In fact, Marico is populated by townships with no proper sewage. The major threat of pollution is during rainy days. There is no more operation because the municipality feared excessive spillages into the river. But, Zeerust WWTW is identified as one of the priority projects and is allocated the highest funding in the North West Province, around 2.8 million of rand. The latest upgrading was in 2012 for materials and maintenance [26], as:

- Replacement of horizontal brush aerators and mixers (4 mixers, 18 aerators),
- Replacement of return sludge pump,
- Replacement of waste sludge pump,
- Installation of flow meters in inlet and outlet work,
- New mechanical step screen,
- Upgrading bulk electricity supply system.

Because of the upgrading, the discharge quality is improving. There are two reasons of possible pollution from the WWTW. The first one is the fair state of the waste sludge lagoons. In fact, the settled sludge and the debris floating on the lagoon surface have to be removed. The second reason is the discharge from the abattoir. Abattoir's sewage is composed of high blood content and has an impact on poor effluent quality. The poor quality of WWTW discharge in Figure 16 was presented in the Green Drop Report of 2014.

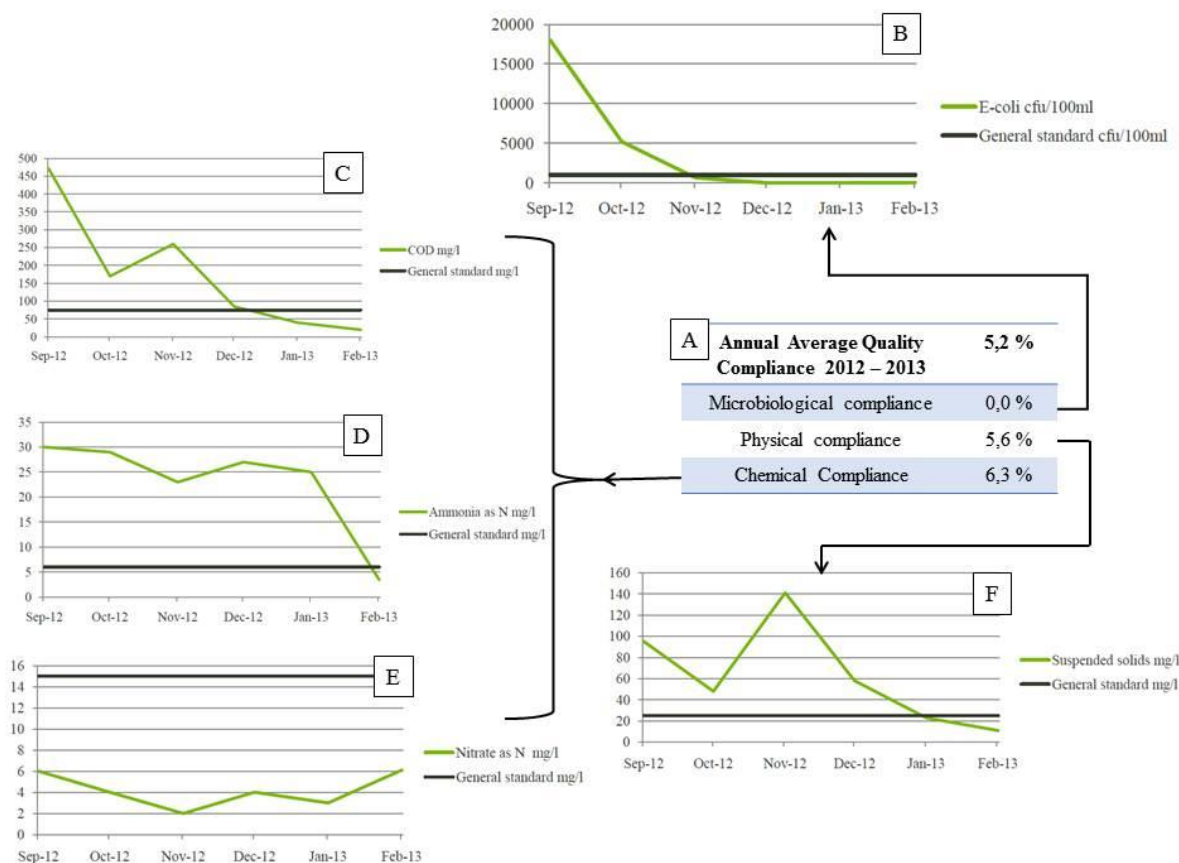


Figure 16: A) Zeerust WWTP compliance in 2012 - 2013 [23], B) E. Coli analysis in Zeerust WWTP discharge [26], C) COD analysis in Zeerust WWTP discharge [26], D) Ammonia analysis in Zeerust WWTP discharge [26], E) Nitrate analysis in Zeerust WWTP discharge [26], F) Suspended Solids analysis in Zeerust WWTP discharge [26].

Figure 16 shows that the discharge of Zeerust WWTP is not compliant to the standards. But, the quality is improving during the rainy season because the raw sewage is diluted. Zeerust WWTP pollutes Kareespruit River which is flowing to Klein-Maricopoort Dam. The priority for improving the discharge quality is the management and the maintenance. Moreover, industries should have their own pre-treatment for sewage.

2.4. Wastewater treatment plants of the Department of Public Works

Two wastewater treatment plants of border posts are located in the RTBAA. These treatment plants depend on the Department of Public Works of South Africa and treat small quantity of wastewater [27].

In Skilpadshiek Border Post, the treatment is realized in reed beds. The wastewater treatment plant is effective since 2008 and presents good compliance from the Green Drop Report [27]. Domestic wastewater treated comes from the border post and the military base.

There is also a wastewater treatment plant in Swartkopfontein Border Post. It was designed for domestic wastewater coming from the border post and the military base. The treatment process is oxidation ponds and the outflow is compliant between 95 and 100% of the standards [28].

3. Conclusion

The settlements not mentioned in the RTBAA are villages with a small population which is using essentially pit latrines or VIP. The impact they have on the aquifer pollution is not significant compare to the major settlements. A summary table of the different types of sanitation facilities in the RTBAA and their efficiency can be found in Appendix 9 for further information.

Figure 17 shows a map with the delineation of the area where data on sanitation is reliable. In green is the area with a comprehensive knowledge of sanitation conditions. Wastewater treatment plants are categorised according to their impact on the environment.

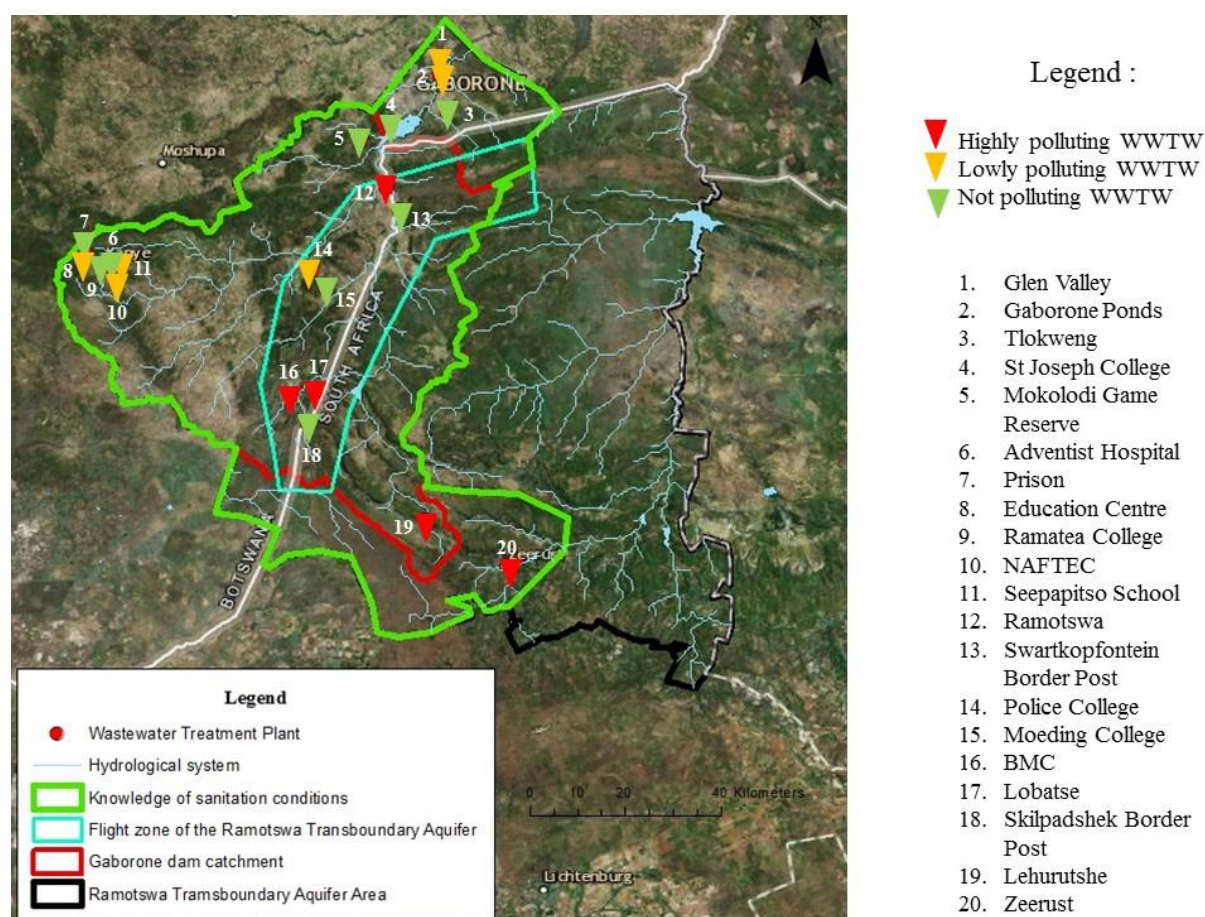


Figure 17: Map of the area with comprehensive knowledge of sanitation conditions.

Sanitation facilities are grouped by indicators of pollution in Table 5: place of discharge, wastewater quality, percentage of on-site sanitation and climate impact. It gives an overview of the sanitation challenges in the area extracted from the current status of sanitation.

Settlements	WWTP facilities	Discharge	Wastewater quality	Percent of on-site sanitation	Climate impact
Gaborone	Glen valley and Gaborone ponds	Ngotwane river	High in heavy metal	35%	x
	Tlokweng Technical	Sportsfield	✓		

	Training Centre				
	Saint Joseph's College	Gaborone Dam	✓		
	Mokolodi Game Reserve	Wetland	✓		
Kanye	Adventist Hospital	Gardens	✓	80%	✗
	Kanye Prison	Vegetable garden	✓		✗
	Kanye Education Centre	Infiltration	High in COD		No outflow during dry season
	Ramatea College	Wetland	✓		✗
	NAFTEC	Wetland	No data		✗
	Seepapitso School	Kanye river	Overflow of raw sewage		✗
Ramotswa	Ramotswa	Ngotwane river	High in COD, SS, nitrate	40%	No outflow during dry season & high groundwater table during wet season
	Swartkopfontein Border		✓		
Otse	Otse Police College	Gardens	Overflow of raw sewage	80%	High groundwater table during wet season
	Otse Moeding College	Sportsfield	✓		
Lobatse	BMC	Spillage in Peleng river	Overflow of raw sewage	38%	High groundwater table during wet season
	Lobatse	Ngotwane dam	High in COD, SS, nitrate		
	Skilpadshek Border	No outflow	✓		
Lehurutshe	Lehurutshe	Ngotwane dam	High in E.Coli, COD, nitrate	94% (compare to South African population of the RTBAA)	Evaporation of wastewater treated during dry season
Zeerust	Zeerust	Klein Maricopoort dam	High in E.Coli, COD, SS, nitrate	5%	✗

Table 5: Statement of sanitation in the RTBAA.

III. Challenges

In the sanitation assessment, some challenges are identified. Sanitation pollution depends on the place of discharge and population density, priority areas have to be defined. Moreover, many wastewater treatment plants treat domestic and industrial wastewater. Some are not adapted for industrial wastewater treatment. Then, wastewater treated is not compliant to the standards and pollutes the environment, particularly the Ngotwane river. In fact, Ngotwane river is mostly supplied by wastewater discharge of Lobatse, Lehurutshe, Ramotswa and Gaborone. This river is a transboundary river and a triggering factor for transboundary pollution.

On-site sanitation facilities are also involved in sanitation pollution by infiltration process. The aquifer is recharged by rainfall, wastewater discharge and infiltration from pit latrines. Water balances and climate conditions play a part in sanitation pollution. During wet season, the recharge is higher than during dry season and increases the level of the water table. So, the aquifer is more vulnerable during the wet season.

1. Vulnerability to pollution of the aquifer and priority areas

The potential vulnerability of an aquifer to pollution depends to its characteristics and human activities. Ramotswa Transboundary Aquifer is an unconfined aquifer which does not have a cover of impermeable material and is susceptible to contamination. The primary protection against groundwater pollution is the soil overlying the water table. Staudt [29] and Alemaw et al. [30] had already studied some parts of the study area by a GIS approach. In this case, to estimate the possible pollution of groundwater, modelling the study area was realized. Saturated zone permeability, aquifer characteristics, climate change, topography, human activities and wastewater facilities were included in modelling [31]. The chosen method is the DRASTIC method with ArcGIS [32].

1.1. DRASTIC Method

The DRASTIC method was developed by US EPA. It provides a basis for evaluating the vulnerability pollution of groundwater resources based on hydrogeological parameters. Moreover, the DRASTIC method can be considered as an approach to evaluate an area based on known conditions without the need for extensive site specific pollution data. By this modelling, an inexpensive method to identify areas that need more investigation was provided.

For using the DRASTIC method, some conditions have to be respected, such as:

- Contamination occurs at the ground surface,
- The contaminant enters the water table when rain falls on the surface and percolates into the saturated zone,
- The contaminant travels with water, at the same rate as water,
- The method will be applied to no greater than 40 hectares,
- The aquifer is unconfined.

The DRASTIC method can be defined by the parameters used in the index [33]. The parameters are presented below:

- Depth to groundwater: the depth from the ground surface to the water table in unconfined aquifer.
- Recharge: the total quantity of water which is applied to the ground surface and infiltrates to reach the aquifer. It is calculated from the rain and evaporation data in the study area.
- Aquifer media: the thickness of consolidated or unconsolidated rock which characterizes the top of the aquifer.
- Soil media: the uppermost portion of the vadose zone characterized by significant biological activity.
- Topography: the slope of the land surface.
- Impact of the vadose zone: the zone above the water table which is unsaturated or discontinuously saturated.

- Conductivity: the ability of the aquifer materials to transmit water.

Each parameter is assigned a rate and a weight. The method to calculate the DRASTIC index is described below:

$$DRASTIC\ Index = D_r \times D_w + R_r \times R_w + A_r \times A_w + S_r \times S_w + T_r \times T_w + I_r \times I_w + C_r \times C_w$$

In this equation, r is the rating for the parameter which ranges between 1 to 10, and w is an assigned weight for the parameter varying between 1 to 5 [32; 34].

DRASTIC Parameters	Weight of parameters
Depth to groundwater	5
Recharge	4
Aquifer media	3
Soil media	2
Topography	1
Impact of the vadose zone	5
Conductivity	3

Table 6: Weight of parameters for the DRASTIC method.

Each of the parameters in the model is grouped into ranges of values or broad categories that are assigned a rate from 1 to 10. There are presented below.

1.2. Depth to groundwater: groundwater head elevation

The raster was given in the Ramotswa database, led by IGRAC International Groundwater Resources Assessment. The piezometric map has been produced following the water level collected during the fieldwork campaign conducted from the 25th – 29th of August 2016 and from the 1st – 5th September 2016 in both South African and Botswana sides on 33 boreholes. Water level is between 998 mamsl and 1403 mamsl which mean that the depth of the water table varies between 7 and 67 m from the surface. These results can change because the fieldwork campaign was realized twice at the end of the dry season when the water table is lower. A classification is attributed for the depth of the water table in Table 7.

Depth of the water table m	Classification	Depth of the water table m	Classification
100 m and more	1	15 to 20	6
50 to 100	2	10 to 15	7
40 to 50	3	5 to 10	8
30 to 40	4	2.5 to 5	9
20 to 30	5	0 to 2.5	10

Table 7: DRASTIC classification of the water table depth.

Groundwater level helps to calculate the flow direction. The flow direction is presented in Figure 18.

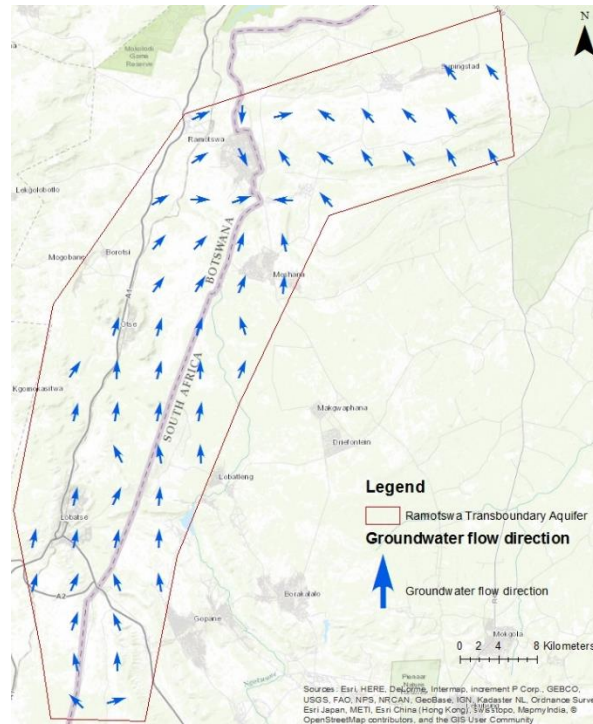


Figure 18 : Flow direction in the Ramotswa Transboundary Aquifer.

This map represents groundwater flow within the aquifer to be initially in north and later in north – easterly direction.

1.3. Recharge: rainfall and evaporation

The recharge capacity has been calculated with the rainfall and evaporation data from 1988 to 2016. Records from six stations were used. There are three stations in Botswana and three stations in South Africa, such as presented below in Figure 19.

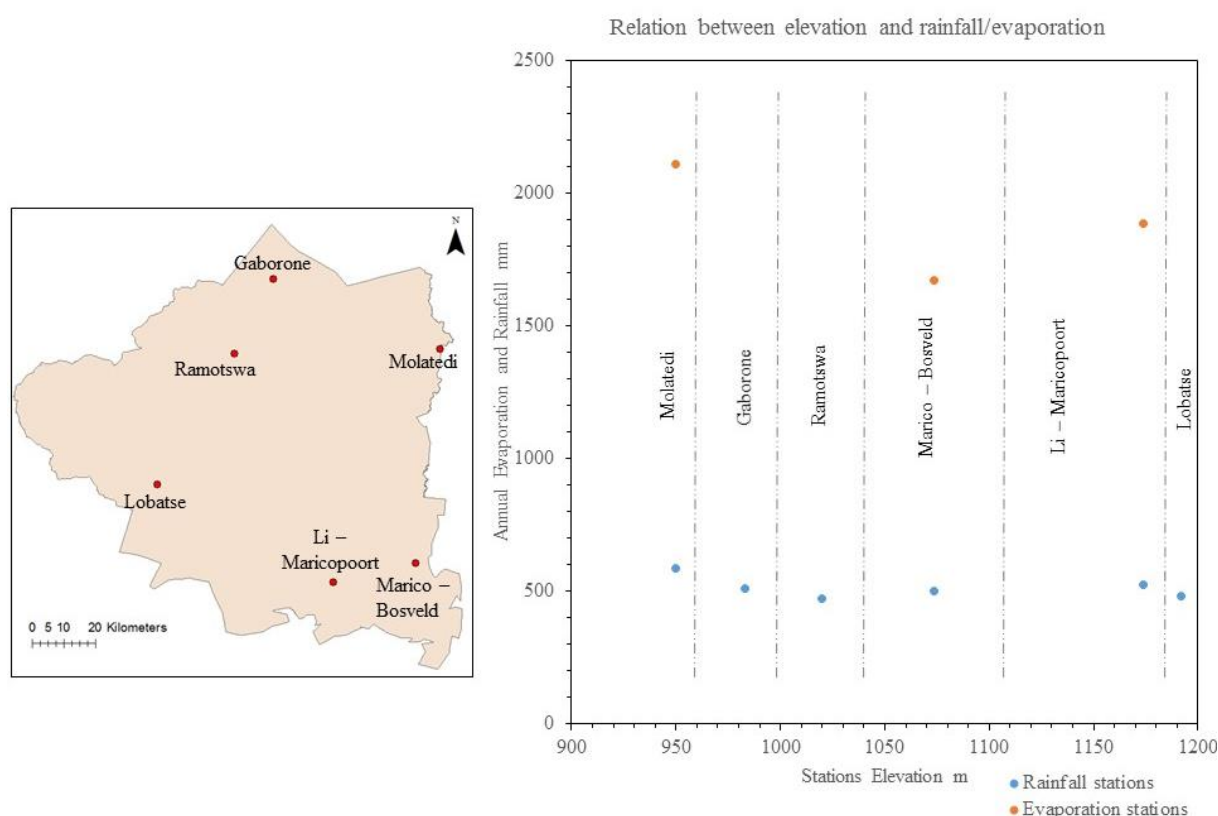


Figure 19: Location map of rainfall and evaporation stations.

Rainfall and evaporation have been interpolated in the study area [35]. The recharge has been calculated by subtracting the evapotranspiration to the rainfall per pixel for the dry season and the rainy season, according to the following equation:

$$Recharge = Rainfall - Evapotranspiration - Runoff$$

Runoff is overlooked for the recharge. Evapotranspiration has been calculated by using evaporation and pan coefficient from the DWA in Appendix 11 [36]. The dry season is from April to September. Contrary to the dry season, the rainy season is from October to March. The recharge, calculated for both season, is sometimes negative. These results are scientifically impossible because it cannot evaporate more water than it is present. This is explained by the simplicity of the recharge calculation in which effective rainfall is not included. Recharge results have been classified for the DRASTIC method from 0 mm to 190 mm. Negative data has been changed in null data. The classification is presented in Table 8. Higher is the category number, more the infiltration and pollution is possible.

