Managed Aquifer Recharge: Southern Africa

Eberhard Braune and Sumaya Israel

THE GROUNDWATER PROJECT

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Managed Aquifer Recharge: Southern Africa

The Groundwater Project
Guelph, Ontario, Canada

Published by the Groundwater Project, Guelph, Ontario, Canada, 2021.

Braune, Eberhard.
Managed Aquifer Recharge: Southern Africa / Eberhard Braune and Sumaya Israel.
- Guelph, Ontario, Canada, 2021.
96 p.

ISBN: 978-1-77470-006-8
DOI: https://doi.org/10.21083/978-1-77470-006-8

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Citation: Braune, Eberhard and Sumaya Israel, 2021, Managed Aquifer Recharge: Southern Africa↗. The Groundwater Project, Guelph, Ontario, Canada. https://doi.org/10.21083/978-1-77470-006-8.

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Cover Image: Infiltration basins which can form an integral part of artificial recharge and recycling systems. Cape Town's Table Mountain is in the background (from Tredoux and Cain, 2010). Photo taken by Ricky Murray.

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Dedication

'Groundwater for Africa' - we dedicate this book to the women of Africa in their continued toil for a safe and secure water supply for their families and communities.

The Groundwater Project Foreword

The United Nations Water Members and Partners establish their annual theme a few years in advance. The theme for World Water Day of March 22, 2022, is "Groundwater: making the invisible visible." This is most appropriate for the debut of the first Groundwater Project (GW-Project) books in 2020, which have the goal of making groundwater visible.

The GW-Project, a non-profit organization registered in Canada in 2019, is committed to contribute to advancement in education and brings a new approach to the creation and dissemination of knowledge for understanding and problem solving. The GW-Project operates the website https://gw-project.org↗ as a global platform for the democratization of groundwater knowledge and is founded on the principle that:

"Knowledge should be free and the best knowledge should be free knowledge." Anonymous

The mission of the GW-Project is to provide accessible, engaging, high-quality, educational materials, free-of-charge online in many languages, to all who want to learn about groundwater and understand how groundwater relates to and sustains ecological systems and humanity. This is a new type of global educational endeavor in that it is based on volunteerism of professionals from different disciplines and includes academics, consultants and retirees. The GW-Project involves many hundreds of volunteers associated with more than 200 hundred organizations from over 14 countries and six continents, with growing participation.

The GW-Project is an on-going endeavor and will continue with hundreds of books being published online over the coming years, first in English and then in other languages, for downloading wherever the Internet is available. The GW-Project publications also include supporting materials such as videos, lectures, laboratory demonstrations, and learning tools in addition to providing, or linking to, public domain software for various groundwater applications supporting the educational process.

The GW-Project is a living entity, so subsequent editions of the books will be published from time to time. Users are invited to propose revisions.

We thank you for being part of the GW-Project Community. We hope to hear from you about your experience with using the books and related material. We welcome ideas and volunteers!

The GW-Project Steering Committee

July 2021

Foreword

There are water crises in many parts of the world due to the combined effects of groundwater depletion and deterioration of groundwater quality. One third of the world's large aquifers are severely dewatered without prospects for recovery over decades or even centuries if all pumping were to stop now. The pumping of fossil groundwater is supporting large populations in dry climates. More severe droughts than those of the past few decades are coming, exacerbated by climate change. Most depletion of aquifers is done in support of irrigated agriculture on an industrial scale, with groundwater that is both pumped from wells and diverted from stream baseflow supporting 70 percent of global agriculture.

The depletion of aquifers has become so excessive that the water from their depletion runs off into the oceans to contribute 25 percent of recent sea level rise. Excessive runoff is enhanced by the cutting of forests and the deterioration of soil health. The only option for reversing this trajectory towards disaster is to reduce the amount of freshwater that escapes to the oceans. For this, the most readily implementable approach is to use engineering to increase the amount of rainfall that recharges groundwater reservoirs so that less escapes to the oceans. This is now widely known as 'managed aquifer recharge' (MAR) or 'artificial recharge" (AR). MAR is not new, it has been practiced in a few countries for more than 70 years, but has had a strong upswing in diversity and sophistication of techniques in the past two decades. However, relative to the benefits that can accrue from MAR and the magnitude of groundwater depletion, MAR is woefully underutilized on the global scale. Recharge can be increased by changing the vegetation and rejuvenating the soil, but these generally require a long period of time. Now, there is sufficient technical understanding of MAR to quickly implement it in areas with the political will.

This book is authored by two South African groundwater scientists. South Africa has the most experience with MAR because there are dozens of substantial MAR applications in diverse hydrologic and geologic conditions ranging from unconsolidated aquifers in semi-arid climates to fractured rocks in desert climates. South Africa is a leader in MAR as a result of more than 50 years of research and practice supported by farsighted government funding. This book is the one of many Groundwater Project books in a planned series of books about MAR in specific countries or regions.

The two authors of this book, Drs. Eberhard Braune and Sumaya Israel, are currently faculty members at the University of the Western Cape, South Africa and have been long standing participants in research concerning MAR and related topics including natural recharge, water resources management and groundwater geochemistry. They bring a holistic perspective to MAR as illustrated by the content of this book.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada,

July 2021

Preface

Key to the African water crisis, often referred to in international forums, is the large spatial and temporal variability of resource availability, going with the more arid climate prevalent in about 60 percent of the African continent and the widespread lack of skilled and experienced human resources to manage the irregular availability of water. Provision of sufficient storage capacity under growing water demand and increasing climate variability is one the main concerns for water managers in the region in the coming decades. The natural storage in aquifers makes conjunctive use of water resources and artificial recharge of aquifers particularly attractive in the region.

Excellent progress has been made with all knowledge-related aspects and promotion of artificial recharge in South Africa. This has been driven by the Water Research Commission with its research and development programs for nearly fifty years now. Among others, it led to the construction of a major borehole injection scheme for the City of Windhoek, Namibia Windhoek's MAR scheme, of particular interest because it involves large-scale borehole injection and recovery in a highly complex, fractured quartzite aquifer. Implementation in South Africa was helped by the detailed Artificial Recharge Strategy developed by the national Department of Water Affairs and Forestry. With 17 reported cases, South Africa has by far the highest MAR implementation in Africa.

With this as background, six cases are discussed, covering different physical and management environments and recharge methods in Southern Africa. They are structured to bring out an understanding of the different driving forces towards the use of MAR techniques, factors that affect the selection of a particular MAR technique and how efficient and effective various MAR techniques have proven to be.

The main stumbling block to a much greater, systematic roll-out of this technology has been a lack of appropriate governance and institutional development for the sustainable utilization and management of groundwater resources in South Africa. This has been failing in Africa in general, despite groundwater's strategic role as an essential resource to help achieve community development and poverty alleviation.

Acknowledgements

The dedication and excellent scientific/technical work of many individuals and institutions, over many decades already, is herewith acknowledged. Particular mention must be made of the pioneering role in the whole region of Dr. Gideon Tredoux of the Council for Scientific and Industrial Research and of Dr. Ricky Murray of Groundwater Africa. The ongoing initiation and funding role of the Water Research Commission (WRC) has been a critical success factor. The now Department of Water Affairs and Sanitation (DWS) has acted as custodian for all AR work over many years and, importantly, has contributed a strategy and a website in this regard. Funding by the Ground Water Division of the Geological Society of Southern Africa has enabled the summary task and is herewith acknowledged. Thanks to the reviewers, the text received fresh structure to bring out the educational purpose with this summary.

We deeply appreciate the thorough and useful reviews of and contributions to this book by the following individuals:

- Yan Zheng, Southern University of Science and Technology, Shenzhen, China
- Bill Alley, National Groundwater Association, San Diego, California, USA
- Dr. Ricky Murray, Groundwater Africa, Somerset West, Western Cape, South Africa

We are grateful for Amanda Sills' (GW-P) oversight of this book and Juliana Apolonio's (GW-P) copyediting. We thank Eileen Poeter (Colorado School of Mines, Golden, Colorado, USA) for copyediting, layout editing and production of this book.

1 Introduction

This book describes the development of Managed Aquifer Recharge (MAR) practices in South Africa. Examples from Namibia are included because the territory (South West Africa) was administered by South Africa until its independence in 1990. Various case studies are used to contrast different environments, the MAR technologies chosen and the results achieved. A concluding assessment is provided regarding its uptake and integration to date into broader country water resource management policies and practices.

Poverty is the dominant development issue in Sub-Saharan Africa and lack of access to clean water is a key cause of poverty. And yet to date, the region has used only a small portion (5 percent) of its available water resources. The African water crisis, as it is often referred to in international forums, is much more complex than water availability. The complicating factors include: the large spatial and temporal variation of resource availability; the arid climate prevalent in about 60 percent of the African continent; and the widespread lack of skilled and experienced human resources to manage the irregular availability of water. Such needed skills include building and balancing water storage, transferring water between water-rich and water-poor areas, and implementing programs to manage water demand and conservation (Braune and Xu, 2008).

Groundwater is the critical underlying resource for human survival and economic development in extensive drought-prone areas across Sub-Saharan Africa. The accessibility of groundwater in traditional shallow hand-dug wells, springs and seepage areas has always controlled the extent of human settlement beyond the major riparian tracts. The widespread introduction of drill rigs and water-well pumps in the 1970s enabled further extension of human activity. Today the dependence of rural water supply on groundwater is indisputable, with successful water wells allowing for functioning villages, clinics, schools, markets and livestock posts over large areas.

In recent years demand for urban water-supply provision has been increasing at a range of scales – from improving water services in innumerable small (but rapidly expanding) towns to supplementary public and private water-supply sources in larger cities. Also, groundwater use for irrigation is forecast to increase substantially – both for high-value crop production at the commercial scale, and for subsistence horticulture and drought-proofing staple-crop cultivation (Foster et al., 2012).

In contrast to its strategic role as an essential resource to help achieve community development and poverty alleviation in Southern Africa and more widely, groundwater has remained a poorly understood and poorly managed resource (Braune et al., 2008). Groundwater aquifers that supply many African mega cities are often heavily polluted (e.g., Dakar, Abidjan, Lagos, Accra, Lomé, Lusaka, Addis Ababa). Groundwater subjected to unplanned and excessive abstraction (pumping of water from the subsurface) in coastal cities is inducing salt water intrusion resulting in permanent damage to coastal aquifers

(Xu and Usher, 2006). Data on groundwater systems are sparse and the current state of knowledge is low. Efforts to improve the situation have been made over the last decade through the publication of syntheses and reviews at the national, regional, and continental levels. MacDonald and others (2012) produced the first quantitative maps of groundwater resources for Africa as a whole. These maps indicate that groundwater storage is typically one to two magnitudes less in Sub-Saharan Africa than in North Africa.

Provision of sufficient storage capacity under growing water demand and increasing climate variability is one the main concerns for water managers in the region in the coming decades. While accurate estimates for required storage capacity do not exist, it is expected that, in five to ten years some multiple of the present storage capacity will be needed to provide sufficient water during dry periods. Importantly for arid areas, water stored in an aquifer is not subject to the same evaporative water losses as water stored in surface reservoirs behind dams, Evaporative losses can be significant depending on dam location and reservoir surface area. The natural storage (water buffer) available in aquifers makes conjunctive use of surface and groundwater particularly attractive and provides a pressing need for investment in drought preparedness at a variety of scales. Investment is required for enhanced management of groundwater storage, including managed aquifer recharge, to buffer drought impacts (Van Steenbergen and Tuinhof, 2009; Tuinhof et al., 2011).

Managed aquifer recharge is not a new concept in Southern Africa. Nearly 40 years ago, the prospect of storing treated sewage water in the sand beds of the Cape Flats in South Africa led the Water Research Commission to fund research in this regard (DWAF, 2010). The Atlantis scheme near Cape Town has been operational for more than 40 years. MAR has been shown to have a range of benefits, particularly if practiced as part of a wider approach to water resource management, and there is growing recognition that MAR often provides the cheapest form of new safe water supply for towns and small communities. Nonetheless, uptake of MAR into practice has remained limited in Sub-Saharan Africa. At a technical level this can be ascribed to a lack of understanding of hydrogeology and/or knowledge of MAR, but at a broad level it can be related to the slow or absent reform of the institutional framework for groundwater governance (Gale, 2005; Foster et al., 2012). This is discussed further in Section 10, Conclusions.

Managed aquifer recharge has gradually replaced the term artificial recharge to emphasize the recharge as a managed process. The term artificial recharge is still used in regulations and guidelines in Southern Africa, and we use the two terms interchangeably in this book.

2 History of Managed Aquifer Recharge in Southern Africa

2.1 Main Learning Outcomes

By the end of this book, you should have a better understanding of:

- water availability in Southern Africa based on rainfall patterns;
- groundwater resources of Southern Africa (their importance, occurrence and association with geological units);
- factors that influence natural recharge in Southern Africa;
- the main drivers of groundwater exploration and Managed Aquifer Recharge in the region; and,
- the different MAR techniques employed in Southern Africa, how they work and their applicability.

2.2 Water Availability in Southern Africa

Water availability in Southern Africa can be illustrated by the rainfall regime, which is generally low and highly variable. Rain falling in intense downpours often runs off into river channels as it falls faster than can be absorbed into the soil where it can recharge groundwater. Many areas, particularly in the south and west, receive very little rain (< 250 mm/year) and are subject to high temperatures and high rates of evaporation. The map below (Figure 1) shows the distribution of average annual rainfall across Southern Africa.

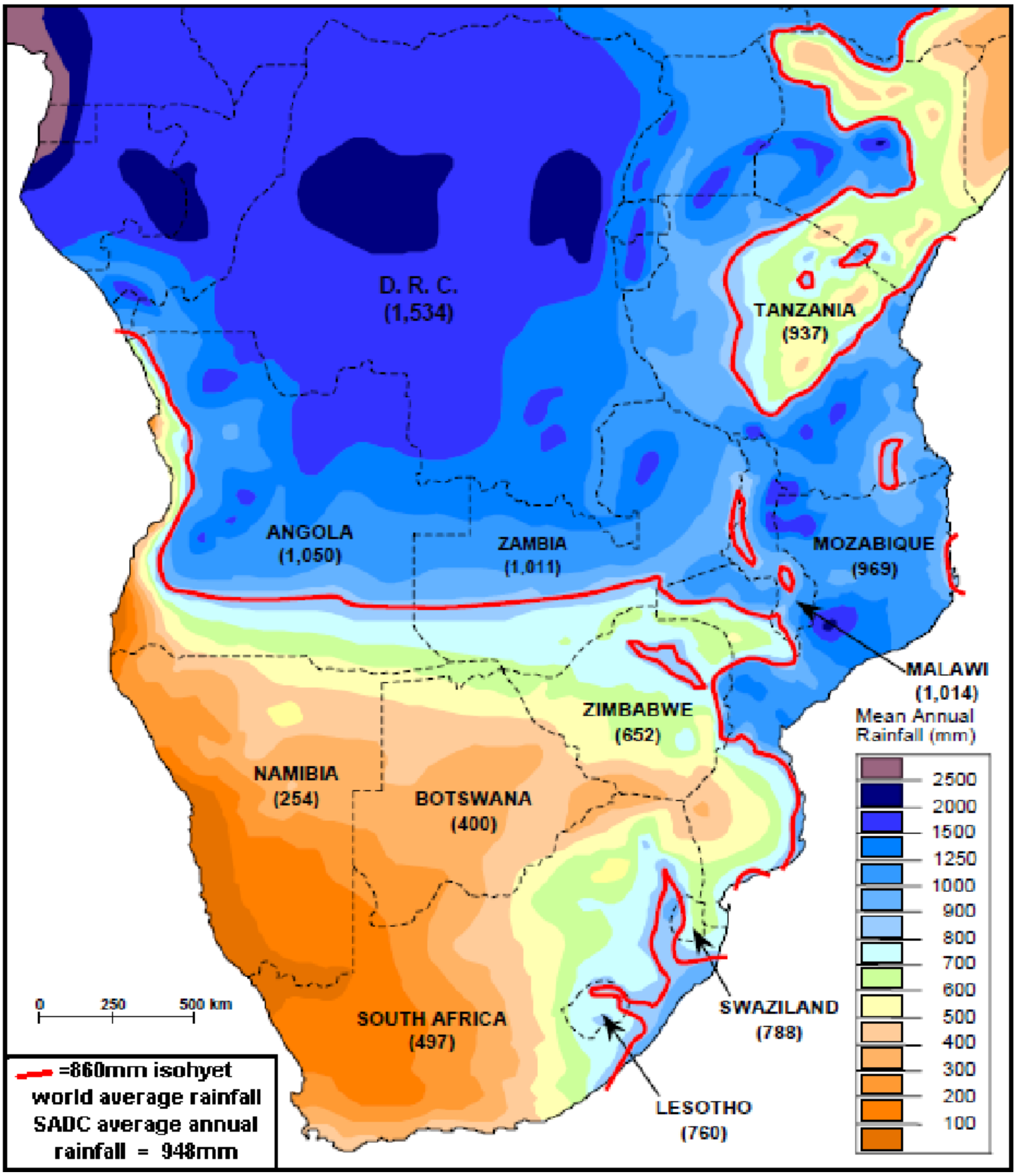


Figure 1 - Mean annual rainfall distribution across the Southern Africa Development Committee (SADC) region (SADC, 2007).

2.3 Groundwater Resources in Southern Africa

Due to the limited availability of surface water resources, groundwater is critical to integrated water resources management, particularly in rural areas not close to large rivers or urban water supply networks. Groundwater occurrence in Southern Africa is characterized by the large variety of geological structures. This is illustrated in Figure 2 from the Hydrogeology Map for Southern Africa (SADC, 2009). Discussion of the main hydrogeological characteristics is largely taken from the Explanatory Brochure accompanying this map (SADC, 2009).

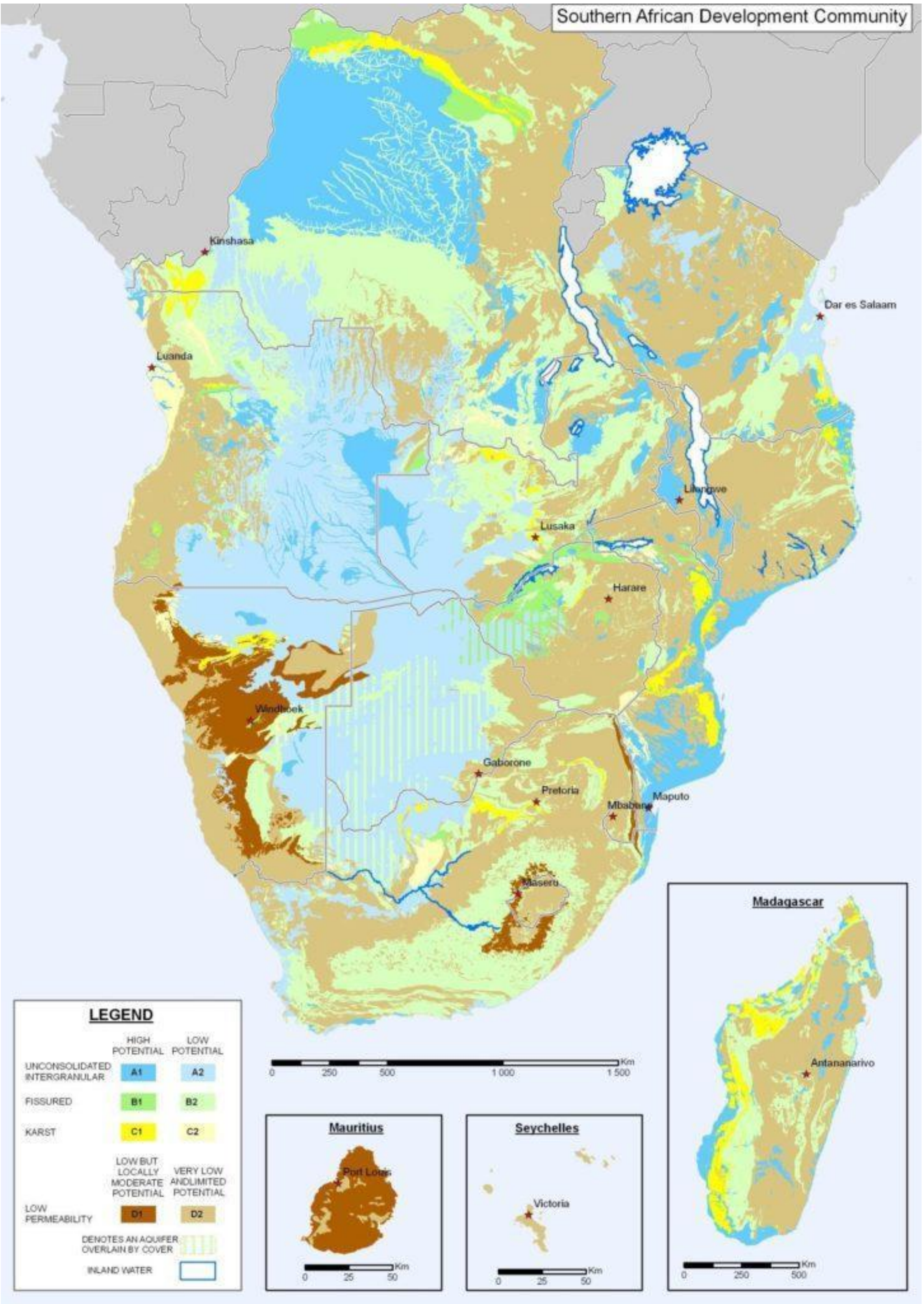


Figure 2 - Hydrogeology Map for Southern Africa (SADC, 2009).

