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TRANSBOUNDARY WATER MANAGEMENT IN SOUTHERN AFRICA

PROJECT BRIEF

Enhancing water security in Southern Africa by tackling nitrate contamination of aquifers and unraveling links to climate change and sanitation: A case from Ramotswa, Botswana

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The quality and quantity of groundwater are threatened by climate change as well as increasing demand from rapid urbanization in southeast Botswana, as is the case in much of southern Africa. A case study of Ramotswa, a growing peri-urban area in southeast Botswana (population about 40,000), revealed the impact of the 2013-2016 drought on groundwater quality. Water shutoffs by the public water supply scheme to ration and save water during the drought made flush toilets and the sewage treatment system inoperable. This increased the number of people relying on pit latrines by about 10,000. Greater use of pit latrines, in turn, increased the volume of human waste leaking into groundwater, which greatly exacerbated the risk of nitrate contamination of the drinking water supply, tapped from the underlying aquifer (Box 1). Ultimately, drinking water, sanitation and groundwater management are interdependent and vulnerable to climate change impacts and extreme events. One promising mechanism to combat the groundwater pollution problem is in-situ bioremediation, which accelerates denitrification, the naturally occurring microbial process that removes nitrate from soil and groundwater. The study revealed the biophysical feasibility of this solution, which is recommended for further exploration and piloting in order to secure the water supply for Ramotswa along with improved sanitation infrastructure.

Phemo Moleje (Botswana Geoscience Institute), Phemelo Makoba (Department of Water Affairs) and Kgabi Gaboutloeloe (University of Botswana) filtering a groundwater sample in January 2017 (*photo:* Bonnie McGill).

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BOX 1

Groundwater in Ramotswa, Botswana.