Recharge mm	Classification	Recharge mm	Classification
0 to 19	1	95 to 114	6
19 to 38	2	114 to 133	7
38 to 57	3	133 to 152	8
57 to 76	4	152 to 171	9
76 to 95	5	171 to 190	10

Table 8: DRASTIC classification of the recharge.

It sounds logical to predict that the aquifer is more vulnerable to wastewater during the wet season because infiltration is more important and the water table is higher. But, it is interesting to assess how much the aquifer is more vulnerable during the wet season than during the dry season.

1.4. *Aquifer media: thickness between the top of the aquifer and the surface*

To create the thickness map, files from the RIMS database were used. For a better understanding of the aquifer, top, bottom, depth, thickness and groundwater head elevation files were studied. Records from these files were selected to create the thickness between the top of the aquifer and the surface. It was obtained by subtracting the top of the aquifer to surface elevation. Values are classified on a scale from 0 to 10 for a thickness between 0 and 450 m in Table 9.

Thickness m	Classification	Thickness m	Classification
100 m and more	1	15 to 20	6
50 to 100	2	10 to 15	7
40 to 50	3	5 to 10	8
30 to 40	4	2.5 to 5	9
20 to 30	5	0 to 2.5	10

Table 9 : DRASTIC classification of thickness.

1.5. *Soil media: Land cover map*

Landcover maps of Botswana and South Africa have been issued by the EarthEnv project (<http://earthenv.org>). The datasets integrate multiple global remote sensing-derived land-cover products and provide consensus information on the prevalence of 12 land-cover classes at 1 km resolution [37].

The reduced version of the consensus land-cover datasets was used. It is the dataset integrating three products, such as:

- GlobCover, 2005-6; v2.2,
- MODIS land-cover product, MCD12Q1; v051,
- GLC2000, global product; v1.1.

Each dataset contains twelve data layers, each provides consensus information on the prevalence of one land-cover class. All data layers contain unsigned 8-bit values and the valid values range from 0-100, representing the consensus prevalence in percentage. All data layers have a spatial extent from 90 N – 56 S and from 180 W – 180 E, and have a resolution of 30 arc-second per pixel.

The twelve data layers downloaded are:

- Evergreen/Deciduous Needle leaf Trees,
- Evergreen Broadleaf Trees,
- Deciduous Broadleaf Trees,
- Mixed/Other Trees,
- Shrubs,
- Herbaceous Vegetation,
- Cultivated and Managed Vegetation,
- Regularly Flooded Vegetation,
- Urban/Built-up,
- Snow/Ice,
- Barren,
- Open Water.

In the Ramotswa Transboundary Aquifer Area, the land covers such as evergreen/deciduous needle leaf trees, evergreen broadleaf trees and snow/ice are not found. Wastewater treatment facilities have been added to the land cover map.

A scale of pollution was attributed for the different land covers between 1 and 10. 10 is the land cover with the most human impact pollution and 1 the less polluted. Sanitation activities are the indicator chosen because it is more representative for possible pollution of the aquifer.

The scale is presented below:

- 2 : barren,
- 4 : vegetation such as broadleaf trees, mixed trees, shrubs, herbaceous vegetation and regularly flooded vegetation,
- 6 : open water,
- 7 : evaporation ponds and wastewater treatment facilities,
- 8 : cultivated and managed vegetation,
- 10 : urban built-up.

Every land cover raster was combined to have one final land cover map. But in some pixels, it is possible to find different types of land cover. For these ones, the kept value of the pixel is the highest one. Wastewater treatment facilities have a lower indicator compare to cultivated vegetation because agricultural activities are also a factor of nitrate pollution. Moreover, urban built-up has the highest indicator because it represents areas with pit latrines unmanaged.

1.6. Topography: slope

The slope map was created because it is one of the key factor for infiltration in the aquifer. In fact, lower is the slope, higher is the infiltration rate. The slope was extracted from the Digital Elevation Model provided by the IGRAC. Its classification is available in Table 10.

Slope %	Classification	Slope %	Classification
80 – 100 %	1	30 – 40 %	6
70 – 80 %	2	20 – 30 %	7
60 – 70 %	3	10 – 20 %	8
50 – 60 %	4	5 – 10 %	9
40 – 50 %	5	0 – 5 %	10

Table 10: DRASTIC classification of slope.

1.7. Impact of the vadose zone: permeability of the unsaturated zone

The vadose zone has been studied with the geological maps available from the Department of Geological Survey Botswana and Council for Geoscience of South Africa. The different type of rocks has been classified according to their permeability capacity. Higher is the class, higher is the scale permeability chosen.

Type of soil	Comments	Permeability scale – Classification
Alluvium	Sand	10
Banded Ironstone	Composed of shales and chert	2
Breccia	Sandstone and conglomerate	8
Chert-free dolomites	Type of limestone	10

Chert-rich dolomites	Type of limestone	10
Dolerite	Volcanics	4
Dolomite	Similar to limestone	10
Granite		6
Gneiss		4
Limestone		10
Marl	Mudstone	2
Quartzites	Sandstone	8
Sandstone		8
Shales	Mudstone	2
Siltstone	Silt	8
Volcanics		4

Table 11 : DRASTIC classification of the permeability rocks in the vadose zone [38].

1.8. Conductivity: hydraulic conductivity

The hydraulic conductivity map was extracted from the results of airborne geophysical survey, led by the company XRI – blue in August 2016. Some of these data are still uncertain. Classification is available in Table 12.

Hydraulic conductivity m.s^{-1}	Classification	Hydraulic conductivity m.s^{-1}	Classification
0 – 2.5	2	7.5 – 10	8
2.5 – 5	4	10 – 12.5	10
5 – 7.5	6		

Table 12: DRASTIC classification of hydraulic conductivity.

1.9. Results

Two vulnerability maps were obtained: one during the dry season from April to September, and one during the rainy season from October to March. They are presented in Figure 20.

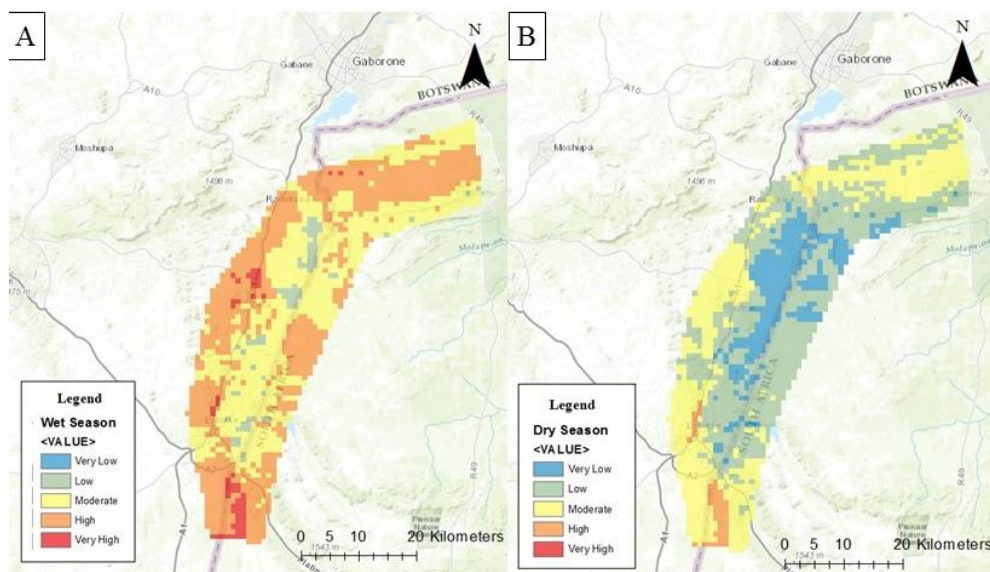


Figure 20 : Vulnerability map for groundwater pollution: A. during the rainy season from October to March; B. during the dry season from April to September.

In Figure 20A, from October to March the groundwater vulnerability map indicates that 0% of the area has very low vulnerability, 4 % has low vulnerability, 44.1 % is moderately vulnerable, 48.8 % is highly vulnerable and 3.1 % is very highly vulnerable. In contrast, from April to September, the Figure 20B shows that 16.1% of the area has very low vulnerability, 45.1 % has low vulnerability, 36.3 % is moderately vulnerable and 2.5 % is highly vulnerable.

The most vulnerable area for groundwater pollution is located on the border area from Lobatse to Ramotswa, ten kilometers from the border on both sides. In conjunction with the aquifer flow direction map in Figure 18, pollution coming from south is flowing to north and contaminates dams and well-fields.

To conclude, Ramotswa Transboundary Aquifer Area is highly vulnerable to pollution if it is not properly managed for wastewater. However, the interpretation of the results has to be cautious due to the sparse and uncertain nature of the basic data used for this interpretation and the availability of the aquifers parameters.

2. Industrial pollution

Most of the wastewater treatment plants in the RTBAA treat domestic and industrial wastewater. For example, the sewage treatment plant in Gaborone treats industrial discharge from breweries, food industries, abattoirs, pharmaceutical companies, and soap manufacturing companies [39; 40; 41]. In some cases, industrial wastewater increases significantly COD, BOD and suspended solids. Higher concentration of heavy metal in sludge is also a consequence of industrial discharge. Figure 21 is a map of biggest industrial activities in the RTBAA.

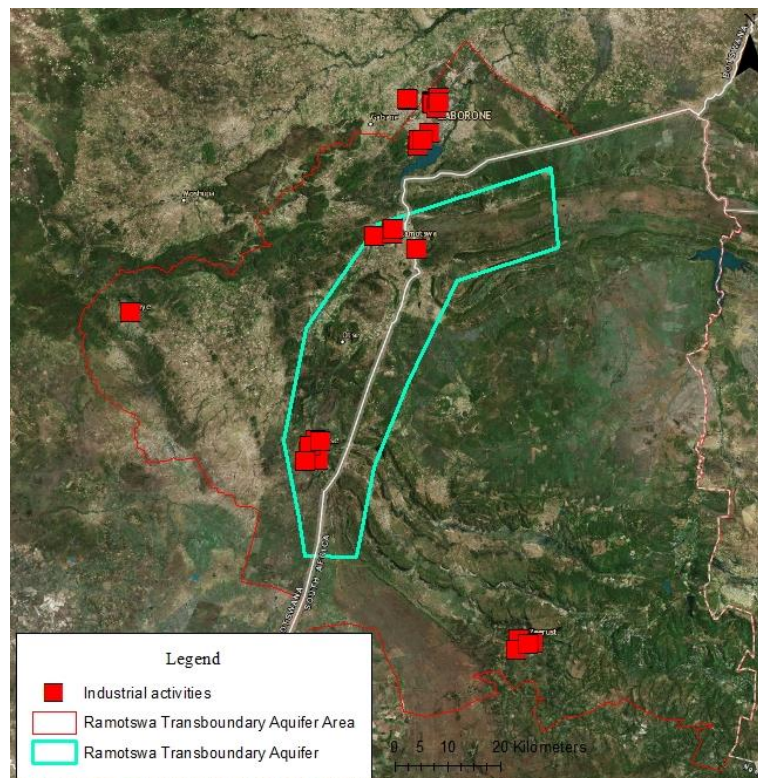


Figure 21: Map of biggest industrial activities in the RTBAA.

Gaborone has the biggest industrial activities. Lobatse is known for the national abattoir, Botswana Meat Commission. Other industries are located in Lobatse such as tannery, clay works, sugar industry, and hospitals. The sewage network in Ramotswa treats industrial wastewater from hospital, food industries (Bolux Milling and Higo Feeds), glass works, and steel and iron industry. In Zeerust, the industrial activity is composed of an abattoir, tannery and a hospital. At last, Kanye has a food industry. Table 13 informs the pollutants which are present in different types of industrial wastewater.

	Food Industry	Abattoir	Tannery	Hospital	Heavy metal industry	Pharmaceutical industry	Sugar industry
Pollutants	COD, BOD, oil and grease, nitrogen, phosphorus, detergent/cleaning products [47, 48]	Phosphorus, nitrogen, TOC, COD, SS, BOD, heavy metal, disinfectant, pharmaceuticals [55, 56, 57]	Sulphide, chromium, volatile organic compounds, solid waste, SS, COD, BOD [52, 54]	Antibiotics, iodinated contrast media, estrogens (E1, E2, E3, EE2), cytostatic agents, COD [45, 46]	Heavy metal (iron, lead, zinc), acid, oil and grease, COD [50]	Endocrine disrupting substances: natural estrogens, synthetic estrogens, bisphenol A or F [44]	TDS, COD, BOD, chloride, sulphate, oil and grease [42, 43]
Recommendations	Adsorption, coagulation [47, 49]	Coagulation/flocculation, electrocoagulation, advanced oxidation processes [55], UV/H ₂ O ₂ [56]	Primary sedimentation and aerobic biological treatment or coagulation, safe disposal sludge [53, 54]	Ozonation, adsorption, activated sludge, membrane bioreactors, integrated anaerobic-aerobic fixed film bioreactor system [45, 46]	Electroprocess (electrocoagulation), precipitation, ion exchange [50]. Possibility to recycle water for the industry. [51]	<u>For non-biodegradable compounds:</u> membrane filtration, adsorption, ozonation <u>For biodegradable compounds:</u> activated sludge (RBC) [44]	Aerobic SBR treatment process [43]

Table 13: Wastewater pollutants from industrial activities.

Recommendations given in Table 13 are different types of treatment which remove specifically pollutants from wastewater with on-site wastewater treatment plant.

3. Surface and groundwater transboundary pollution

As mentioned above, the most vulnerable area for groundwater pollution is located on the border area. In this part, the aim is to determine if pollution from sanitation in Botswana has an impact on South Africa water or vice versa.

In the border area, there are different cases of pollution from sanitation facilities which are directly or indirectly contaminating Ramotswa Transboundary Aquifer, shown in Figure 22. In fact, transboundary pollution exacerbates by interaction between water surface and groundwater. Surface water and groundwater systems are connected by three basic ways. First, streams gain water from inflow of groundwater through the streambed. Then, streams lose water by outflow through the streambed. They do both depending upon the location along the stream.

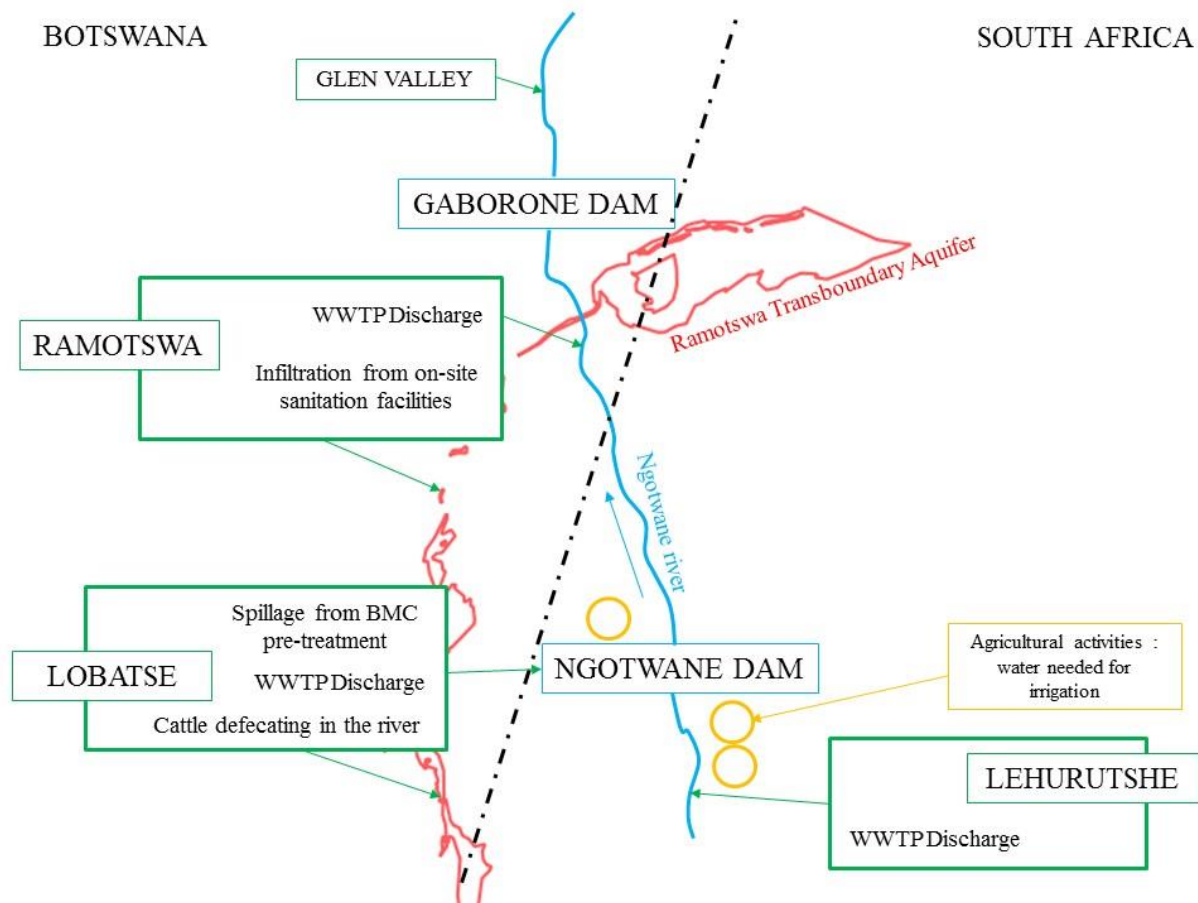


Figure 22: Simplified scheme of transboundary pollution in the RTBAA. Not to scale.

Transboundary pollution means that an environmental agreement should be developed between the two countries affected, such as Botswana and South Africa.

3.1. Surface water pollution

Ngotwane River is a transboundary river. Some wastewater treatment plants are discharging in it and its tributaries. Lehurutshe, Lobatse and Ramotswa ponds and rainfall constitute the base flow of the Ngotwane River in the south of the RTBAA. In the north, Gaborone Dam cuts off the flow of water to the Ngotwane River. When the dam overflows in monsoon period, water re-enters the Ngotwane River. The wastewater effluent from Glen Valley ponds feeds the river.

Surface water pollution exists in Lobatse area. Two sources of pollution are identified in Figure 23: one from the Lobatse WWTP discharge and another one from spillage in the BMC pre-treatment.

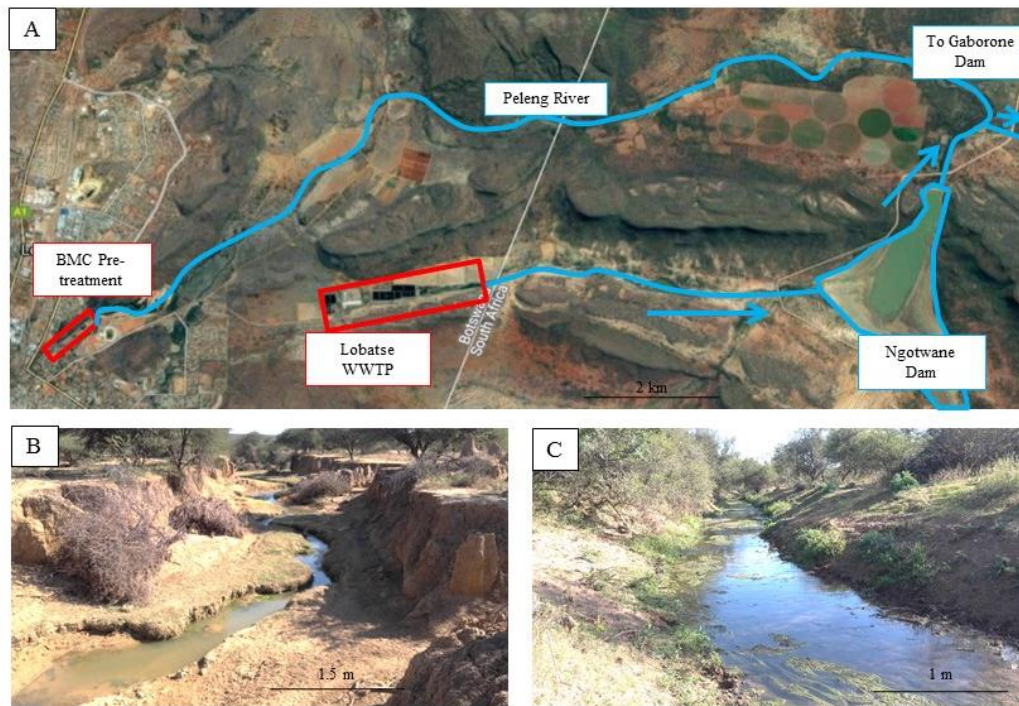


Figure 23: A. Identification of surface water pollution in Lobatse area; B. Picture of the stream from Lobatse WWTP discharge; C. Picture of Peleng River.

Figure 23B is Ngotwane dam tributary with wastewater flowing from Lobatse Wastewater Treatment Plant, Botswana. The stream flow is about $89 \text{ m}^3 \cdot \text{h}^{-1}$ with high load of chemical oxygen demand, suspended solids ($57 \text{ kg} \cdot \text{d}^{-1}$), free saline ammonia ($10 \text{ kg} \cdot \text{d}^{-1}$) and tendency for eutrophication process. The stream is discharging in the Ngotwane dam where water is used for agriculture and drinking water for cattle. Figure 23C is Peleng River with overflow and seepage of raw wastewater from Botswana Meat Commission (BMC) pre-treatment in Lobatse. The stream flow is about $86 \text{ m}^3 \cdot \text{h}^{-1}$ with high content of fats and suspended solids. Ten kilometers downstream from Lobatse, the river turns to the east and flows towards the Ngotwane River, downstream Ngotwane dam.