Approximately 55 percent of the region is covered by low permeability formations (brown colors, D1 and D2). These are largely basement rocks with aquifer systems developed in the weathered overburden and fractured bedrock. The aquifers developed in these areas are unconfined, locally developed and not spatially extensive. In general, only modest groundwater supplies can be abstracted sustainably from these aquifers and large-scale groundwater well field developments are not feasible.

Fissured aquifer systems (green colors, B1 and B2) are associated particularly with the Karoo formations (interlayered shales and sandstones) found extensively throughout Southern Africa. The formations are normally low-yielding, but where the rocks have been subjected to deformation and intrusion of dolerites, a secondary permeability resulting in good aquifers may be found.

The unconsolidated intergranular aquifer systems (blue colors, A1 and A2) occur as large inland basins, such as the Kalahari and Congo basins, in coastal aquifers and in alluvial aquifers in river channels, banks and flood plains. The Kalahari basin consists of complex deposits of unconsolidated to semi-consolidated sediments, including sands, calcrete, aeolianite, gravel, clay and silcrete. Saline groundwater tends to occur in these basins in the more arid areas in Botswana and Namibia.

Karst aquifers (yellow colors, C1 and C2) constitute some of the most productive aquifers in Namibia, Botswana, Zimbabwe and South Africa. They occur in highly soluble rock, most notably limestone and dolomite. Groundwater flow is concentrated along secondarily enlarged fractures and fissures and other connected openings, where water from slightly acidic rain can dissolve minerals.

The recharge potential of groundwater is related to climatic conditions such as average temperatures and evapotranspiration and geological factors such as porosity and infiltration rates. Recharge potential is relatively low across much of Southern Africa although it improves to the north due mostly to increased precipitation. Figure 3 shows reported recharge values, including those from more humid Southern African regions, in the widely quoted review by Beekman and Xu (2003). In arid regions, groundwater recharge may be 3 percent or less of rainfall; in regions where rainfall exceeds 600 mm/year, groundwater recharge can reach 20 percent. Determination of groundwater recharge in arid and semi-arid areas is neither straightforward nor easy, Xu and Beekman (2019). This is a consequence of the temporal variability of precipitation in arid and semi-arid climates, and spatial variability in soil characteristics, topography, vegetation and land use.

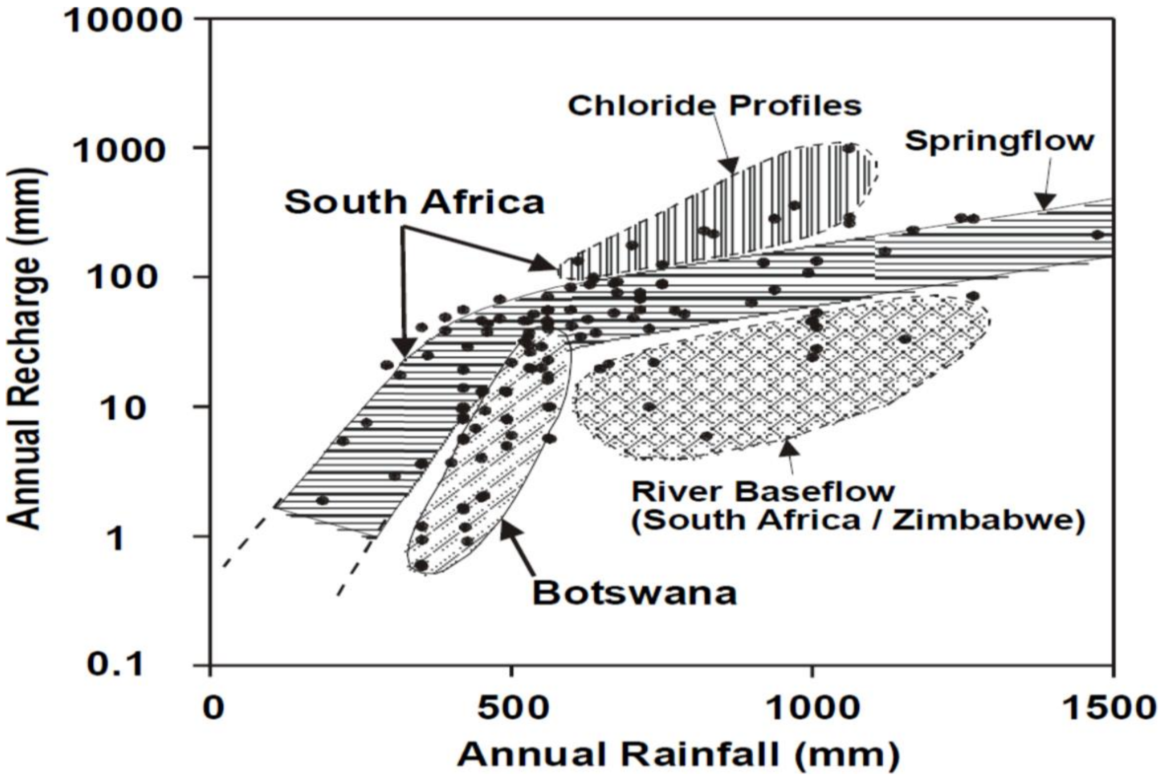


Figure 3 - Results of various groundwater recharge studies in Southern Africa, indicating the region and type of study (Beekman and Xu, 2003).

2.4 Increased Demand for Groundwater Resources

The political objective of economic growth and poverty reduction in the region requires that all potential water resources are appropriately protected and utilized. Groundwater is a significant resource in the region, but has been neglected in management. In drier countries with a strong dependence on groundwater, such as Botswana, Namibia and Mauritius, the level of development in the groundwater sector is quite high. The recurring droughts in the region have also reinforced the potential value of groundwater. The role of groundwater in the region includes (SADC, 2009):

- meeting the domestic water requirements of a significant percentage of the population;
- supplying smaller towns and settlements;
- playing a conjunctive use role in larger urban settlements;
- contributing to water security during drought conditions;
- achieving food security for rural households; and,
- maintaining environmental functions.

Groundwater's changing role can best be illustrated using South Africa as an example. Until the new National Water Act of 1998, groundwater was defined in law as "private water" and was viewed to have only local importance. The predominantly hard rock systems, of which basement aquifers make up a major part, contributed only about 12 percent to the water supply. With the democratization of the country in 1994, there was a strong policy shift towards providing basic services, including water and sanitation services, to the entire population as soon as possible. At the time, approximately 15 million people or about 40 percent of the population did not have the most basic water supply. Focused strategies and action plans reduced this service backlog to less than 5 percent of the population by 2013. Overall, groundwater had become the domestic supply for 60 percent of communities and up to 90 percent in some provinces (Braune et al., 2014).

A recently drafted National Groundwater Strategy (DWAF, 2017) foresees an incremental institutional path moving from:

1. technical development of the resource, to;
2. groundwater management, taking account of its real value and unique characteristics; and ultimately to,
3. groundwater governance as part of integrated water resource management.

All aspects of sustainable resource utilization, including conjunctive use of groundwater and other water sources as well as artificial recharge of groundwater sources, will have to be addressed, together with appropriate regulations, clear guidance, and ongoing raising of awareness through education and training initiatives.

2.5 Traditional Water Conservation Techniques

Traditional water conservation techniques have been practiced in dry areas under a wide range of ecological conditions over millennia. Besides domestic water use, early populations used water mainly for small-scale agriculture involving raising crops, or livestock, or a mixture of the two. Minimization of runoff losses (in combination with increased infiltration) and the collection and concentration of rainfall (including storage) are the most important approaches for making better use of scanty rainfall in dry regions. Typical approaches included small pits with worked soil and stone lines across fields for in-situ moisture conservation (Mali, Burkina Faso), runoff harvesting in excavated shallow natural depressions (Namibia, Angola) and wells dug in the sands of dry riverbeds (Kenya, Namibia) as documented by Postel (1992) and Braune (2007).

Runoff harvesting, for example via excavation dams and pump-storage dams (Figure 4), was systematically introduced by the government in central-northern Namibia (former Ovamboland) during the 1950s and 1960s. Effectiveness was increased by building a fully enclosed dam, several meters high, around the depression with the excavated material. Water is pumped into these pump-storage dams (capacity between 23,000 and 105,000 m^3) during the short flooding period of the Cuvelai River in Namibia. To prevent evaporation of this very expensive water, the surface of the dam was often covered with floating material (Stengel, 1963). A German cooperative research project, from 2006 to 2015, aimed to bolster the region's water resources. The project combined new and adapted technologies (rainwater harvesting; small-scale, decentralized groundwater desalination; subsurface water storage; as well as sanitation and water reuse) in a multi-resource mix for water supply and sanitation (CuveWaters, 2015).

Figure 4 - Satellite image of Onandjokwe pump-storage dam in Northern Namibia (Drießen and Jokisch, 2011).

The practice of water storage in sandy river beds in Namibia has a long history. It was advanced from the beginning of the 20th century by the then German colonial administration and again from the 1950s onwards by the South West Africa Administration. The key proponent was Otto Wipplinger, director of the Department of Water Affairs in the former South West Africa. His study of various types of sand storage dams, "The Storage of Water in Sand", focused on the artificial creation of sand basins by building low walls in river basins (Wipplinger, 1953). The innovation was to build a wall just high enough to break the flow of the water and allow the deposition of coarse sediments, while the very fine material (clay) passes over the wall with the flood. Once the basin fills up, the wall is raised and the process of building the sand dam carries on (Figure 5). A sand basin can take from 10 to 20 years to reach full capacity and can be synchronized with a rising demand for water. Such dams are now widely used in Namibia, especially by the farming community, but also for large-scale use. The key benefit is that water stored in the sand is largely protected from evaporation, which can be up to 2000 mm/year from an open water surface in the area. It is also a major conservation measure through which groundwater levels and groundwater quality have been restored to their original levels (Lau and Stern, 1990).

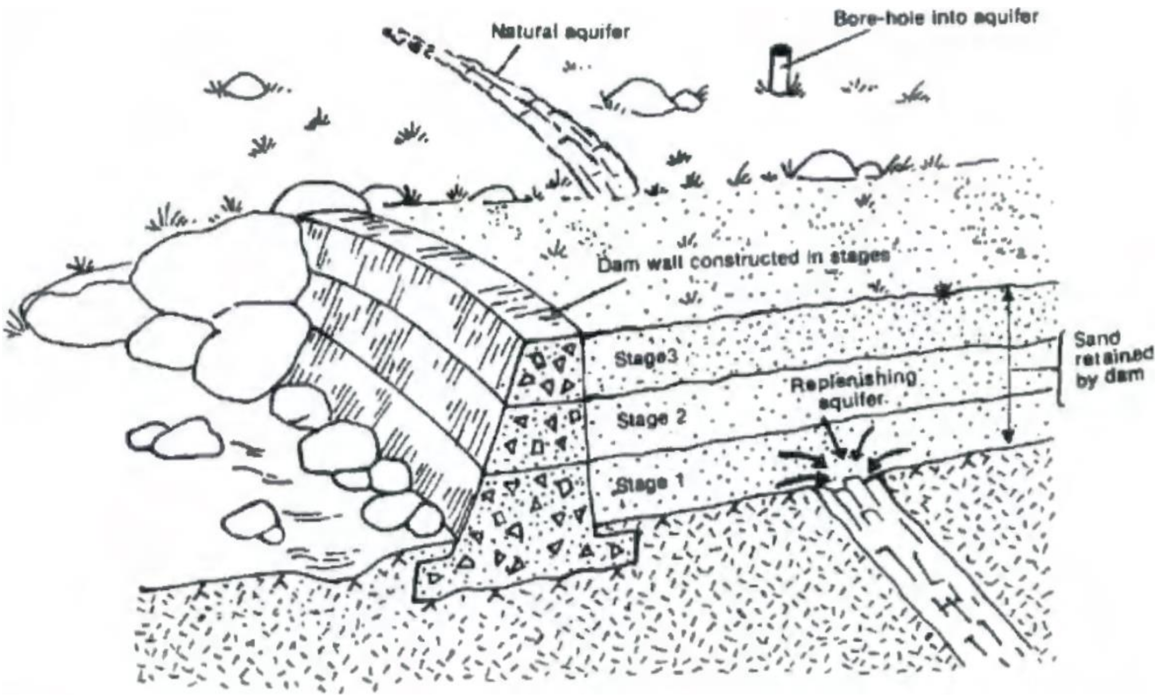


Figure 5 - Sand-storage dam built in stages (Sauermann, 1966).

Various small-scale groundwater damming techniques have also been developed and applied in many other parts of the world, notably in Southern and East Africa, and in India (Nilsson, 1988). The first Kenyan dams were built in the 1950s. There was a significant increase in the number of sand dams built in Kenya between 1980 and 2010, driven predominantly by the work of the Utooni Development Project (UDO) and Sahelian Solution (SASOL). In the early 2020s, approximately 150 dams were built each year, of which 100 are in Kenya. Sand dams have also recently been introduced into Mozambique, Ethiopia and Sudan (Excellent, 2012).

The Namibia experience showed that the small-scale appropriate technologies and their various improvements are generally not known to the farmers, nor the agricultural agencies whose forte is crop production, nor the water agencies whose main focus is bulk water supply. The particular focus and international leadership of the former South West Africa in small-scale water supply options throughout the 1950s and 1960s came about through the initiative of a small number of highly knowledgeable and dedicated individuals in the right place at the right time (Stengel, 1963). Under their successors, in a period of renewed focus on bulk water supply (mines and larger towns), the small-scale approaches and technologies were virtually forgotten within a period of 20 years (Lau and Stern, 1990).

2.6 Modern Managed Aquifer Recharge in Southern Africa

In South Africa, following a period of serious water shortage, modern MAR technologies took their rightful place when systematic water research was initiated with the promulgation of the Water Research Act (Act number 34 of 1971) and the establishment of the Water Research Commission. Some of the first projects addressed the storage of river run-off, stormwater, and reclaimed water (treated sewage effluent) in the sand deposits of the Cape Flats aquifer for later abstraction and augmentation of fresh water supplies of the Cape Peninsula.

South Africa's oldest MAR scheme was inspired by the above-mentioned pilot-scale testing of artificial groundwater recharge in the Cape Flats. Indirect recycling of water at the newly established industrial town, Atlantis, on the arid South African west coast started shortly after development of the town commenced in the mid-1970s, Tredoux and others (2002). Treated domestic effluent (from maturation ponds) is blended with urban stormwater runoff and discharged into recharge basins in the coastal dune area.

A surge of research commissioned by the Water Research Commission in the late 1990s and early 2000s (Murray and Tredoux, 1998; Murray and Tredoux, 2002) laid a foundation for the practical implementation of MAR in the region. Among others, it led to the construction of a major borehole injection scheme for the City of Windhoek, Namibia (Murray, 2002; Murray, 2016). Windhoek's MAR scheme is of particular interest because it involves large-scale borehole injection and recovery in a highly complex, fractured quartzite aquifer. Prior to this scheme, MAR had not been practiced anywhere in the world at a large scale in complex geological environments. The risk of losing water was generally considered too high. By undertaking a comprehensive feasibility study, it was demonstrated that water losses would be negligible if the scheme was designed and operated correctly (Murray, 2002).

Importantly, in 2007, the South African government, through its Department of Water Affairs and supported by the Water Research Commission, developed and rolled out a national Artificial Recharge Strategy (DWAF, 2007). Its purpose was *"to use natural sub-surface storage as part of Integrated Water Resource Management wherever technologically, economically, environmentally and socially feasible."*

The strategy had three main thrusts:

- increasing awareness of artificial recharge;
- incorporating artificial recharge into relevant planning documents; and,
- developing successful demonstration sites.

A comprehensive list of site-specific areas for potential artificial recharge for each of the 19 Water Management Areas was produced as a follow up to the strategy (DWAF, 2009). A website is maintained by the Department as a resource for research and education and as an information hub for water practitioners in government and the private sector (https://www.artificialrecharge.co.za/↗).

Implementation has been slow since then. Apart from the larger schemes of Windhoek and Atlantis mentioned above, some small to medium scale MAR schemes have been implemented in South Africa and feasibility studies have been conducted with the intention of implementation in the near future. One major feasibility study was undertaken for the Botswana government with the aim of assessing the value of MAR for the more populated eastern part of the country (Groundwater Africa, 2012; Lindhe, et al., 2014).

While the main purpose of MAR in Southern Africa is to augment water supplies and to enhance water security, two schemes are for mine water disposal to comply with environmental regulations. In these cases, it is not permitted to dispose of surplus water from the mines' dewatering processes on the land surface, so aquifer recharge has become the chosen alternative and local farmers benefit from it (Murray, 2016).

The total MAR volume in Southern Africa by 2015 was 10.3 Mm^3/year, or 0.2 percent of groundwater use, compared to a global average of 2.4 percent (Murray, 2016; Dillon et al., 2019). While the volume is small, it remains an important aspect of groundwater development on the African continent. The vast majority of African countries have not implemented MAR. MAR is practiced most commonly in South Africa (17 reported cases), followed by Tunisia (11 cases), Kenya (8 cases), and Algeria (5 cases). Of the South African cases, 12 represent open well, shaft and borehole injection, four are the surface spreading/infiltration method, and one is in-channel modification (Ebrahim et al., 2020).

While MAR activities in Southern Africa are limited, it is evident that MAR practices on a greater scale could substantially enhance the region's water security (Murray, 2016).

2.7 Selection of Case Studies

MAR systems are generally discussed in terms of five major components (National Research Council, 2008):

1. source of water to be stored;
2. recharge method;
3. storage method and management approach;
4. recovery method; and,
5. end use of recovered water.

Opportunities and issues related to the selection, development, use, and regulation of MAR systems are typically tied to these components, and discussion regarding hydrogeology and hydraulics, water quality, legal, regulatory and economic issues, and management of systems are usually tied to one or more of these components. While issues related to water sources and end uses may be common to both underground and surface storage of water, many of these issues are unique to underground storage systems, such as potential interactions between stored water and native water in the surrounding aquifer.

Figure 6 illustrates the above-mentioned major MAR components, along with some associated criteria, that affect system selection and design (National Research Council, 2008). Note that many MAR systems contain some form of pretreatment before recharge and post-treatment during recovery. Monitoring of the stored water is often required. A source of water is required for all systems, but selection of the source is tied to the end use (particularly with respect to whether that end use is to be potable or not), as are treatment and management during recharge, storage, and recovery. Major factors that impact the selection of recharge methods include aquifer type, land availability, and proximity to the water source.

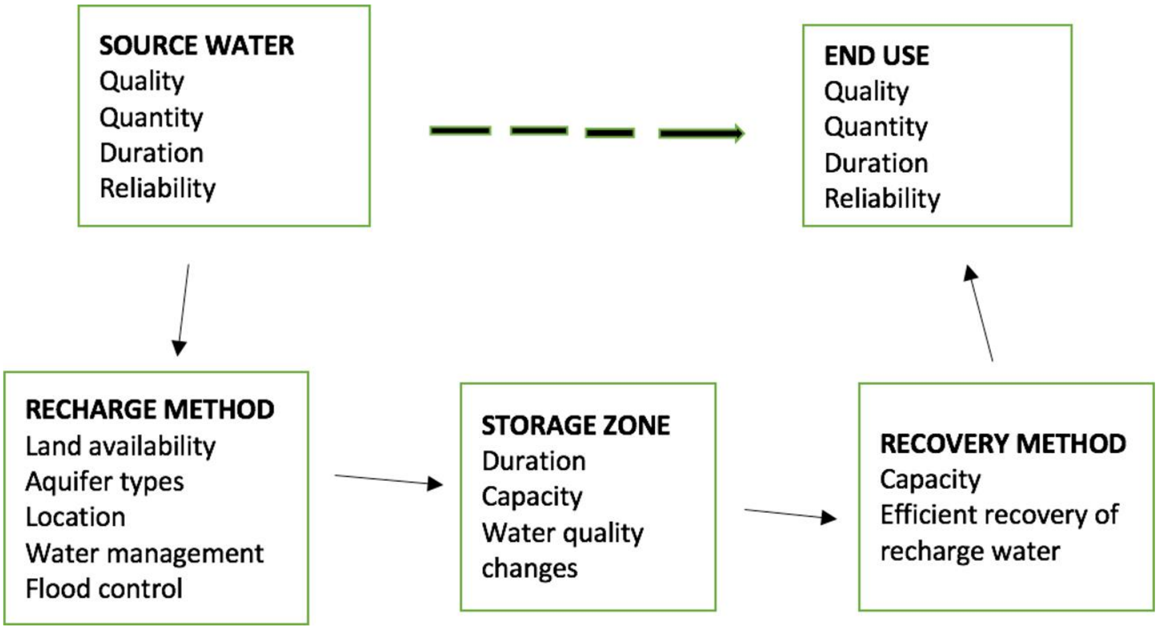


Figure 6 - Technical components of a MAR system (after National Research Council, 2008).