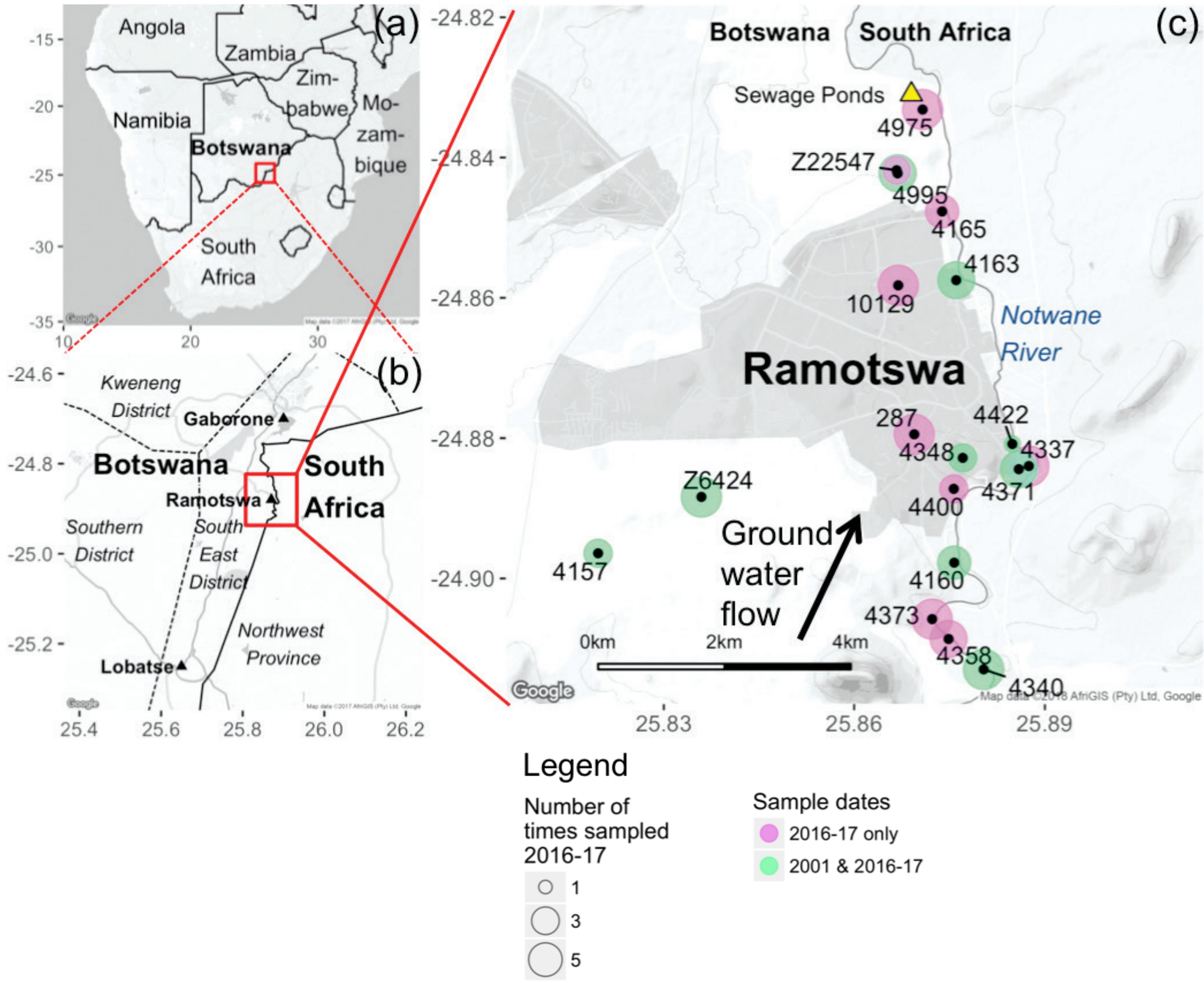
Ramotswa (Figure 1) is a town located on an outcrop of the transboundary Ramotswa aquifer (an underground natural storage of water held between rocks and sediments). An outcrop is an area where the aquifer formation emerges at the Earth's surface (Figure 2). This aquifer spans parts of Botswana and South Africa, and is the most important groundwater resource for the urban and peri-urban settlements of southeast Botswana. The aquifer is vulnerable to contamination from the surface, especially in the outcrop areas where there are no overlying geological layers protecting the aquifer. Nitrate concentrations up to 29 mg L^{-1} as nitrogen have been found in the area (Figure 3[b]). The World Health Organization (WHO) standard for drinking water is 10 mg L^{-1} nitrate as nitrogen (or 45 mg L^{-1} nitrate as nitrate), although new research suggests nitrate at even lower concentrations can increase the risk of some forms of cancer. The mean depth to the water table in Ramotswa is 14 m. Recharge of the aquifer occurs mainly through cracks and channels eroded into the dolomite formation constituting the aquifer, where water from the surface or holes dug into the ground, such as pit latrines, rapidly pour into the aquifer. The lack of significant soil or sediment layers means there is little to no natural filtration and purification of the recharge water. Lined pit latrines help prevent human waste from infiltrating into the aquifer. In Ramotswa, there are thousands of pit latrines (Figure 4), but it is unknown how many are lined. When a pit latrine fills, the resident can choose to build a new one (pairs of pit latrines are a common sight [Figure 4]) or pay the water utility company USD 50 to pump and empty the waste from the pit latrine, which is then taken to the sewage treatment ponds.