In the north part of the RTBAA, Mladenov et al. [58] worked on a DO model with different scenarios to assess the wastewater impacts on the Ngotwane River and to provide an evaluation of the suitability of the Ngotwane river water for reuse. Glen valley ponds discharge and the artificial wetland in Gaborone Game Reserve are the only sources of water for the river after the Gaborone Dam. Downstream Glen Valley WWTP in the Ngotwane River, eutrophic conditions were encountered. Some perennial stream standards of the DWA were not respected for DO, COD, dissolved P and faecal coliforms. Quality varies with seasons. Scenarios suggest a better quality during winter than summer because of the low average temperatures of approximately 17°C which produce high DO concentration. In any case, the Ngotwane river is polluted by wastewater treated.

3.2. Groundwater pollution

Ramotswa Transboundary Aquifer is a karstic aquifer with a shallow water table. Pollutants enter the karst aquifer easily by layer and sinkhole and spread quickly by covering the area of the karst aquifer [Appendix 12]. There is no natural attenuation process which makes the karst aquifer more vulnerable to pollution. Moreover, the groundwater table is high. It was reported water levels vary between 5 and 40 m of depth in the transboundary aquifer [8; 9]. The pit's depth of on-site sanitation is approximate-

ly 5 m which means pit latrines and the aquifer are in contact. On-site sanitation facilities contaminate directly the aquifer by percolation. Latrines are not recommended in areas with high water table.

Groundwater flow is to the north, from the South African side in the south of the study, then moves in a north-easterly direction towards the village of Ramotswa in Botswana. Wellfield monitoring was undertaken by some studies. Spatial distributions of TDS, E. Coli and total coliforms in groundwater are presented respectively in Figure 24, 25 and 26.

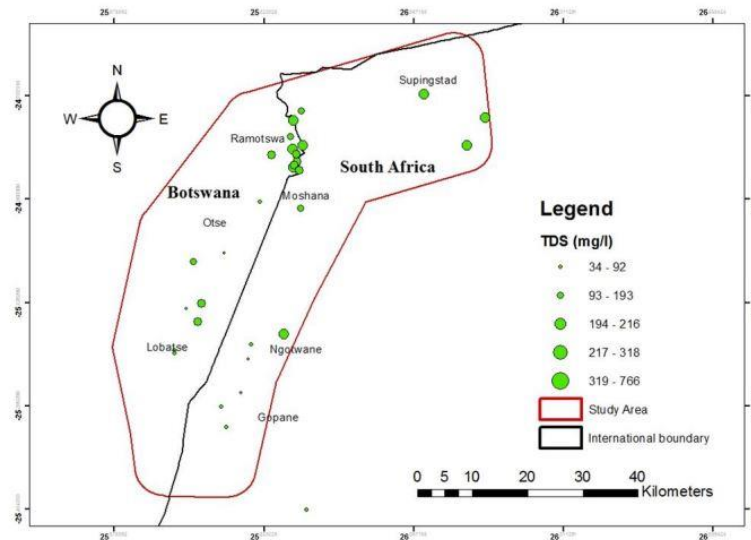


Figure 24: Spatial distribution of the total dissolved solids in the TBA [59].

Sum of nitrate and nitrite was also sampled in the RTBAA, available in Appendix 13 [59]. Two sites were identified with high concentration of the sum of nitrate and nitrite. In Supingstad, the concentration is 45 mg.L^{-1} , which is higher than the South African guideline limit of 6 mg.L^{-1} . The second site is in Ramotswa with a concentration of 99.9 mg.L^{-1} . Both sites are located in the north-easterly region where groundwater table is shallow. This pollution comes from on-site sanitation infiltration. Biological decomposition of nitrate in the soil from sanitation is shown in Figure 25.

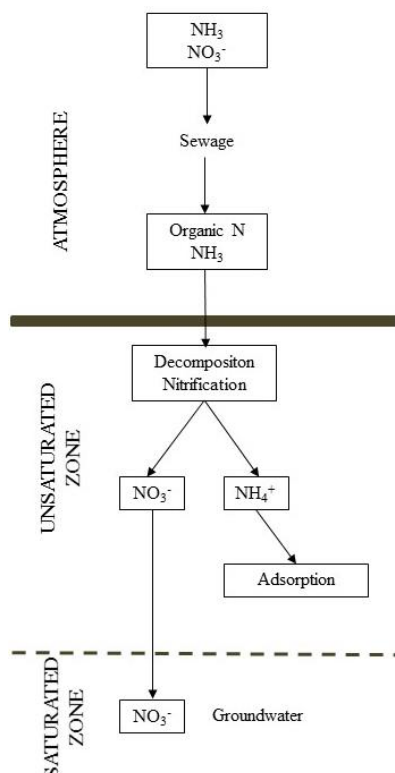


Figure 25: The fate of nitrate from sanitation in the environment.

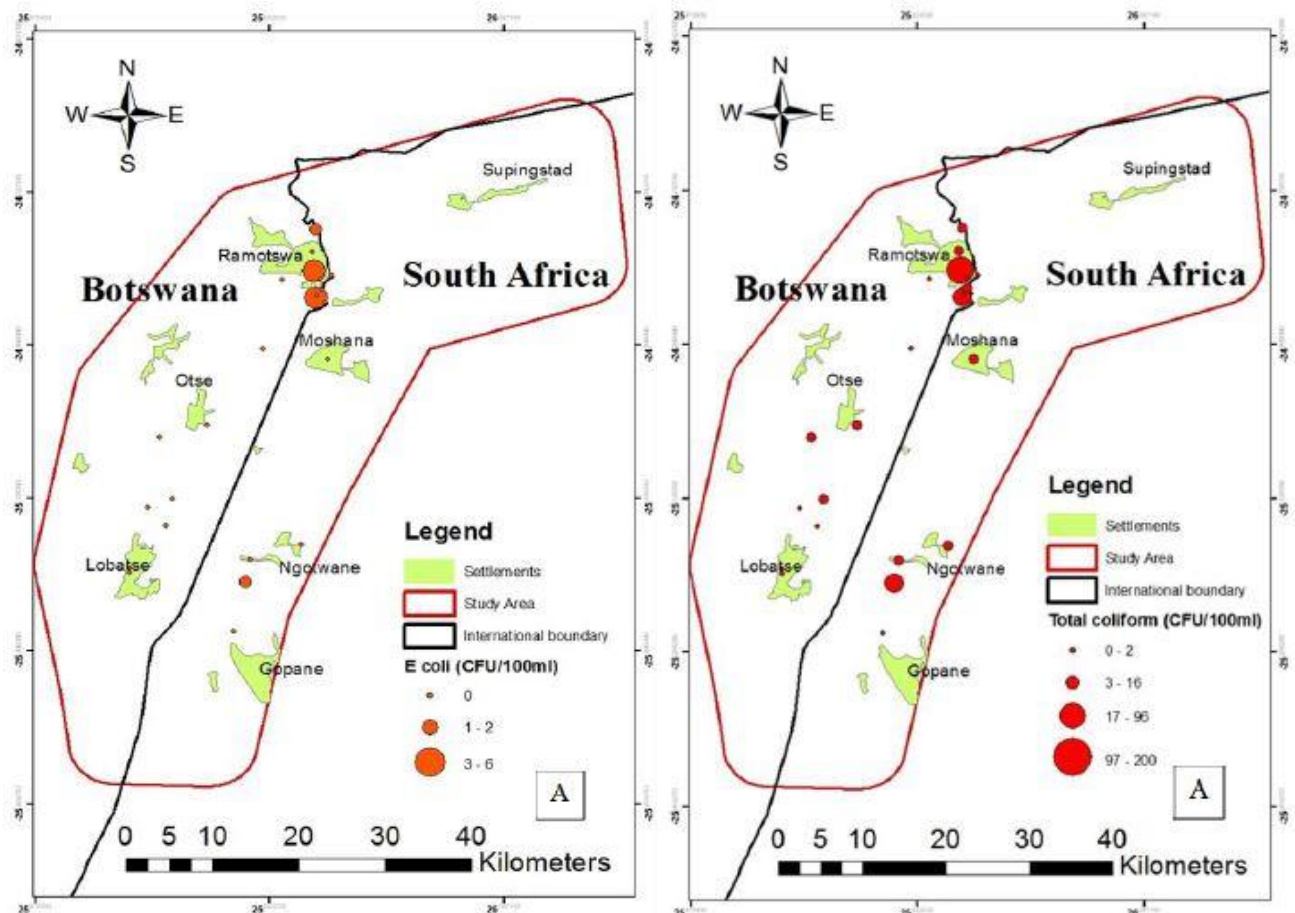


Figure 26: Spatial distributions of E.Coli and total coliforms, respectively on the left and on the right [59].

Spatial distributions of E.coli and total coliforms show high concentration rate in Ramotswa and Ngotwane. High concentration in Ramotswa is logical because of the high population density, use of pit latrines and north-easterly groundwater flow. Near Ngotwane dam, density population using pit latrines is lower than in Ramotswa. On-site sanitation is not the only source of pollution. Infiltration from the river bed is considered. In fact, fairly regular groundwater recharge takes place from Ngotwane River and its tributaries. Von Hoyer et al. [60] specify the main valley of Lobatse with high potential but variable groundwater recharge. Recharge depends on the degree of karstification and transmissivities [8]. For the dolomite aquifer, transmissivity range varies from $10 \text{ m}^2 \cdot \text{d}^{-1}$ to up to $400 \text{ m}^2 \cdot \text{d}^{-1}$ [61]. Outflow from wastewater treatment plant is a source of pollution for the Ramotswa Transboundary Aquifer.

4. Water balances

Water balance is one of the tools to understand the impact of sanitation on the Ramotswa Transboundary Aquifer. Figure 27 shows inflow and outflow.

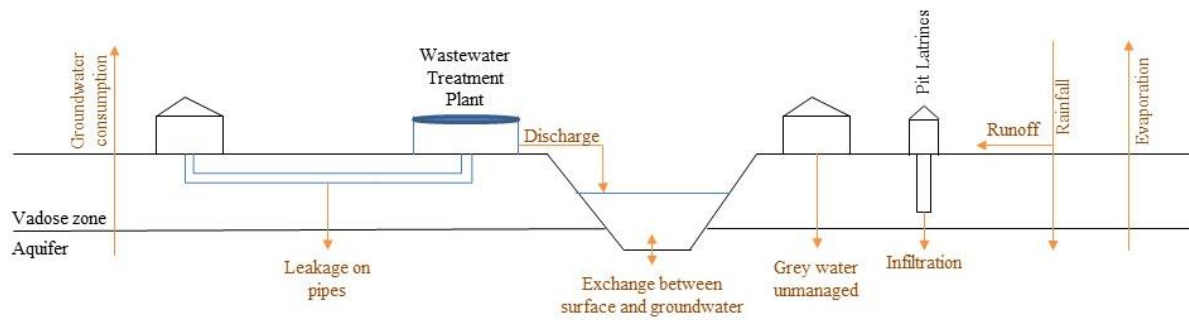


Figure 27: Scheme of water balances in the RTBAA.

Infiltration from on-site sanitation, grey water unmanaged, leakages on sewage network and non-compliant discharge from wastewater treatment plant are pollutants for the aquifer. Their quantity relies on the water supply and their quality depends on the facilities efficiency.

From the water supply, wastewater treated in WWTP and wastewater flowing to on-site sanitation are estimated. The quantity is based on the water consumption per capita in major villages between 1998 and 2008, extracted from Botswana Water Statistics [62]. Percentage of household connected to sewage network is used to determine the quantity of wastewater treated in WWTP [3; 5]. The consumption of water in township and rural areas includes a range between $5\text{L.d}^{-1}.\text{person}^{-1}$ and $60\text{L.d}^{-1}.\text{person}^{-1}$. Details are available in Appendix 10.

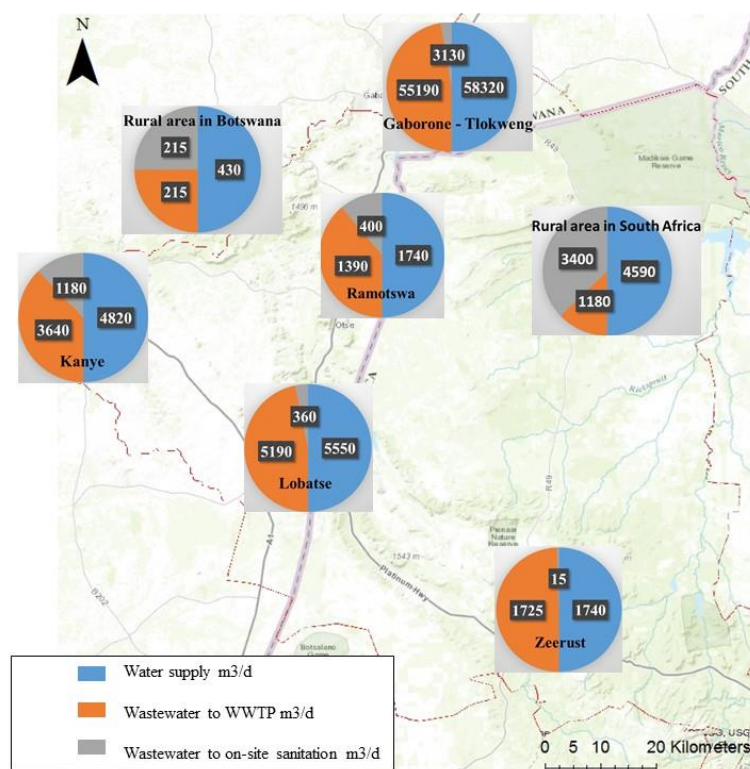


Figure 28: Scheme of the water consumption and wastewater according to their sanitation facilities in the RTBAA.

Compare to the design capacity of plants, wastewater treated in WWTP corresponds to these results. Figure 29 presents a range of possible losses on sewage networks.

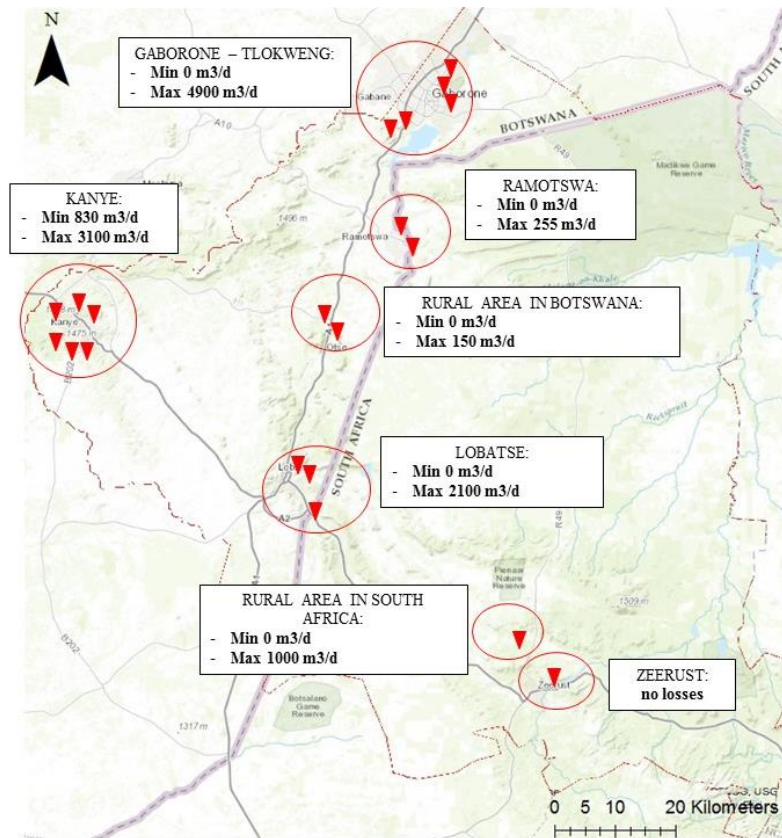


Figure 29: Range of losses on the sewage network in the RTBAA.

Sewage network has a life time of thirty years. Some pipes have fails but there is no maintenance on leakage. Maintenance on sewage network is a challenge because it prevents direct infiltration of raw wastewater in the aquifer.

Wastewater from on-site sanitation facilities percolates to the aquifer with a rate of $10 \text{ L.m}^{-2}.\text{d}^{-1}$ [63]. A range of wastewater infiltrating from on-site sanitation and grey water unmanaged is presented in Figure 30. It was calculating by using the sludge accumulation rate in latrines in wet conditions, a range of water consumption [64] and the quantity of wastewater going to areas which sanitation facilities are mainly on-site sanitation.

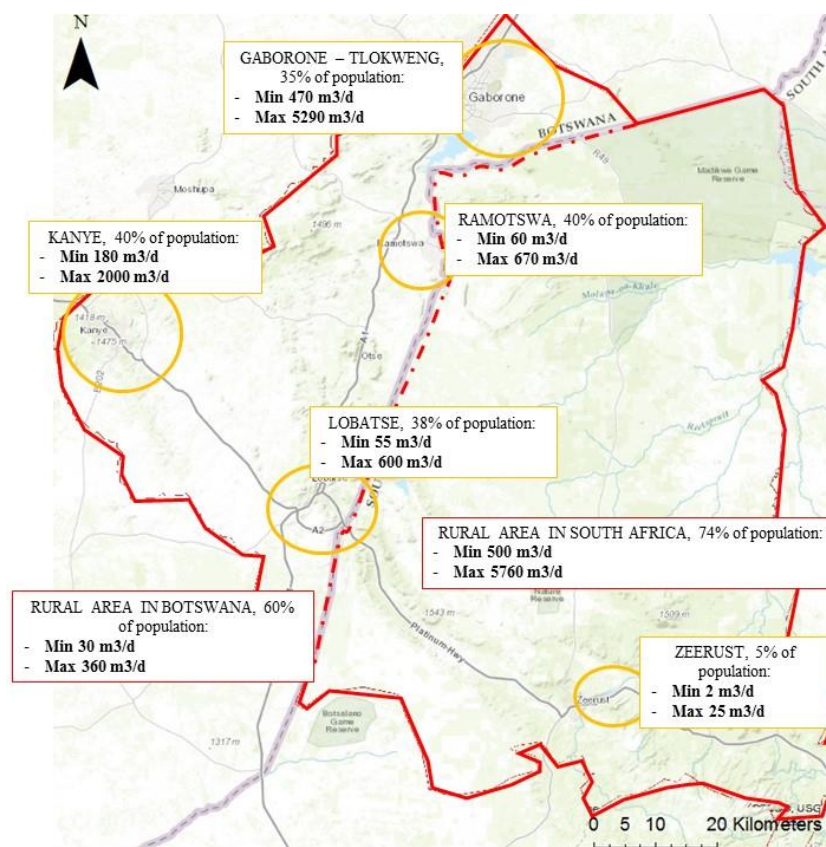


Figure 30: Unmanaged grey water and wastewater infiltrating from on-site sanitation in the RTBAA.

For household relying on on-site sanitation, the water consumption is lower than for household connected to sewage network because of the way of living and the economy. Range of wastewater infiltrating involves domestic wastewater, which means grey water and black water. For pit latrines and VIP, pits contain just black water. In this case, grey water is disposed of into the environment. If the household is connected to a septic tank, grey water and black water are stored in the tank. Moreover, the rate of sludge accumulation used is the same for every area. No information on cleansing materials was found, so the basic rate of sludge accumulation has been chosen ($0.05 \text{ m}^3/\text{person}/\text{year}$). A lower rate of sludge accumulation increases the quantity of wastewater infiltrating the soil.

For the towns of Kanye, Ramotswa and the rural areas, most of on-site sanitation facilities are not maintained. In fact, no data is available on the maintenance of on-site sanitation. When the pit is full, it is covered and a new pit latrine is built. Some people use chemicals to decompose the sludge.

5. Climate change

Climate change is studied to determine how it is affecting the wastewater quality and the environmental pollution. In the RTBAA, climate is divided in two seasons: the wet season from October to March and the dry season from April to September. The region knows a drought period which can be attributable to climate change. Botswana Department of Meteorological Services and the Hydrological Service of the Department of Water and Sanitation of South Africa provided long term rainfall and evaporation records which demonstrate drought trends in the area.

Average monthly rainfall is calculated from 1988 to 2016 with the Thiessen method on 6 stations. In contrast, because evaporation data is not available in the Botswana side, average monthly evaporation

is calculated on the same period as rainfall with the Thiessen method on 3 stations located in South Africa.

Long term rainfall and evaporation records are in Figure 31. If the calculation of recharge explained above in III.1.3. is closed to zero, it means the RTBAA is in a drought area. But from August to December, recharge is lower than during the rest of the year, the climate is drier. The driest month is October [Appendix 14]. The average calculation of natural recharge during 29 years is 4 mm. In the nineties, the calculation is very lower than this value, it was an important drought period. However, this small value shows that even the wet season is not enough important to recharge the groundwater resource.