With this as background, six cases have been selected covering different physical and management environments and recharge methods in Southern Africa. Table 1 includes the Cape Flats and Sedgefield cases, as well as the widespread use of sand dams, but these are not discussed as case studies. Each of the different recharge methods in these selected Southern African cases is illustrated in general in Figure 7, using a conceptual diagram and some pointers to its applicability and relative cost (from Murray and Harris, 2010).

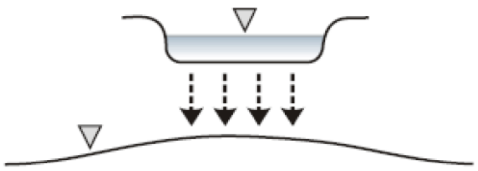
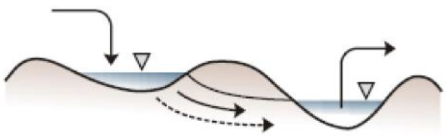
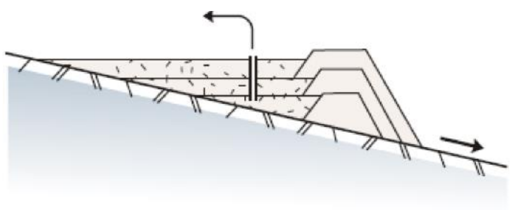
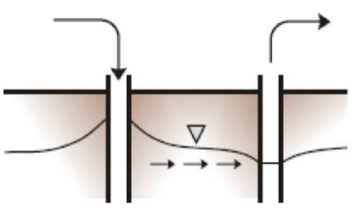
	**Infiltration basin** Basins constructed in sand or gravel aquifers. Surface water is diverted to basins and allowed to infiltrate through an unsaturated zone to the underlying unconfined aquifer. ● For sandy unconfined aquifers – not suited to clayey soils. ● Treatment: infiltration is more rapid with clean water than turbid water; treatment lengthens the “runs” before having to scrape the basins and remove fine material. The unsaturated zone provides natural treatment. ● Costs: moderate – can recharge up-gradient of existing boreholes.
	**Dune Infiltration** The infiltration of water through a sand dune and abstraction from boreholes/wells/ponds downstream ● For unconfined sedimentary aquifers. ● Treatment: minimal pre-treatment; source water should be reasonably clear to prevent clogging ● Costs: low – only shallow abstraction required
	**Sand dam** Built in ephemeral streams in arid areas on low permeability lithology. They trap coarse sediment when flow occurs and following successive floods, the sand dam is raised to create an “aquifer”. Often, they are built on fracture features in the landscape to speed up recharge of the natural aquifer underneath. Abstraction can also be from the sand aquifer. It takes years to create the artificial aquifer, but the approach allows for a phased implementation.
	**Borehole Injection - Aquifer Storage and Recovery (ASR is a term commonly used for MAR using wells in the United States and Australia)** The injection of water into a borehole for storage and recovery (mostly from different boreholes) ● Suitable in both confined and unconfined aquifers. ● Treatment: usually high treatment required – need to remove sediment/debris to prevent borehole clogging ● Cost: moderate to high

Figure **7 -** General description of recharge methods discussed in Southern Africa case studies (Murray and Harris, 2010).

Table 1 - Selected case studies of active MAR schemes in Southern Africa.

Scheme name	Aquifer type	Water source	Recharge method	Recharge capacity (Mm^3/year)[1]	Status
Cape Flats[2]	Sand	Treated waste water and storm water	Infiltration basin	-	Pilot scale
Atlantis	Sand	Urban storm water & treated waste water	Infiltration basin	2.7	In operation
Sedgefield[3]	Sand	Treated waste water	Dune infiltration	0.5	Desk study
South Africa and wider[4]	Alluvium	Ephemeral river flood water	Sand dams feeding deeper aquifer	small	In operation
Omdel (Namibia)	Alluvium	Ephemeral river flood water	Dam to hold back flood water – releases to d/s aquifer	7.9	In operation
Langebaan	Cenozoic sediments	River water and treated wastewater.	Borehole injection	14	Initial injection tests
Windhoek (Namibia)	Fractured quartzite	Surface water impoundments	Borehole injection	12	In operation
Kharkams	Fractured gneiss	Ephemeral spring	Borehole injection	0.005	In operation
Plettenberg Bay	Fractured quartz-arenites	River runoff	Borehole injection	0.8	Pre-feasibility

[1] Million cubic meters per year
[2] Discussed in concluding section
[3] Referred to under Plettenberg Bay
[4] Under traditional technologies

For purposes of comparison and overall assessment, each case study will be discussed under the following headings:

- need for artificial recharge – setting the scene;
- source water;
- aquifer hydraulics;
- water quality;
- scheme elements;
- water resource management environment; and,
- evaluation and way forward.

The case study section will conclude with some thoughts on the roll-out of MAR to date as part of sustainable groundwater resource development in the region.

3 Case Study: Atlantis, Cape Town South Africa

The aim of presenting many case studies in this book is to discuss:

- different driving forces towards the use of MAR techniques;
- factors that affect the selection of a particular MAR technique;
- different MAR techniques and their applicability in specific settings;
- efficiency and effectiveness of various MAR techniques;
- importance of water quality and mixing of different water types when applying MAR techniques;
- Southern African legislative processes involved with implementing MAR;
- monitoring and sustainability of MAR techniques implemented in Southern Africa; and,
- lessons learned in Southern Africa regarding implementation of MAR.

This section, Section 3, presents MAR to the Atlantis Aquifer.

3.1 The Need for Artificial Recharge – Setting the Scene

The town of Atlantis is approximately 50 km north of the City of Cape Town, South Africa, forming part of the Cape Town metropolitan area. Atlantis experiences a Mediterranean climate with most of its 450 mm mean annual rainfall occurring in winter, between April and September. Up to 30 percent of the rainfall recharges the underlying groundwater system, particularly through unvegetated dune areas. The town was established as an industrial town, based on the "new town concept", being far enough from the center of Cape Town to be self-contained, where everyone living would be employed in the town, Tredoux and Cave (2002). A summary of the Atlantis water supply is provided in Table 2.

Table 2 - Atlantis Water Supply Scheme.

Name of scheme	Atlantis Water Supply Scheme
Location	Atlantis Aquifer, Cape Town, South Africa
Mean annual rainfall	450 mm/year
Source of water	Storm water and secondary treated wastewater
Type of aquifer	Primary aquifer, predominantly sand, some calcrete and peat
End use of water	Industrial and domestic use
Type of managed aquifer recharge	Large infiltration basins
Current average volume of water recharged	7500 m^3/d storm water and treated waste water
Volume of water recovered	2.7 Mm^3/year
Year commenced	1979
Owner/management of scheme	City of Cape Town
Unique attributes of this MAR scheme	Water re-use, both wastewater and stormwater, good example of integrated water resource management

The initial groundwater supply planned for Atlantis was insufficient to support the population and growing industry within the area, Tredoux (1987). The closest alternative water source was the Berg River, which is 70 km away and piping water to Atlantis would be too costly, Tredoux and Cave (2002). Thus, groundwater resources were further explored and the Witzand and Silwerstroom wellfields were developed (Figure 8). Stormwater detention basins were constructed and much of the water infiltrated into the sandy soils, inadvertently recharging the groundwater.

The shift to intentionally, artificially recharging the aquifer came as a result of a change in national legislation, which introduced a strict permitting system for wastewater discharge and a stringent monitoring protocol. Until the 1970s, marine discharge of treated wastewater was common practice in South Africa. The costs associated with adhering to the new pollution control measures became prohibitive for Atlantis. Based on the results of successful pilot studies in Cape Flats (1973-1979) to investigate alternative applications of wastewater, recharging the local aquifer with treated wastewater was initiated in Atlantis in 1979 (DWAF, 2010; Quayle, 2012). Figure 8 shows the town, industrial area, and all the major components of the water management system.

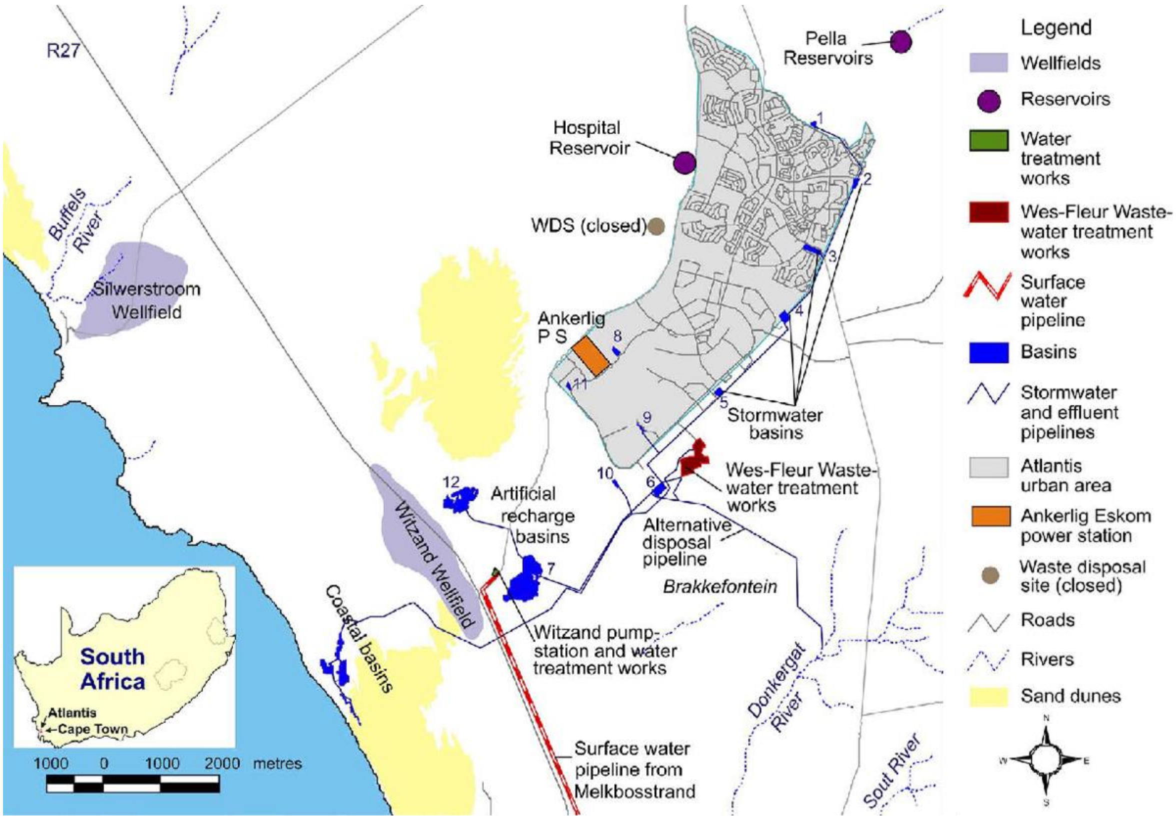


Figure 8 - Town of Atlantis along the west coast of South Africa (Bugan et al., 2016).

3.2 The Source Water

There are no major rivers flowing through the Atlantis area. The only surface water features in the area include the Buffelsriver at Silwerstroom, and during winter, the

Donkergat and Sout rivers which flow to the south of the Atlantis area (DWAF, 2010). All of these are non-perennial rivers that dry up during summer. Perennial springs feeding the Buffelsriver at Silwerstroom have been used for water supply since 1976. Due to the large infiltration capacity of the soil in Atlantis, there is minimal overland flow in the area.

In the case of Atlantis, stormwater and treated domestic wastewater became the *source water*. The town (17 km^2) generates large volumes of stormwater due to the presence of extensive impermeable surfaces. The recharge basins in Atlantis receive on average about 750 m^3/d of stormwater and domestic wastewater which equates to approximately 2.7 Mm^3/year contribution to the Atlantis water supply. This is equivalent to 30 percent of the area's water supply.

A total of 12 stormwater retention and detention basins capture stormwater from the residential and industrial areas. Industrial stormwater is separated from residential stormwater due to the potential of higher salinity water from industrial activities (Tredoux et al., 1999). The combined stormwater from the residential area and the treated wastewater is directed to the artificial recharge basins as shown on Figure 8 (DWAF, 2010). Industrial effluent and excess stormwater are directed to coastal recharge basins, and seep into the ocean via the subsurface, also preventing saline intrusion (Bugan et al., 2016).

3.3 Aquifer Hydraulics

The Atlantis Aquifer, a primary coastal system, is comprised of Cenozoic sediments of Tertiary (66 to 2.6 million years ago) and Quaternary (2.6 million years ago to present) age, overlying the Malmesbury Group bedrock which consists of greywacke and phyllitic shale as shown on Figure 9 (Van Der Merwe, 1983; Rogers, 1980).

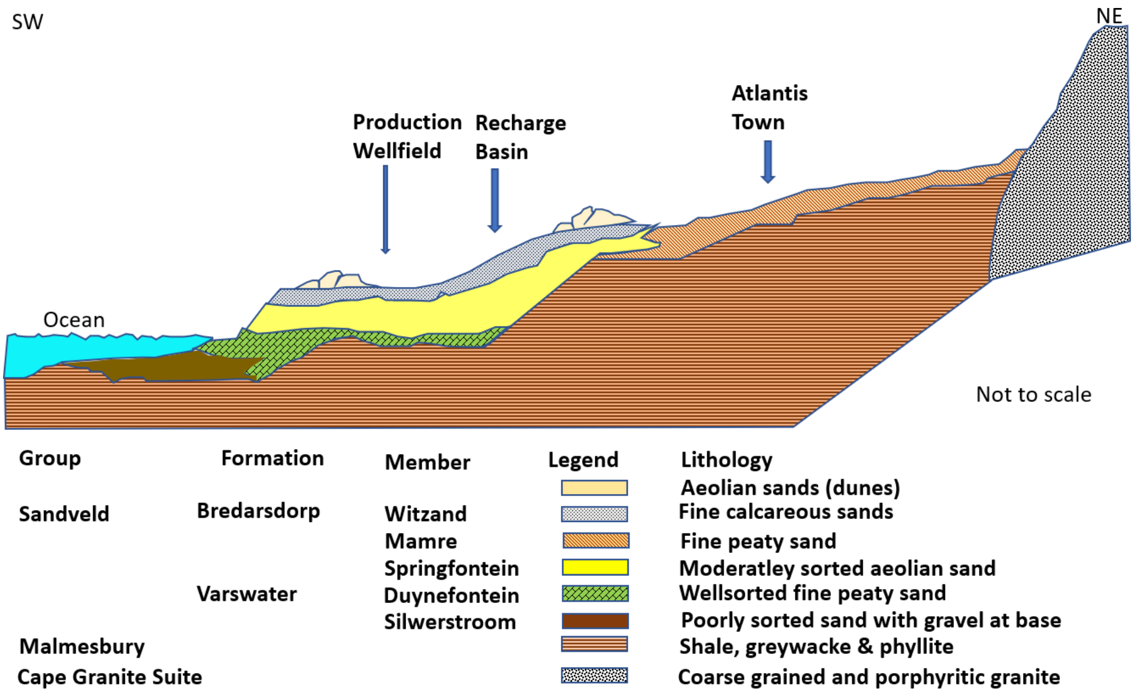


Figure 9 - Stratigraphy of the primary coastal aquifer system in the Atlantis area (DWAF, 2010).

The aquifer covers an area of about 130 km^2, stretching inland from the Atlantic Ocean to the town in the east. The thin aquifer, seldom exceeding 35 m thickness, slopes steeply in a south-westerly direction from a maximum elevation of about 160 m in the north down to sea level in the west. (Tredoux et al., 2009a).

3.4 Water Quality

Pollution

Point sources of pollution in an area relate to land uses like cemeteries, landfill/waste disposal sites and a more recently installed power station which runs on diesel fuel. *Non-point sources* include informal settlements which are un-serviced, small scale farming practices and industrial activities. *Emerging contaminants* only came to light through a special study in Atlantis, indicating that trace organic compounds and pharmaceuticals are present within the system.

Water Quality Improvement and its Monitoring

Water quality is measured intensively, both in the aquifer and in the urban water management system. The aquifer water quality is assessed by sampling boreholes within the developed wellfields as well as monitoring points spread throughout the Atlantis water management area on a five-week cycle. For the urban water management system, critical monitoring points (control points) were selected that take into account the various steps within the MAR system at which significant changes could occur (Tredoux et al., 2009a). These critical control points are explained in Section 3.5. The full extent of water quality monitoring of the area is shown in Figure 10.

Electrical conductivity in the Witzand wellfield ranges between 40 and 120 mS/m. The northern part contains more calcium bicarbonate ($CaHCO_3$) water while the southern parts contain more sodium chloride (*NaCl*) rich water. Water abstracted from this wellfield often has to undergo softening to remove temporary hardness. Several of the boreholes in the southern most parts of the wellfield have been decommissioned to avoid abstraction of water with high salinity and sulfate content (Bugan et al., 2016).

Electrical conductivity within the Silwerstroom wellfield for the last few decades ranges between 40 and 180 mS/m with an average of about 80 mS/m. This wellfield has lower natural calcium (Ca) levels compared to the Witzand wellfield. Only electrical conductivity and iron (which can occur at levels of 0.1 to 0.3 mg/L) fall outside of the drinking water standards in South Africa (SANS, 2011; DWAF, 1998), but these concentrations are removed in the final softening treatment.

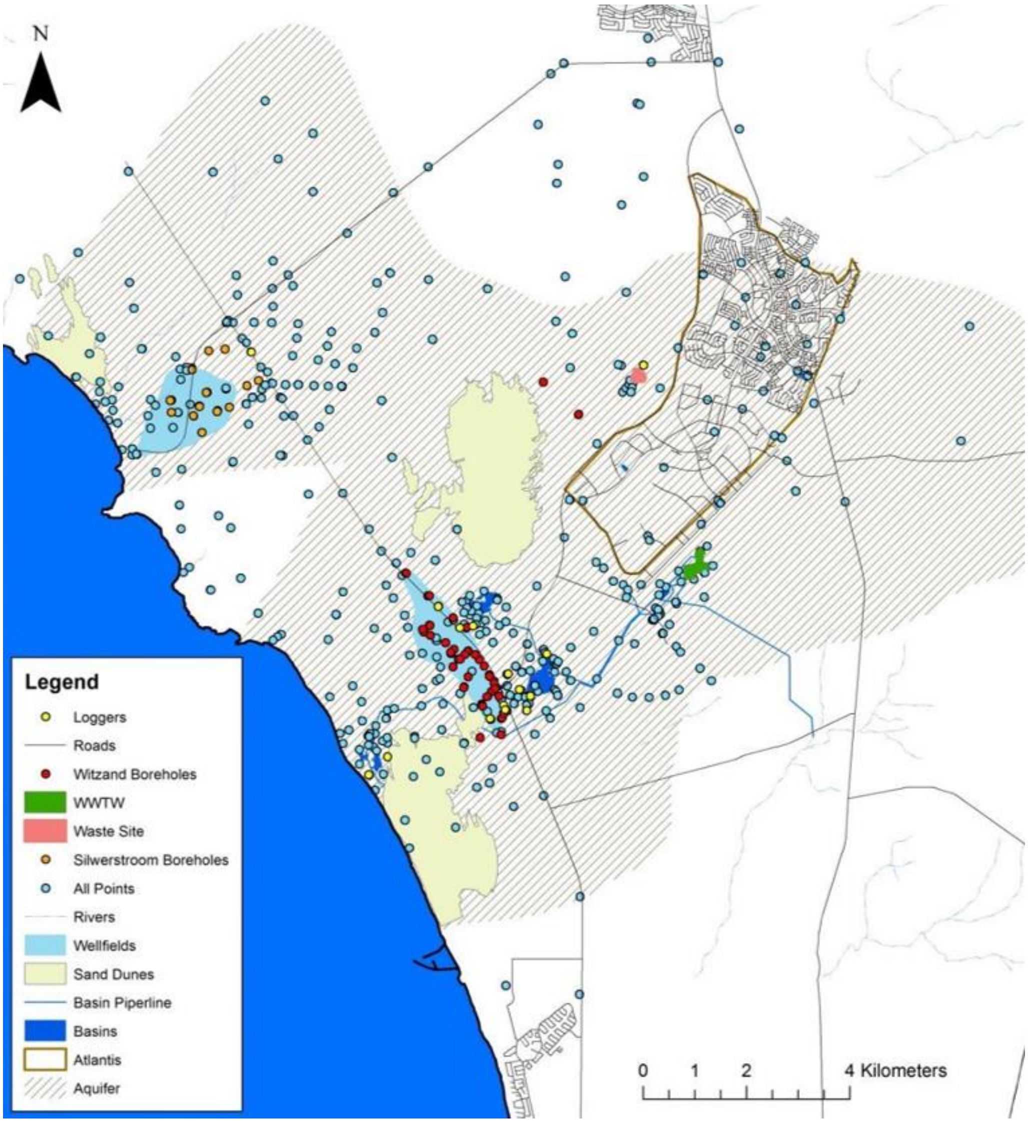


Figure 10 - Monitoring and production borehole locations throughout the Atlantis system (Bugan et al., 2016).