Sources: Altchenko et al. 2016, 2017

KEY FINDINGS

- **Climate change is significantly affecting water supply in southern Africa.** Over the last 50 to 100 years, southern Africa's temperature has risen, most rapidly in the last two decades. Also, rainfall has become more variable, and generally the climate has become drier in southeast Botswana. Floods and droughts are becoming more frequent. This creates huge challenges for water supply and implicitly water security.
- **Groundwater supports about 75% of the sub-Saharan African (SSA) population.** Groundwater extractions have intensified as the surface water quantity is becoming less reliable due to climate change, and as surface water quality is degrading due to human activity.
- **Rapid urbanization in SSA often results in levels of water infrastructure use that exceeds design capacity, and onsite sanitation (pit latrines) that is too densely located and not properly maintained – ultimately polluting the underground water resource.** Pit latrines are the most common means of human waste disposal in peri-urban areas, often where communities also rely on groundwater for drinking. Human waste contaminates water with pathogens, such as cholera, as well as nitrate, which can cause Blue Baby Syndrome.
- **Water supply and sanitation infrastructure is affected by biophysical realities.** Such infrastructure can have *impacts on* and *be impacted* by natural systems, such as climate and groundwater. For example, sanitation can contaminate groundwater systems, and climate can affect the way people use sanitation. Designing and managing infrastructure with these connections in mind will strengthen a community's water security and resilience in the face of urbanization and climate change.
- **Nitrate removal can be accelerated by bioremediation.** In order for denitrification to occur in the aquifer system, the microbes require low oxygen conditions, nitrate and plenty of organic carbon. Without sufficient organic carbon, denitrification stops and nitrate persists. It is possible to enhance denitrification and speed up the restoration of the contaminated aquifer by adding an external source of carbon into the aquifer.

FIGURE 1. Maps of (a) Southern Africa, (b) Botswana's South-East District, indicating location of Ramotswa, and (c) Location of boreholes.