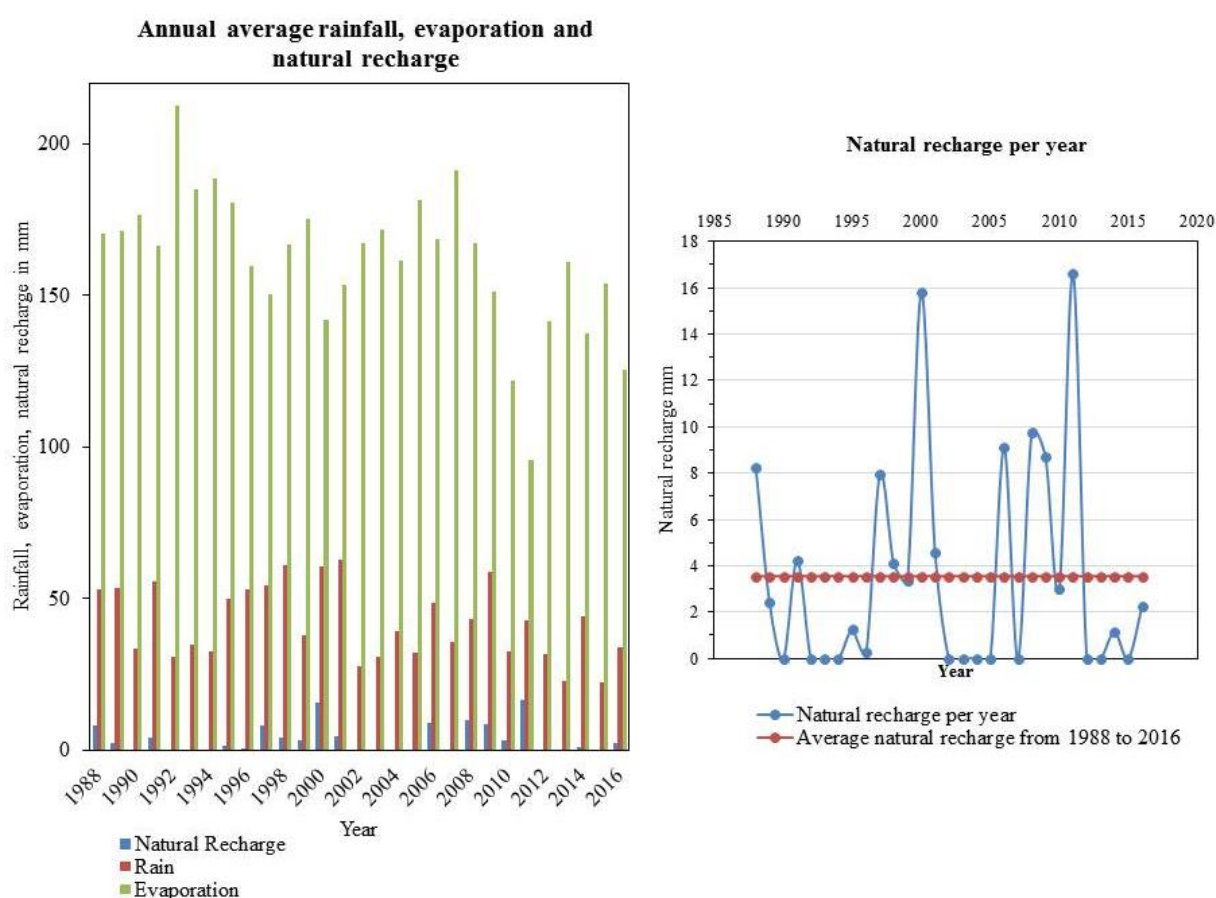


Figure 31: Annual average natural recharge.

Trends of the both seasons change over the last 30 years, particularly for the minimums and the maximums. Rainfall and evaporation total are grouped by season and percentiles, respectively in Figure 32 and Figure 33. By a regression analysis, the trends of the seasons are determined. The model p is below 0.001 and the adjusted R^2 is 90% [Appendix 15]. In fact, the wet season's upper 10th percentile of rainfall and evaporation are stable. The dry season's upper 10th percentile of evaporation is getting drier over time. But both seasons' lower 10th percentiles are getting drier which means more drought.

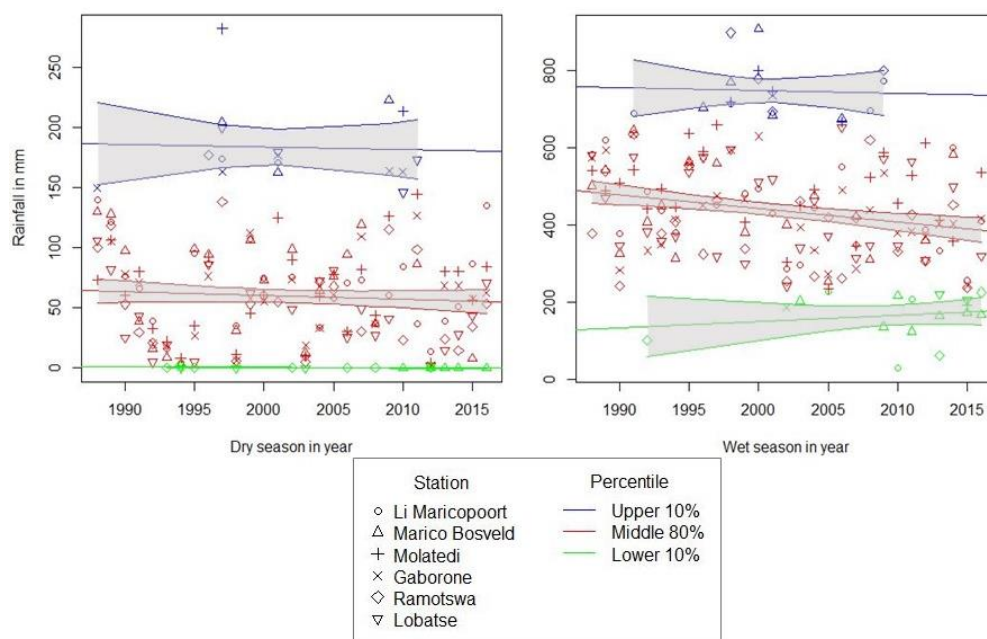


Figure 32: Rainfall trends from 1988 to 2016 in the RTBAA.

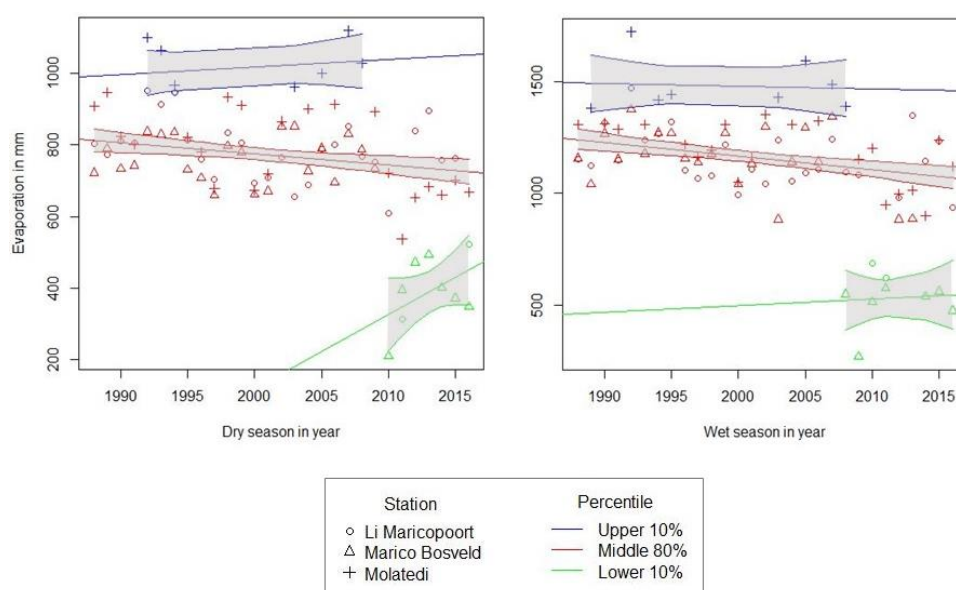


Figure 33: Evaporation trends from 1988 to 2016 in the RTBAA.

More drought in the area impacts on sanitation. In fact, during drought, there is no water for flushing toilet, the use of on-site sanitation increases. Moreover, drought impacts on the wastewater treatment in WWTP. Pollutants are more concentrated and the inflow decreases which impacts on the residence time in ponds. This affirmation is confirmed by prediction work. A work on the river flow would be interesting but no data is available on the Gaborone catchment. During a rain event, the flood timing should be forecast by a Gumbel distribution. By using data from Marico catchment, it is estimated wastewater is diluted to 45% during a rain event.

To conclude, rainfall and evaporation data are indicators of wastewater pollution, drier is the year, higher is the pollution coming from wastewater. But during a wetter year, the groundwater table is higher and facilitates infiltration from on-site sanitation in the aquifer.

IV. Recommendations and opportunities

1. On-site sanitation improvement

1.1. Recommendations for on-site sanitation

Pit latrines are one of the most common human excreta disposal systems in low-income regions. Their use is on the rise as countries aim to meet the sanitation-related target of the Millennium Development Goals, as Botswana and South Africa. But, pit latrines are a concern with the discharge of microbial and chemical contaminants to groundwater which may negatively affect human health.

Pit latrines, VIP and septic tanks function by infiltrating liquid waste into the surrounding soil. Pollution from latrines takes two forms: bacterial and chemical. Bacterial pollution is usually quickly rendered harmless by natural processes in the soil. Provided the bottom of the pit is more than 2 metres above the water-table, bacterial pollution of the groundwater is highly unlikely. But the RTBAA is characterized by a shallow water table and fractured hard rock aquifer [65], as a study site in India where high concentrations of faecal coliforms were found in domestic wells located near pit latrines and septic tanks [66]. During the wet season, water table can reach pits. In this case, an alternative has to be found. Moreover, a safe distance of 75 metres between on-site sanitation and groundwater abstraction points has to be respected [67].

Chemical pollution is predominately nitrogenous and can increase the level of nitrates in the groundwater. Consumption of high concentrations of nitrate in drinking water is known to cause methemoglobinemia syndrome in humans. Chemical pollution is more potentially harmful than bacterial pollution because it lasts longer, travels further and is more difficult to remove.

The potential pollution from pit latrines is also affected by social factors, as latrine use, latrine densities, maintenance and groundwater pumping. Contamination can be influenced by latrine type, design, materials and construction quality.

Different recommendations can be given for minimizing latrine effects on groundwater quality. Reviews suggest to discourage installing pit latrines in rocky areas with shallow water table but latrines are the cheapest and easiest way of sanitation. Parameters such as the depth of the water table, soil characteristics and rock strata should be considered prior to install pit latrines. Some alternatives are proposed and presented in Table 14 as:

- Upgrading latrines in rural areas as raised VIP latrines,
- Upgrading latrines in urban areas as alternative twin-pits VIP latrines,
- Maintaining septic tanks in areas where a maintenance service exists.

	Raised VIP Latrines	Alternative twin-pits VIP latrines
Area	Rural	Urban
Design	<ul style="list-style-type: none"> ➤ Raised portion of the pit surrounded by a mound of soil ➤ Small free space at the top of the pit: 0.5 m 	<ul style="list-style-type: none"> ➤ 2 Rectangular pits lined ➤ Reinforced cover slab (80 mm thick) in 8 sections: 2 central with apertures for vent pipes and 6 re-

	<ul style="list-style-type: none"> ➤ Rectangular concrete ring beam, the top of the ring beam reinforced by single central 8 mm diameter mild steel bar ➤ Vent pipe ➤ Round spiral structure 	<ul style="list-style-type: none"> ➤ moval for emptying ➤ Vent pipe for each pit ➤ One superstructure
Calculation of the effective volume	$V(m^3) = \text{rate sludge accumulation} \times \frac{\text{people}}{\text{household}} \times \text{number of year before emptying}$ <p>Rate sludge accumulation used for dry conditions: 0.06 m³/people/year</p>	
Dislodge	During dry season, every year by the maintenance service with vacuum tanker	During dry season, every 2 years for each pit by the maintenance service with vacuum tanker
Pit life	± 15 years	± 10 years
Costs	<ul style="list-style-type: none"> ➤ Investment: 70 \$ with skilled labor for building ➤ Maintenance: 31 \$/year ➤ Total cost: 36 \$/year 	<ul style="list-style-type: none"> ➤ Investment: 100 \$ with skilled labor for building ➤ Maintenance: 63 \$/year ➤ Total cost: 73 \$/year
Advantage	<p>Deal with shallow water table:</p> <ul style="list-style-type: none"> ➤ Pit excavated as deep as possible ➤ Artificial unsaturated zone (use fine sand) to a depth of at least 800 mm 	<ul style="list-style-type: none"> ➤ For urban areas with > 300 people.ha⁻¹ ➤ 2 separate pits for alternating when one is full ➤ Pit less than 1m depth
Disadvantage	Dry pit: biodegradation process slower in dry conditions, rate of sludge accumulation = 0.06 m ³ /people/year	<ul style="list-style-type: none"> ➤ Dry pit: biodegradation process slower in dry conditions, rate of sludge accumulation = 0.06 m³/people/year ➤ Price higher than for simple pit

Table 14: Details of on-site sanitation improvement [63; 68; 69; 70].

The volume of the pit increases of 50% if population uses cleansing materials. Moreover, some details might be added to these two types of latrines, such as:

- painting latrine ventilation tubes black to increase daytime ventilation rates,
- increasing the pH of latrine contents to increase ammonia volatilization,
- sealing pits to prevent nitrate leaching and promote denitrification,
- diverting urine for use as a fertilizer for deep-rooted crops.

Some septic tanks are still used in the RTBAA. For example, Kanye administration quarter relies on a septic tank. Because of the poor ground conditions, these are to be reinforced. Septic tank can be kept where there are maintenance services. This system has to be checked and the design done by an engineer, it is quite important for the efficiency. It needs to be used in an area where there is water restriction to flush.

Emptying has to be done by vacuum tankers and not manually because of pathogens. One of the inconvenient of vacuum tankers is the maintenance: it must be kept running all day. For this, management and supervision of emptying services have to be developed. The solution proposed needs the investment in 10 vacuum tankers for South Africa and 40 vacuum tankers for Botswana. A tanker life is around three years and the maintenance costs 30000 \$ per tank per year [63]. The investment in maintenance services has been included in the cost of the solution proposed.

To install on-site sanitation improvement, awareness session for population has to be organized. Specifically for women who are responsible of sanitation facilities because they clean and maintain it. They are also responsible for the security aspects for their children. Inappropriate design precludes young children from the use of the facility. Women's opinion in the choice of technology is essential to a successful upgrading of sanitation facilities. Without their approval, all systems will fail to reach the stated objectives of the programme [71].

1.2. Grey water management

Greywater is the wastewater collected from household activities except toilet wastewater. Household using pit latrines or VIP discharges its greywater untreated into the environment. Greywater corresponds to kitchen, laundry, and bathroom wastewater and represents 70% of domestic wastewater. They are concentrated in BOD, COD, phosphorous, oil and grease, surfactants and coliforms [72; 73]. Their discharge without adequate treatment contributes to surface and groundwater pollution. After treatment, greywater can be used for agricultural and gardening application.

To reuse greywater, the system design must consider public health risk, greywater chemical properties, prevention of pollution of soil and water and reuse purpose. Household with no greywater management and using on-site sanitation have low income. An easy and cheap way of domestic greywater treatment is recommended. The greywater tower garden was already applied in the Gauteng Province, South Africa. A primary treatment with a grease and grit trap can be installed. The structure of the greywater management system consists of poles and shading material surrounding soil and a central stone-packed drain, presented in Figure 34. The water flow throughout the column is spread because of the stones. Into the slits, leafy vegetables such as spinach are planted. On top of the column, tomatoes and onions may be planted. Two to three buckets of greywater are needed per day to prevent the soil from drying out. A puddle on the top of the column means an excess of water. This kind of greywater management is adapted for bath, shower, laundry and kitchen wastewater. The tower should be fenced in if free animals share the same space. It is not recommended to consume raw harvested vegetables.

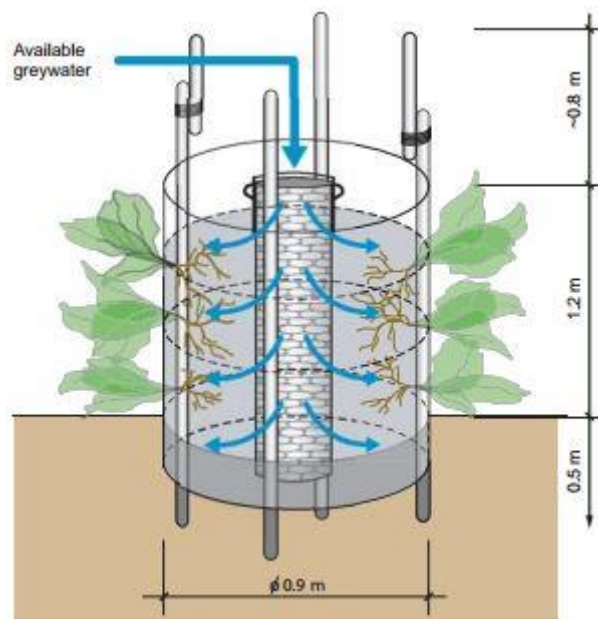


Figure 34: Scheme of greywater management column [74].

For greywater just coming from bath and shower, the greywater may be stored in drum dugs and directly reused for gardening crops. This method was applied in a vegetable gardening area of 150 m at a clinic in Lobatse. The garden was only irrigated with water from sink and hand washing for a period of one year. Water used for washing drug containers and equipment for medical tests was not reused. This method shows successful results on plants [75].

2. Wastewater treatment efficiency

2.1. Improvement of wastewater treatment efficiency

Wastewater treatment processes available are not adapted to treat specifically industrial wastewater. A pre-treatment system should be established for every industrial activity. Moreover, the incompliance to the standards for treated wastewater comes from the lack of knowledge, maintenance and monitoring. Recommendations are given for the maintenance of the wastewater treatment plants and for the monitoring of sanitation.

2.1.1. Maintenance of wastewater treatment plants

Only wastewater treatment plants which have highly risk of pollution for the environment, mentioned in Figure 17, are approached in this part. These recommendations can be also applied for all the wastewater treatment plants in the region. Recommendations are given in Table 15.

Sanitation facility	Issue	Recommendation	Cost
Ramotswa WWTP (Waste Stabilization ponds)	Not enough inflow, WWTP working as evaporation ponds and no respect of the residence time	Upgrade the wastewater lifting station for the village	2000 USD
	Debris floating in the ponds	Upgrade the screen with a smaller space between bars	200 USD
	Green maturation pond and bad treatment efficiency	Site clearing and algae removal of the ponds to maximize photosynthesis	2500 USD
	No record of dislodging and bad treatment efficiency	Remove sludge: - Anaerobic pond: every 1 to 2 years - Facultative pond: every 10 years, - Maturation pond: every 15 years	30000 USD
Lobatse WWTP (Waste Stabilization ponds)	Debris floating in the ponds	Upgrade the mechanical screen	40000 USD
	Green maturation pond and bad treatment efficiency	Site clearing and algae removal of the ponds to maximize photosynthesis	2000 USD
	No records of dislodging and bad treatment efficiency	Remove sludge: - Anaerobic pond: every 1 to 2 years - Facultative pond: every 10 years,	30 000 USD

		- Maturation pond: every 15 years	
	No fence	Secure the perimeter with fences	4500 USD
Lehurutshe WWTP (Waste Stabilization ponds)	Green maturation pond and bad treatment efficiency	Site clearing and algae removal of the ponds to maximize photosynthesis	500 USD
	No records of dislodging and bad treatment efficiency	Remove sludge: - Anaerobic pond: every 1 to 2 years - Facultative pond: every 10 years, - Maturation pond: every 15 years	35000 USD
	No fence	Secure the perimeter with fences	1500 USD
Zeerust WWTP (Activated Sludge)	Low dissolved oxygen rate and degradation of the treatment	Maintenance of aerators, material needed such as spanners	200 USD
	No proper laboratory for monitoring in the area	Upgrade on-site laboratory	200 000 USD
	Spillage of raw sewage in the environment before the inlet works	Change the raw sewage inlet pipe	1000 USD
	Just one channel for the inlet works is working	Change the channel sluice gate valves for inlet works	1000 USD
	No disinfection system	Upgrade chlorination tank	50 000 USD
	No records about waste sludge lagoon	Remove waste and sludge in waste sludge lagoon	15000 USD
	Deteriorated admin building	Upgrade admin building	50 000 USD
	No fence	Secure the perimeter with fences	600 USD

Table 15: Recommendations for WWTP with high risk of polluting the environment [25; 26; 76; 77][Appendixes 3; 4; 6; 9].

For waste stabilization ponds, anaerobic and facultative ponds remove BOD and COD compare to the maturation pond which removes pathogens and nutrients [78]. A good treatment efficiency relies on the hydraulic retention time into the ponds, presented in Table 16.

Pond	BOD removal	Pathogen removal	Hydraulic retention time
Anaerobic pond	50 to 85%	-	1 to 7 days
Facultative pond	80 to 95%	-	5 to 30 days
Maturation pond	60 to 80%	90%	15 to 20 days

Table 16: Hydraulic retention time and removal in function of type of pond [76].

Anaerobic ponds need a higher pH. Currently, wastewater treated in the ponds in the RTBAA are domestic and industrial wastewater. Industrial wastewater participated to an acidic pH which disrupts BOD removal [79].

During the wet season, quality of treated wastewater is better than during the dry season. In fact, pathogens and organic matters removal depends on the sunlight exposure and temperature which are lower during the dry season. Moreover, the wastewater is diluted during the wet season because of the rainfall which participates to a better wastewater quality [80].

2.1.2. Monitoring Plan

In the RTBAA, Water Utilities Corporation is sampling the outflow of Gaborone, Ramotswa and Lobatse WWTPs for pH, temperature, dissolved oxygen, total coliforms, faecal coliforms, *Escherichia Coli* and faecal streptococci. These ones are the only quality data available in the area for wastewater. No quantity data is available. Monitoring services should be developed to improve the sanitation systems and to follow the proper operation of plants. Measurement and records are parts of this monitoring plan [81; 82]:

- Measurement of inflow and outflow every month during a week day at different time such as 7:00 AM, 10:00AM, 01:00PM, 4:00PM and 7:00PM,
- Quality measurement of the outflow every month for pH, temperature, BOD, COD, phosphorus, nitrogen, total coliforms, faecal coliforms and E.Coli,
- Development of a record system with quantity and quality data for sharing information,
- Measurement of the groundwater level every month to assess the risk of contact between pits of on-site sanitation and the groundwater,
- Development of a record system with the dislodging of pit latrines and VIP per household,
- Development of a record system with the frequency of sludge removal in WWTP,
- Harmonize wastewater treated standards in Botswana and South Africa.