The monitoring system has shown that potassium (*K*) and nitrate (NO_3^-), which are frequently used as tracers of wastewater, are elevated in the wastewater. However, all parameter concentrations are reduced considerably as water moves through the water management system. This demonstrates the efficiency of soil as a natural filter during infiltration of water.

Of particular importance for human health is the impact of the treatment system on bacteria. Stormwater tends to have higher microbial counts than the treated wastewater effluent. Bacterial counts at various points in the system illustrate the importance of the subsurface passage as a safety barrier in the system (Figure 11). Tredoux and others (2009a) report that not only do indicator organisms like *E. coli* decrease substantially as water moves through the system, but pathogens, including viruses, follow a similar pattern of logarithmic reduction, providing the necessary safety margins for the recycling system.

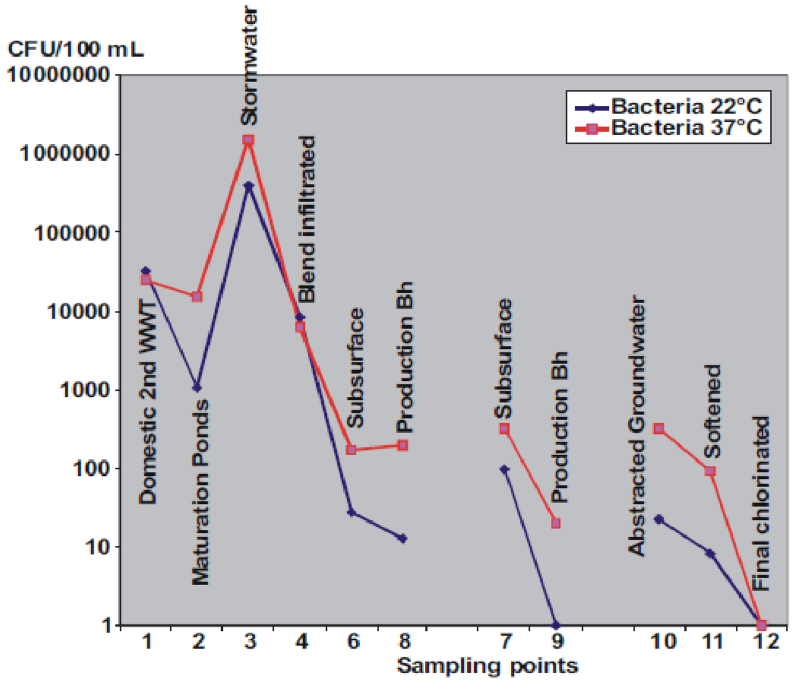


Figure 11 - Bacterial removal in the recycling system of Atlantis (Tredoux et al., 2009a).

Emerging contaminants are not routinely monitored, and occur at very low concentrations. An order of magnitude reduction in concentrations of measured parameters was observed as they move from surface to groundwater to abstracted water to the distribution point. Although some degree of degradation or adsorption on the geological material in the subsurface is expected, it would seem that most of the reduction could be ascribed to dilution. The results demonstrate subsurface passage of water as a successful method to reduce the health risk for potable reuse (Tredoux et al., 2009a).

Since the 1990s, *borehole clogging* has been a recurring problem in the Atlantis wellfields, which resulted in reduced borehole yields. The occurrence of borehole clogging may be attributed to (Bugan et.al., 2016):

- the presence of naturally available iron and manganese in the aquifer (Smith, 2006);
- the occurrence of natural soil bacteria which accumulate iron and manganese due to fluctuating groundwater levels and dissolved oxygen concentrations;
- borehole construction; and,
- the pumping schedule (e.g., over pumping during drought conditions).

In-situ iron removal to prevent iron clogging in production boreholes was recently investigated in the Atlantis Aquifer (Robey and Tredoux, 2013). Ozone was generated on-site and injected back into the aquifer by means of well points. Results of the experiment showed that iron and manganese concentrations in the dissolved phase were reduced considerably. A full-scale implementation of this experiment is currently underway in the area. Successful implementation of this method could significantly reduce the cost of water treatment and production well maintenance costs.

3.5 Scheme Elements

The various components of the Atlantis Water Supply Scheme are presented in Figure 12.

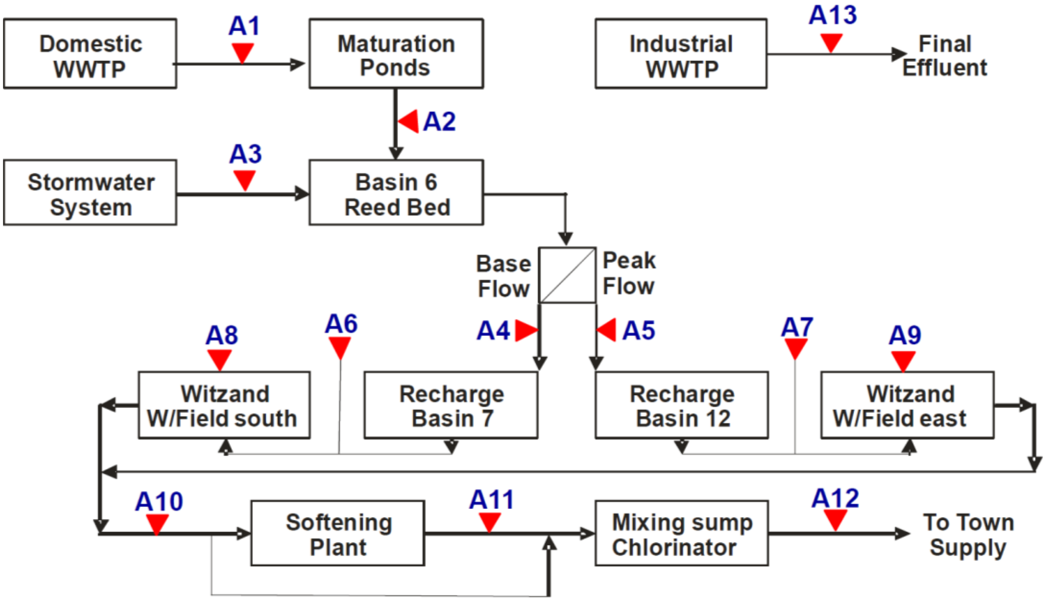


Figure 12 - Atlantis Water Supply Scheme with critical control points selected for monitoring shown as A1 through A13 (DWAF, 2010).

Domestic and industrial wastewaters are treated separately and only the domestic wastewater is recycled. The effluent from secondary settling tanks is polished in a series of maturation ponds. This is released to a reed bed basin. Stormwater runoff is collected via a stormwater collection system of 12 detention and retention basins. The peak flow and base flow in the stormwater system are channeled to different recharge basins to maintain good quality water in selected areas of the aquifer (Tredoux et al., 2009a). Treated domestic effluent from the maturation ponds is blended with low salinity urban stormwater runoff before being discharged into the main recharge basins (Tredoux and Cavé, 1997). The two recharge basins are shown in Figure 13.

The more saline effluent from the industrial wastewater treatment plant is discharged into coastal recharge basins and seeps into the ocean through the subsurface (Wright, 1991; Wright and Parsons, 1994). This also serves as a mitigation measure against potential seawater intrusion (Figure 14).

Figure 13 - Infiltration basins which form an integral part of the artificial recharge and recycling system in Atlantis. Cape Town's Table Mountain is in the background (DWAF, 2010).

Figure 14 - Coastal recharge basin for treated industrial wastewater disposal (DWAF, 2010).

Groundwater is abstracted at the Witzand and Silwerstroom wellfields. Figure 15 shows the trend in abstraction at the respective wellfields. Abstraction rates have declined since the addition of surface water to the system in 1999. However, the artificial recharge of treated domestic wastewater and urban stormwater has continued, resulting in elevated groundwater levels, particularly in the vicinity of and downstream of the artificial recharge basins. The elevated groundwater levels have possible negative consequences in terms of attenuation of potential contaminants, due to reduced thickness of the unsaturated zone and shorter groundwater residence times. Abstraction is also reduced because of iron-related bacterial clogging of production wells and lack of effective routine maintenance to address the clogging problem (Bugan et al., 2016).

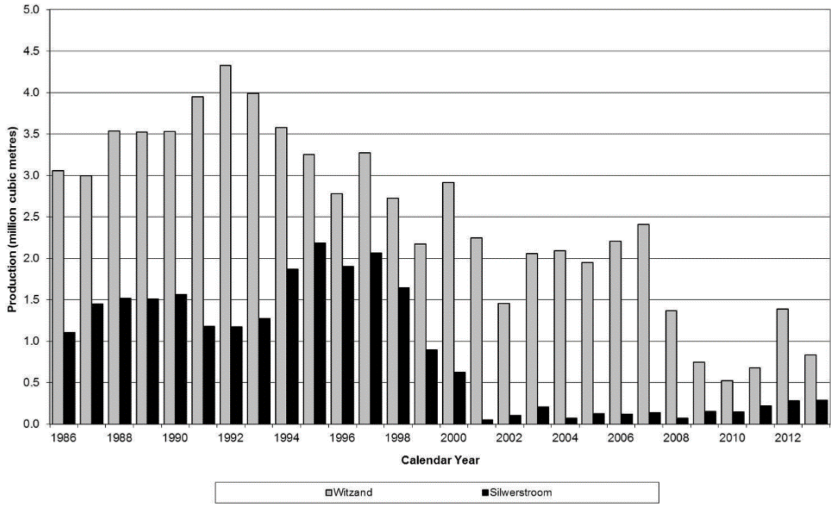


Figure 15 - Trend in production volumes at Witzand and Silwerstroom wellfields (Bugan et al., 2016).

3.6 Water Resource Management Environment

The integrated nature of the scheme and the local adaptation that has taken place ensure that the system is locally viable and acceptable. Consumer relations for the Atlantis Water Supply Scheme are maintained through quarterly meetings with both industry and the community. Industries have assisted in the continued development of the scheme. The Atlantis Water Supply Scheme provides 48 jobs in the operation and maintenance of the system, further contributing to the local economy and community.

Long-term sustainability of the complex large-scale water supply system depends on proper maintenance of all components, requiring a multidisciplinary approach. Prior to July 1997, Atlantis was managed as an independent town, thus management of the key components of the scheme (water supply and quality, wastewater treatment and urban stormwater management) was locally concentrated, allowing for close control. Post 1997, Atlantis was incorporated within the Cape Town metropolitan area, resulting in the redistribution of functions over several departments such as bulk water, wastewater, roads and stormwater, parks and forests. All of these departments, together with consultants appointed by the City of Cape Town regularly discuss issues related to the Atlantis Water Supply Scheme in order to improve and optimize the scheme, its operation and monitoring. Consultants may vary from time to time. Groundwater as a water supply source is a relatively new concept to the City of Cape Town and “ownership” still needs to be embedded at all administrative levels.

Early financing for capital works and construction was relatively accessible. However, operational finance has decreased resulting in increased difficulty of funding further works. This has a corresponding negative impact on Atlantis and could hamper upgrades of the system. The operation of the system is economical compared to the alternatives, i.e., transporting surface water 70 km from the Berg River or desalinization. It also safely deals with wastewater.

3.7 Evaluation and Way Ahead

The Atlantis Water Supply Scheme is an excellent example of wise and efficient water use, including water recycling for potable services. It has also alleviated some of the pressure on the surface water resources in the region, especially with impending impacts of climate change and further population/economic growth. The availability of surface water may eventually be restricted due to the rapid development of the Cape West Coast and the lack of local water resources. Hence, the groundwater resources and the associated water recycling system will remain of critical importance for ensuring a water supply to Atlantis. This, however, requires that the Atlantis Water Supply Scheme be managed efficiently.

Proper management and operation of MAR systems is complex, but it is of utmost importance in order to secure required water volumes and quality. Suggested aspects for improved management and operation of the Atlantis Water Supply Scheme system include the following (Bugan et al., 2016; Tredoux et al., 2009a).

- Interventions to stem the declining abstraction rates and rising groundwater levels require (e.g., de-clogging existing boreholes or drilling and establishment of new production wells). The implementation of such interventions would greatly improve the security of water supply.
- Reinstatement of monitoring activities that have been declining since 2005 because current monitoring only provides for empirical computation of the water balance. It is essential that a monitoring program be maintained for all the water balance components. The scheme will need dedicated staff for specialist monitoring and assessment. It cannot continue to rely on consultants. A number of guidelines and manuals have recently been developed (Jovanovic et al., 2014) that can serve for capacity building of staff in the management and operation of the system.
- Development and implementation of a groundwater protection plan because the aquifer is unconfined and vulnerable to pollution.
- Development and implementation of a risk management plan with updated monitoring to prevent risks from new and emerging contaminants.
- Improvement of wastewater treatment processes based on the outcomes of the studies done in Atlantis and preparation for potential stormwater treatment to ensure that water quality remains acceptable.

The general success and operation of the Atlantis Water Supply Scheme is promising in terms of establishment of similar systems in the arid and semi-arid areas of South Africa and the entire African continent in order to mitigate water stresses. Many lessons learned from the Atlantis experience can be transferred to other sites. However, each site will have to design unique engineering and management solutions depending on the specific sources of water, water demand and hydrogeological settings.

4 Case Study: Omaruru Delta, West Coast, Namibia

4.1 The Need for Artificial Recharge – Setting the Scene

Namibia is the most arid country south of the Sahara, with scarce, unpredictable rainfall and perennial rivers only on its borders. Many Namibian settlements are situated in the coastal area of the arid Namib Desert (e.g., Walvis Bay, Swakopmund and Henties Bay) and depend on groundwater stored in the coastal aquifers of the ephemeral Kuiseb, Swakop and Omaruru Rivers that originate more than 300 km inland at altitudes near 2,000 m and rarely flow to the ocean. Table 3 summarizes salient features of the Omaruru Delta system.

Table 3 - Omaruru Delta (OmDel) Scheme.

Name of scheme	Omaruru Delta (OmDel) Scheme
Location	West coast area of Namibia
Mean annual rainfall	< 50 mm/year
Source of water	Regulated flood water
Type of aquifer	Alluvial aquifer
End use of water	Domestic and mining use
Type of managed aquifer recharge	Infiltration ponds
Current average volume of water recharged	7.9 Mm^3/year
Volume of water recovered	4.6 Mm^3/year
Year commenced	1991-1995
Owner/management of scheme	Namibia Water Corporation (NamWater)
Unique attributes of this MAR scheme	Storage and slow release of flood waters to significantly increase recharge of downstream alluvial aquifer

In the mid-1970s, the rapidly growing water demand associated with these coastal settlements and a large uranium mine increased to 8.4 Mm^3/year. This is 15 to 20 percent more than the mean annual exploitable recharge of the three aquifers combined. The situation had been further exacerbated by a series of very dry years (Water Scarcity Solutions, 2015). In the existing wellfield in the delta aquifer of the Omaruru River (an area with less than 50 mm/year precipitation extending 35 km inland up to the Namib Plain) abstraction had become almost twice the safe yield and groundwater levels had dropped tens of meters (Zeelie, 2004).

To reverse the negative trend, a research project was initiated in 1988 with the aim of investigating whether the sustainable yield of the aquifer could be increased by artificial recharge. The Omdel scheme was subsequently constructed during the period from 1991 to 1995. It consists of a dam with a storage capacity of 41 Mm^3 and a series of infiltration basins in the riverbed 6 km downstream, where the present river channel crosses deep paleo river channels (Zeelie, 2004; Murray, 2009; Christelis, 2019).

4.2 The Source Water

Sand Rivers

Non-perennial rivers characterize Namibia's hydrology. Because of the country's arid climate, potential evaporation is almost six times greater than average rainfall, with only approximately 2 percent of rainfall becoming runoff and 1 percent entering the groundwater. Periodic floods recharge the sand river channel of ephemeral rivers and only occasionally reach the Atlantic (Heyns et al., 1998). The catchment of the Omaruru River covers 15,700 km^2, of which the mountainous source area receives 200 to 450 mm/year of rainfall. Most floods originate in the mountains. The flood waters recharge the sand river channel (Figure 16) as they move downstream and finally reach the ocean if rainfall continues long enough. Much slower flow also takes place as groundwater throughflow in the sand river aquifer (Stengel, 1966). A major challenge is the very infrequent flood events in the lower part of the catchment. In a 22-year period from 1994 (when the scheme was completed) to 2016, there were six periods with flooding in the lower catchment and only three of these with a significant impact on aquifer recharge.

Figure 16 - Ephemeral Omaruru River (Baumeler, 2018) CC BY-SA 4.0↗.

The Omaruru River, like all westward flowing rivers, carries a high silt load. Previous research had indicated that natural recharge in the system was decreasing due to silt sealing the river bed. As a result, most of the water was flowing over the silt and out to sea. Therefore, it was proposed that the flood waters be contained for a time in a holding dam, allowing the silt to settle out. The clean water could then be released into the infiltration areas, thus ensuring that most of the flood water would reach the underground aquifers. This required careful application of operational rules (Water Scarcity Solutions, 2015) as follows:

- water is released when suspended solids are less than 20 mg/L;
- maximum hydrostatic head is maintained at all infiltration beds;
- infiltration beds are cleared of sediment twice yearly; and,

- water levels at infiltration basin observation boreholes are continuously monitored.

4.3 Aquifer Hydraulics

The delta aquifer consists of deeply incised paleochannels filled with sediments, underneath the present river channel, with a total storage capacity at 150 Mm^3 (Figure 17). The Omdel wellfield of 33 boreholes was developed here in the 1970s to augment coastal supplies. The production wells tap the 70 to 110 m thick sandy-gravel alluvium (Christelis and Struckmeier, 2001; Geyh and Ploethner, 1995).

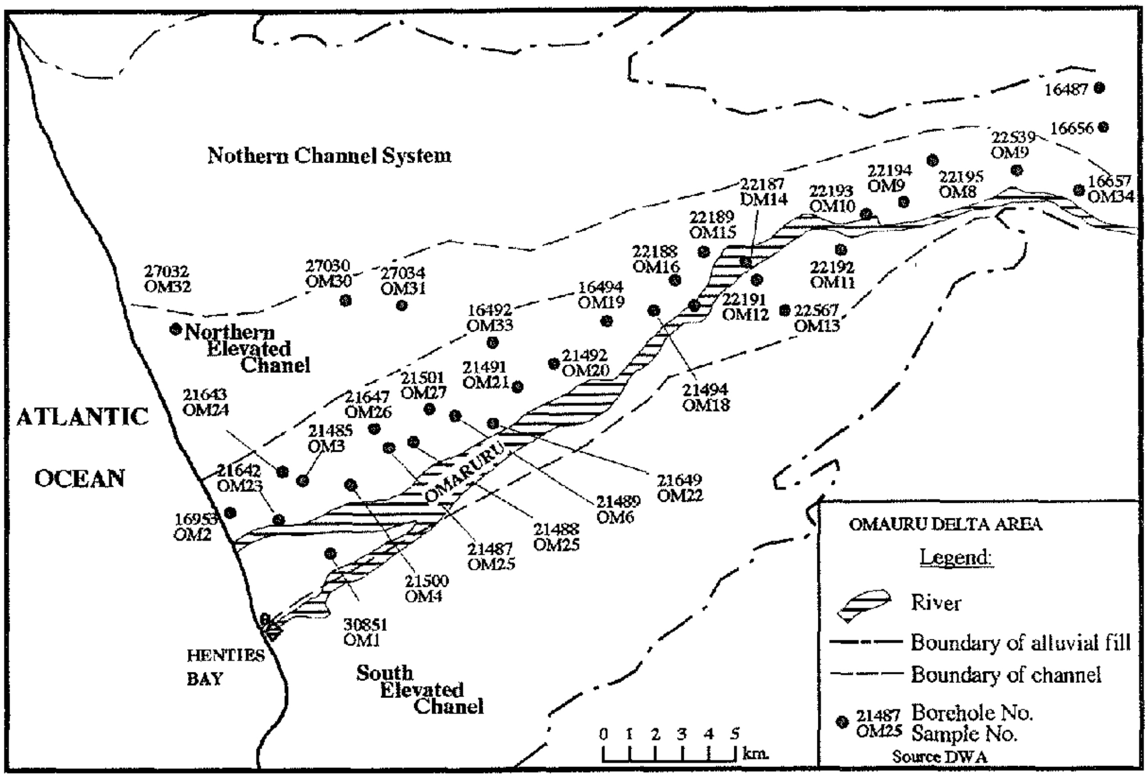


Figure 17 - OMDEL aquifer with the main channel and side channels (Geyh and Ploethner, 1995).

4.4 Water Quality

The aquifer of the main channel contains fresh to slightly brackish groundwater, recharged by throughflow and surface flood flow. In the shallower channels, flanking the main channel on both sides, brackish groundwater predominates (Christelis and Struckmeier, 2001; Geyh and Ploethner, 1995). Electrical conductivity measurements of flood and aquifer water collected in 1997 illustrate the importance of regular flood recharge (Table 4).