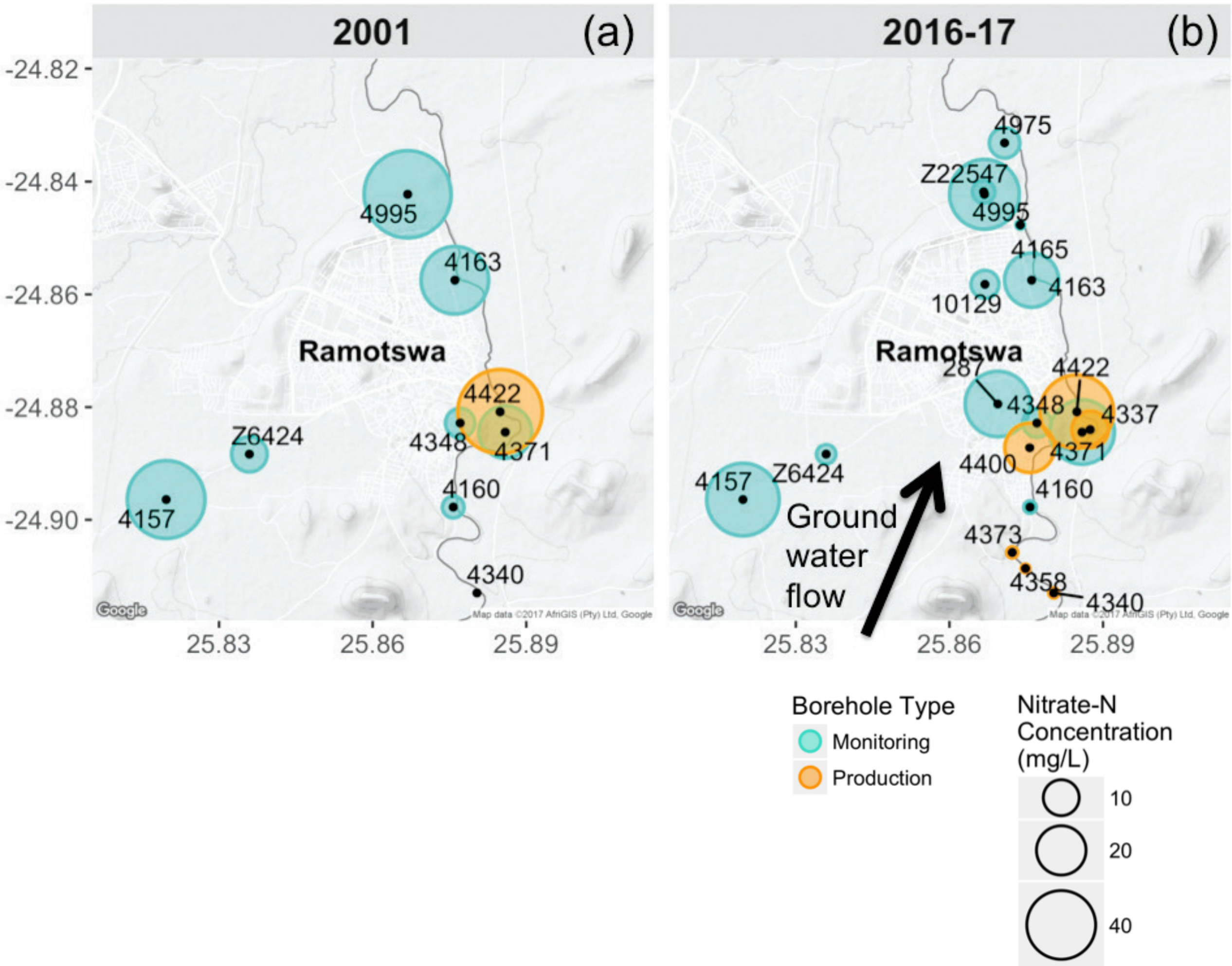


Source: McGill et al. 2019.

FIGURE 2. Outcrop of dolomite rock in Ramotswa (with lens cap for scale). The "elephant skin" texture is the result of weathering away of the rock. The same process creates channels below the surface allowing recharge water (or leaking pit latrines) to quickly infiltrate the aquifer.

Photo: Bonnie McGill

FIGURE 3. Changes in nitrate concentrations (mg L^{-1} nitrate as nitrogen) in Ramotswa boreholes from 2001 to 2016-2017. Circle size indicates borehole nitrate concentrations.



Source: McGill et al. 2019.

Notes: (a) Concentrations in 2001 (Staudt 2003) compared to (b) mean concentrations measured during the period 2016-2017 (McGill et al. 2019).

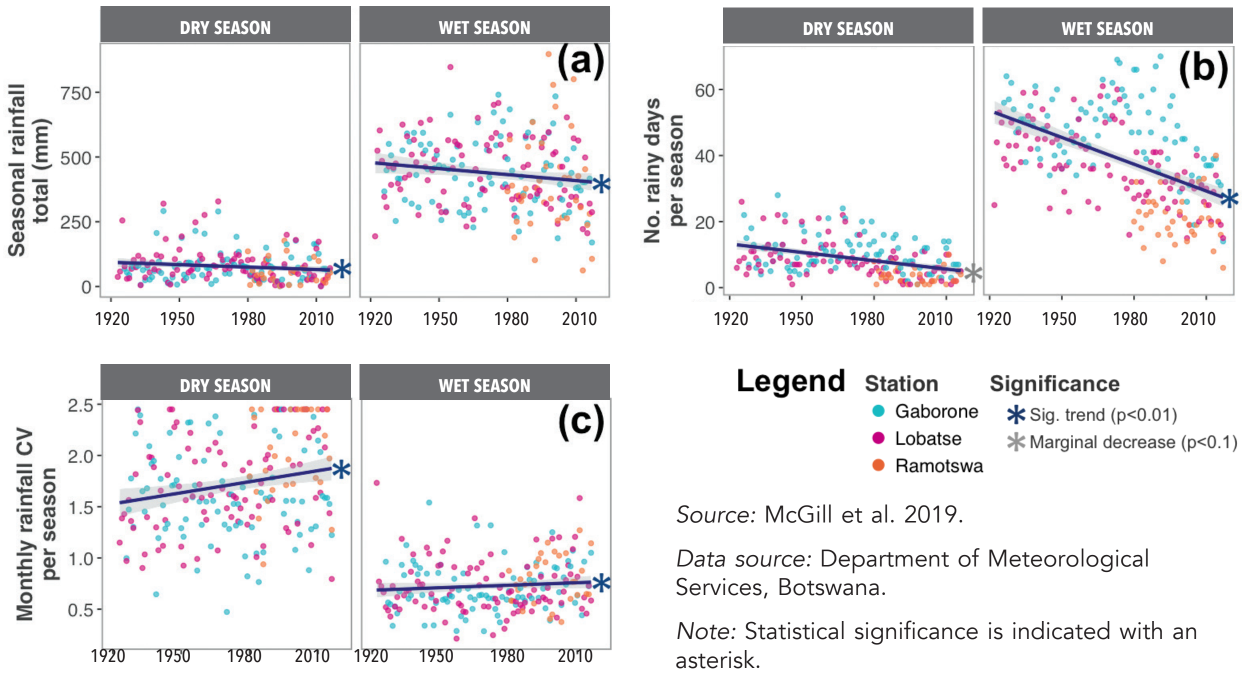
FIGURE 4. Pit latrines in Ramotswa. Pairs of pit latrines are common; as one fills up, a new one is built rather than pumping out the pit latrine that is full.

