Windhoek, Namibia: From conceptualising to operating and expanding a MAR scheme in a fractured quartzite aquifer for the city's water security



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Murray, R., Louw, D., van der Merwe, B. and Peters, I. (2018). Windhoek, Namibia: from conceptualising to operating and expanding a MAR scheme in a fractured quartzite aquifer for the city's water security. Sustain. Water Resour. Manag. 4:217–223 <u>https://doi.org/10.1007/s40899-018-0213-0</u> This is the final accepted manuscript of this journal paper in author-provided format and is freely available at IAH-MAR web site <u>https://recharge.iah.org</u> with permission of Springer.

Abstract: The City of Windhoek lies in the centre of Namibia some 700 km from the nearest perennial river. The concept of recharging the highly complex Windhoek aquifer was first considered in 1997 as an alternative to piping water from the distant Okavango River. This fractured quartzitic aquifer was studied in detail to establish its flow characteristics and boundaries. Four borehole injection tests were conducted and they provided the confidence to design and construct the first stage of the scheme which initially included 6 injection boreholes with a combined recharge capacity of 10,000 m3/day. Borehole injection started in 2006 and continued until 2012 when the targeted recharge area could not receive any more water. The scheme's success led to two expansion phases with a third planned for 2017. The expansion phases consisted of drilling additional injection boreholes and "deep" abstraction boreholes. Most of the existing abstraction boreholes are less than 250 m deep, but in order to maximize the aquifer's available storage, it became necessary to drill "deep" boreholes with depths ~300 - 500 m. The first expansion phase resulted in drilling an additional 10 recharge boreholes with a combined injection capacity of 16 000 m3/day and 10 "deep" abstraction boreholes with a combined recovery capacity of 18,000 m³/day. The second drilling phase will be completed in June 2017. Eleven of the planned 12 "deep" abstraction boreholes have been drilled and their abstraction capacities range up to 3,600 m³/day. The aim is to be able to utilize as much of the aquifer's available storage space as possible. The source water is surface water from the city's supply dams and a portion of reclaimed water; both of which are treated to drinking quality standards prior to recharge.

Keywords: fractured aquifer; hard rock aquifer; borehole injection; artificial recharge; water banking, aquifer storage and recovery (ASR)

1. Introduction

The City of Windhoek lies in the centre of Namibia, the most arid country south of the Sahara Desert. The average annual rainfall in Windhoek is 360 mm, while the average annual evaporation is 2,170 mm (Mendelsohn, et al. 2009). There are no perennial rivers within the country's borders. The nearest perennial river to Windhoek is the Okavango which is 700 km north of the city and constitutes the northern border of the country. The city relies on three dams, the Windhoek Aquifer

and direct reclamation to provide for its population of 326,000. By 2050 the population is expected to reach 790,000 and the water demand increase from the current supply of 27 Mm³/a to ~50 Mm³/a.

In the 1990s numerous water supply options were proposed to augment the city's future requirements and the most cost effective one was considered to be artificial recharge or Managed Aquifer Recharge (MAR). Murray and Tredoux (2002) and Murray (2002) proposed using the Windhoek Aquifer as a water bank whereby treated surface water would be transferred to the aquifer for safe storage and use when needed. This option was keenly taken up by the municipality and the first major MAR scheme in the world in a complex, fractured, hard-rock aquifer was constructed.

With the increasing demand and the threat to water supply security posed by droughts and climate change, MAR turned out to be the most favourable augmentation option, and the scheme was expanded. By 2011, ten new injection and ten new abstraction boreholes had been drilled with combined capacities of 675 m³/h (injection) and 745 m³/h (abstraction), and in 2016 twelve additional boreholes (up to 500 m depths) were drilled primarily for abstraction purposes. Most of the existing abstraction boreholes are less than 250 m deep, but in order to maximize the aquifer's available storage, it became necessary to drill "deep" abstraction boreholes with depths ~300 – 500 m. Dual injection and abstraction boreholes are being considered as an alternative to separate boreholes for these purposes, but to date it has been cheaper to drill separate boreholes.

The aim is to utilize as much of the aquifer's storage as practically possible, as this will significantly enhance the city's water supply security. The most probable long term effects of climate change on water supply are increased maximum temperatures with accompanying higher evaporation rates from surface reservoirs and more frequent droughts with an estimated decline of 20% of the average rainfall in the Central Area of Namibia (Midgley, et al. 2005 and Turpie, et al. 2010). With these considerations in mind, the municipality opted to increase the aquifer's storage and recovery capacity to its maximum potential.