Table 4 - Electrical Conductivity 1997 (mS/m) (Murray, 2009).

Omdel Dam water	~57
Recharge Site I (6 km down-stream)	~110

Water abstracted from the aquifer	~190

4.5 Scheme Elements

Key elements of the scheme (recharge and abstraction) are illustrated in Figure 18. It is useful to note the points below when viewing Figure 18 (Water Scarcity Solutions, 2015):

- the dam and associated storage in which the silt from flood waters can be allowed to settle;
- the dam is constructed without a foundation cut-off wall extending to bedrock thus permitting groundwater throughflow;
- a multi-level off-take pipe to allow transfer of clear water to the infiltration beds;
- two large infiltration areas downstream of the dam; and
- silt removal around the abstraction tower (Figure 18b).

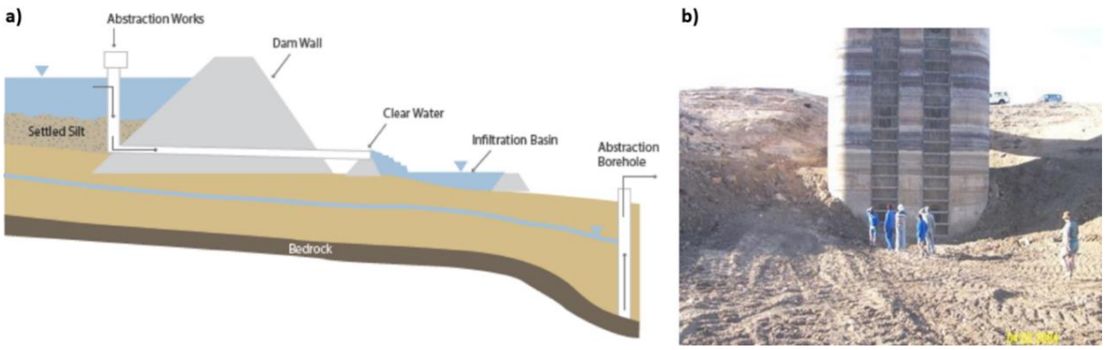


Figure 18 – Omdel Scheme: a) schematic of the recharge and abstraction process (Water Scarcity Solutions, 2015); and b) photo of silt removal around abstraction tower (Mostert and Matengu, 2019).

When the dam fills with water, it is allowed to stand for 9 weeks so that silt settles out. Then, clean surface water is skimmed off by an abstraction tower and flows through a pipe under the wall to four infiltration ponds (Figure 19). These are operated in a routine cycle of infiltrating, drying, scraping and refilling (Zeelie, 2004).

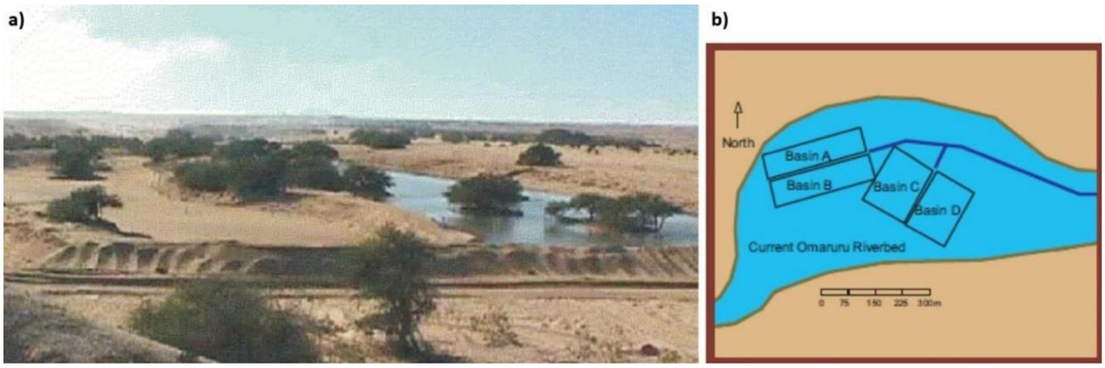


Figure 19 – a) Photograph of two Omdel infiltration basins. b) Map of Omdel basins. (Zeelie, 2004).

During flooding, the artificial recharge ranged between 52 to 89 percent of the surface water flow. Despite the infrequent flooding, infiltration through the basins increased the annual recharge from 5.8 to 7.9 Mm^3/year and the estimated sustainable yield increased from 2.8 to 4.6 Mm^3/year (Mostert and Matengu, 2019). The capital cost of the project was US$ 16.8 million, resulting in a very favorable unit cost of water of US$ 0.25/m^3 (Water Scarcity Solutions, 2015).

Because of demand pressures and uncertainty over the sustainable yield, the aquifer had been operated at an average withdrawal of 6.3 Mm^3/year since artificial recharge implementation. This resulted in an overdraft, as reflected in declining aquifer water levels. The large aquifer storage sustained the scheme and for better access to the available storage, 17 additional production boreholes were drilled during this period.

4.6 Water Resource Management Environment

Water Supply Institutional Approach

Namibia has a unique water supply institutional approach. For smaller supplies, communities are asked to take ownership of their local infrastructure by funding and performing routine maintenance with the support of a rural water extension officer. For most urban centers with more than 2,000 people, a state-owned enterprise called the Namibia Water Corporation (NamWater) takes some of the responsibilities of the national Department of Water Affairs. NamWater extracts water from ground and surface resources via boreholes and dams. The water is sold as bulk water to local authorities such as municipalities, who then supply residents. The commercialization of bulk water supply improved management by phasing out state subsidies and instituting full cost recovery and generation of investment funds, as well as flexible planning of internal (financial, personnel, technical) and external (free market) operations (GWP, 2009).

4.7 Evaluation and Way Ahead

As a result of nearly doubling the sustainable yield of the Omdel scheme by means of MAR, the construction of a major capital project, a seawater desalination plant, was delayed (Water Scarcity Solutions, 2015).

The rate of reservoir sedimentation is a major concern. Removal of sediment from the reservoir during the dry season is not economically viable, so reducing the rate of sedimentation through improved watershed management practices is important. Rotational grazing and de-stocking during dry periods can be instrumental in reducing land degradation (Amwele et al., 2004).

In a very arid country such as Namibia, it is imperative to seek innovative mechanisms to conserve water. Groundwater use makes up 38 percent of all water use and 60 percent of all urban use. Major mines in the coastal region have been completely dependent on groundwater, although new desalination plants have reduced dependency (Earthwise contributors, 2019). Elements of water demand management – for example conjunctive use of water and use of unconventional sources – are developed, implemented and well accepted by decision makers in Namibia. Improved management along with the commercialization of bulk water supply is probably giving Namibia an edge in this regard. Planning of Omaruru Delta scheme benefitted from both the research and practical experience related to storage of water in sand that was gained over many years in Namibia. For a sustainable water service in this challenging environment, the importance of adequate technical capacity within government and the private sector, in addition to theoretical understanding of integrated water resource management, cannot be over-emphasized (GWP, 2009).

5 Case Study: Langebaan, West Coast, South Africa

5.1 The Need for Artificial Recharge- Setting the Scene

Langebaan is located approximately 100 km north of Cape Town, along the west coast of South Africa. The Berg River is the dominant perennial river in the region, draining north-westerly into the Atlantic Ocean. The Mediterranean climate of the region (DWAF, 2008) has warm dry summers and cool wet winters, with mean annual precipitation from 310 to 400 mm. Rainfall generally occurs between the months of May through August. A summary of the Langebaan system is provided in Table 5.

Table 5 - Langebaan Scheme.

Name of scheme	Langebaan
Location	Cape West Coast, South Africa
Mean annual rainfall	310-400 mm/year
Source of water	Secondary treated wastewater and excess river water
Type of aquifer	Layered sedimentary aquifer, unconfined and confined, plus bedrock aquifer
End use of water	Industrial and domestic use
Type of managed aquifer recharge	Proposed to be a combination of infiltration basins and borehole injection
Current average volume of water recharged	Testing phase - 14 Mm^3/year envisaged
Volume of water recovered	Still in testing phase
Year commenced	Not yet commenced – testing since 2008/2009
Owner/management of scheme	West Coast District Municipality
Unique attributes of this MAR scheme	Primary and secondary aquifer; participation of large stakeholder group essential

Water Resources Planning Leads to MAR

The towns along the west coast of South Africa have struggled with water shortages due to extreme drought weather conditions since 2014. The national Department of Water

Affairs and Sanitation's regional water supply strategy envisioned a reduction in the reliance on surface water through the provision of 14 Mm^3/year to the water supply system from local aquifers.

Early work (2008/2009) in this area to test the feasibility of MAR by injection was funded by the Department of Water Affairs and Sanitation (then Department of Water Affairs and Forestry). Recent research work is funded by the Water Research Commission and implementation is funded by the Saldanha Bay municipality. This case study is based on reports by the WRC project team.

The decision to use MAR was informed by periodic studies of the Langebaan Road Aquifer System and the adjacent coastal aquifers on the west coast by the Geological Survey and the Department of Water Affairs. As a result of this work, the Saldanha Subterranean Government Water Control Area was declared in September 1976 to protect this strategic resource for future urban and industrial use. A 2008/2009 investigation by the CSIR (Council for Scientific and Industrial Research), carried out for the then Department of Water Affairs and Forestry, proposed to pursue MAR at the already established wellfield at Langebaan Road as part of a suite of suitable and appropriate water supply augmentation schemes for the sub-region based on sustainability principles for the west coast (Seyler et al., 2016; Tredoux and Engelbrecht, 2009).

The Langebaan Road wellfield had already been initiated for one of the local municipalities, Saldanha Bay, during the early 1990s. It has four production boreholes, authorized to withdraw 1.46 Mm^3/year (4000 m^3/d) as indicated by the West Coast District Municipality (2005). The planned 14 Mm^3/year was to be met from the Langebaan Road Aquifer System, operated conjunctively with MAR and with development of a wellfield in the as yet untapped Elandsfontyn Aquifer System (Figure 20) as reported by the West Coast District Municipality (2009). The strategy proposed that by 2021 excess winter runoff from the Berg River would be stored in the aquifer in the winter months and be used in the summer months when the water demand is higher (DWS, 2016; Seyler et al., 2008).

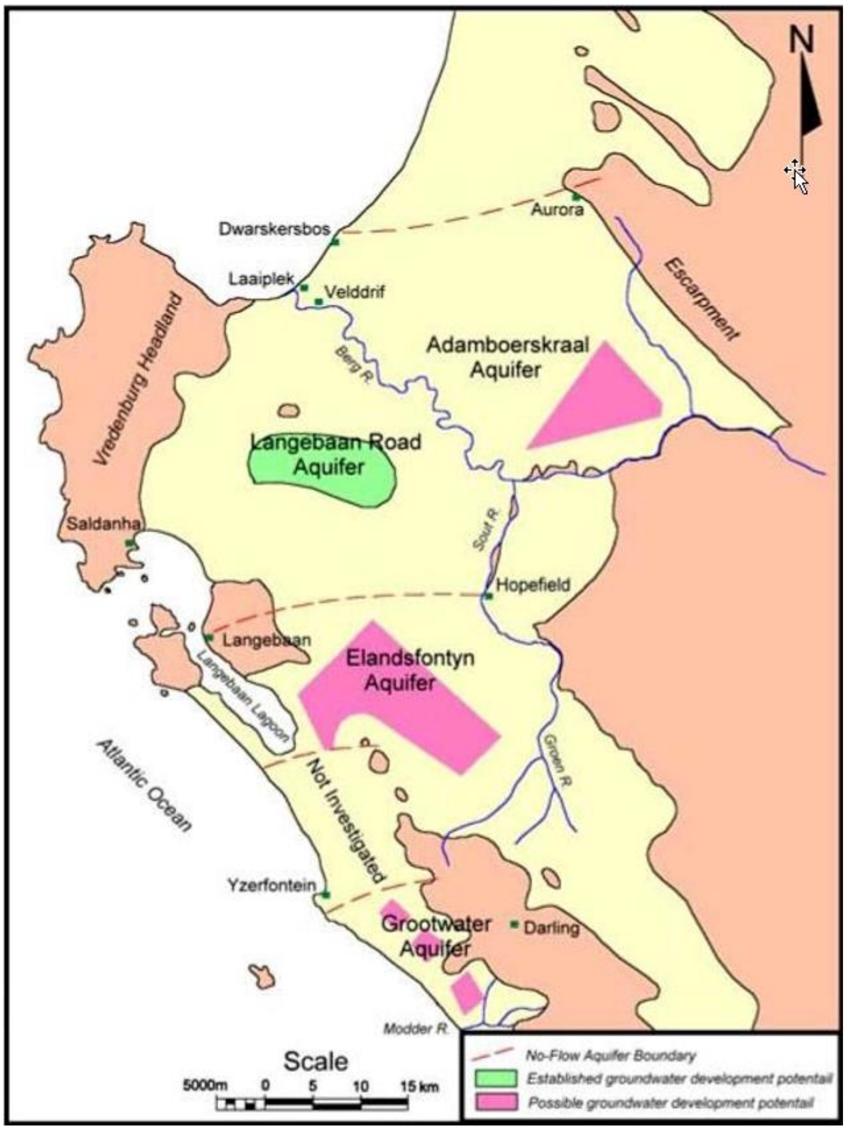


Figure 20 - Cape West Coast of South Africa including the Langebaan Road and Elandsfontyn aquifer systems (Du Plessis, 2009).

5.2 The Source Water

Possible water sources for the scheme were excess volumes from the Berg River during the winter season and secondary treated wastewater. Prior to injection/infiltration, modeling and/or testing was conducted on blending of waters to determine whether any mineral precipitates were likely to form. Source water from wastewater requires additional tests for organic compounds and pharmaceuticals, known to occur in the area. Because the water composition of the source water may vary significantly from time to time, regular monitoring would be necessary. It would also be necessary to evaluate whether water/rock interaction alters the water composition of the infiltrated/injected water within the aquifer and whether the abstracted water would require treatment.

5.3 Aquifer Hydraulics

The topography is dominated by the underlying geology (Seyler, et al., 2016), with sand dunes along the coastal areas reaching elevations up to 100 m, relatively flat-lying sandy plains across most of the inland area especially in the flood plain of the Berg River, and intrusive granite plutons forming hills reaching elevations up to 500 m in the area. The dominant land uses in the study area are cultivated land (dryland), shrubland as well as low and high fynbos (a biome of the South African southern coastal region, characterized by a diverse richness of endemic plant species).

The area is composed of two paleochannels: the northern Langebaan paleochannel and the southern Elandsfontein paleochannel (Woodford et al., 2003). These paleochannels coincide with thick water-bearing sedimentary sequences. The sediments attain a thickness of nearly 80 m and are characterized by varying permeabilities and semi-confining peat and clay layers (Timmerman, 1985). A clay several meters thick, extending over a large part of the area, effectively separates the sediments into an unconfined and a confined aquifer (Timmerman, 1988). Significantly, the clay distribution is discontinuous and in particular, west of Hopefield, a "clay-missing window" exists. Fractures in the Malmesbury Shale or Cape Granite bedrock yield water and thus the bedrock itself is also considered to be an aquifer (Seyler, 2016). Figure 21 presents a conceptual model of this aquifer environment developed by Tredoux and Engelbrecht (2009), as modified by Jovanovic and others (2019).

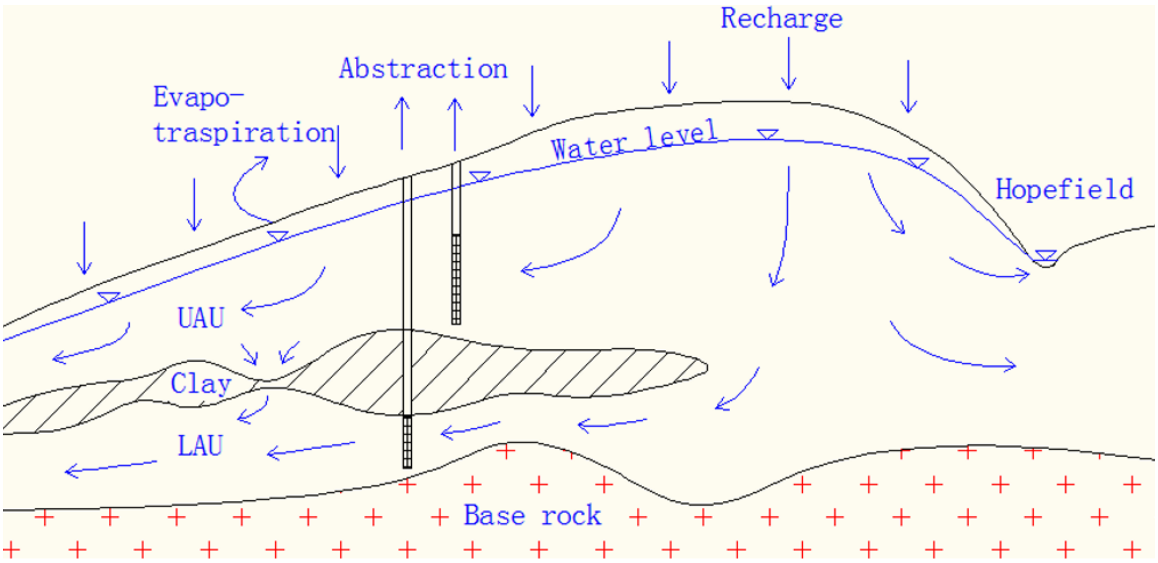


Figure 21 - Conceptual model of lithological layers showing upper and lower aquifer units and discontinuous clay (Jovanovic et al., 2019).

5.4 Water Quality

The dominant water types in the coastal aquifers are NaCl and $CaHCO_3$ (Figure 22). There is a marked difference in salinity between the upper and lower aquifer units. In the lower aquifer unit, the electrical conductivity is commonly less than 120 mS/m, whilst in the upper aquifer unit it is generally > 250 mS/m and often exceeds 500 mS/m near the Berg River and the Saldanha Bay.

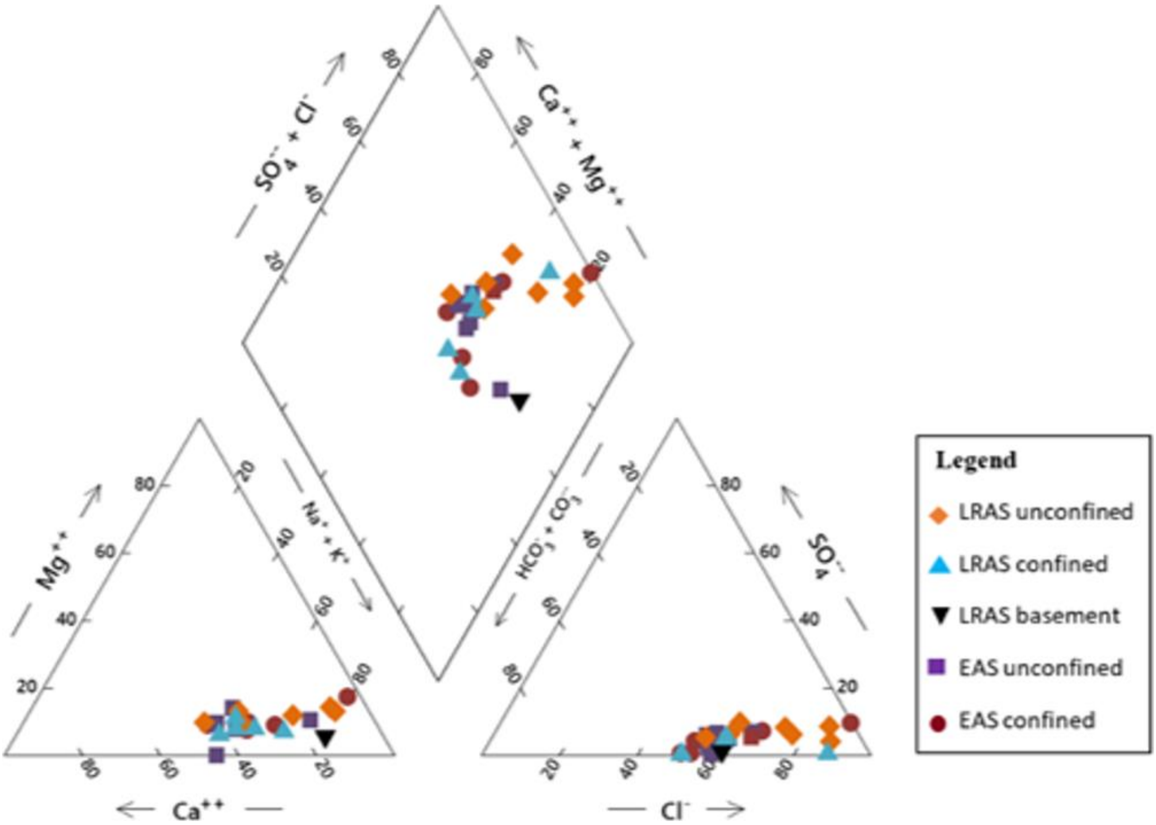


Figure 22 - Tri-linear piper plot for West Coast water samples collected in 2017/2018. LRAS is the Langebaan Regional Aquifer System and EAS is the Elandsfontyn Regional Aquifer System (Jovanovic et al., 2018).