Photo: Bonnie McGill

Changes in rainfall and water infrastructure increase the vulnerability of groundwater to nitrate contamination

Less rainfall and more extreme weather events in southeast Botswana. Nearly a century of rainfall records from southeast Botswana, including Ramotswa and the nearby cities of Gaborone and Lobatse, show several highly significant trends (Figure 5). First, in both the wet and dry seasons, total rainfall has decreased by about 5 mm every 10 years (Figure 5[a]). Second, in the wet season, the number of days with rain has decreased by 2 days every 10 years (Figure 5[b]). Third, rainfall variability has increased significantly in both seasons (Figure 5[c]). These trends enhance the risk of drought, water shutoffs and the reliance on pit latrines. At the same time, these trends allow for more episodic recharge during extreme rainfall events and contamination of the aquifer.

FIGURE 5. Dry- and wet-season rainfall patterns over time at Gaborone, Lobatse and Ramotswa weather stations. (a) total rainfall, (b) number of rainy days, and (c) seasonal coefficient of variation (CV) among monthly rainfall totals, i.e., seasonal rainfall variability.



Source: McGill et al. 2019.

Data source: Department of Meteorological Services, Botswana.

Note: Statistical significance is indicated with an asterisk.

Infrastructure and historical response to drought. Supplying water to half a million people in southeast Botswana in a semi-arid environment with no major surface water sources is an immense challenge. As a result, the integrated water supply scheme for the area is complex, drawing from multiple wellfields, far-away dams and many kilometers of pipelines. The capital, Gaborone, and surrounding villages and towns, including Ramotswa, are dependent on the same integrated conjunctive system. Ramotswa is located amidst the wellfield drawing water for its public supply.

Drought triggers additional nitrate contamination

Impacts of multi-year drought. During the 2013-2016 drought, when reservoirs had been heavily depleted, water supply to communities south of Gaborone was shutoff for several days a week every week. However, Ramotswa relies on treated water from Gaborone Dam to dilute its high-nitrate groundwater before distributing it to residents. Of the one-third of Ramotswa households connected to the sewage system, only a few store water for flushing their toilets during water shutoffs and, as such, most households reverted to pit latrines. During a shutoff, the volume and flow of sewage to the treatment facility is dramatically lowered, as most people who have a flush toilet switch to their pit latrine.

Elevated nitrate levels. Nitrate levels were well above the drinking water standard during the study period (2016-2017) in Ramotswa boreholes (Figure 3[b]). The boreholes with high nitrate were primarily in the town and downstream of the town (but not upstream), indicating that the town is the source of the contamination. Fecal coliforms were also present in several monitoring boreholes in the town and downstream of the town. Natural sources of nitrate, nitrogen fertilizer and livestock waste were not likely to be the major sources of nitrate contamination in the groundwater. The presence of caffeine in the groundwater suggested a human source. The most likely source of contamination was the thousands of pit latrines in Ramotswa.