2. Hydrogeology of the complex, fractured, hard-rock Windhoek Aquifer

The hydrogeology of the Windhoek Aquifer is dominated by faulted and fractured quartzite and schist rocks (Figure 1). The quartzites are brittle and highly fractured, and as a result of folding and faulting, have developed secondary porosity and permeability. The schists on the other hand are ductile and have poorly developed secondary permeability. Both the schists and the quartzites are considered to have no primary porosity. The dominant groundwater flow direction is northwards from the quartzite mountains south of the city towards the city which is underlain by schists. The flow follows preferential pathways along the numerous faults and fracture zones that transect the area. The quartzites can be divided into pure quartzites that form the Auas Mountains south of Windhoek (primarily the Auas Formation), and impure or micaceous quartzites that lie between the city and the Auas Mountains (primarily the Kleine Kuppe Formation). Interbedded and north of the micaceous quartzites are the impermeable schists.

The transmissivity values obtained from the highest-yielding boreholes range between 100 – 1000 m²/d for the early-time fracture flow component of the constant discharge pumping tests, and the late-time transmissivities which reflect the permeability of the micro-fracture network range between 50 – 350 m²/d (Murray, 2002). The storage coefficients reflect the predominantly confined nature of the aquifer: The pure quartzites (0.009 – 0.010), the micaceous quartzites (0.005 – 0.008) and the schists (0.001) (Murray, 2002).

An example of the complexity of this aquifer can be seen in the area containing boreholes 9/8 – 9/9. During the feasibility study (prior to the scheme's construction), water was injected into borehole 9/8A and a tracer test using a fluorescent dye was carried out between boreholes 9/8A and 9/9 located 787 m apart. A surprisingly rapid flow velocity 216 of m/hour was obtained (Van Wyk , 2000). This showed that the injectant flowed very rapidly along the highly permeable fault zones on which these boreholes are located.



Figure 1. Simplified geology of the Windhoek Aquifer (Murray 2002)

Natural recharge is estimated to be on average 1.73 Mm³/a. This value was obtained after calibrating a finite difference numerical flow model with 51 years of groundwater level and abstraction data. Groundwater salinity reflects the lithology-dependent rate of recharge, with the highest recharge occurring in the pure quartzites, which have groundwater electrical conductivity (EC) values of 200 – 600 μ S/cm followed by the micaceous quartzites (with EC values ranging between 500 – 800 μ S/cm) and in the schists (with EC values ranging between 1000 – 2000 μ S/cm) (Murray 2002). The groundwater flow path is from the higher lying quartzite-dominated areas where the chloride values are low, towards the city where the chloride values are higher, and the evolution of groundwater down its flow path from the quartzites to the schists follows the characteristic trend from calcium-bicarbonate waters to sodium-chloride waters (Murray, 2002). The micaceous quartzites (20 – 40 pmc). The concentration of dissolved organic carbon (DOC) in the aquifer is very low with values generally being <1 mg/L, (Murray, 2002).

The arsenic concentrations in the aquifer are generally very low and close to the detection limit of 0.005 mg/L. However, the highest concentration of 0.013 mg/L occurs in groundwater associated with mineralized faults in the schists in the northernmost part of the aquifer. The groundwater temperatures in this zone are significantly higher than the rest of the aquifer, reaching temperatures up to 80°C, and thereby demonstrating a deep groundwater flow path. Recorded arsenic concentrations are near or below the World Health Organization guideline value as well as the maximum allowable level of 10 μ g/L. The Water Bank area is located away from these low-permeability, schistose areas with the slightly elevated arsenic concentrations. Hence it is

considered highly unlikely that the arsenic guideline levels will be exceeded because of the MAR operations, and monitoring has confirmed this but is ongoing. Likewise, the concern around the potential for clogging due to water temperature differentials between the injected and the aquifer water is unlikely to be a significant problem because the injection boreholes are all located in the pure and micaceous quartzites where temperatures range between $25 - 30^{\circ}$ C which are similar to the temperatures of the injectant.

3. The feasibility of MAR in this fractured, anisotropic aquifer

3.1. Historic water level data and the needto augment recharge

Since the onset of large-scale abstraction from the Windhoek Aquifer in the 1950s, and by the time MAR was investigated in the late 1990s, water levels had dropped by about 40 m in the micaceous quartzites which constitute the main wellfield areas, and were steadily declining in the pure quartzite areas (Figure 2). Even after 5 year rest periods (e.g. 1970 – 1975), the water levels never recovered to their original levels. The aquifer had effectively been over-pumped or "mined" and it would take up to a decade for water levels to recover to their pre-abstraction levels.

The volume of water that had been abstracted from storage since 1950 was estimated in 2002 using a finite difference numerical model to be 28 Mm³. The water level data showed the need to artificially recharge the aquifer in: i) the wellfield/micaceous quartzite areas to replenish the localized water level depressions, and ii) in the pure quartzites to replenish the main "water bank" where most of the aquifer's storage is held, and which had actually been dewatered the most as a result of the large-scale abstraction since the 1950s.