5.5 Scheme Elements

The scheme contains two wellfields, Langebaan Road and Elandsfontyn (Figure 20), already connected to the municipal water supply pipeline. Based on modeling and field observations, boreholes forming part of the extension of the Langebaan wellfield were constructed to be used both for abstraction and injection. The borehole injection method (Figure 23) had already been pilot-tested for this aquifer, because a key part of the aquifer is confined (Tredoux and Engelbrecht, 2009). The Elandsfontyn wellfield is a new wellfield and infiltration tests will be required, as infiltration may be better suited for this area.

Figure 23 - Borehole injection testing at Langebaan Road Aquifer (Weekend Cape Argus – 7.12.08).

Based on data from a regional water level and water quality monitoring program run by the national Department of Water and Sanitation, a model was developed for the area to aid in selecting suitable MAR techniques and locations. It was used as a decision support tool for interacting with stakeholders about the progress of research and potential for implementation. Four scenarios, which involved a mixture of injection and infiltration basins, were presented to stakeholders (Figure 24).

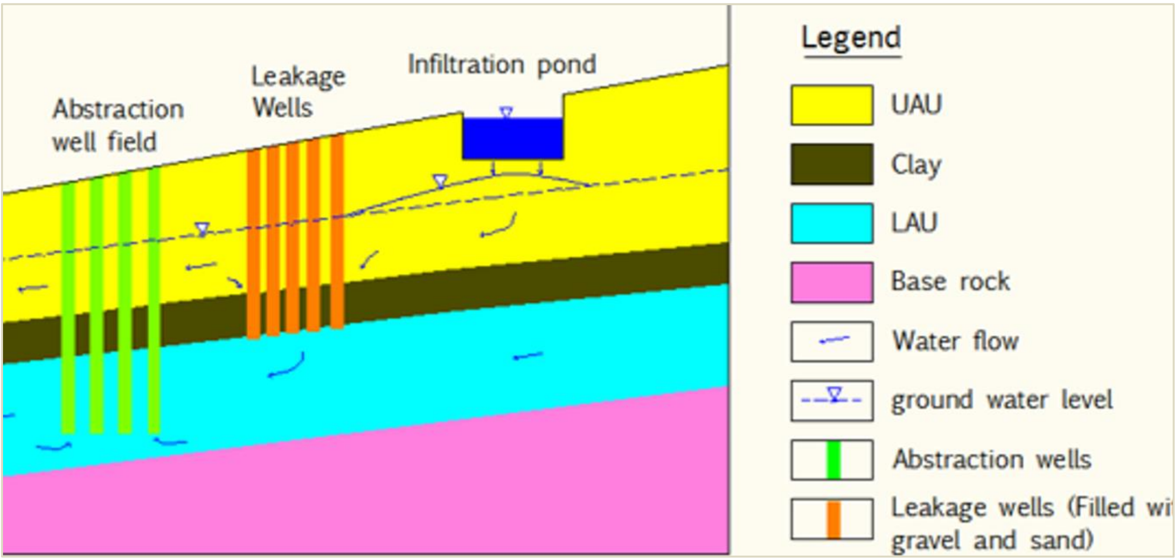


Figure 24 - Scenario for MAR involving infiltration basins, leakage wells to facilitate movement of water from the upper (UAU) to lower (LAU) aquifer units and abstraction wells in the LAU for the Cape West Coast (Jovanovic et al., 2019).

Selection of Sites for Recharge

Research in the area indicated that good hydrogeological data combined with a multidisciplinary science approach to interpret the data, is essential as a forerunner to actual MAR implementation. Earlier injection tests (2008) resulted in downstream boreholes overflowing, thus failing to keep water stored underground as initially expected. By using a two-step approach of combining GIS-based analysis for an overall spatial perspective with modeling of groundwater flow, it was shown that only a relatively small area of the aquifer could benefit from recharging the present wellfield (Zhang et al., 2019).

Major recommendations from the new research phase include the following (Jovanovic et al., 2019):

- monitoring (including water levels and water chemistry) needs to be strengthened around the "clay missing window" area as discussed in Section 5.3 "Aquifer hydraulics", as this is the natural recharge area for the Langebaan and Elandsfontyn aquifers;
- deep boreholes are needed in the "clay missing window" area to improve understanding of the stratigraphic distribution of the clay layer and the real hydraulic conductivity around this window, and the connectivity between the Langebaan and Elandsfontyn aquifers;
- more detailed analysis of existing available water level records needs to be completed to better understand the hydraulic connectivity between the two aquifers; and,
- monitoring of water levels, water chemistry, clogging potential as well as injection trials to obtain parameters needed for the implementation of MAR.

5.6 Water Resource Management Environment

Local and district municipalities in the Cape West Coast are working together to explore and study the groundwater system, to understand it and successfully implement sustainable water supply schemes. The approach taken in this MAR research and implementation project can be best described as an inclusive one which integrates water resources social and scientific elements of the system/region – in essence an integrated water resource management approach.

Achieving Stakeholder Engagement

Even before consideration of MAR, development of the Langebaan Road wellfield had shown that structured participation in the management of these local groundwater resources was of critical importance and that success could not be achieved without cooperation between all parties, in particular the various government departments. These stakeholders all participate in some capacity in decision making regarding the testing, implementing and monitoring of MAR in the Langebaan and Elandsfontein areas. An independent monitoring committee was considered to be of utmost importance to ensure the successful management of a sustainable groundwater resource (du Plessis, 2009).

Stakeholder engagement complemented the hydro-sciences component of the implementation. To achieve engagement, a stakeholder map was developed to identify the linkages between stakeholders, get their input into the project and engage them further to identify emergent political, social, cultural and economic dynamics related to the MAR scheme. The range of stakeholders (Table 6) identified in this way can provide insight into the complexity of integrated water resource management.

Table 6 - Stakeholders in the Langebaan scheme.

Government	National Department of Public Works; National Department of Water, Sanitation and Human Settlements; National Department of Environment, Forestry and Fisheries; SANParks; SA National Defence Force; Cape Nature; Western Cape Department of Environmental Affairs and Development Planning; Western Cape Department of Agriculture; Western Cape Regional Office of Water, Sanitation and Human Settlements; West Coast Tourism; West Coast District Municipality; Swartland Local Municipality; Berg River Local Municipality; Saldanha Bay Local Municipality
Civil Society and NGOs	West Coast Biosphere; Saldanha Bay Water Quality Forum; St Helena Bay Water Quality Forum; the West Coast Fossil Park; West Coast Botanical Society; Birdlife SA
R&D	CSIR; University of the Western Cape; Anchor Environmental Consultants
Water users	Ward Committees; Farmers Associations in Hopefield and Vredendal; the Aquaculture Society in Langebaan; land owners and farm owners; the Berg-Olifants proto Catchment Management Association; Berg River and Wilge River Irrigation Boards; mines; other industrial users; small-scale farmers
Media	Swartland and Weslander newspapers

5.7 Evaluation and Way Forward

The local and district municipalities together with local consultants and universities are currently conducting research and running scenarios. Scheme management will most likely be run in the same fashion, with the Saldanha Bay municipality and West Coast District Municipality taking ownership of the scheme and working with local institutions and consultants with expertise to monitor and guide the scheme's efficiency and sustainability. Though not yet implemented, the approach adopted with MAR development on the Cape West Coast can already provide lessons.

A Phased Implementation Approach

The area requires a phased approach to MAR implementation including the following:

- behavior of newly drilled abstraction wellfields needs to be established prior to testing of artificial recharge options;

- different options can start being tested after water chemistry tests have been done to evaluate mixing of groundwater sources and final water composition;
- evaluate the suitability of the area that has been identified as a potential site for artificial recharge, and consider alternatives if necessary;
- evaluate whether the preliminary estimates of the major infrastructure requirements are accurate and improve the estimates as needed;
- conduct infiltration tests prior to basin construction;
- evaluate whether treatment of final water is necessary and design the treatment if needed; and,
- monitor changes in pH, redox potential, temperature and relevant ion concentrations over time as early warning signs of clogging.

6 Case Study: Windhoek, Namibia

6.1 The Need for Artificial Recharge – Setting the Scene

This case study focuses on the water resource situation in arid countries like Namibia, which are approaching or have reached the end of their conventional water resources. In these cases, there is no option but to use and enhance local groundwater resources. Hard-rock aquifers (a feature of the hydrogeology of Africa) and their associated MAR issues provide a further focus. A summary of the Windhoek system is provided in Table 7.

Table 7 - Windhoek MAR Scheme.

Name of scheme	Windhoek MAR Scheme
Location	City of Windhoek, Namibia
Mean annual rainfall	360 mm/year
Source of water	Surface water impoundments
Type of aquifer	Fractured quartzite
End use of water	Domestic and industrial use
Type of managed aquifer recharge	Borehole injection
Current average volume of water recharged	12 Mm^3/year
Volume of water recovered	19 Mm^3/year during drought abstraction
Year commenced	2006
Owner/management of scheme	City of Windhoek together with Namibia Water Corporation (NamWater)
Unique attributes of this MAR scheme	Large-scale deep borehole injection into hard-rock aquifer; aquifer storage used as 'water bank', covering up to 3 years of city's water supply during a drought cycle.

Namibia is located along the arid south-west coast of Africa. The capital, Windhoek (population 326,000 in 2011), is situated in a semiarid region of the country's central highlands (Figure 25). The average annual rainfall in Windhoek is 360 mm and the average evaporation is 2170 mm/year. River systems originating in the Auas and Eros Mountain ranges are draining away from the city in all directions. As a result, local surface water resources are very limited and most of the city's water supply is obtained from surface impoundments located tens to hundreds of kilometers from the city. Large fluctuations in annual rainfall aggravate the situation (Kirchner and van Wyk, 2001; Murray, 2017).

Figure 25 - Windhoek central city and mountains in background (Pixabay↗).

Windhoek owes its existence to the presence of springs, which provided an ample supply of water when the area was first settled around 1840. The mostly thermal springs emerged from deep-seated faults in quartzites that form the main aquifer. The town continued to rely on groundwater and in 1911 a wellfield development was initiated. In 1933 a small surface storage dam was added. As a result of overuse of the aquifer, another surface storage dam, located further away, was added in 1957. In the years from 1966 to 1969, use of the aquifer had grown to 2.5 times the estimated average natural recharge of 1.7 Mm^3/year, so development of supplementary water sources became urgent (Murray, 2017; Kirchner and van Wyk, 2001).

Augmentation Options in a Water-Scarce Country

By 1974 a new water master plan included an Eastern National Water Carrier to supply water to the central areas from the Okavango River some 750 kilometers to the north. Construction of the carrier began in the late 1970s in several phases. First, a 94-kilometer pipeline was built from the Von-Bach Dam at Okahandja to the Omatako Dam. From there an open water canal was constructed for approximately 300 km to Grootfontein and groundwater from the Berg Aukas mine was pumped into the canal. The last phase of the Eastern National Water Carrier, connecting Grootfontein to the Okavango River near Rundu, was never built. However, the latest information indicates that due to the current drought, a pipeline from Rundu to Grootfontein is being considered again to augment the water supply for the central areas of Namibia (Weidlich, 2019).

By 2000, the water demand stood at 20 Mm^3/year and most of the city's water was coming from the surface water supply scheme consisting of three interconnected dams as discussed in Section 3 "The Source Water". The wellfield contribution was about 10 percent of the city's total water supply and another 10 percent was coming from the wastewater reclamation.

In 1968, headlines in South African papers read: "Windhoek drinks sewage water." Following pilot studies from the early 1960s regarding direct reclamation of sewage water, a full plant was built in 1968. In 2001, the New Goreangab Reclamation Plant was built with a capacity of 7.7 Mm^3/year, which was one of the largest of its kind in the world at the time. Windhoek had become one of the first cities in the world to introduce direct recycling of effluent for drinking purposes (du Pisanie, 2006).

An important water demand management measure has been the use of wastewater for the restricted irrigation of sports fields, parks and cemeteries within the city. Since 2002, the New Goreangab Reclamation Plant supplies a better quality of water for unrestricted irrigation. Approximately 1.4 Mm^3 was produced for irrigation in 2002 and the supply from this system is expected to increase further (van Rensburg, 2006).

Still, Windhoek was fast outgrowing the available water resources and attention turned to MAR. From 1997 to 1998, four borehole injection tests were conducted in the Windhoek Aquifer and an economic feasibility study by the city indicated that artificial recharge was the most viable water supply augmentation option available. In 2002, construction of the first stage of the scheme took place. It included six injection boreholes with a combined recharge capacity of 10,000 m^3/day (Murray et al., 2018).

Actual 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. This included the drilling of new deep boreholes of up to 500 m depth for abstraction purposes. The aim is to utilize as much of the aquifer's storage as practically possible (as a water bank), as this will significantly enhance the city's water supply security (Murray, 2017; Murray et al., 2018).

The cost of the entire MAR scheme (from 2016 onwards) is estimated to be US$ 52.4 million, including borehole siting, drilling and testing, borehole pump installations, bulk supply pump stations, pipelines and power supply infrastructure. The City of Windhoek has already spent over US$ 8.4 million on the scheme, and is looking to fund an additional US$ 9.6 million which they will have to source externally (Murray, 2017).

The MAR Opportunity

A 2013 cost comparison by the Windhoek city engineer (Figure 26) shows the available alternatives – the Tsumeb aquifer (450 km north) and the Okavango River pipeline (700 km north) – to be 1.9 and 2.7 times more expensive than the MAR option. MAR is 1.8 times more expensive than reclaiming Windhoek's sewage water to drinking water quality. The city engineer closed a presentation about the Windhoek Managed Aquifer Recharge with a quotation (Peters, 2014):

> *"We are faced with a series of great opportunities brilliantly disguised as impossible situations" (adapted from Charles Swindoll).*

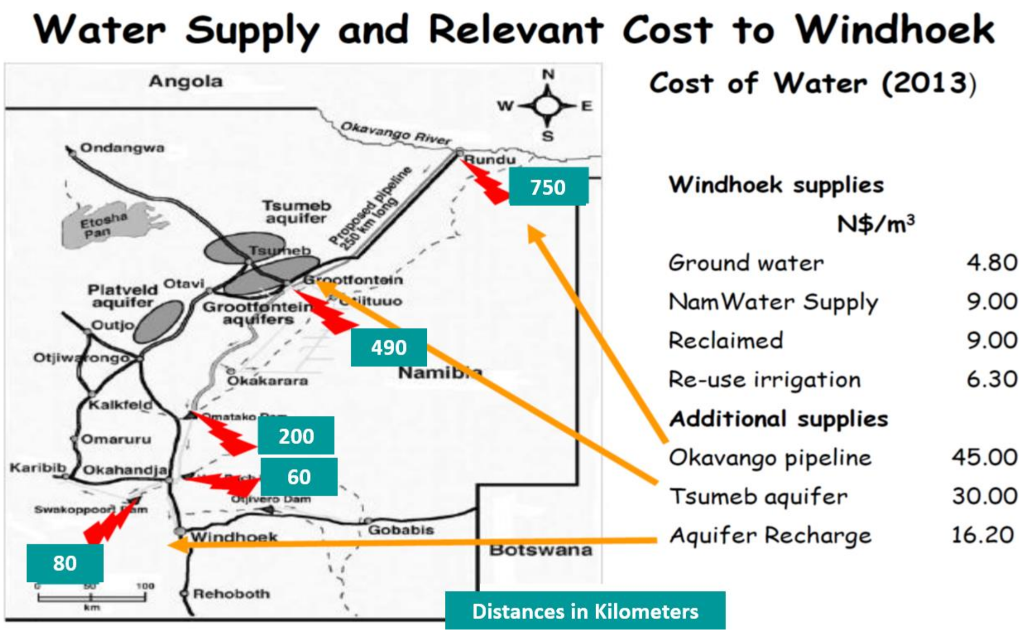


Figure 26 - Windhoek water supply locations and a more recent cost comparison (Peters, 2014).

6.2 Aquifer Hydraulics

The Windhoek aquifer is located to the south of the city, extending northwards from the Auas Mountains for 20 to 25 km to the city center. For MAR to succeed, an aquifer is needed that allows easy access to a relatively large storage capacity.

Favorable Conditions in Hard-Rock Aquifer

Whereas the rock hosting the Windhoek Aquifer consists largely of quartzite with no primary porosity, secondary porosity is present in the aquifer for several reasons. The geological formations within the area were folded in the process of orogenesis and subjected to a number of episodes of faulting including thrusting and rifting. Quartzite and schist horizons with transverse faults and fractures are prevalent throughout the aquifer. The quartzite, being brittle, is highly fractured because of folding and faulting and has developed secondary porosity and permeability. The schist on the other hand is ductile and does not have well developed secondary permeability. Therefore, fractured quartzite has a larger storage capacity per unit volume compared to an equal volume of fractured schist (Murray & Redox, 2002; Redox et al., 2009).

The transmissivity values obtained from the highest-yielding boreholes range between from 100 to 1000 m^2/d for the early-time fracture flow component of the constant discharge pumping tests; late-time transmissivities, which reflect the permeability of the micro-fracture network, range between 50 and 350 m^2/d (Murray, 2002). A tracer test between two boreholes located approximately 800 m apart along a highly permeable fault zone established a surprisingly rapid flow velocity of 216 m/hour, suggesting low effective porosity. The storage coefficients reflect the predominantly confined nature of the aquifer: with the pure quartzites on the order of 0.009 to 0.010, micaceous quartzites ranging from 0.005 to 0.008 and schists with a value of about 0.001 (Murray, 2002).

Hydrogeologically, the aquifer can be divided into three main units of decreasing permeability: quartzite, micaceous quartzite, and schist. The dominant groundwater flow direction is northwards from the quartzite mountains south of the city towards the city which is underlain by schists (Figure 27). The flow follows preferential pathways along the numerous faults and fracture zones that transect the area. The aquifer is bounded by impermeable formations on all sides. (Tredoux et al., 2009c; Murray, 2017).

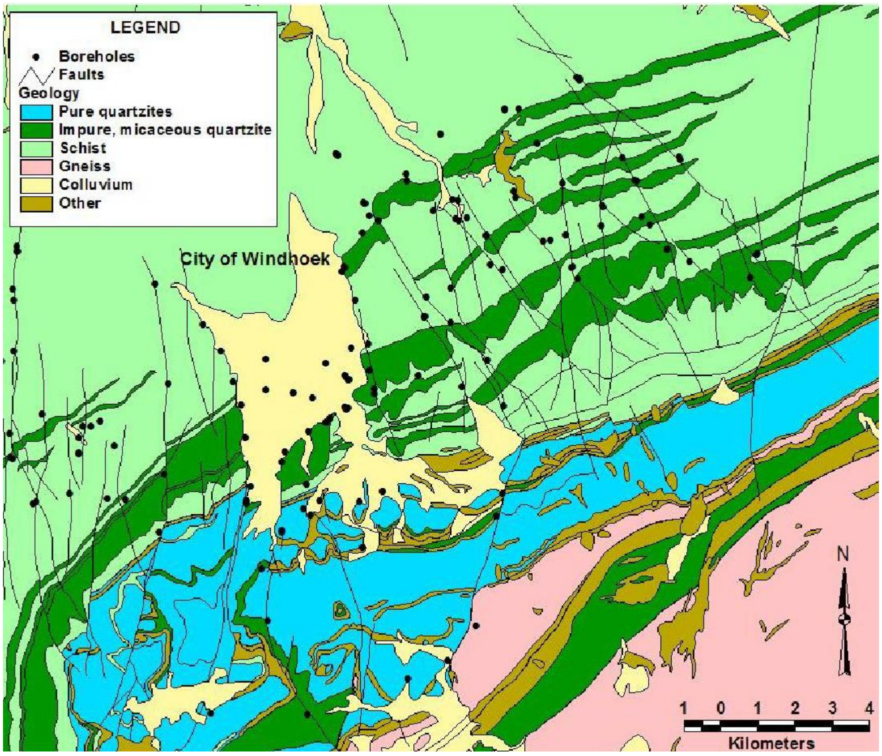


Figure 27 - Simplified geology of the Windhoek Aquifer (Murray, 2002).

Over-Abstraction from Aquifer Storage

Since the onset of large-scale abstraction from the Windhoek Aquifer in the 1950s, in particular during extended drought periods, water levels have dropped tens of meters. Even after five-year rest periods (e.g., from 1970 to 1975), water levels did not recover to their original levels (Figure 28). The aquifer had effectively been over-pumped or "mined". For some periods of high abstraction, water levels would nearly recover to their pre-abstraction levels more than a decade after the event, but then a new period of increased demand would occur. In 2002, the volume of water that had been abstracted from storage since 1950 was estimated to be 28 Mm^3. This available storage presented a major opportunity for artificial recharge (Murray et al., 2018).