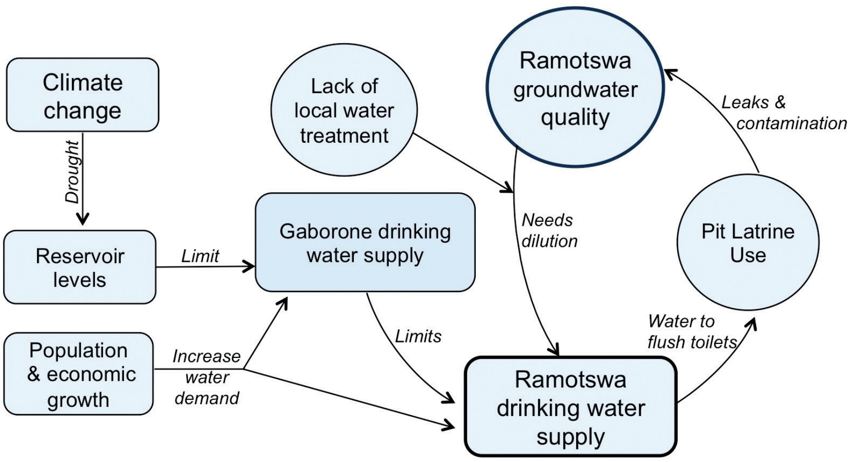
This drought-induced change in water supply and sanitation behavior is likely to exacerbate nitrate contamination in the future due to the following four reasons:

1. Increased likelihood of droughts, threatening reservoir levels and disrupting water supply.
2. The increased use of pit latrines during periods of drought.
3. Despite having abundant groundwater resources, Ramotswa is vulnerable to drought, because the town does not have water treatment infrastructure to treat the groundwater and is now dependent on dilution by water from surface reservoirs and other sources.
4. Rapid urbanization – the population of Ramotswa increased by 50% between 2001 and 2011 (most recent figures available). This is a major challenge for providing safe and adequate drinking water and sanitation services.

Recommendations for a holistic path forward

Account for real-world context. Water supply relies on natural resources that are dependent on climate. As the climate changes, water infrastructure must be designed accordingly to account for larger uncertainty and variability. For example, technology and practices for water saving, recycling and reuse need to be enhanced. Human activity can also degrade the water resource we rely on, so functional sanitation systems are critical for safe groundwater-reliant water supply systems – keeping the resource clean is cheaper than removing contaminants later. A holistic approach that considers the connections between water and sanitation infrastructure, groundwater and climate (Figure 6) will lead to more resilient water security in a rapidly changing world. This approach should incorporate both biophysical and social considerations.

FIGURE 6. Conceptual diagram of the connections between climate, water and sanitation infrastructure, and groundwater quality in Ramotswa, Botswana.



Source: McGill et al. 2019.

Reduce the source of contamination to benefit all. Pit latrines will likely remain a part of the sanitation infrastructure in Ramotswa and much of SSA – indeed, the recent drought and water shutoffs incentivized the building of pit latrines in new homes with flush toilets. Incentivizing lining of new pit latrines and those that have been emptied, and reducing the cost of emptying full or abandoned pit latrines are required, e.g., through innovative business models to recycle and reuse the waste. It is also required to reduce the cost of connecting households to the public sewage system, and finally to expand the sewage network into older neighborhoods, which would enhance recycling of wastewater and the implementation of water-saving toilets. Spatial data (e.g., pit latrine locations and depths) should be collected and compared to hydrogeological mapping of the International Water Management Institute (IWMI) to identify the areas of the aquifer that are most vulnerable to contamination. The improved sewage network and flush toilets are not just a quality-of-life improvement – reducing contamination provides benefits to all. The Ramotswa aquifer is a plentiful source of water in the region, so protecting it and preventing contamination in the first place will benefit all those who depend on it, including other communities in the water supply scheme and downstream South African neighbors. However, in order for an improved sewage system to prevent contamination, it requires a reliable water supply (see below).