Figure 2. Borehole water level decline due to large-scale abstraction and subsequent response to artificial recharge (the different water level responses are due to differing aquifer characteristics between the pure- and micaceous quartzites)

3.2. Borehole injection tests

In order to establish the feasibility of recharging this complex aquifer system four borehole injection tests were carried out in both the pure- and micaceous quartzites between 1997 and 1999. The injectant was treated, potable water mainly from the Von Bach Water Treatment Plant which derives its water from three dams (the Von Bach, Omatako and Swakoppoort Dams). Despite the very different hydraulic characteristics between the two quartzite formations influenced by preferential flow paths and barriers to flow, in total 450 342 m³ was recharged successfully. Figure 3 presents an example of a borehole injection test - borehole 12/3 which was recharged at 118 m³/h (32.7 L/s) for 35 days and water levels were monitored in the surrounding boreholes.



Figure 3. Water level response in metres above mean sea level in monitoring boreholes to injection at 118 m³/h into Bh 12/3 located in the pure quartzites

Following the success of the injection tests it was evident that this aquifer could be artificially recharged, and that recharge should focus both in the existing wellfield areas (the micaceous quartzites) and the main natural recharge and storage area (the pure quartzites).

4. Operation

4.1.Injected water volume and water level response

By 2004, four boreholes were equipped for recharge and by 2011, an additional two boreholes were equipped bringing the combined recharge capacity to 10 000 m³/day. Five of the six injection boreholes were placed in the micaceous quartzite/wellfield areas, and one in the main storage area of the pure quartzites. In all cases, the injection water was fed under gravity from municipal water supplies.

Between 2006 and 2012, the first period of "production" artificial recharge (i.e. excluding the tests during the feasibility study), a total of 2.83 Mm³ of water was injected into the aquifer via the six recharge boreholes, and this resulted in some of the wellfield areas being replenished to their pre-abstraction water levels. Accounting for injection trials of 0.5 Mm³, in total the volume of artificially recharged water up to 2012 was 3.3 Mm³. This is about twice the estimated annual natural recharge rate of 1.73 Mm³. Figure 2 shows the water level response to artificial recharge.

Since the onset of artificial recharge the water levels in Bh 9/6 in the micaceous quartzites rose by ~50 m and the aquifer in this area was replenished to the pre-abstraction water levels. The average annual rainfall from 2002-2011 was 536 mm which exceeded the average rainfall of 360 mm recorded since 1890 for Windhoek. Coincidentally, this higher rainfall experienced in Namibia occurred during the same time as the first operational period of artificial recharge. While the rise in water levels observed in the aquifer can be attributed to artificial recharge, the exceptionally high rainfall and natural recharge over this period certainly contributed to this.

Following the 2006-2012 period of artificial recharge and high rainfall there was little inflow into the city's supply dams and groundwater abstraction resumed at rates higher than most previous years, particularly from 2014 until the end of 2015 (Figure 4). While the water levels in the aquifer dropped accordingly, this level of abstraction may not have been possible without the preceding period of artificial recharge.



Figure 4. Total aquifer abstraction, injection, rainfall and average water level from all boreholes

The first phase of artificial recharge (2006-2012) was considered successful in that it replenished the storage in the wellfield areas (the micaceous quartzites), and to a much lesser degree, where only one injection borehole exists, in the prime storage areas, the pure quartzites. The success of this first artificial recharge phase provided the impetus to expand the scheme – particularly in the prime aquifer areas of the pure quartzites.

4.2. Water quality

The injectant is treated potable water with very strict water quality guidelines that were developed to prevent the deterioration of groundwater quality and to minimize clogging of the boreholes and aquifer. The injectant is blended at a ratio of 3 to 1 from dam water (3 parts) with reclaimed/re-used water that has been treated to drinking quality standards (1 part). On average, its salinity has been 680 μ S/cm or 456 mg/L TDS (based on a 95% percentile) and the Dissolved Organic Carbon (DOC) 4.9 mg/L (based on a 95% percentile) and 2.9 mg/L (median). The water is

injected directly into the hard-rock fractured aquifer via boreholes at depths below the piezometric level where it blends with the natural groundwater.

To date the recovered water quality has had an average salinity of 910 μ S/cm or 610 mg/L TDS (based on a 95% percentile) and an average DOC of 1.1 mg/L (based on a 95% percentile) and 0.4 (median). At the onset, the following guiding principles for the injectant were set:

- No significant negative environmental impact.
- Sustainable use of water from the Windhoek Aquifer for drinking water purposes preferably without treatment or at most with limited treatment such as stabilisation and disinfection:
 - The recharge water should meet modern drinking water standards.
 - No additional health risk for the residents of Windhoek as compared to present sources.
- No significant technical problems should arise due to injection water quality such as clogging, corrosion and demand for extensive treatment before distribution.
- Accept a deterioration of certain quality parameters of the water within the aquifer provided that the water quality after abstraction complies with acceptable water quality guidelines.