2.2. Sludge treatment and reuse

In the RTBAA, the faecal sludge management is not really developed and monitored. Two types of faecal sludge exist, one from the on-site sanitation and the second one from wastewater treatment plants. In Zeerust, Gaborone and Lobatse, sludge from pit latrines and VIP are transferred to the wastewater treatment plants. In the rest of the area, faecal sludge from on-site sanitation are disposed in a dumping site, or burnt, or destroyed by chemicals. Moreover, only Gaborone WWTP and Zeerust WWTP have sludge treatment system. The quantity of sludge produced per day in WWTP is presented in Table 17. In the study area, on-site sanitation produces around $75 \text{ m}^3.\text{d}^{-1}$ of sludge containing cleansing materials biodegradable. Sludge is high in solids concentration, BOD, COD, nutrients, pathogens and metals.

WWTP	Faecal sludge not dewatering $\text{m}^3.\text{d}^{-1}$
Gaborone	770
Lobatse	5
Ramotswa	5
Kanye	3
Lehurutshe	11
Zeerust	38

Table 17: Quantity of sludge produced in WWTP per day [83].

A bad sludge management has an impact on the environment. In fact, in Lobatse, sludge from the WWTP is discharged in the landfill. Areola et al. reported the landfill of Lobatse contaminates surface water in BOD, sulphate, nitrate and chloride [84]. Areola et al. just dealt with surface water pollution but bad sludge management is also a threat for the groundwater resources. In this part, recommendations given are for developing sludge management services. Waste development plan already exists for

the town of Gaborone and Tlokweng where faecal sludge is treated by filter press. The objectives are to reduce, reuse and recycle waste. Moreover, benefits are included in this development plan such as job creation, poverty reduction and reduce waste collection costs [85].

Developing a treatment process for faecal sludge in this area has different objectives such as dewatering, pathogens removal, nutrients removal and stabilisation. In this faecal sludge treatment facility, sludge from the WWTP which contains pit humus and faecal sludge from the sewage network are treated. Drying beds are recommended because of the cost-effectiveness and the high rate of evaporation in the area. Drying beds process is based on two principles shown in Figure 35. The first one is evaporation which removes the bound water fraction and this process takes place over a period of days to week. The second principle is percolation of the leachate through sand and gravel which is returning to the wastewater treatment process, particularly in the facultative pond for waste stabilisation ponds. Drying beds have to be built near the wastewater treatment plant to limit the cost for the sludge transfer. The wet season can be accommodated by not using the beds in that period. Ponds must be dislodged during dry season to transfer and to dry the sludge during the dry season.

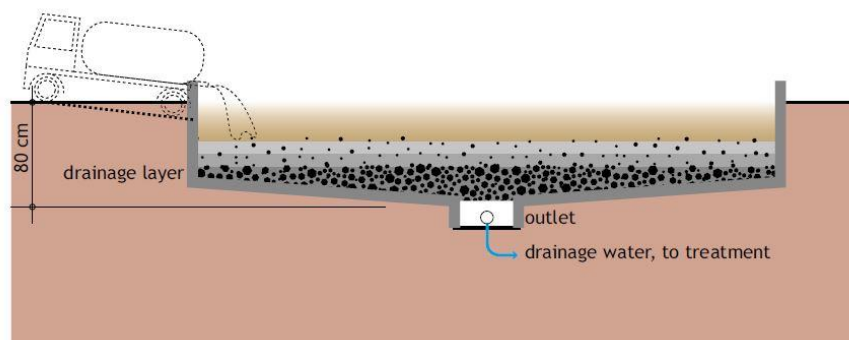


Figure 35: Drying bed scheme [76].

Recommendations for the design of drying beds are presented in Table 18. For example, Ramotswa WWTP produced $5 \text{ m}^3 \cdot \text{d}^{-1}$ of faecal sludge and pit humus is estimated around $730 \text{ m}^3 \cdot \text{y}^{-1}$. The following design for Ramotswa faecal sludge management is determined in Table 19.

Sizing of the beds:	Production of filter layers:
25 – 30 cm sludge layer on beds	Reduce pressure flow via splitting chamber, inlet channel, and splash plates
100-200 kg TS/m ² /year (TS stands for total solids)	Drying bed removal efficiency:
0.08 m ² /cap	97% SS (suspended solids), 90% COD (chemical oxygen demand), 100% HE (helminth eggs)
Untreated sludge characteristics:	Dried sludge production:
Partly stabilised (septage or mixture of septage and public toilet)	0.1 m ³ per m ³ fresh FS
Sludge with ≤ 30 % share of public toilet sludge	Hygienisation necessary prior to use in agriculture as biosolids
Sand characteristics:	Leachate:
Sand particles do not crumble	Quality fairly comparable to tropical wastewater
Sand easily available locally	Salinity too high for irrigation
Sand thoroughly washed prior to application onto the gravel base	Leachate treatment

Table 18: Technical and design details for drying beds [86].

2700 m ³ .y ⁻¹ of FS, use of drying beds during the dry season (6 months per year)	Hydraulic load on drying bed: 30 cm.cycle ⁻¹
3 dewatering.month ⁻¹	Surface of sludge drying bed: 84 m ² , radius: 5m
Volume of FS treated: 150 m ³ .cycle ⁻¹ , 450 m ³ .month ⁻¹	FS volume reduction though dewatering assumed: 90%
6 drying beds for one cycle	Dried sludge produced: 270 m ³ .y ⁻¹ , 15 m ³ .cycle ⁻¹

Table 19: Design details for Ramotswa faecal sludge management.

In the drying bed, there is a lower layer of coarse gravel of 20-30 mm, a medium gravel layer of 10-15 mm and an upper layer of sand of 25-30 mm. A splash plate has to be built just next to the drying bed. The pond needs to be made impermeable. The sludge is removed when it is dry three times per month during the dry season and it can be reused as a soil conditioner. This can decrease the use of chemical products as fertilizers. With drying beds process, most of pathogens are removed from the sludge. But, further storage or composting of the dried sludge might be required before use in agriculture. No expert is needed for this process, but a trained community should be required [76].

3. Reuse of wastewater

Botswana and South Africa are both semi-arid countries with erratic rainfall, high level of evaporation and drought conditions. The use of treated wastewater is a potential to scale down water scarcity. Two ways of reuse have been investigated: reuse of treated wastewater for irrigation and recharge of the aquifer. In fact, in the RTBAA, 69% of groundwater consumption is used for agriculture. Reuse wastewater for irrigation is a profitable alternative. In Botswana, the water consumption by agricultural sector represents 41% of the total water consumption. Reuse helps to decrease the agricultural water consumption. Moreover, wastewater treated costs 0.47 Pula.m⁻³ (Ministry of Agriculture of Botswana) compare to drinking water which is sold more than 10 Pula.m⁻³ (WUC). Agricultural production can improve with reuse, it diversifies Botswana's and South Africa's economy and decreases dependance on imported food to feed the growing population and to promote

environmental sustainability. It seems logical to prioritize the reuse of wastewater treated for agriculture and then to recharge the aquifer with the excess. But, all the outflow of wastewater treated cannot be used because of the environmental flows.

3.1. Quality issue

3.1.1. Reuse of treated wastewater for irrigation

The major problem to agriculture development is the competitive demand for water. Using treated wastewater for irrigations improves agricultural productivity and enhances the livelihood of the small-holder farmers in the production system. An example of irrigation application by treated wastewater exists in Glen Valley WWTW, located in the study area.

In Gaborone, wastewater treated is reused for vegetable production in Glen Valley using secondary treated wastewater from Glen Valley WWTW (activated sludge) and disinfection ponds. The crops irrigated are tomato, spinach, olive, green pepper, okra, maize, Lucerne, butternut squash, water melon, cabbage and lettuce [87]. The irrigation division at the Ministry of Agriculture pumps the effluent from Gaborone WWTP to ponds near Phakalane and then pumps back to Glen Valley for private farmers. Farmers use drip irrigation. The effluent is not compliant to BOBS standards for temperature, SS, and COD. Some traces of heavy metal and E.Coli have been found in treated sewage water soils and plants [88; 89; 90; 91]. These traces come from industrial wastewater. Phosphorus and potassium levels in treated wastewater also increase soil salinity [92]. Some functioning problems have been encountered by the private farmers for treated wastewater supply because of poor design of the system, losses and lack of maintenance.

Two guidelines for wastewater reuse in irrigation are available. These guidelines correspond to unrestricted irrigation with a standard for faecal coliform and restricted irrigation without faecal coliform. Recommendations from the World Health Organization guidelines are presented in Table 20.

Category of irrigation	Reuse conditions	Wastewater treatment expected
A	Unrestricted irrigation: vegetable and salad crops eaten uncooked, sports fields, public parks	Well designed waste stabilization ponds
B	Restricted irrigation: cereal crops, industrial crop, fodder crops, pasture and trees	Waste stabilization ponds including maturation ponds
C	Localized irrigation of crops in category B	Pre-treatment as required by the irrigation technology, not less than primary sedimentation

Table 20: Recommendations from the World Health Organization for irrigation with wastewater [93].

In the RTBAA, most of the wastewater is treated by waste stabilization ponds or activated sludge. The outflow does not always comply with the standards of both countries in Appendix 8C for organic matter, nutrients (nitrogen) and heavy metal.

Pollutants	Impacts on the environment
Organic matter	<ul style="list-style-type: none"> - Development of sludge deposits causing anaerobic conditions - Plugging of irrigation equipment
Nutrients such as nitrogen	<ul style="list-style-type: none"> - Potential to cause nitrogen injury, excessive growth, delayed growing season and maturity - Groundwater pollution with health and environmental impacts
Heavy metal	<ul style="list-style-type: none"> - Toxic to plants and animals

	<ul style="list-style-type: none"> - Cause salinity and associated adverse impacts - Affect permeability and soil structure
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Table 21: Impacts of pollutants on the irrigation scheme [94].

If recommendations presented above in IV.2.1. are followed, wastewater treatment is enough efficient to comply with the standards.

Potential impacts of wastewater reuse are interesting to be monitored:

- Health impact: heavy metal and nitrogen participate to a poorer health if it is ingested in a sufficient concentration. To assess health impact, the actual risk that makes people fall ill has to be monitored.
- Crops development: growth rate of the crops is increased by nutrients but a high level in nutrients impacts on the soil fertility and causes economic loss to farmers.
- Soil impact: salinity erodes soil structure which decreases the soil productivity. Salinity has to be monitored in the wastewater treated for irrigation and can be resolved by application of natural or artificial soil amendment [95; 96].

3.1.2. Excess of treated wastewater for recharge

Recharge can be realized via direct well injection or with infiltration of secondary treated wastewater. The system soil aquifer treatment is the issue to infiltrate secondary treated wastewater and to recharge the aquifer. This treatment uses the soil of the vadose zone as natural filter with infiltration basins. The characteristics of the soil are important because it has to provide good filtration and quality improvement of the effluent as it passes through. But, according to the Food and Agriculture Organization of the United Nations, fractured rock aquifers are not recommended for the SAT or should be protected by a soil mantle of adequate texture and thickness. Well injection is not directly practicable because the wastewater quality is not compliant to the standards of drinking water. Treating the groundwater for drinking water has an expensive cost which cannot be ignored in this case. To use well injection, wastewater treatment has to be reinforced or completed [97; 98].

The injected wastewater treated has to be potable and meets the standards enforced in Botswana and South Africa or contained in the WHO Guidelines for Drinking-water Quality (WHO, 1996), presented in Appendix 8B [99]. To reach this quality, activated sludge and rotating biological contractors are more adapted to treat wastewater for recharge aquifer with a direct potable use. Oxidation ponds do not provide an acceptable quality to recharge the aquifer [76]. But, the estimated cost for trickling filters and activated sludge processes is estimated about 0.1 USD.m⁻³ treated compare to oxidation ponds which is 0.02 USD.m⁻³ treated [100]. At least, before being injected, wastewater should finish its treatment in a disinfection tank with chlorine or UV or ozonation to remove pathogens. Residual chlorine has negative impacts on the environment such as carcinogenic effects, but chlorine disinfection is the most cost effective process [101].

In the RTBAA, the water table is not sufficiently deep to prevent excessive rises of the groundwater table due to infiltration. Injection in the aquifer of wastewater treated increases the water table which is in contact with pit latrines 5 meters below the soil. Wastewater quantity injected has to be controlled.

3.2. Quantity issue

Four sites are chosen for their potential in wastewater reuse according to their proximity to the aquifer and agricultural activities presented in Figure 36, and the availability of wastewater treated. These sites are Lobatse WWTP, Ramotswa WWTP, Lehurutshe WWTP and Glen Valley WWTP. The quantity of wastewater treated for reuse is divided in three parts, the environmental flow requirement, the potential need for agriculture and the excess for recharge. The environmental flow maintains river channel, natural recharge of the aquifer and ecology. Estimated environmental flow requirement for the Ngotwane sub-catchment of the Limpopo Basin is 24% [102]. The potential need for agriculture is based on the wastewater consumption of Gaborone which is around $10 \text{ to } 11 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{d}^{-1}$. In fact, Gaborone WWTP discharges $35\,000 \text{ m}^3 \cdot \text{d}^{-1}$ of treated wastewater, which is 55% of the inflow. Wastewater reuse is around 3.5 % of inflow and 6.5 % of outflow, which represents $2275 \text{ m}^3 \cdot \text{d}^{-1}$. The quantity of treated wastewater covers 203 ha of 47 farms of different sizes (1 – 10 ha) [103]. Table 22 shows the quantity of wastewater for each potential reuse.

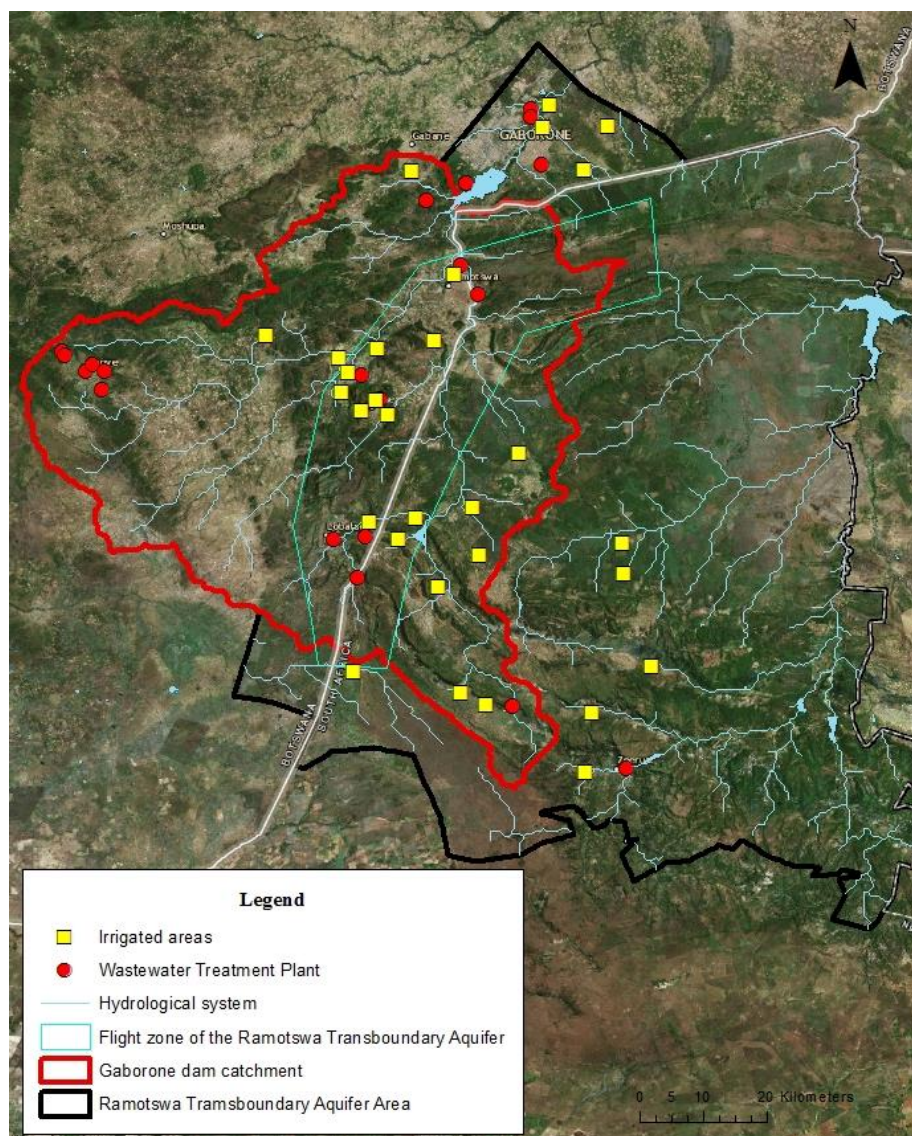


Figure 36: Map of wastewater treatment plant and irrigated areas.

Sites	Wastewater outflow $\text{m}^3.\text{d}^{-1}$	EFR $\text{m}^3.\text{d}^{-1}$	Local irrigated areas ha	Reuse for agriculture $\text{m}^3.\text{d}^{-1}$	Recharge of the aquifer $\text{m}^3.\text{d}^{-1}$
Glen Valley WWTP & Ponds	13200	3170	203	2275	7755
Ramotswa WWTP	600	145	40	400	55
Lobatse WWTP	1240	300	45	450	490
Lehurutshe WWTP	360	90	5	50	220

Table 22: Potential for reuse and recharge.

Irrigation site near Lehurutshe is just estimated to 5 hectares. In this area, farmers rely on the Dinokana eye and the Ngotwane dam. Wastewater from Zeerust WWTP is also available for agricultural activities. Zeerust WWTP discharges around $2200 \text{ m}^3.\text{d}^{-1}$, and the environmental flow requires 20% in the Marico sub-catchment, which is $440 \text{ m}^3.\text{d}^{-1}$. From Zeerust WWTP, $1760 \text{ m}^3.\text{d}^{-1}$ can be reused for irrigation purpose.

The irrigation division at the Ministry of Agriculture is responsible for pumping the effluent from WWTP to private farmers. Drip irrigation is suitable for vegetables crops and greenhouses such as in Ramotswa. This system allows to apply slowly the water on the soil to avoid runoff. Drip irrigation minimizes leakage and fertilizer losses. Soil erosion is also lessened in this area where soil erosion is a huge problem near Ngotwane dam [104].

4. Social involvement

Recommendations are given but their application depends on the stakeholder's involvement. Policy positions in South Africa and Botswana are for developing hygiene education by ongoing activities and the involvement of the community [20]. Recommendations for sanitation services must include awareness campaigns and a long term sustainable operation of the system:

- Awareness campaign in the communities should be realized for sharing sanitation education and information,
- Agriculture and environmental conservation has to be promoted,
- Sanitation grant should be provided to people to ensure equitable access to basic sanitation,
- Workshop training should be organized for employees working in the wastewater treatment plants. Training groups might focus on laboratory skills, purpose of sludge reuse, maintenance and dislodging process.

The objectives of these recommendations are to develop a sustainable water system in a region where water is a scarcity. A summary of these objectives are available in Figure 37.

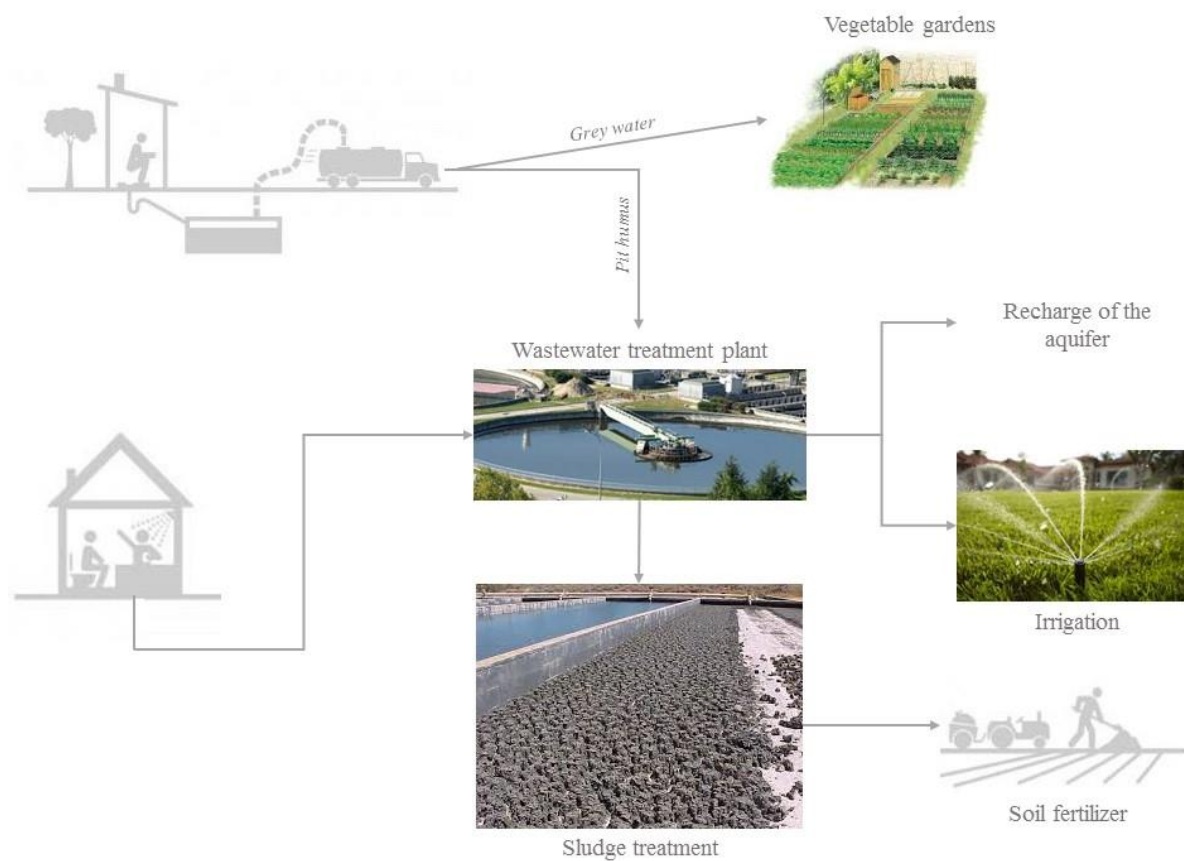


Figure 37: Summary scheme of a sustainable sanitation system in the RTBAA.