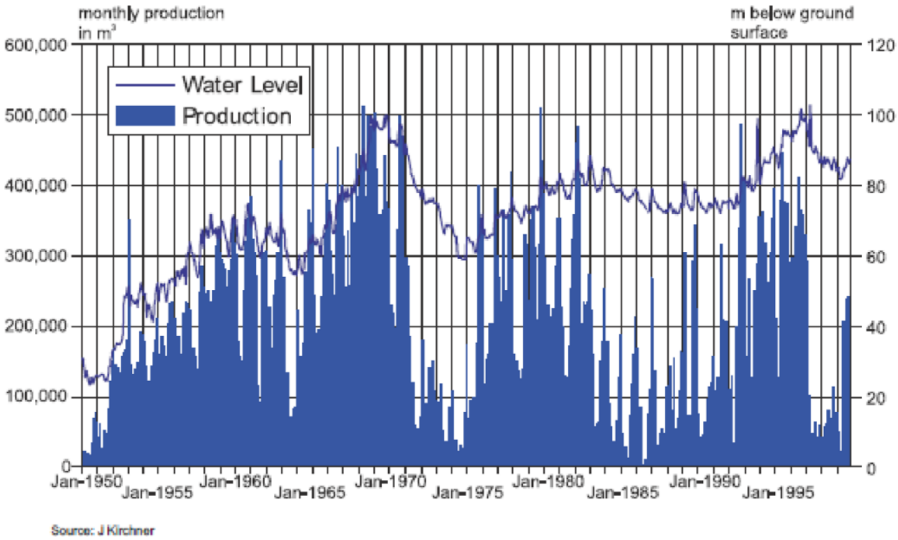


Figure 28 – Production rates and water levels in the Windhoek Aquifer (Kirchner and van Wyk, 2001).

6.3 The Source Water

Source water for injecting into the Windhoek Aquifer (Figure 29) is treated dam water plus reclaimed wastewater.

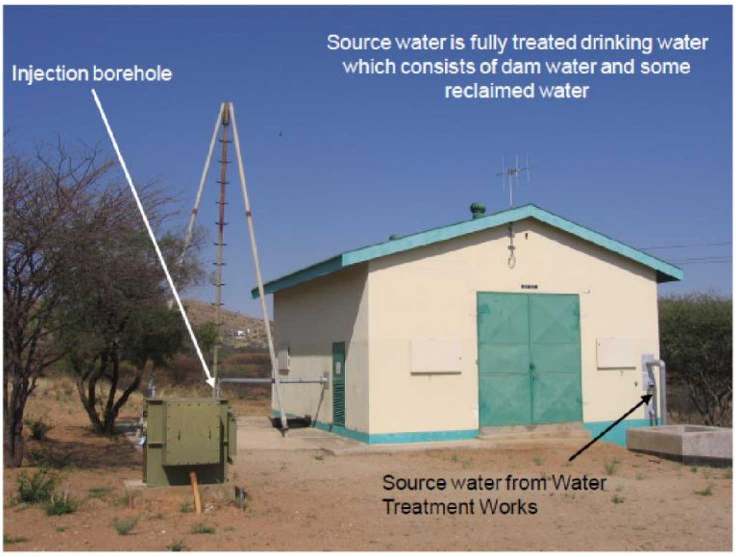


Figure 29 - Injection borehole site with indication of source water (Murray, 2017).

The main source of water supply to Windhoek is the Eastern National Water Carrier, a pipeline that connects the Omatako dam in the north and the Swakoppoort dam in the west with the Von Bach dam located in the central area (Figure 30).

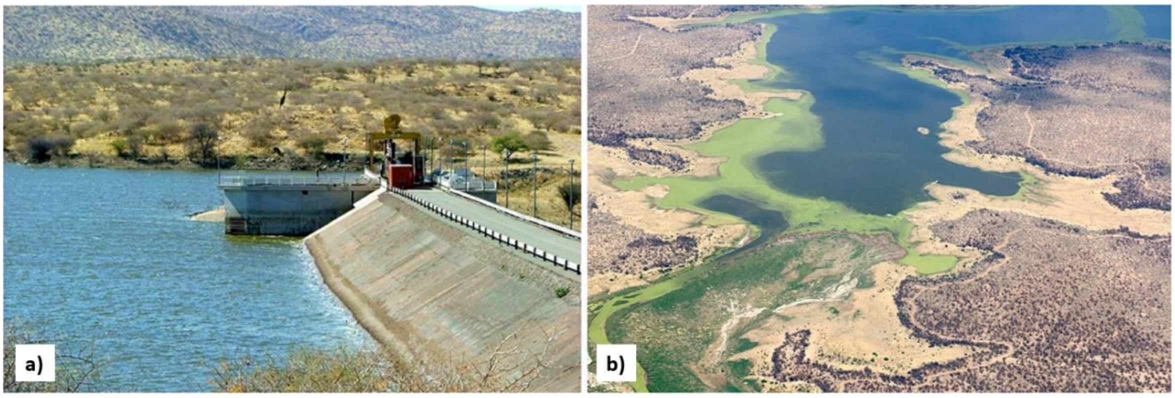


Figure 30 - a) Von Bach Dam, Photo by Menges, 2020 in The Namibian↗. b) Swakoppoort Dam↗, Photo by Baumeler, 2017.

In 2005, the demand of 21 Mm^3/year was met by: 1 Mm^3 from boreholes, 5 Mm^3 from the New Goreangab Water Reclamation Plant (Figure 31), and 15 Mm^3 from surface water in reservoirs (van Rensburg, 2006). The reclamation process is based on the multiple treatment barriers concept to reduce associated risks and improve the water quality. This includes pre-ozonation, enhanced coagulation/dissolved air flotation/rapid sand filtration, and subsequent ozonation, biological and granular activated carbon, filtration/adsorption, ultrafiltration, and chlorination (van Rensburg, 2006; du Pisanie, 2007).

Figure 31 - New Goreangab Water Reclamation Plant (van Rensburg, 2006).

6.4 Water Quality

While the final water quality from the Von Bach Dam Water Treatment Plant has low salinity (as indicated by electrical conductivity) and inorganic constituents, the dissolved organic carbon concentration is very high. Thus, further treatment is essential. Surface/dam water is blended with reclaimed water at a ratio of 3:1 and is further treated by granular activated carbon filtration and chlorination (Figure 32) to reduce the dissolved organic carbon concentration and minimize bacterial growth potential in the aquifer (Tredoux et al., 2009c; Murray et al., 2018).

Figure 32 - Final treatment of the source water (Murray, 2017).

Guiding Principles for Quality of Water Directly Injected into Aquifer

As the recharge water is injected directly into the aquifer without seeping through the unsaturated zone, it was concluded that the injection water quality must conform to drinking water requirements. The following guiding principles for injecting recharge were set (Tredoux et al., 2009):

- 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 stabilization and disinfection;
- the recharge water should meet modern drinking water standards;
- no additional health risk for the residents of Windhoek as compared to sources used in 2004;
- no significant technical problems should arise due to injection water quality such as clogging, corrosion and/or demand for extensive treatment before distribution; and,
- 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.

Aquifer water quality aspects that had a bearing on the decision regarding pre-treatment of the injected water, are briefly touched on below (Tredoux et al., 2009).

- *Salinity:* Low salinity water occurs over most of the aquifer. Groundwater in the Auas Formation quartzites generally has very low chloride concentrations from 4 to 10 mg/L, increasing to a maximum of ~60 mg/L in the deep circulating hot water issuing forth in the city center, reflecting the long residence time at depth.
- *Sulfate:* Sulfate occurs in high concentrations throughout the aquifer due to iron sulfide in the form of pyrite in the host rocks of the Windhoek Aquifer. Dissolved oxygen entering the aquifer with the rainwater during natural recharge oxidizes the sulfide to sulfate. In this way, sulfate is generated in the aquifer until the dissolved oxygen is exhausted. Under natural conditions, the groundwater easily attains sulfate concentrations of 200 to 300 mg/L. In areas where the soil has been disturbed, as in residential areas, the sulfate concentration increases as more of the pyrite is exposed to oxygen entering the aquifer with the rainwater.
- *Iron and manganese:* Iron is ubiquitous in the groundwater in the Windhoek Aquifer. Similarly, manganese is present in the aquifer, which is also mobilized by changes in the redox potential in the aquifer. As a result, borehole clogging is a distinct possibility. Monitoring of the various iron species will be important in order to gain a better understanding of clogging potential.
- *Arsenic:* Fluid-rock interactions in some MAR systems have released arsenic and metals into recharged waters causing an unacceptable deterioration in water quality. The arsenic concentrations in the Windhoek Aquifer are generally very low and close to the detection limit of 0.005 mg/L. 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 in a zone of significantly higher temperatures. The water bank 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 ongoing monitoring confirms this.
- *Water temperatures:* 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. Injection boreholes are all located in the pure and micaceous quartzites where temperatures range between 25 and 30 °C, similar to the temperatures of the injectant (Murray et al., 2018).
- *Dissolved organic carbon:* The concentration of dissolved organic carbon (DOC) in the aquifer is very low, with values generally being < 1 mg/L, except in polluted areas such the Kupferberg waste disposal site and shallow boreholes in the schist (Murray, 2002).

Special Water Quality Concerns Associated with the Borehole Injection

From the available data, it would seem that changes in the oxidation-reduction potential in the subsurface might be the main factor affecting the hydrochemical environment of the Windhoek Aquifer. Major changes in salinity and sulfate were associated with pilot scale injection tests, but such changes are also due to variations in the abstraction regime due to water level fluctuations in the aquifer. The intensity of the effects will depend on the recharge technique, method, and abstraction regime. Injection through a deep borehole at depth will be the preferred technique as cascading of the water through the unsaturated zone will exacerbate any adverse reaction, such as the oxidation of pyrite (Tredoux et al., 2009).

Managing injection water quality according to the set criteria should maintain the high quality of the water stored in the aquifer. To date, the recovered water has had an average salinity of 91 mS/m or 610 mg/L TDS and an average dissolved organic carbon of 1.1 mg/L (Murray, 2017). Mass transport modeling is seen as essential for determining the longer-term impact of the injected water on aquifer water quality (Tredoux et al., 2009).

Special attention will need to be given to protection of the aquifer against all forms of pollution. The threat is illustrated through the Kupferberg waste disposal site in the south-western part of the aquifer. This area has elevated concentrations of chloride, sulfate, organic compounds and iron. Once artificial recharge is fully operational, the water level will rise and the need for protection will further increase (Tredoux et al., 2009, Mapani, 2005).

6.5 Scheme Elements

Borehole injection is the preferred technique for applying managed aquifer recharge in Windhoek. In order to establish the feasibility of recharging this complex aquifer system, it was studied in detail to determine flow characteristics and boundaries. Four borehole injection tests were carried out in both the pure- and micaceous quartzites between 1997 and 1999. Despite the very different hydraulic characteristics between the two quartzite formations that are influenced by both preferential flow paths and barriers to flow, in total 0.5 Mm^3 was successfully recharged (Murray et al., 2018).

The success of the injection tests showed that MAR had the potential to optimize the available resources in the area by injecting the excess water from the three surface reservoirs into the aquifer for use in times of short supply. The injection tests and the historic water level data showed that artificial recharge should be focused in the existing wellfield areas (the micaceous quartzites) and the main natural recharge and storage area (the pure quartzites). This would utilize as much of the aquifer's available storage space as possible as shown on Figure 33 (Murray, 2017).

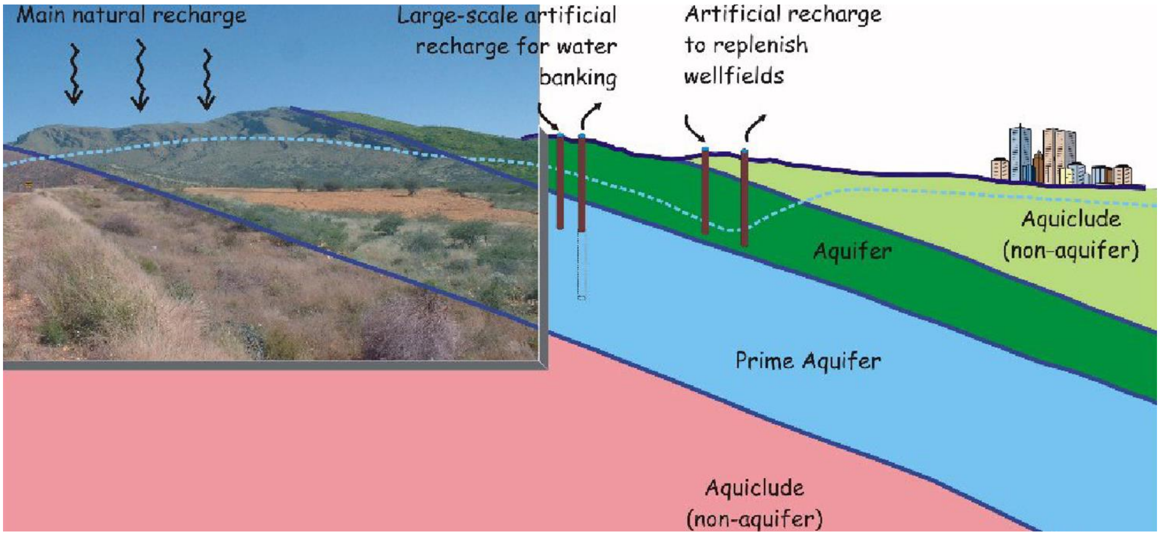


Figure 33 - Schematic of the main lithologies and injection areas (Murray, 2017).

MAR was developed in phases. Borehole injection started in 2006 and continued until 2012 when the targeted recharge area could not receive any more water. The first stage included six injection boreholes with a combined recharge capacity of 10,000 m^3/day. The scheme's success led to two expansion phases with a third planned for 2017.

The first expansion phase resulted in drilling an additional 10 recharge boreholes with a combined injection capacity of 16,000 m^3/day, which is equivalent to 40 percent of the city's annual water requirements, compared to the 10 percent achieved through the previous borehole abstraction scheme. To allow for abstraction of this water when required, 10 "deep" abstraction boreholes with a combined recovery capacity of 18,000 m^3/day were also drilled. 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 m^3/day (Murray et al., 2018).

Benefits of Windhoek MAR Scheme

Windhoek's city engineer outlined the expected benefits of the scheme in an interview in 2004 (van Rensburg, 2006):

- it will reduce the evaporation losses by banking water underground in years when there is surplus run off into the surface storage dams which would otherwise have evaporated, effectively increasing the yield of the reservoirs;
- it is estimated that with the use of deep wells (400 to 500 m depth) in the Windhoek aquifer there will be a "bank" of at least 100 Mm^3 available for abstraction in years of water shortage that can be replenished again in years of abundance; and,
- having a large bank of water available at the point of consumption makes it possible to meet peak demand from the aquifer so the large-capacity, bulk-supply schemes of NamWater, which traverse hundreds of kilometers, will

not have to be designed to supply the peak demand, but only the average demand, effecting a substantial cost saving.

Planning and implementation are continuing. The best estimate of the potential water bank is 90 Mm^3 or about three times the current annual water use. At this stage the existing boreholes cannot access all this water and new deep boreholes are being drilled. The following goals were set:

- increase recharge to 12 Mm^3/year by 2019;
- equip boreholes for drought abstraction of 19 Mm^3/year from 2019; and,
- increase the storage capacity of the water bank from 41 Mm^3 to 71 Mm^3/year after completion of boreholes and infrastructure from 2018 to 2019 (Murray, 2017).

6.6 Water Resource Management Environment

Windhoek is a city that does not have the luxury of permanent fresh water bodies in close proximity. Consequently, it has been committed to the integration of all dimensions of integrated water resource management to secure the supply of water to the city (van Rensburg, 2006). In particular, the city introduced water demand management in 1992, whereas previous water authorities had pursued a policy of unlimited water supply at low cost to the consumer. The demand management strategy concentrates on changing consumer habits by increasing public awareness of the importance of water saving and implementing a block tariff system that steeply increases cost with increasing water consumption. Other measures include the reduction of residential plot sizes, implementation of legislation to address water conservation in Windhoek, and improved maintenance and technical measures to reduce leaks. Evidence for the success of water demand management is the remarkable reduction in the water consumption by the late 1990s. In 1997, the total water use was equivalent to that of 1990, despite a 45 percent population increase (Kirchner and van Wyk, 2001; van Rensburg, 2006).

Reliance on local groundwater sources has a history in Namibia and has greatly helped to make the complex MAR scheme a reality. Conjunctive use was already practiced before MAR, after the much more unreliable surface water storages were added. The dams were used during periods of plenty and the aquifer during droughts. There was also the wisdom of regular investment into drilling and expansion of the well field during periods of plenty (Kirchner, 1981). The storage of surface water underground could be seen as a next logical step.

Finance Model for the MAR Scheme

Financing the operation of the MAR scheme, for which there was no precedent, posed new challenges and a unique model was developed:

- the source water, obtained primarily from the three-dam supply system, is bought from the bulk supply authority NamWater and sold to the municipality for storage in the municipal-run aquifer;
- the City of Windhoek pays NamWater the operational costs for the recharge water so that 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 of Windhoek to consumers, at which time the city pays NamWater an additional amount for each cubic meter the city supplies from the Windhoek Aquifer;
- the evaluation of whether the city is serving artificially recharged water 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" of 1.73 Mm^3/year;
- the plan benefits both organizations and consumers as it improves the security of supply during extended periods of drought and affords NamWater income during droughts (when they sell less water); and,
- it can be argued that low-value water, which would have evaporated from the source dams, is now stored in the aquifer 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 (Murray et al., 2018).

6.7 Evaluation and Way Ahead

Since 2013, the water demand in the Central Area of Namibia was well above the 95 percent safe yield of the available resources. The water demand for the City of Windhoek alone is expected to nearly double by 2050. In 2014 an Environmental Impact Assessment recognized the positive socio-economic impacts of the MAR scheme in creating a sustainable water source for the Central Area of Namibia. MAR is therefore considered an essential component for securing the future of the population in the central area and will play a key role in sustaining development and socio-economic health (Murray, 2017).

In the recent drought (2015 to 2016), borehole water together with strict demand management provided Windhoek's water security. This was possible because the aquifer had been replenished via borehole injection prior to the drought. 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.

The Windhoek Aquifer is especially vulnerable along the quartzites in the Auas Mountains and along the foothills of the mountains, which lie on the southern edge of the Windhoek basin. Concerns were expressed about the wide range of threats to the aquifer, e.g., sewer pipe bursts and leakages from septic tanks, filling stations, dumpsites and cemeteries. Unplanned settlements were likely to become major sources of contamination in the future. Special care is therefore needed to fully preserve this strategic water source for the future (Mapani, 2005). The City of Windhoek seems to be fully committed and has addressed this in town planning from the beginning. All future development areas south of the existing (2004) development were identified as areas with a high to very high pollution potential and as such were deemed "no development zones". Various other already developed zones have restricted and prohibited uses. In some instances, the city had no choice but to relocate industries with a high pollutant potential. The commitment by the city is highlighted by the fact that two hydrogeologists were appointed to specifically address the protection of the Windhoek Aquifer (van Rensburg, 2006; du Pisanie, 2007).

7 Case Study: Kharkams, Semi-Arid Interior, South Africa

7.1 The Need for Artificial Recharge – Setting the Scene

Kharkams is a small village with a population of 1700 in the semi-arid Namaqualand region of South Africa. Namaqualand receives winter rainfall, on average less than 200 mm. There are no perennial rivers in the area and water is obtained from subterranean sources. During the short spring in this region, between August and September, a few drops of rain transform the arid landscape with vast expanses of wild flowers of every shape and color, creating carpets of bright orange and yellow as shown on Figure 34 (Travel Guide, 2020). A summary of the Kharkams system is provided in Table 8.

Figure 34 - Wild flowers in Namaqualand (Travel Guide, 2020).

Table 8 - Kharkams scheme.

Name of scheme	Kharkams
Location	Village in Namaqualand, South Africa
Mean annual rainfall	< 200 mm
Source of water	Flood water (irregular)
Type of aquifer	Hard rock (granites and gneisses) aquifer
End use of water	Domestic use
Type of managed aquifer recharge	Borehole injection
Current average volume of water recharged	1 L/s maximum injection rate
Volume of water recovered	0.005 Mm^3/year
Year commenced	1995
Owner/management of scheme	Kamiesberg local municipality
Unique attributes of this MAR scheme	Only source in arid remote area; cheap and simple technology

7.2 The Source Water

The source water is from a local ephemeral river. Although there is no visible flow in the river for most of the time, it does experience flooding events from time to time. Because such floods carry a significant sediment load, filtration of debris and clay is necessary before injection into a borehole.

Small-Scale Water Supply in a Semi-Arid Area

The village depends solely on groundwater, pumped from the municipality's three abstraction boreholes. Natural groundwater recharge is very low and as a result of abstraction since the mid-1990s, groundwater levels had dropped tens of meters and the water quality (salinity) had deteriorated significantly. The aim of artificial recharge is to reverse this negative trend by rapidly replenishing the aquifer when river runoff is available. This action significantly increases the borehole yields and improves water quality. People living in this remote, arid area depend on the functioning of this scheme.