Some of the provisional water quality parameters are listed in Table 1 (Tredoux , 2007). These guidelines are based on the premise that at least 75% of the injectant will originate from surface water sources (i.e. no more than 25% will be reclaimed water).

Parameter	Provisional Injection Water Quality Limits
DOC (mg/L)	4
AOC (growth rate/h)	0.15
EC (mS/m)	60*
Chloride (mg/L)	100
Sulphate (mg/L)	50
Nitrate & Nitrite (as mg N/L)	5

Table 1. Provisional Water Quality Guidelines for Recharge Water

*The maximum EC of injectant may be adjusted upward to a maximum of 70 mS/m in accordance with the prevailing groundwater EC in the recharge area.

4.3. Institutional Arrangements

Significant challenges were overcome prior to the operation of the scheme. These included assessing whether the aquifer could receive and store water, constructing the conveyance infrastructure and ensuring the quality of the injectant met the agreed requirements. However, probably the biggest challenge was on the institutional side. The source water, obtained primarily from a 3-dam supply system, is bought from the bulk supply authority NamWater and sold to the municipality for storage in the municipal-run aquifer. Since there was no precedent for such an arrangement, this posed new challenges and a unique model was developed.

The City of Windhoek pays NamWater the operational costs for the recharge water. That is, NamWater recovers its costs for the recharge water, but does not make a profit on water it sells to the municipality for banking in the Windhoek Aquifer. A profit is only realized when it is deemed that the artificially recharged water is being supplied by the City to consumers. At this point, the City pays NamWater an additional amount for each m³ it supplies from the Windhoek Aquifer.

This point is assessed on an annual basis and becomes applicable only if more water is withdrawn from the aquifer in a given year than the aquifer's average natural recharge rate, the agreed "safe yield" (1.73 Mm³/annum). For example, if 2 Mm³ of NamWater's water is injected into the aquifer in Year 1, the City only pays NamWater the cost of supplying the 2 Mm³; but in Year 2, if the City withdraws 2.73 Mm³ from the aquifer, it pays NamWater an additional fee for 1 Mm³ (the volume over the 1.73 Mm³ mark).

This model benefits both organisations and consumers as it improves the security of supply during extended periods of drought and affords NamWater income during droughts (when normally they would sell less water).

It can be argued that low-value water which would have evaporated from the source dams is now stored in the aquifer or water bank for use during times of water scarcity; thereby transforming it from low-value water to high-value water at the time of supply to consumers.

5. Conclusions

Between the late 1990s and the early 2000s the viability of artificially recharging the complex Windhoek Aquifer was demonstrated. Later in the 2000s, six injection boreholes were equipped and after seven years of recharge parts of the aquifer were filled to their highest levels since the 1950s when large scale abstraction began. The success of the scheme led to the drilling of an additional ten injection and abstraction boreholes, and the scheme is currently being expanded again with the drilling of 12 "deep" (400 - 500 m) injection and abstraction boreholes. The aim is to maximize the use of the aquifer's available storage, and with this in mind, another expansion phase is planned for the near future. When fully developed, it is expected that the city's water bank will be able to provide security for three-years as the sole water resource during drought conditions.

Since 2013 the water demand in the central area of Namibia was well above the 95% safe yield of the available resources, and the water demand for the City of Windhoek alone is expected to nearly double by 2050. To date virtually all of the local and regional water sources considered viable within the central area of Namibia have been fully developed except for the Windhoek Managed Aquifer Recharge Scheme (WMARS). Since 2002 several studies identified the WMARS as the best option to improve water supply security to the central areas of Namibia.

In 2014 an Environmental Impact Assessment was conducted and it acknowledged the positive socio-economic impacts of the project in relation to its significance in creating a sustainable water source for the central area of Namibia. This project is therefore considered an essential component for securing the future of the population in the City of Windhoek and will play a key role in sustaining development and socio-economic health.

Author Contributions: Dr R Murray, the project's hydrogeologist, assessed the feasibility of the scheme, delineated the aquifer, assessed the storage capacity, identified the prime sites for recharge and abstraction and quantified the recharge and abstraction rates. Mr D. Louw is the municipality's hydrogeologist and is responsible for data management. Mr B. van der Merwe initiated the pilot recharge tests (1996), made an assessment of the technical and financial viability of the project including optimization of abstraction and injection infrastructure, and is the project leader in the current expansion phase of the project. Mr H. I. Peters was responsible for the implementation and continuation of the project until the end of October 2015 when he retired from the Windhoek municipality. He is now involved as a consultant to the City of Windhoek on this project.

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