V. Conclusion

In the Ramotswa Transboundary Aquifer Area, two types of pollution occur caused by the sanitation system. The first one comes from on-site sanitation. On-site sanitation such as VIP, pit latrines and septic tank pollute the aquifer because of the lack of maintenance and knowledge. Moreover, on-site sanitation has to be improved because they are not adapted to the soil which is a rock-fractured soil with a high groundwater table, particularly during wet season. The second cause of pollution is the wastewater treatment plant. Treated wastewater quality does not comply with the standards because of the bad treatment efficiency. In fact, inflow contains industrial wastewater and the treatment is not specifically adapted for industrial wastewater. Moreover, a lack of maintenance and monitoring lead to deteriorate the treatment efficiency. These cases of pollution depends also on climate conditions. In fact, the aquifer is more vulnerable to on-site sanitation pollution during the wet season because of a higher water table. Compare to the wet season, the aquifer is more vulnerable to treated wastewater during the dry season which deteriorates the treatment efficiency because of lower temperature and sunlight exposure. In any case, on-site sanitation pollution is the most important because of the pit latrines density. A priority area is delimited according to the sanitation assessment. From ten kilometres to each side of the border and from Radikhudu to Ramotswa, this aquifer area is more exposed to sanitation pollution.

Some recommendations are given to decrease the risk of aquifer pollution. These recommendations can be applied but need a community involvement for the long term. At first, sanitation improvement can be done on households which are not connected to the sewer system. The most important is to deal with the high water table, pits of on-site sanitation should be decreased or raised. Moreover, grey water management plan should be introduced. Then, a maintenance plan for wastewater treatment plant is proposed, followed by a monitoring plan. At last, by establishing a sustainable sanitation plan, benefits can be done for the community and stakeholder. Improving the sludge treatment leads to the possibility of reuse it as soil fertilizer. By a better treatment efficiency of wastewater, discharge becomes a source of water for irrigation and recharge of the aquifer.

Many projects are following this sanitation assessment. One of them is focused on irrigation scheme in the RTBAA. It consists in improving irrigation management of smallholder farmers by using monitoring sensors to assess the quantity and quality needed for water in terms of agricultural activities larger than two hectares. This project will help to estimate wastewater needed for irrigation purposes. The second project is the hydrogeological model of the Ramotswa Transboundary Aquifer to understand the resource and assess the recharge possibilities from the river and treated wastewater. The model will focus on one transboundary compartment of the aquifer which is located in Ramotswa.

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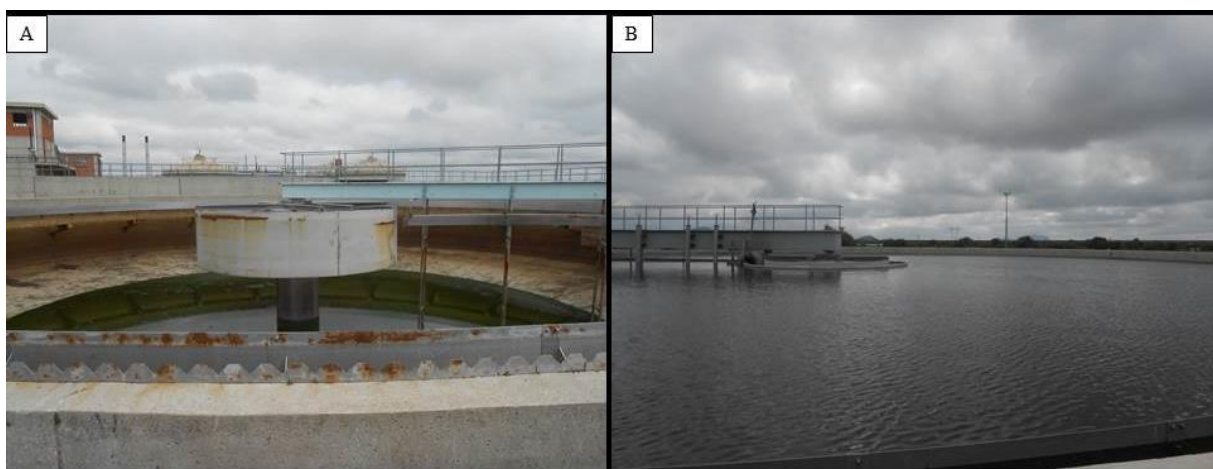
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Appendix 1: Pictures of Glen Valley WWTP, Gaborone

1.1. Glen Valley inlet works



1.2. Comparison of the two phases in Glen Valley WWTP: A) Clarifier in the second phase, B) Clarifier in the first phase



Appendix 2: Interview of Mr. Lekgaba, manager of Glen Valley WWTP on 2nd February 2017

Persons present: I. Lekgaba, N. Martin

Date: February 2nd, 2017

Place: Wastewater treatment plant of Water Utilities Corporation in Glen Valley, Gaborone, Botswana

- *When was the wastewater treatment plant built? What type of treatment do you use?*

The plant is based on activated sludge. The outflow is discharged in disinfection ponds. The wastewater treatment plant was built in 1996. A second phase happened in 2001 because of the population increasing and to improve the treatment efficiency. The discharge respects the standards of BOBS 93:2012. The old plant can treat 40 000 m³.d⁻¹. Both plants can treat 90 000 m³.d⁻¹. The plants are composed of screens, grit chambers, primary and secondary treatments, discharge and disinfection ponds. The septic tanks and pit latrines are dislodged in the inflow of the WWTP before the screens.

- *You reuse the wastewater for irrigation, could you tell me more?*

Treated wastewater is used for irrigation in twenty farms, which are about 10 to 12 hectares. The wastewater treatment plant takes care of the treatment quality for reuse. Then, the water is pumped by the Minister of Agriculture. The types of crops irrigated are tomato, butternut and spinach.

- *What type of wastewater do you treat?*

Domestic and industrial wastewater are treated in Glen Valley. The industrial wastewater comes from textile industry, soft drink industry and cannery.

- *How often and what type of maintenance are you doing?*

The work team is composed of 40 persons. The maintenance is often done for:

- Fixing information,
- Dislodging,
- Preventive maintenance.

- *What are you doing with the sludge?*

There are two types of sludge: the one from the anaerobic tank and the other one from the aerobic tank. The sludge is dried with a filter press then it is sold to farmers. A part of the sludge is used for methanisation. Gas is used for heating the tanks.

- *What would you want to improve?*

To improve the water quality, it will be interesting to improve the quality of the maintenance and to record everything.

Appendix 3: Report of the interview of Mr. Mareme, manager of Ramotswa WWTP on January 2017 from Bonnie McGill

Persons present: M. Mareme, B. McGill

Date: January, 2017

Place: Water Utilities Corporation in Ramotswa, Botswana

Mr. Mareme estimates the number of people who use pit latrines in Ramotswa to be about 20%, compare to the 2011 census which said 15% in Ramotswa. He blames the water shortages and inability to use flush toilets for keeping that number high. He estimates that 75% of people have access to a flush toilet. And he said roughly 15% of people use septic tanks.

During water rationing / restrictions Ramotswa would have water one or two days a week, this went on for at least a year. Last year here was a diarrhea out break, it was during a water restriction time, when people were stealing water directly from one of the production borehole's valves used for sampling. They suspect the people who had diarrhea were the ones who stole water. They have since removed the sampling valve.

If there is no water coming from the north / Gaborone dam to blend the Ramotswa wellfield water with, they have to turn the borehole pumps off. They cannot supply it directly to the people because of its quality. So water supply in Ramotswa is reliant on Gaborone water supply.

The reverse osmosis facility is stalled due to payment issues with the contractor. But in theory it would allow them to no longer rely on blending water with the north in order to supply water to the village.

The sludge from the treatment ponds gets dredged, dried and either sold to farmers as manure or sent to the South East Gaborone Landfill on the Lobatse road.

Wastewater from the final treatment pond is disposed into the Ngotwane river. Also sometimes they have "internal over spillage", which also contaminates the Ngotwane river, which flows into the Gaborone Dam. He used the word "contaminates".

WUC is not responsible for developing new systems / improving old ones; they only run the infrastructure provided by the government. DWA, he said, is in charge of improving systems.

He said people are aware that their water comes from the ground and that it is contaminated by pit latrines, because when the borehole pumps were stopped in 1996 it was a big deal. And they knew it was because of the pit latrines. However that is 20 years ago, so it is not possible to know how many people still remember that or teach the kids. Before the borehole pumps were stopped there were cases of blue baby syndrome from the high nitrates, so people were also aware of the water quality problems because of that.

Before 2010, each town works on its own WWTP. In 2010, WUC centralized and nationalized all the WWTP.

Appendix 4: Interview of Mr. Mareme, manager of Ramotswa WWTP on 30th January 2017

Persons present: M. Mareme, N. Martin

Date: January 30th, 2017

Place: Wastewater treatment plant of Water Utilities Corporation in Ramotswa, Botswana

- *When was Ramotswa wastewater treatment plant built?*

The wastewater treatment plant was built in 1981 for the people who have flush toilets. In 2001, a second phase of building appears because of the population increasing and the network sewage. A third phase should happen around 2025 because of the population increasing. The lift pump is not working because the pump building is too low compare to the ground level. A little pump was put for the inflow. A secondary channel is bringing inflow by gravity.

- *How is the wastewater treatment plant working?*

The plant has three types of ponds: anaerobic, facultative, and maturation. There are three facultative ponds. The design data was lost. But, the depth of the ponds is not more than two meters. Two phases of building happened. When the first phase is full of wastewater, the second phase is opened.

- *What do you think about the efficiency of the treatment?*

The water quality does not respect anymore the discharge limit from the standards of BOBS 93:2012.

- *How often and what maintenance are you doing?*

Water Utilities Corporation is doing the maintenance. An independent team is doing the minima to save money. Moreover, the screen is not adequate, waste can pass though the screen. For dislodging, there is no data available. Mr. Mareme took the manager's job nine months ago. There is no data available before this date. Since he is the manager, the sludge of the ponds was not evacuated. To have a better maintenance, they should invest around 1 000 000 Pula (100 000 USD).

- *What could you tell me about the dry season and the rainy season?*

During the dry season, the wastewater treatment plant is working as evaporation ponds. But, it is not designed to work like that. Moreover, during the rainy season, the treated wastewater is diluted, and the outflow quality is better. The residence time in the ponds has an impact on the treatment efficiency but it changes with the seasons. For example, the residence time for an anaerobic pond is 4 to 5 days. But, during the dry season, it can be 30 days.

- *What types of wastewater do you treat?*

The inflow is composed of two types of wastewater: domestic and industrial. The industrial wastewater comes from a milling industry, Bolux Milling.

- *What would you want to improve?*

To improve the treatment, the most important is to respect the residence time in the ponds. The second phase increases the capacity of the plant. Moreover, it should be interesting to invest flow meters for the inflow and the outflow. The problem about the evaporation system during the dry season should be fixed too.

- *What do you think about REUSE?*

They have lots of crops in the town near the wastewater treatment plant. But, the treated wastewater is not used for irrigation because of lands conflict between the Town Council and Water Utilities Corporation. It should be interesting to reuse the wastewater for irrigation and gardens because people use drinking water right now.

- *Where do you discharge?*

There is no discharge in the river to protect the environment. The outflow is going in the land. No water can be seen in the land. In fact, a channel is going underground. It can be supposed the water is flowing in the aquifer. Moreover, some wetland can be seen in the plant, they might be losses or discharge from the ponds.

Appendix 5: Ramotswa WWTP samples analysis

Sample Identification	Unit	Inflow Ramotswa 1 st day	Inflow Ramotswa 2 nd day	Outflow Ramotswa	BOBS 93:2012
Date	-	31-Jan	02-Feb	02-Feb	-
Time	-	10:00 AM	11:20 AM	11:30 AM	-
BOD	mg.L ⁻¹	-	-	26	20
COD	mg.L ⁻¹	-	23900	59	30
Total Coliforms	/100 mL	-	-	960	20000
Faecal Coliforms	/100 mL	-	-	300	1000
Suspended Solids	mg.L ⁻¹	165	19322	111	-
Chloride	mg.L ⁻¹	59	1608	102	600
Sulphate	mg.L ⁻¹	13	<2	58	400
Nitrate	mg.L ⁻¹	<0.1	<0.1	<0.1	2
Nitrite	mg.L ⁻¹	<0.05	<0.05	<0.05	-
Total Phosphate	mg.L ⁻¹	7.5	930	1.7	-
Organic Nitrogen	mg.L ⁻¹	1.6	953	5.3	-
Oil and grease	mg.L ⁻¹	4	1238	<1	-
Kjeldahl Nitrogen	mg.L ⁻¹	51.6	2488	6.4	-
Free and saline ammonia	mg.L ⁻¹	50	1535	1.1	1
Comments	-	Grey and diluted, important inflow	Almost no inflow, black/grey, sandy	Open the tap on 31/1 to have an outflow	-

Appendix 6: Interview of Mr. Khan, manager of Lobatse WWTP on 1st February 2017

Persons present: K. Khan, N. Martin

Date: February 1st, 2017

Lieu: Wastewater treatment plant of Water Utilities Corporation in Lobatse, Botswana

- *How many people are using flush toilets and pit latrines?*

Pit latrines are used by 25% of the population. Flush toilets are used by 75%, but 25% are evacuated in septic tanks and 50% are evacuated in the sewage network.

- *When was the wastewater treatment plant built?*

The wastewater treatment plant was built in 1989, then increased in 1995 because of the population increasing. There is no third phase planned for the next years coming. Lobatse has a slow population increasing. The wastewater system is based on ponds. There are 14 ponds: 3 primary anaerobic ponds, 2 secondary anaerobic ponds, 6 facultative ponds and 3 maturation ponds.

- *What type of wastewater do you treat?*

They treat industrial and domestic wastewater. The major industrial wastewater comes from the Botswana Meat Commission. An agreement in the end of 2016 has been signed, it will be effective by the end of 2017. Botswana Meat Commission will be disconnected from the sewage network and will have its own wastewater treatment plant. Some industries discharge their wastewater in the sewage network: tannery, cannery, milling industry and local shops.

- *What are you doing with the sludge?*

The sludge is disposing in a dumping site or they take it to the landfill. The ponds have never been completely dislodged.

- *How often and what maintenance are you doing?*

The maintenance is the biggest challenge for the wastewater treatment plant. In fact, because of a lack of money, the ponds have never been completely dislodged. Moreover, the inflow has two channels with two screens: one manual and the other one mechanical. The mechanical screen is not working. There is no screening during the night because they use the manual screen from 7:00 AM to 4:00 PM.

- *What do you think about the treatment efficiency?*

The discharge limits are following the standards of BOBS 93 :2012. The treatment is quite efficient. Some parameters as COD and BOD₅ respect the limits.

- *Wastewater is discharged into the Ngotwane river. Some South African people complained the pollution came from your plant. What do you think?*

The downstream pollution is not coming from the plant. There is cattle near the river. They are defecating in the land, this is why the COD is increasing downstream.

- *Could you tell me the benefits and the disadvantages of the WWTP?*

About the treatment, the anaerobic digestion is a benefit. It is cheaper because it does not need oxygen. But, there is algae synthesis in the maturation ponds, which explains the greener colour of the pond. To improve the treatment, it will need around 10 million of Pula (1 million of USD) to:

- Dislodge the ponds,
- Create dry beds for the sludge,
- Put irrigation pumps,
- Fix the mechanical screen,
- Construct safety around the ponds.

- *What could you tell me about the dry season and the rainy season?*

During the dry season, there is always discharge into the river. But, the discharge quality is not as good as during the rainy season. In fact, the wastewater is diluted during the rainy season.

- *What would you want to add?*

The pollution in the Ngotwane River has an impact on the dam in the north part of South Africa.

10 000 m³ of wastewater cost 35 Pula (3.5 USD).

Some funds should be approved by the beginning of April 2017.

Appendix 7: Lobatse WWTP samples analysis

Sample Identification	Unit	Inflow Lobatse	Outflow Lobatse	Upstream Lobatse	Downstream Lobatse	BOBS 93:2012
Date	-	01-Feb	01-Feb	01-Feb	01-Feb	-
Time	-	10:30 AM	10:00 AM	09:30 AM	09:12 AM	-
BOD	mg.L ⁻¹	170	15	15	10	20
COD	mg.L ⁻¹	420	167	111	122	30
Total Coliforms	/100 mL	-	1280	3400	5530	20000
Faecal Coliforms	/100 mL	-	100	460	620	1000
Suspended Solids	mg.L ⁻¹	164	46	50	110	-
Chloride	mg.L ⁻¹	45	67	67	62	600
Sulphate	mg.L ⁻¹	23	33	34	32	400
Nitrate	mg.L ⁻¹	<0.1	0.8	0.9	0.9	2
Nitrite	mg.L ⁻¹	<0.05	0.4	0.5	0.7	-

Total Phosphate	mg.L⁻¹	6.8	6.9	6.8	7.5	-
Organic Nitrogen-	mg.L⁻¹	4.4	4.8	2.6	3.2	-
Oil and grease	mg.L⁻¹	13	<1	1	<1	-
Kjeldahl Nitrogen	mg.L⁻¹	36.4	13.4	10.6	10.6	-
Free and saline ammonia	mg.L⁻¹	32	8.6	8	7.3	1

Appendix 8A: Treated wastewater discharge standards

Determinands	Unit	Botswana BOBS 93:2012	South Africa 1999
pH	-	6.5 - 9	5.5 - 9.5
Temperature	C	35	-
BOD	mg.L⁻¹	20	-
COD	mg.L⁻¹	30	75
Colour	TCU	30	-
Fat, Oil and Grease	mg.L⁻¹	-	2.5
Total Coliforms	/100 mL	20000	-
Faecal Coliforms	/100 mL	1000	1000
Total Dissolved Solids	mg.L⁻¹	1000	-
Suspended solids	mg.L⁻¹	-	25
Free and saline Ammonia N	mg.L⁻¹	1	3
Nitrate N	mg.L⁻¹	2	15
Ortho Phosphorus P	mg.L⁻¹	1.5	10
Conductivity	mS.cm⁻¹	-	70
Arsenic	mg.L⁻¹	0.1	0.02
Boron	mg.L⁻¹	0.5	1
Zinc	mg.L⁻¹	5	0.1
Copper	mg.L⁻¹	1	0.01
Phenols	mg.L⁻¹	0.005	0.1
Lead	mg.L⁻¹	0.05	0.01
Cyanide	mg.L⁻¹	0.1	0.02
Total Chromium	mg.L⁻¹	0.05	0.05
Cadmium	mg.L⁻¹	0.005	0.005
Mercury	mg.L⁻¹	0.001	0.02
Selenium	mg.L⁻¹	0.01	0.02
Iron	mg.L⁻¹	1	0.3
Manganese	mg.L⁻¹	0.1	0.1
Sodium	mg.L⁻¹	400	-

Sulphate	mg.L⁻¹	400	-
Chlorides	mg.L⁻¹	600	-
Fluorides	mg.L⁻¹	1.5	1

Appendix 8B: Drinking water standards

Determinands	Unit	Botswana BOBS 32:2009	South Africa 1999	WHO 2006
Colour	TCU	15	15 Pt-Co	-
Conductivity at 25°C	S.cm ⁻¹	1500	-	-
Dissolved Solids	mg.L ⁻¹	1000	450	600
Odour	TON	-	1	-
pH at 25°C	pH	5.5 - 9.5	6 – 9	-
Turbidity	NTU	1	1	-
Ammonia	mg.L ⁻¹	1	1	-
Calcium	mg.L ⁻¹	150	80	-
Chloride Residual	mg.L ⁻¹	200	100	-
Fluoride	mg.L ⁻¹	1	1	1.5
Magnesium	mg.L ⁻¹	70	30	-
Nitrate NO ₃	mg.L ⁻¹	50	6	50
Nitrate NO ₂	mg.L ⁻¹	3	6	3
Potassium	mg.L ⁻¹	50	50	-
Sodium	mg.L ⁻¹	200	100	-
Sulphate	mg.L ⁻¹	250	200	-
Zinc	mg.L ⁻¹	5	3	-
Aluminium	µg.L ⁻¹	200	150	-
Antimony	µg.L ⁻¹	20	-	20
Arsenic	µg.L ⁻¹	10	10	10
Cadmium	µg.L ⁻¹	3	5	3
Chromium	µg.L ⁻¹	50	50	50
Cobalt	µg.L ⁻¹	500	-	-
Copper	µg.L ⁻¹	2000	1000	2000
Cyanide free	µg.L ⁻¹	70	-	-
Cyanide recoverable	µg.L ⁻¹	70	-	-
Iron	µg.L ⁻¹	30	100	-
Lead	µg.L ⁻¹	10	10	10
Manganese	µg.L ⁻¹	100	50	400
Mercury	µg.L ⁻¹	6	1	6
Nickel	µg.L ⁻¹	70	-	70
Selenium	µg.L ⁻¹	10	20	10