Remediate to speed up restoration of the aquifer. Most of the groundwater in Ramotswa has little organic carbon, an essential ingredient for denitrification to naturally remove nitrate in the aquifer. Otherwise, the conditions in the aquifer are suitable for denitrification, as demonstrated by the very high concentrations of dissolved nitrous oxide gas (a by-product of denitrification and harmless to health) in the groundwater. This suggests that denitrification is removing some of the nitrate, but running out of organic carbon, and hence the process stops before removing all the nitrate. Therefore, supplying the denitrifying microbes with a non-hazardous source of organic carbon (such as vegetable oil injected into the aquifer) could increase their capacity to remove nitrate. This so-called in-situ bioremediation has the potential to be less costly and energy intensive than removing nitrate after pumping the water to the surface. Obtaining good-quality water from the aquifer would free Ramotswa from the regional water supply scheme (relying on the Gaborone Dam for dilution water), and enable households in the area to easily access clean drinking water and flush their toilets regardless of what is happening in Gaborone. This, along with expanding the sewage collection network, will reduce the reliance on pit latrines and contamination of the aquifer. However, many factors must be taken into consideration to test the feasibility of bioremediation, e.g., site-specific hydraulic characteristics and effects on downstream geochemistry. Bioremediation will not totally replace water treatment before supplying the water to residents, but it will likely reduce costs.

Measure success. Monitoring groundwater and drinking water quality is critical for measuring the success of investments in infrastructure, remediation and water treatment. It also has to be understood that improvements in groundwater quality take time.

Table 1 gives a summary of the overall recommendations.

TABLE 1. Summary of recommendations.

Reduce the source of contamination	• Incentivize the installation of liners at the bottom of new and old pit latrines • Reduce the cost of emptying pit latrines and the cost of connecting households to the sewage network • Develop business models to make the recycling and reuse of waste from pit latrines cost-effective • Enhance technologies and practices of wastewater recycling and water saving
Remediate	• Test the feasibility of in-situ bioremediation and consider downstream risks • Bioremediation will not totally replace water treatment, but it will likely lower overall costs • If the source of contamination is curtailed, bioremediation will be temporary
Monitor	• Monitor groundwater quality for measuring the success of investments in infrastructure and water treatment • Monitor drinking water quality at the tap - schools and homes • Map and assess spatial data on sanitation infrastructure and status

The findings and recommendations from this work are likely to have broader significance across Southern Africa and in certain transboundary settings similar to Ramotswa.

References

Altchenko, Y.; Lefore, N.; Villholth, K.G.; Ebrahim, G.; Genco, A.; Pierce, K.; Woolf, R.; Mosetlhi, B.B.T.; Moyo, T.; Kenabatho, P.; Nijsten, G-J. 2016. *Resilience in the Limpopo Basin: The potential role of the transboundary Ramotswa aquifer*. Baseline report. Colombo, Sri Lanka: International Water Management Institute, Pretoria, South Africa. Available at https://drive.google.com/file/d/0B-Ajpddeja2IX0JidWVlWE95aW8/view (accessed on April 01, 2019).

Altchenko, Y.; Genco, A.; Pierce, K.; Woolf, R.; Nijsten, G-J.; Ansems, N.; Magombeyi, M.; Ebrahim, G.; Lautze, J.; Villholth, K.G.; Lefore, N.; Modisha, R.C.O.; Baqa, S.; McGill, B.; Kenabatho, P. 2017. *Resilience in the Limpopo Basin: The potential role of the Transboundary Ramotswa aquifer*. Hydrogeology report. Pretoria, South Africa: International Water Management Institute (IWMI). Available at http://conjunctivecooperation.iwmi.org/wp-content/uploads/sites/38/2019/02/Hydrogeology-Report-2017.pdf (accessed on April 01, 2019).

McGill, B.M.; Altchenko, Y.; Hamilton, S.K.; Kenabatho, P.K.; Sylvester, S.R.; Villholth, K.G. 2019. Complex interactions between climate change, sanitation, and groundwater quality: A case study from Ramotswa, Botswana. *Hydrogeology Journal*. https://doi.org/10.1007/s10040-018-1901-4

Staudt, M. 2003. *Environmental hydrogeology of Ramotswa, South East District, Republic of Botswana*. Gaborone, Botswana: Department of Geological Survey. Available at https://services.geodan.nl/public/document/AGRC0001XXXX/api/data/AGRC0001XXXX/mim/Staudt_2003.pdf_6m5981m9s (accessed on April 01, 2019).

Project

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