Appendix 8C: Irrigation standards for unrestricted irrigation

Determinands	Unit	Botswana BOBS 463:2011	South Africa 1999	WHO 2006
Dissolved Oxygen	mg.L ⁻¹	-	-	-
pH		6.5 - 8.4	6.5 - 8.4	-
EC	µS.cm ⁻¹	3000	4000	-
Turbidity	NTU	-	-	-
TDS	mg.L ⁻¹	2000	50	-
Calcium	mg.L ⁻¹	-	-	-
Magnesium	mg.L ⁻¹	-	0.02	-
Sodium	mg.L ⁻¹	230	70	-
Nitrate	mg.L ⁻¹	30	5	-
Phosphate	mg.L ⁻¹	-	-	-
Potassium	mg.L ⁻¹	-	-	-
Chloride	mg.L ⁻¹	350	-	-
Sulphate	mg.L ⁻¹	200	-	-
Iron	mg.L ⁻¹	5	5	-
Manganese	mg.L ⁻¹	0.2	0.02	-
Copper	mg.L ⁻¹	0.1	0.2	-
Lead	mg.L ⁻¹	-	0.2	-
Intestinal Enterococci	/100mL	-	-	-
Faecal coliform	/100mL	<1000	<10000	<1000

Appendix 9: WWTP in the RTBAA

WWTP Facilities	Date construction	Second phase date	Design type	Design inflow m ³ .d ⁻¹	Current inflow m ³ .d ⁻¹	Outflow m ³ .d ⁻¹	Compliance	Sludge Treatment	Reuse
Glen valley and Gaborone ponds	1996	2001	Activated sludge	90000	65000	33000	Yes	Filter Press	Agriculture
Tlokweng Technical Training Centre	2002	No	Wetland	20	20	19	Yes	No	Sportsfield
Saint Joseph's College	1996	No	Ponds	100	100	40	Yes	-	No
Mokolodi Game Reserve	2002	No	Wetland	10	10	10	Yes	No	No
Adventist Hospital	No data	No	Rotating Biological Contractors	20	20	20	Yes	-	Gardens
Kanye Prison	1997	No	Wetland	25	30	29	Yes	No	Vegetable gardens
Kanye Education Centre	2001	No	Ponds	106	50	0	-	No	-
Ramatea College	1998	No	Wetland	15	15	14	Yes	No	No
NAFTEC	2000	No	Wetland	10	10	10	-	No	No

WWTP Facilities	Date construction	Second phase date	Design type	Design inflow m ³ .d ⁻¹	Current inflow m ³ .d ⁻¹	Outflow m ³ .d ⁻¹	Compliance	Sludge Treatment	Reuse
Seepapitso School	1996	No	Ponds	100	425	170	No, overloaded	No	No
Ramotswa	1981	2001	Ponds	3000	1500	600, No outflow during dry season	No	No	No
Swartkopfontein Border Post	-	-	Oxidation Ponds	>200	-	-	Yes	-	-
Otse Police College	2000	No	Rotating Biological Contractors	260	200	200	Yes	-	Gardens
Otse Moeding College	1998	No	Rotating Biological Contractors	50	50	50	Yes	-	Sportsfield
BMC	1978	No	Ponds	1700	1000	400	No	Dumping site	No
Lobatse	1989	1995	Ponds	6200	3100	1240	No	Dumping site	Irrigation
Skilpadshek Border Post	2008	-	Reed beds	>200	-	-	Yes	-	-
Motswedi	1980	No	Bioreactor, Chlorination tank	80	Not in operation				
Lehurutshe	1980	No	Oxidation Ponds	1500	900	360	No	No	No
Zeerust	1960	1993	Activated sludge	3500	4000	2200	No	Sludge lagoons`	No

RAMOTSWA	
Total surface m ²	45000
Design Capacity m ³ /d	3000
Treatment plant	Inlet works 1 old plant from 1981 1 new plant from 2001
Old plant	1 Anaerobic pond: 17200 m ² 2 Facultative ponds: 2650 m ² /ponds 4 Maturation ponds: 2650 m ² /ponds
New plant	2 Primary anaerobic ponds: 4300 m ² /ponds 2 Secondary anaerobic ponds: 31000 m ² /ponds 1 Facultative pond: 47700 m ² 3 Maturation ponds: 8000 m ² /ponds

LEHURUTSHE	
Total surface m ²	88000
Design Capacity m ³ /d	1500
Peak flow	2250
Inflow m ³ /d	2265
Design loading COD kg/d	975
Inflow loading COD kg/d	585
Sludge produced dry tonnes/d	0.002
Solid waste disposal m ³ /d	0.02
Treatment plant	Inlet works 3 Anaerobic ponds : 475 m ² /ponds 1 Aerobic oxidation pond : 10500 m ² 3 Maturation ponds : 6300 m ² /ponds

BMC	
Total surface m ²	45000
Design Capacity m ³ /d	1700
Treatment plant	Inlet works 3 Anaerobic ponds: 2300 m ² /ponds 1 Maturation pond: 1200 m ² 2 Bio-filters & 2 clarifiers Sludge dumping site

LOBATSE	
Total surface m ²	516000
Design Capacity m ³ /d	6200
Treatment plant	Inlet works 3 Primary anaerobic ponds: 4000 m ² /ponds 2 Secondary anaerobic ponds: 11500 m ² /ponds 6 Facultative ponds: 15000 m ² /ponds 3 Maturation ponds: 5000 m ² /ponds 3 Tannery evaporation ponds: 26000 m ² /ponds

ZEERUST	
Total surface m ²	32000
Design Capacity m ³ /d	3500
Peak flow	4500
Inflow m ³ /d	4000
Design loading COD kg/d	2275
Inflow loading COD kg/d	2600
Sludge produced dry tonnes/d	0.01
Solid waste disposal m ³ /d	0.1
Treatment plant	Inlet works 2 Biological reactor tanks 2 Clarifiers 1 Chlorination tank 2 Sludge lagoons : 3500 m ² /ponds

Appendix 10: Mass balances between water supply and wastewater treated

	Population 2011	Water consumption m ³ /d/person	Total water consumption m ³ /d	Percent connected to sewage %	Wastewater treated in WWTP m ³ /d	WWTP current inflow m ³ /d	Wastewater stored in on-site sanitation m ³ /day	Comments
Gaborone – Tlokweng	268932	0.22	58324	65	55191	65130	3133	Wastewater from on-site sanitation dislodged in WWTP
Kanye	45196	0.11	4824	20	3644	540	1180	On-site sanitation contaminating aquifer
Lobatse	29007	0.19	5548	62	5189	3100	360	Wastewater from on-site sanitation dislodged in WWTP
Zeerust	9093	0.19	1739	95	1724	4000	15	Contamination from WWTP discharge
Ramotswa	30382	0.06	1787	60	1390	1500	397	On-site sanitation and WWTP contaminating aquifer
Others areas in Botswana	10956	0.04	427	40	213	250	215	On-site sanitation contaminating aquifer.
Others areas in South Africa	141222	0.03	4590	26	1179	900	3411	On-site sanitation contaminating aquifer

Area	Minimum water consumption m³/d/person on census	Maximum water consumption m³/d/person on census	Minimum wastewater treated in WWTP m³/d	Maximum wastewater treated in WWTP m³/d	Minimum wastewater infiltrating from on-site sanitation m³/day	Maximum wastewater infiltrating from on-site sanitation m³/day
Gaborone	0.175	0.386	29494	65056	467	5293
Tlokweng	0.078	0.171	2272	4982		
Kanye	0.075	0.131	1377	3644	176	1994
Lobatse	0.148	0.252	2591	5189	54	608
Zeerust	0.148	0.252	1341	2284	2	25
Ramotswa	0.022	0.074	522	1754	59	670
Others areas in Botswana	0.018	0.06	178	394	32	362
Others areas in South Africa	0.015	0.05	578	1926	508	5762

Appendix 11: Conversion method of evaporation to evapotranspiration

In this part, the conversion method of evaporation to evapotranspiration given by the Department of Water and Sanitation of South Africa is explained. Two types of evaporation readings are given, one is for class A evaporation (station: Molatedi) and the second one is data from Symons tank (stations: Li-Maricopoort and Marico-Bosveld).

To convert evaporation readings to reservoir data:

- For Symons tank to reservoir:

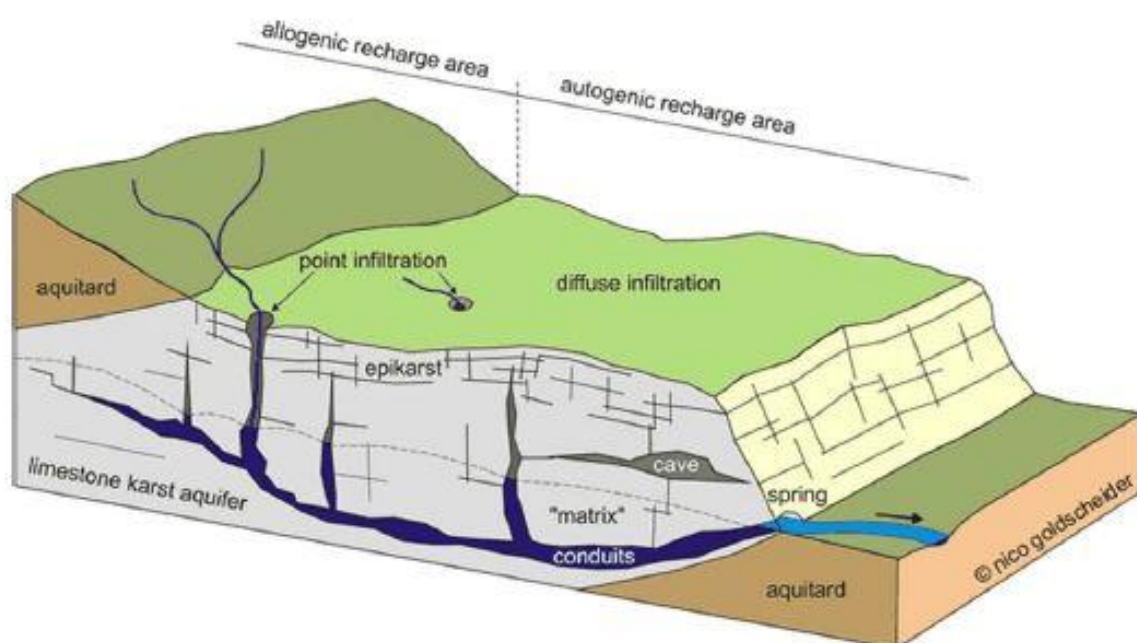
$$Evapotranspiration_{\text{Symons tank}} = \text{monthly factor} \times \text{evaporation}$$

Monthly factor			
January	0.84	July	0.83
February	0.88	August	0.81
March	0.88	September	0.81
April	0.88	October	0.81
May	0.87	November	0.82
June	0.85	December	0.83

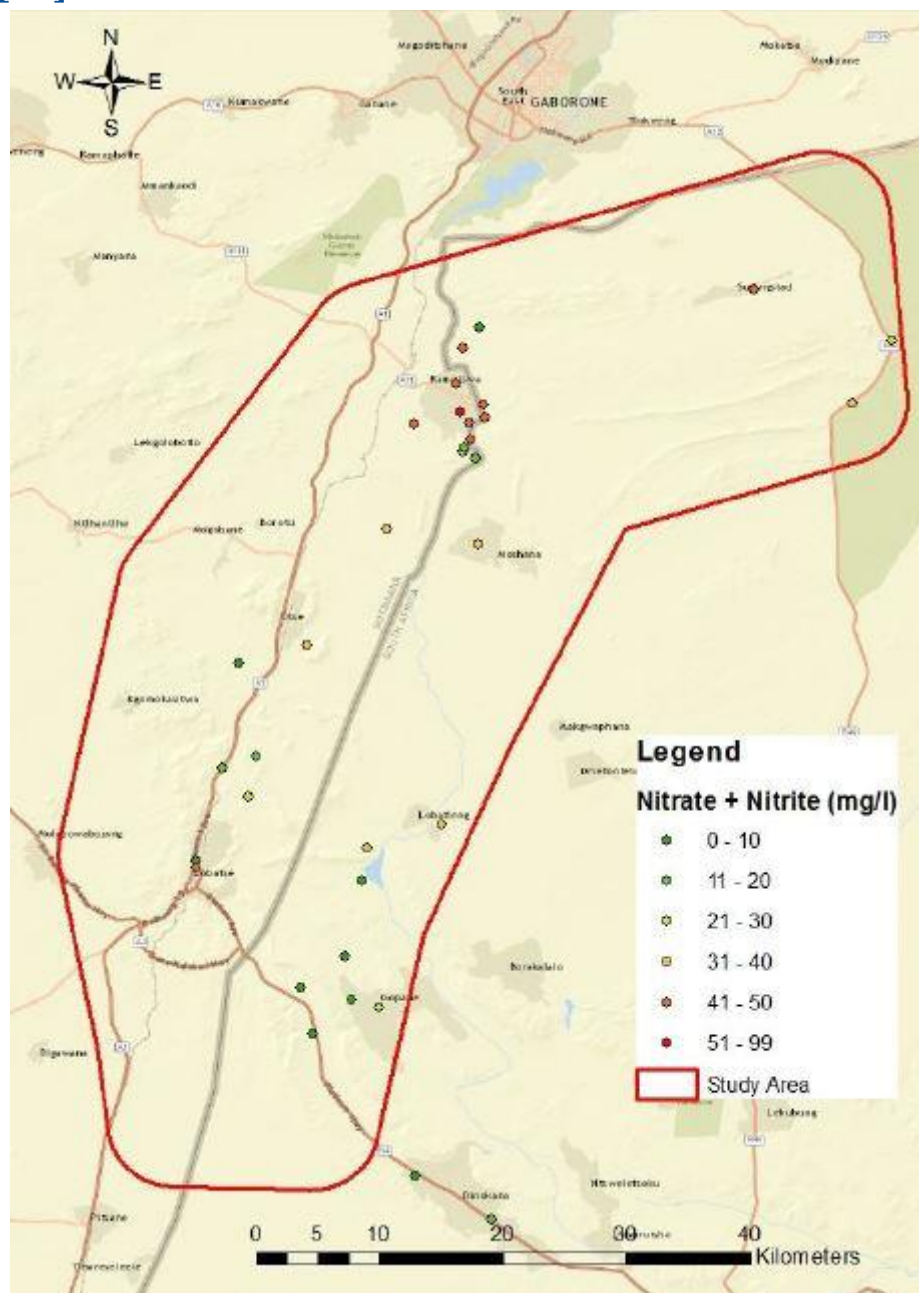
- For Class A: same method as Symons tank, then divided by 1.3,

$$Evapotranspiration_{\text{Class A}} = \frac{\text{monthly factor} \times \text{evaporation}}{1.13}$$

Appendix 12: Conceptual model of a karst aquifer [105]



Appendix 13: Spatial distribution of sum of nitrate and nitrite in the RTBAA [59]



Appendix 14: Monthly and annual average calculation of natural recharge

Month	Monthly average rain mm	Monthly average evaporation mm	Year	Annual average natural recharge mm	Year	Annual average natural recharge mm
January	99	200	1988	8,3	2003	0
February	87	172	1989	2,4	2004	0
March	71	159	1990	0	2005	0
April	33	132	1991	4,2	2006	9,1
May	13	117	1992	0	2007	0
June	6	99	1993	0	2008	9,7
July	2	110	1994	0	2009	8,7
August	1	142	1995	1,2	2010	3
September	8	182	1996	0,3	2011	16,6
October	38	216	1997	7,9	2012	0
November	65	210	1998	4,1	2013	0
December	81	203	1999	3,4	2014	1,1
			2000	15,8	2015	0
			2001	4,6	2016	2,2
			2002	0	For 29 years	3,5

 High drought

Appendix 15: Rainfall and evaporation trends

Rainfall and evaporation totals are grouped by season, stations and percentile, respectively in Figure 33 and Figure 34. The regression analysis is realized by the software R (the R project for statistical computing) with the following equation:

$$\text{seasonal total rainfall or evaporation} \sim \text{year} * \text{percentile group} * \text{season}$$

An example of code is presented below. This code matches the analysis of rainfall during the wet season.

#Data loading

```
setwd(dir="H:/stat/Rainfall_DATA")
```

```
dataw<-read.table(file="rain_wet_sea.txt",dec=".",sep=";",header=TRUE)
```

#Percentile wet season

```
quantile(dataw[,3], probs = seq(0, 1, 0.1), na.rm = FALSE,names = TRUE, type = 5)
```

#result percentile wet season

```
#0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
```

#29.7	235.21	307.23	347.41	387.89	438	480.72
	539.75	582.91	666.63	907		

#Data loading with percentile

```
setwd(dir="H:/stat/Rainfall_DATA")
```

```
datawt<-read.table(file="rain_wet_sea_trier.txt",dec=".",sep=" ",header=TRUE)
```

#creation table wett10

```
wett10<-datawt[datawt[,4]!="0.5",]
```

```
wett10<-wett10[wett10[,4]!="0.9",]
```

#creation table wett90

```
wett90<-datawt[datawt[,4]!="0.5",]
```

```
wett90<-wett90[wett90[,4]!="0.1",]
```

#creation table wett50

```
wett50<-datawt[datawt[,4]!="0.1",]
```

```
wett50<-wett50[wett50[,4]!="0.9",]
```

#creation table wli10, wli50, wli90

```
wli10<-wett10[wett10[,1]!="Maric",]
```

```
wli10<-wli10[wli10[,1]!="Molat",]
```

```
wli10<-wli10[wli10[,1]!="Gabor",]
```

```
wli10<-wli10[wli10[,1]!="Ramot",]
```

```
wli10<-wli10[wli10[,1]!="Lobat",]
```

```
wli50<-wett50[wett50[,1]!="Maric",]
```

```
wli50<-wli50[wli50[,1]!="Molat",]
```

```
wli50<-wli50[wli50[,1]!="Gabor",]
```

```
wli50<-wli50[wli50[,1]!="Ramot",]
```

```
wli50<-wli50[wli50[,1]!="Lobat",]
```

```
wli90<-wett90[wett90[,1]!="Maric",]
```

```
wli90<-wli90[wli90[,1]!="Molat",]
```

```
wli90<-wli90[wli90[,1]!="Gabor",]
```

```
wli90<-wli90[wli90[,1]!="Ramot",]
```

```
wli90<-wli90[wli90[,1]!="Lobat",]
```



```
#creation table wma10, wma50, wma90
wma10<-wett10[wett10[,1]!="LiMar",]
wma10<-wma10[wma10[,1]!="Molat",]
wma10<-wma10[wma10[,1]!="Gabor",]
wma10<-wma10[wma10[,1]!="Ramot",]
wma10<-wma10[wma10[,1]!="Lobat",]
wma50<-wett50[wett50[,1]!="LiMar",]
wma50<-wma50[wma50[,1]!="Molat",]
wma50<-wma50[wma50[,1]!="Gabor",]
wma50<-wma50[wma50[,1]!="Ramot",]
wma50<-wma50[wma50[,1]!="Lobat",]
wma90<-wett90[wett90[,1]!="LiMar",]
wma90<-wma90[wma90[,1]!="Molat",]
wma90<-wma90[wma90[,1]!="Gabor",]
wma90<-wma90[wma90[,1]!="Ramot",]
wma90<-wma90[wma90[,1]!="Lobat",]
```

```
#creation table wmo10, wmo50, wmo90
wmo10<-wett10[wett10[,1]!="LiMar",]
wmo10<-wmo10[wmo10[,1]!="Maric",]
wmo10<-wmo10[wmo10[,1]!="Gabor",]
wmo10<-wmo10[wmo10[,1]!="Ramot",]
wmo10<-wmo10[wmo10[,1]!="Lobat",]
wmo50<-wett50[wett50[,1]!="LiMar",]
wmo50<-wmo50[wmo50[,1]!="Maric",]
wmo50<-wmo50[wmo50[,1]!="Gabor",]
wmo50<-wmo50[wmo50[,1]!="Ramot",]
wmo50<-wmo50[wmo50[,1]!="Lobat",]
wmo90<-wett90[wett90[,1]!="LiMar",]
wmo90<-wmo90[wmo90[,1]!="Maric",]
wmo90<-wmo90[wmo90[,1]!="Gabor",]
wmo90<-wmo90[wmo90[,1]!="Ramot",]
wmo90<-wmo90[wmo90[,1]!="Lobat",]
```

```
#creation table wga10, wga50, wga90
wga10<-wett10[wett10[,1]!="LiMar",]
wga10<-wga10[wga10[,1]!="Maric",]
wga10<-wga10[wga10[,1]!="Molat",]
wga10<-wga10[wga10[,1]!="Ramot",]
wga10<-wga10[wga10[,1]!="Lobat",]
wga50<-wett50[wett50[,1]!="LiMar",]
wga50<-wga50[wga50[,1]!="Maric",]
wga50<-wga50[wga50[,1]!="Molat",]
wga50<-wga50[wga50[,1]!="Ramot",]
wga50<-wga50[wga50[,1]!="Lobat",]
wga90<-wett90[wett90[,1]!="LiMar",]
wga90<-wga90[wga90[,1]!="Maric",]
wga90<-wga90[wga90[,1]!="Molat",]
wga90<-wga90[wga90[,1]!="Ramot",]
wga90<-wga90[wga90[,1]!="Lobat",]
```

```
#creation table wra10, wra50, wra90
wra10<-wett10[wett10[,1]!="LiMar",]
wra10<-wra10[wra10[,1]!="Maric",]
wra10<-wra10[wra10[,1]!="Molat",]
wra10<-wra10[wra10[,1]!="Gabor",]
wra10<-wra10[wra10[,1]!="Lobat",]
wra50<-wett50[wett50[,1]!="LiMar",]
wra50<-wra50[wra50[,1]!="Maric",]
wra50<-wra50[wra50[,1]!="Molat",]
wra50<-wra50[wra50[,1]!="Gabor",]
wra50<-wra50[wra50[,1]!="Lobat",]
wra90<-wett90[wett90[,1]!="LiMar",]
wra90<-wra90[wra90[,1]!="Maric",]
wra90<-wra90[wra90[,1]!="Molat",]
wra90<-wra90[wra90[,1]!="Gabor",]
wra90<-wra90[wra90[,1]!="Lobat",]
```

```
#creation table wlo10, wlo50, wlo90
```

```
wlo10<-wett10[wett10[,1]!="LiMar",]  
wlo10<-wlo10[wlo10[,1]!="Maric",]  
wlo10<-wlo10[wlo10[,1]!="Molat",]  
wlo10<-wlo10[wlo10[,1]!="Gabor",]  
wlo10<-wlo10[wlo10[,1]!="Ramot",]  
wlo50<-wett50[wett50[,1]!="LiMar",]  
wlo50<-wlo50[wlo50[,1]!="Maric",]  
wlo50<-wlo50[wlo50[,1]!="Molat",]  
wlo50<-wlo50[wlo50[,1]!="Gabor",]  
wlo50<-wlo50[wlo50[,1]!="Ramot",]  
wlo90<-wett90[wett90[,1]!="LiMar",]  
wlo90<-wlo90[wlo90[,1]!="Maric",]  
wlo90<-wlo90[wlo90[,1]!="Molat",]  
wlo90<-wlo90[wlo90[,1]!="Gabor",]  
wlo90<-wlo90[wlo90[,1]!="Ramot",]
```

```
plot(datawt$year,datawt$mm,col="white",xlab="Wet season in year",ylab="Rainfall  
in mm")  
points(wli10$year,wli10$mm,pch=1,col="green")  
points(wli50$year,wli50$mm,pch=1,col="red")  
points(wli90$year,wli90$mm,pch=1,col="blue")  
points(wma10$year,wma10$mm,pch=2,col="green")  
points(wma50$year,wma50$mm,pch=2,col="red")  
points(wma90$year,wma90$mm,pch=2,col="blue")  
points(wmo10$year,wmo10$mm,pch=3,col="green")  
points(wmo50$year,wmo50$mm,pch=3,col="red")  
points(wmo90$year,wmo90$mm,pch=3,col="blue")  
points(wga10$year,wga10$mm,pch=4,col="green")  
points(wga50$year,wga50$mm,pch=4,col="red")  
points(wga90$year,wga90$mm,pch=4,col="blue")  
points(wra10$year,wra10$mm,pch=5,col="green")  
points(wra50$year,wra50$mm,pch=5,col="red")  
points(wra90$year,wra90$mm,pch=5,col="blue")  
points(wlo10$year,wlo10$mm,pch=6,col="green")
```

```
points(wlo50$year,wlo50$mm,pch=6,col="red")  
points(wlo90$year,wlo90$mm,pch=6,col="blue")
```

```
w10<-lm(wett10$mm~wett10$year)  
summary(w10)  
anova(w10)  
w10  
abline(w10,col="green")
```

```
pred.frame<-data.frame(wett10$year)  
pred10 <- predict(w10, interval="confidence",level=.9,newdata=pred.frame)  
lines(smooth.spline(wett10$year,pred10[,2]),col="green")  
lines(smooth.spline(wett10$year,pred10[,3]),col="green")
```

```
w50<-lm(wett50$mm~wett50$year)  
summary(w50)  
anova(w50)  
w50  
abline(w50,col="red")
```

```
pred.frame<-data.frame(wett50$year)  
pred50 <- predict(w50, interval="confidence",level=.9,newdata=pred.frame)  
lines(smooth.spline(wett50$year,pred50[,2]),col="red")  
lines(smooth.spline(wett50$year,pred50[,3]),col="red")
```

```
w90<-lm(wett90$mm~wett90$year)  
summary(w90)  
anova(w90)  
w90  
abline(w90,col="blue")
```

```
pred.frame<-data.frame(wett90$year)  
pred90 <- predict(w90, interval="confidence",level=.9,newdata=pred.frame)  
lines(smooth.spline(wett90$year,pred90[,2]),col="blue")  
lines(smooth.spline(wett90$year,pred90[,3]),col="blue")
```

Appendix 16: Introduction translated in french

Dans la région de l'aquifère transfrontalier de Ramotswa, située au nord du Limpopo entre le Botswana et l'Afrique du Sud, les étendues d'eau de surface sont devenues rares et dépendent des saisons. Ainsi, la population est devenue lourdement dépendante de la ressource en eau souterraine. Etant donné cette dépendance, il est important que la qualité d'une telle eau soit assurée afin d'éviter des impacts sur la santé des consommateurs. Cependant, les conditions sociales et économiques ont mené le Botswana et l'Afrique du Sud à développer un système d'assainissement autonome reposant principalement sur l'emploi de latrines, dont l'utilisation est en lien avec la pollution des ressources en eau dans d'autres régions [6 ; 7]. C'est pourquoi il est essentiel d'évaluer la qualité et la quantité actuelle de la ressource en eau, ainsi que les risques de pollution dans la région de l'aquifère transfrontalier de Ramotswa.

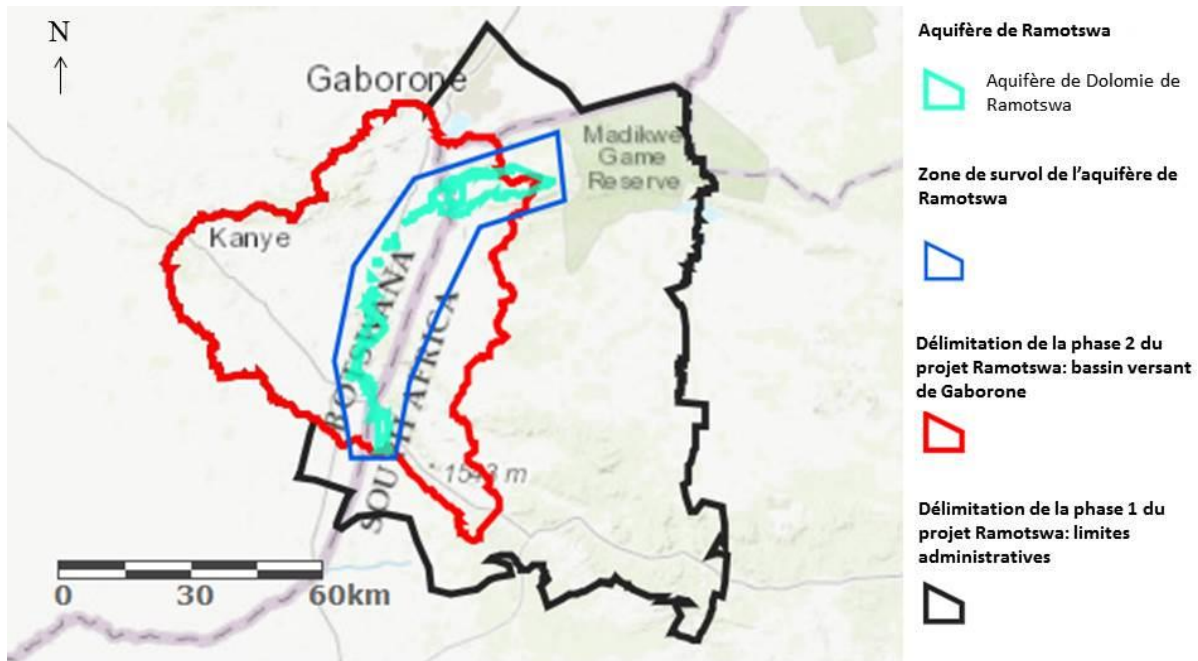
Malgré quelques études sur la qualité de l'eau et la pollution dans la région, aucune étude axée sur la totalité de l'aquifère n'a été entreprise. Quelques études hydrogéologiques ont été réalisées à Ramotswa et Lobatse, respectivement par Beger [8] et Staudt [9]. Ces rapports exposent les différentes caractéristiques de l'aquifère transfrontalier de Ramotswa du côté du Botswana et dénoncent la forte concentration en nitrate, source de pollution de l'eau. Contrairement à cette étude qui prête attention aux deux pays chevauchés par l'aquifère, les précédentes investigations n'ont étudié l'aquifère que du côté du Botswana. En effet, Ranganai [1] a lié l'extrême vulnérabilité de la ressource en eau souterraine à la pollution anthropique due au développement de l'assainissement. En effet, de nombreux ouvrages tels que des fosses septiques, des latrines, des rejets de station d'épuration et des décharges sont situés à proximité du champ de captage d'eau potable de Ramotswa. Ces études montrent également que les sources de pollution se trouvent à même profondeur que le niveau d'eau souterrain. Les caractéristiques de l'aquifère et du sol telles que la profondeur du niveau d'eau, ou encore la nature de la matrice du sol, sont des paramètres clés impliqués dans le développement du processus de pollution de l'aquifère.

La présente étude évalue les impacts du système d'assainissement sur la qualité et la quantité de l'eau souterraine dans la région de l'aquifère transfrontalier de Ramotswa à cheval sur le Botswana et l'Afrique du Sud. Les informations nécessaires à cette étude ont été collectées à l'aide d'une analyse de documents, d'entretiens avec les locaux, et d'échantillonnage d'eaux usées. Une carte GIS a été établie afin de déterminer les zones les plus vulnérables de l'aquifère et les sources de pollution. Les résultats de cette évaluation des risques ont été utilisés afin de conseiller une amélioration du système d'assainissement tout en tenant compte du contexte social, du climat et des conditions économiques des deux pays affectés. Les eaux usées sont considérées comme la « nouvelle eau » dans les pays où l'eau est une denrée rare. Certaines alternatives, comme la réutilisation des eaux usées, sont proposées pour l'agriculture, la recharge d'aquifère, et la réutilisation domestique.

1. Présentation de la zone d'étude

La zone d'étude est la région de l'aquifère transfrontalier de Ramotswa (RTBAA) situé entre le Botswana et l'Afrique du Sud. La RTBAA chevauche la frontière entre les deux pays. La délimitation de la RTBAA est le bassin versant de Gaborone. Cependant, cette étude cible ce bassin versant et s'étend sur les districts administratifs du Sud-Est du Botswana et du Nord-Ouest de l'Afrique du Sud. Du côté

du Botswana, l'étude porte sur la région Sud-Est et une partie de la région sud. La population y est très densifiée et se concentre sur les deux capitales juridique et économique, Lobatse et Gaborone. Cette région est majoritairement urbaine avec une forte croissance économique. A contrario, la municipalité locale de Ramotshere Moiloa de la province Nord-Ouest d'Afrique du Sud compose la partie sud-africaine de l'étude. Cette municipalité locale s'étend sur 7193 km² et dispose d'une croissance économique stagnante avec une densité de population faible. La zone urbaine principale se nomme Zeerust.



La RTBAA dispose d'un climat semi-aride. L'année est divisée en deux saisons. L'hiver se caractérise par une saison sèche avec un fort taux d'évaporation et a lieu d'avril à septembre. Au contraire, d'octobre à mars a lieu l'été connu sous le nom de la saison des pluies. Les pluies apparaissent lors de cette période. Les températures moyennes annuelles varient entre 18 et 20°C.

L'aquifère de Ramotswa se situe précisément dans le sous-bassin versant de Ngotwane, présent dans la partie haute du bassin fluvial du Limpopo. Géologiquement, la zone d'étude est dans la partie ouest du Transvaal Supergroup dans le Kraapvaal Craton. L'unité principale de l'aquifère est la dolomie. La dolomie de Ramotswa est introduite par trois failles verticales créant des compartiments. L'aquifère de dolomie à Ramotswa est fracturé et possède des zones karstiques avec une forte transmissivité et un fort coefficient d'emménagement. L'aquifère se recharge naturellement par les pluies. Le niveau moyen d'eau souterraine est de 9 mètres sous le sol. Il existe entre 0 et 12 mètres d'épaisseur de surface sédimentaire non consolidée [2]. La qualité de l'eau souterraine est essentielle dans la RTBAA étant donné son utilisation pour l'agriculture (69%), l'industrie (1%), et particulièrement l'eau potable (30%) [2].

La RTBAA s'étend sur 10533 km² et recensait une population de 534 788 en 2011. Actuellement, 50% de la population est connecté à un réseau d'assainissement communal tandis que plus de 50% de la population dispose d'un système d'assainissement autonome tel que des latrines. Les latrines doivent leur importance aux variations climatiques, plus particulièrement la sécheresse qui limite la consommation d'eau. En zone urbaine, les latrines sont plus ou moins bien maintenues et sont vidangées puis

transférées en entrée de station d'épuration. En zone rurale, les latrines sont entretenues selon les moyens des habitants. L'activité principale de la région est l'agriculture. Les eaux souterraines sont aussi utilisées afin d'irriguer les champs et abreuver les animaux.

2. Présentation de la structure d'accueil: l'International Water Management Institute

L'International Water Management Institute dirige le projet de l'aquifère transfrontalier de Ramotswa en partenariat avec le Ministère de l'Eau et de l'Assainissement d'Afrique du Sud, le Ministère des Eaux du Botswana, Limpopo Watercourse Commission, Southern African Development Community, et les universités des environs. L'International Water Management Institute est une organisation de recherche scientifique sans but lucratif s'intéressant au développement durable des ressources dans les pays en voie de développement en Afrique et en Asie. Le projet Ramotswa a été développé en 2015 pour soutenir la gestion et la coopération des ressources en eau souterraine partagées dans la région supérieure du Limpopo afin de réduire la pauvreté, l'inégalité et l'insécurité. Les objectifs principaux du projet Ramotswa sont de comprendre l'importance socio-économique de l'aquifère dans la région, évaluer la faisabilité de la recharge artificielle de l'aquifère, établir la coopération entre les deux pays et améliorer la gestion et le contrôle de la ressource. Les attentes de ce projet sont la mise en place d'échanges entre les différentes parties, un plan d'action stratégique pour le développement et la gestion de l'aquifère, une analyse diagnostique transfrontalière, un outil pédagogique pour développer la maîtrise du système et un système de gestion de l'information dénommé RIMS et géré par l'IGRAC.

3. Méthodes employées

Cette étude a été menée en cinq étapes : une analyse de documents, une étude statistique du bilan hydrique et de la population, des entrevues et visites, une modélisation de carte de vulnérabilité, et la détermination des différents enjeux.

i) Analyse de documents

La plupart des documents analysés sont des documents de lois et des rapports environnementaux issus du Ministère des Eaux du Botswana, du Ministère de l'Eau et de l'Assainissement d'Afrique du Sud, des organisations présentes dans la zone transfrontalière et les études précédentes réalisées dans la zone d'étude, telles que les rapports d'hydrogéologie de Michael Staudt [9] et Katharine Beger [8]. L'analyse de documents a été réalisée dans un ordre chronologique et par catégories afin de compléter et actualiser les données. Les documents ont été classifiés tout d'abord par pays puis en cinq catégories qui sont les stations d'épuration, les systèmes d'assainissement autonomes, les études hydrogéologiques, les activités développées et les plans de développement pour l'environnement.

ii) Etude statistique du bilan hydrique et de la population

Les rapports de recensement des régions Sud-Est [3] et Sud [4] du Botswana de 2001 et 2011 ont été collectés. De même, les rapports de recensement de la province Nord-Ouest en Afrique du Sud de 1996 [10], 2001 [11], 2011 [5] et 2016 [12] ont été étudiés. Ces rapports sont utilisés pour évaluer le taux de croissance de la population, la consommation d'eau par foyer et le développement du système d'assainissement au cours du temps.

iii) Entrevues et visites

Les visites de terrains ont permis de réaliser des entrevues avec les employés des stations d'épuration de Lobatse, Ramotswa, et Gaborone [Annexes 2, 3, 4, 6] et de collecter des échantillons d'eaux usées [Annexe 5, 7]. Les entrevues ont eu lieu afin de préciser la capacité de traitement et le type de traitement des eaux usées. Elles ont également permis d'évaluer l'impact potentiel des rejets d'eaux usées dans l'environnement et de comprendre les mœurs en termes d'assainissement dans la région. De plus, les entrevues ont permis de corriger ou confirmer les informations contenues dans les documents concernés. Aucune interview n'a été possible du côté sud-africain.

iv) Modélisation de carte

Les visites et l'analyse de documents ont aidés à créer la carte GIS de la zone d'étude. Le but de cette carte est de localiser les zones les plus vulnérables en termes de pollution des ressources. Pour cela, la méthode DRASTIC a été employée pour modéliser la vulnérabilité de l'aquifère, en utilisant la profondeur du niveau d'eau souterraine, la recharge, les caractéristiques du milieu poreux, les caractéristiques du sol, la topographie, l'impact de la zone non saturée et la conductivité.

v) Détermination des différents enjeux

Après avoir réalisé ces quatre premières étapes, une évaluation du système d'assainissement du Botswana et d'Afrique du Sud a été réalisée. Cette étude compile chaque information dans un ordre chronologique. Cinq enjeux ont été principalement identifiés en combinant les informations de chaque étape :

- Les zones prioritaires : la carte GIS modélise les différentes zones prioritaires sur lesquelles le système d'assainissement doit être revu ou amélioré. Ces zones sont sélectionnées selon leur vulnérabilité en termes de pollution.
- Les eaux industrielles : l'analyse de documents et les visites ont permis d'évaluer la qualité des rivières et des eaux usées traitées. De fortes concentrations en polluants (métaux lourds, huile et graisse, et demande chimique en oxygène) ne viennent pas seulement des eaux domestiques traitées. Les activités industrielles sont impliquées dans la détérioration de la qualité des eaux usées traitées. Dans cette étude, les plus grosses activités industrielles et leurs polluants ont été déterminés.
- Pollution transfrontalière : l'estimation de la qualité des eaux et la modélisation ont permis de se concentrer sur la pollution transfrontalière, plus précisément la rivière Ngotwane qui sert de frontière naturelle. Les eaux de surface et les eaux souterraines sont liées selon l'analyse de documents.
- Bilan hydrique : une étude statistique du bilan hydrique et de la population montre la consommation d'eau et le nombre d'installation sanitaire en augmentation qui ont un impact sur l'accroissement des pertes d'eaux contaminées. Le bilan hydrique est quantifié en se basant sur les statistiques.
- Le changement climatique : les entrevues et les documents montrent que les observations sont différentes en été et en hiver. De plus, cette région a connu des périodes prolongées de sécheresse. Le changement climatique a un impact sur les pluies et les taux d'évaporation qui influent à leur tour sur l'assainissement. Ces données ont été fournies par le Ministère de l'Eau et de l'Assainissement d'Afrique du Sud et le Ministère des Eaux du Botswana.

Une fois les enjeux établis, des recommandations sont présentées afin d'améliorer le système d'assainissement. Une meilleure qualité de traitement ainsi que des systèmes d'assainissement mieux adaptés à la région peuvent aider à diminuer la pollution. Les eaux usées traitées peuvent être aujourd'hui un réel bénéfice pour la ressource en eau et les populations.

Appendix 17 : Conclusion translated in french

Dans la région de l'aquifère transfrontalier de Ramotswa, le système d'assainissement est à l'origine de deux types de pollution. L'une provient des systèmes d'assainissement autonomes. En effet, les latrines et les fosses septiques polluent l'aquifère à cause du manque d'entretien et de connaissances de ces ouvrages. De plus, les systèmes d'assainissement autonomes ont besoin d'être améliorés car ils ne sont pas adaptés aux conditions du sol qui est un sol fracturé avec un niveau d'eau de la nappe élevé, particulièrement durant la saison des pluies. La seconde cause de pollution est le système de station d'épuration. La qualité des eaux usées traitées ne correspond pas aux limites de rejet imposées par le gouvernement. Cela vient d'un problème d'efficacité de traitement. En effet, les entrées de station d'épuration contiennent des eaux domestiques et des eaux industrielles. Or, le traitement implanté n'est pas adapté au traitement des eaux industrielles. De plus, le manque d'entretien et de surveillance conduisent à la détérioration du système de traitement. Ces cas de pollution dépendent aussi des conditions climatiques. En effet, l'aquifère est plus vulnérable à l'infiltration provenant des latrines durant la saison des pluies à cause du niveau d'eau de la nappe élevé. Au contraire, en hiver, l'aquifère est plus vulnérable aux eaux usées traitées sortant de station d'épuration. Cette période de l'année a un impact sur l'efficacité de traitement à cause des températures plus basses et de l'exposition solaire amoindrie. De manière générale, la pollution venant des latrines est la pollution la plus problématique en se référant au nombre important de latrines dans la région. Une zone de priorité a été délimitée selon les conditions sanitaires. Cette zone s'étend sur 10 km de chaque côté de la frontière allant de Radikhudu à Ramotswa.

Certaines recommandations ont été proposées afin de diminuer le risque de pollution de l'aquifère. Ces recommandations peuvent être facilement mises en place mais demandent l'implication de la communauté sur le long terme. Tout d'abord, il est important de connecter les foyers sans système d'assainissement au réseau. Puis, le plus important est de réagir face au niveau élevé de la nappe phréatique. Pour cela, les fosses des latrines doivent être diminuées en taille ou surélevées. De plus, des plans de développement de la ressource en eau devraient être mis en place. La maintenance et l'entretien des systèmes sont proposés et peuvent être complétés par l'auto-surveillance. Enfin, en établissant un plan d'assainissement durable, certains bénéfices peuvent être faits pour la municipalité. L'amélioration du traitement des boues peut mener à la réutilisation dans le domaine agricole. De même, une meilleure qualité des eaux usées traitées permettrait de les réutiliser pour l'agriculture et/ou la recharge d'aquifère.

Différents projets suivent cette étude. L'un d'eux est le développement d'un schéma d'irrigation dans la RTBAA. Celui-ci consiste en l'amélioration de la gestion de l'irrigation pour les fermes locales en utilisant des capteurs de surveillance afin d'évaluer la quantité et la qualité d'eau nécessaire en fonction du type d'agriculture sur des fermes de plus de deux hectares. Ce projet permettrait d'estimer les besoins en eau pour l'agriculture. Le second projet est la modélisation hydrogéologique de l'aquifère transfrontalier de Ramotswa. Ce projet a pour but de mieux comprendre le fonctionnement de la ressource et d'estimer les possibilités de recharge artificielle de l'aquifère à partir de point d'injection au niveau de la rivière de Ngotwane. La modélisation de l'aquifère est spécifique à un compartiment transfrontalier de l'aquifère situé à Ramotswa.