One of the key management functions of any MAR scheme is to avoid clogging, the potential for which is especially high in borehole injection schemes. Schemes in primary aquifers – those made up of unconsolidated sand – are not as susceptible to this problem because they normally rely on infiltration to get the recharge to the aquifer. The scheme at Kharkams includes a sand filter that is built in the bed of the river. Most of the water, when available, flows over and past the filter, but some infiltrates the sand filter and flows to the injection boreholes (Murray, 2004).

7.3 Aquifer Hydraulics

Namaqualand is characterized by a hard-rock geology. The Kharkams aquifer consists of granites and gneisses cut by major faults on which high yielding boreholes are sited.

7.4 Water Quality

The groundwater quality is characterized by relatively high salinities (~250 mS/m), and high fluoride (~3 mg/L). The water quality changes from relatively fresh water near the surface to older, more stagnant water at depth.

7.5 Scheme Elements

Artificial recharge began at the site in 1995 and based on initial experience, the CSIR team made some modifications to the design. In line with the small demand, the scheme only has a maximum injection rate of 1 L/s. The basic scheme elements are illustrated in Figures 35 and 36.

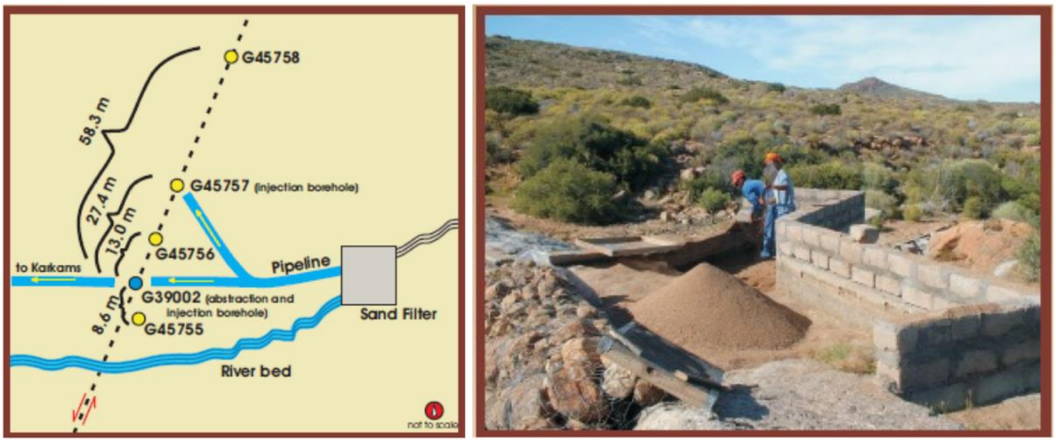


Figure 35 - Scheme layout with sand filter – river sand is sieved for the filter (Murray, 2004).

Figure 36 - Sand filter with injection and abstraction borehole (pump house) in the background (Murray, 2008).

Three controlled injection runs from 1999 to 2001 had the effect of reversing the declining water level trend. During the longest test, which lasted for 138 days, 6,567 m^3 was injected. This is more than twice the annual sustainable yield of the borehole (2,400 m^3/year).

The water quality improved significantly after injecting the clear filtered river water. With three consecutive years of artificial recharge, the electrical conductivity values decreased from over 250 mS/m prior to injection to less than 100 mS/m after injection as shown in Figure 37 (Murray, 2004).

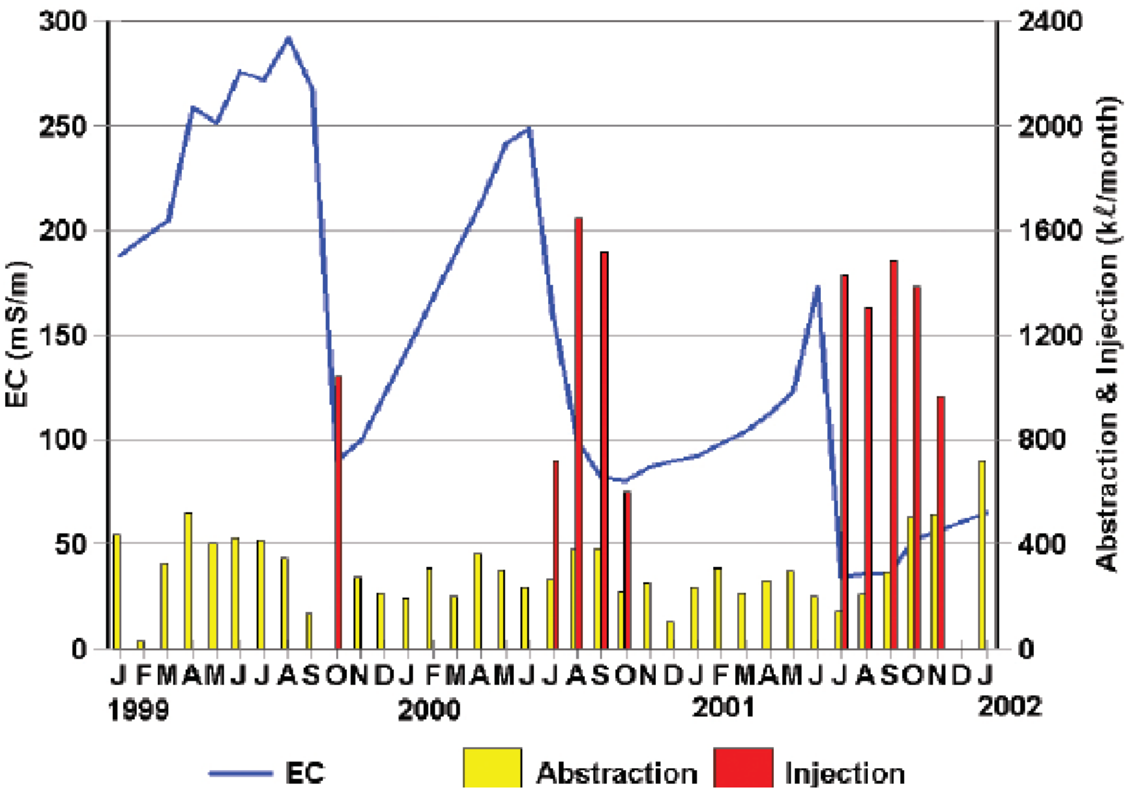


Figure 37 - Water quality at Kharkams abstraction borehole (Water Wheel, 2003).

Even though the scheme is small and relatively simple, basic maintenance is required otherwise efficiency will decline. In the case of Kharkams, the only maintenance required during operation is weekly removal of the fine sediment that settles on the filter since it slows down infiltration.

7.6 Water Resource Management Environment

The Kamiesberg local municipality provides services to 16 small towns and villages, including Kharkams. It provided the three abstraction boreholes. The national Department of Water Affairs and Forestry has been very supportive of MAR and drilled four monitoring boreholes, one of which became the new injection borehole.

7.7 Evaluation and Way Ahead

This semi-arid area supports mainly sheep and goat farming and is sparsely populated. The scheme meets the community needs and demonstrates the value of opportunistic artificial recharge in semi-arid areas, even if it is only practiced on a small scale.

The scheme is ingenious in its simplicity. *"All it involves is taking some of the river flow when it rains, draining it through a sand filter in the river bed, and then gravity-feeding it into a borehole,"* says Dr. Murray. *"There are no pumping costs, and the maintenance costs – merely removing debris and clay from the sand filter between injection runs – are insignificant. It's almost crazy not to do it, because it's so cheap and simple."* Cheap and simple it may be, but the recharge is potentially enough to double the sustainable yield of the borehole. An added advantage is that it improves water quality significantly.

The scheme received praise at both the local level and at the highest international level:

- Dr. Ricky Murray, champion of MAR in South Africa and beyond: "Groundwater in Namaqualand is generally quite saline, and the injection of freshwater dilutes it. We got feedback from the residents of Kharkams that this is the best water they've ever had!"
- Dr. Peter Dillon, Chairman of the International Association of Hydrogeologists' Commission on Managing Aquifer Recharge: judged the Kharkams scheme an *"unqualified success". "This is a low-cost technology and will be of great value in achieving South Africa's plan for enhancing water supplies to rural and remote communities."* (Water Wheel, 2003).

8 Case Study: Plettenberg Bay, Southern Cape, South Africa

8.1 The Need for Artificial Recharge- Setting the Scene

Plettenberg Bay is a popular tourist destination along the garden route on the Cape South Coast (Figure 38). It has a local population of 29,000 (2011 census), but there is a large tourist influx and a large proportion of second homes used exclusively during peak holiday periods around December. It is typified by an extremely mild maritime temperate climate with few extremes of rainfall or temperature. Average rainfall is 945 mm/year (Wikipedia, 2016). Past periods of inadequate supply in towns along the Cape South Coast must be seen as institutional rather than hydrological. A summary of the Plettenberg system is provided in Table 9.

Figure 38 - Plettenberg Bay↗.

Table 9 - Plettenberg Bay scheme.

Name of scheme	Plettenberg Bay
Location	Plettenberg Bay, Southern Cape, South Africa
Mean annual rainfall	945 mm/year
Source of water	River water
Type of aquifer	Hard rock (quartz-arenites) aquifer
End use of water	Domestic supply
Type of managed aquifer recharge	Borehole injection
Current average volume of water recharged	Feasibility: injection rate > 10 L/s 0.4 Mm^3/year (over 3 months)
Volume of water recovered	0.8 Mm^3/year (over 5 peak months)
Year commenced	Not yet (pre-feasibility in 2007)
Owner/management of scheme	Bitou Local Municipality
Unique attributes of this MAR scheme	Injection during winter for peak demand period in summer; capital costs one third of desalination plant.

Plettenberg Bay has both a high demand for water in the summer and a surplus of water in the winter, making it potentially a good candidate for artificial recharge. The main objective of artificial recharge in this case would be to allow an aquifer to deliver more water during times of peak demand than would otherwise be possible. An artificial recharge assessment was conducted in 2007 (Murray, 2007) with the idea of injecting water from the Keurbooms River, which discharges into the bay, into an aquifer already tapped by the Bitou municipality, the responsible local authority within the Eden District Municipality (Figure 39).

Figure 39 - Eden District Municipality, Western Cape, including Bitou and Knysna local municipalities (EMG, 2011).

Despite an excellent MAR pre-feasibility study to which a number of different parties contributed, implementation has not taken place, more than ten years later. Because of a similar failure to consider MAR at the neighboring Knysna municipality and because of implications for the whole coastal region, the Plettenberg Bay case study is included. Discussion of the existing water resource governance framework can hopefully add insight to the evaluation of remaining bottlenecks discussed in Section 9.2 "Roll-Out of the Artificial Recharge Strategy".

8.2 The Source Water

Water supply and artificial recharge will take place within the water supply system combining the town of Plettenberg Bay and its township, Kwanokathula. At present, the town depends on surface water from the Keurbooms River for most of its domestic water supply needs. Water quality in the Keurbooms is generally very good. During periods of low demand, raw water bypasses the treatment plant and is piped to the Roodefontein Dam, where it can be retrieved when necessary. The salinity of Roodefontein Dam's water, however, is high, and this makes blending with "pure" Keurbooms River water necessary prior to supply. In addition to the surface water resources, there is a groundwater source in the Kwanokathula area used solely in the township. The combined average yield of the Kwanokathula boreholes is not sufficient to meet the total demand of Kwanokathula, and the balance is drawn from the Keurbooms River via the water treatment works.

8.3 Aquifer Hydraulics

Underlying the township of Kwanokathula is the Peninsula Formation, a quartzite unit of the Table Mountain Group (Figure 40) that occurs as a roughly east to west, one-to-two-kilometer-wide band.

Figure 40 - Jointed and fractured Peninsula Formation Quartzite at Plettenberg Bay (Murray 2007).

MAR Considerations in a Fractured Aquifer

Aquifers of the Table Mountain Group have been exploited for their high-quality groundwater for decades by farmers, smallholders and other private users. The Table Mountain Group consists mainly of quartz-arenites, with subordinate and often thin shales and siltstones. It was intensely deformed and thickened by the Permo-Triassic Cape Orogeny, leading to often overturned folds, and strong fracture cleavage. Primary porosity and permeability in the quartz-arenites is negligible, and both storage and transmission of groundwater is via fractures, fault planes and other secondary features (Pietersen and Parsons, 2001). Borehole yields in these rocks can exceed 30 L/s. Key issues relating to possible MAR in this aquifer include (Murray and Ravenscroft, 2010):

- Is the aquifer sufficiently permeable to accept recharged water?
- What is the storage capacity of the aquifer?
- Will the recharged water be recoverable? Or put another way, will the recharged water remain in storage until it is needed?

The pre-feasibility work provided some important insights into these questions. The injection test (Figure 41) indicated that the aquifer is highly permeable. It has a very high storage capacity and can easily accept injection water at a rate of > 10 L/s, with water flowing rapidly away from the point of injection. Initial groundwater level interpretation indicated that aquifer storage should not be operated above an elevation of 60 m in order to minimize the chance of water losses. This must be confirmed in a more detailed study of the flow system. Considering the aquifer dimensions and a conservative storage coefficient of 0.3 percent, it was estimated that, to achieve an artificial recharge target of 400 million liters, it would require about 30 m of vertical aquifer thickness as shown on Table 10 (Murray and Ravenscroft, 2010).

Figure 41 - Production borehole converted for conducting injection test (Murray and Ravenscroft, 2010).

The boundaries of the Kwanokathula Aquifer are the Cedarberg shales to the north and Cretaceous rocks including the Enon conglomerates to the south (including a possible fault). It is considered unbounded for practical purposes to the east (where it underlies the ocean) and to the west, where it continues for many kilometers. A north-south cross-section of the aquifer is shown in Figure 42.

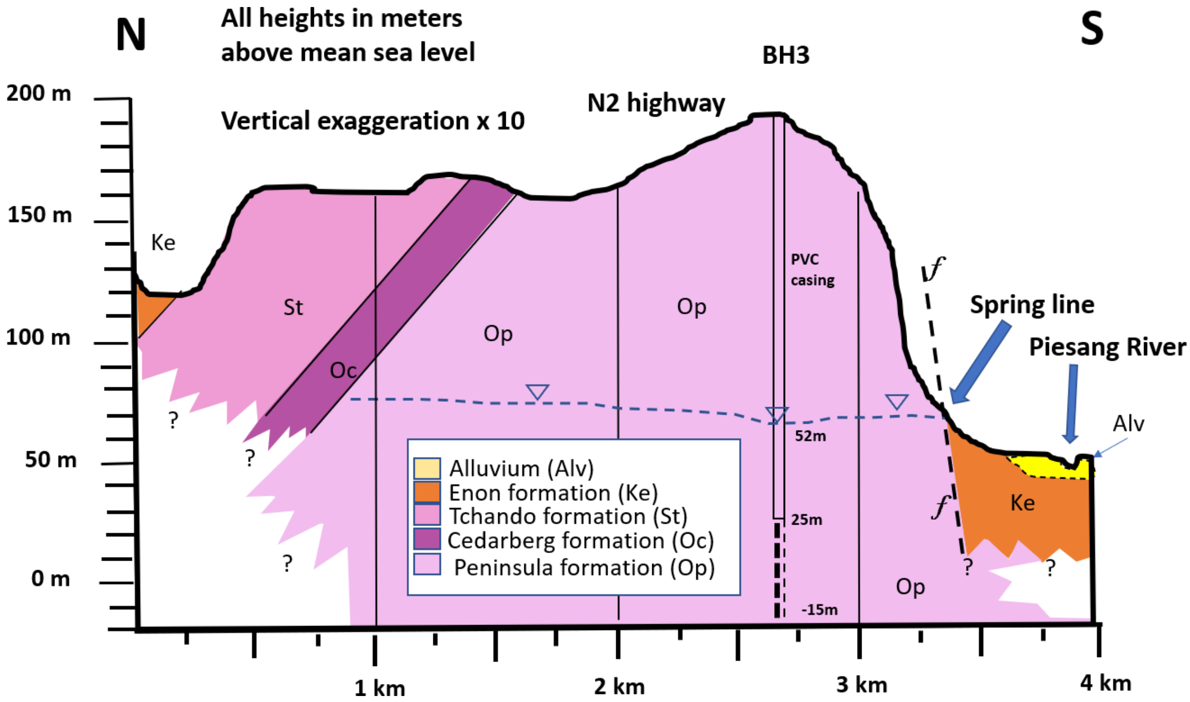


Figure 42 - North-south hydrogeological cross-section of the Kwanokathula Aquifer (Murray, 2007).

Table 10 - Summary of Kwanokathula Aquifer properties (Murray, 2007).

Total aquifer area	22 km^2
Transmissivity	70 m/d
Storage coefficient	0.5%
Groundwater gradient	1:150 (0.007), roughly from west to east
Recharge	7% of total rainfall
Average thickness	70 m

8.4 Water Quality

The chemical water quality of the Keurbooms River is very high. The water flows over the relatively inert sandstones of the Table Mountain Group. This is in contrast to Roodefontein Dam's water quality, which is significantly more saline, being located on the saline Enon conglomerates.

Dissolved Iron and Borehole Clogging

Iron-related problems are common in the Table Mountain Group aquifers, specifically in boreholes which target both the Peninsula and Nardouw groups in the Eastern Cape (Smith, 2006). Iron is known to occur in some of the boreholes in the Kwanokathula Aquifer. These should be avoided as a recharge location if possible. An option may be to fix iron in these locations by injecting oxygenated water in this area.

The preferred option for MAR is to use treated water from the Keurbooms River (Murray, 2007) because dissolved organic carbon (DOC) and iron concentrations in the untreated water might encourage borehole clogging and plugging of aquifer fractures around the injection boreholes. Aeration and filtration will usually remove some of the dissolved iron. Treatment also removes dissolved oxygen, which improves the likely success of artificial recharge, particularly if microbial reactions are contributing to the oxidation of iron in the aquifer. Another benefit of treatment is that the water is disinfected by chlorination. It was also recommended that the production boreholes be pumped at a continuous low(er) rate rather than intermittently at a higher rate. This avoids the oxidation and iron precipitation problems in the aquifer and on the steel borehole casing associated with repeatedly raising and lowering the water level which allows aquifer water to flow back into these zones (Tredoux, 2007).

8.5 Scheme Elements

The presently authorized groundwater use of 11.5 L/s (about 1,000 m^3/day) from the Kwanokathula Aquifer could potentially be tripled to about 3,000 m^3/day through MAR. The aquifer would need to hold the recharged water from winter when it is recharged until summer when the water is abstracted again during the peak season. The summer peak demand for Plettenberg Bay is 12 to 13 million liters/day and the peak week Christmas-New Year is 17 to 18 million liters/day. The water supply scheme elements are shown in

Figure 43. The MAR pre-feasibility study indicated how the scheme could be expanded (Figure 44).

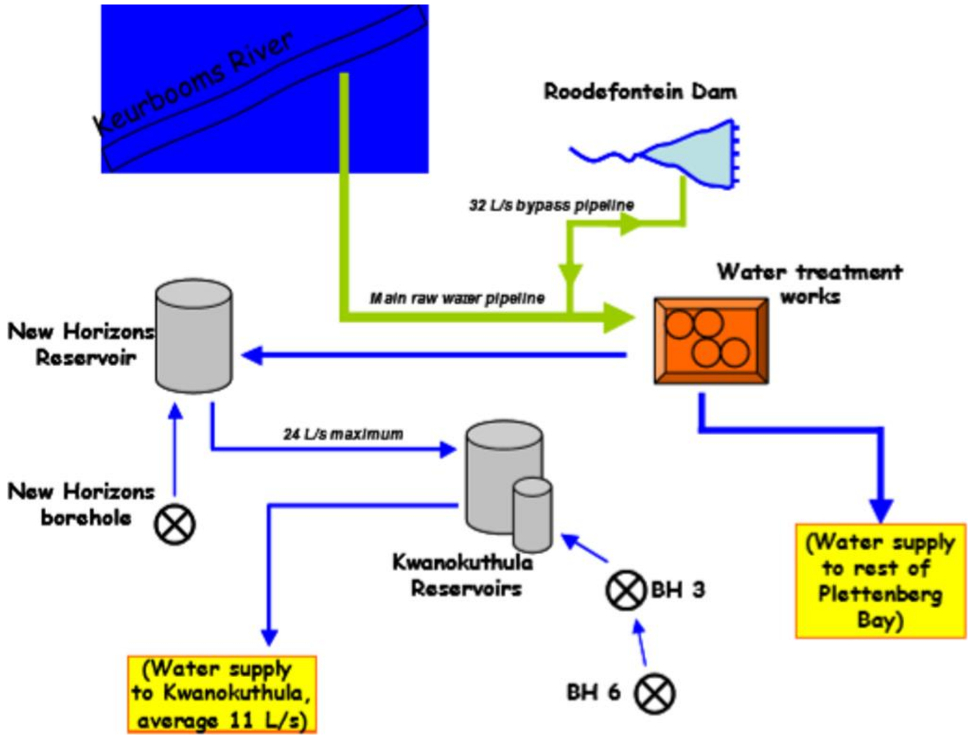


Figure 43 - Schematic diagram of the existing water supply arrangements for Greater Plettenberg Bay (Murray, 2007).

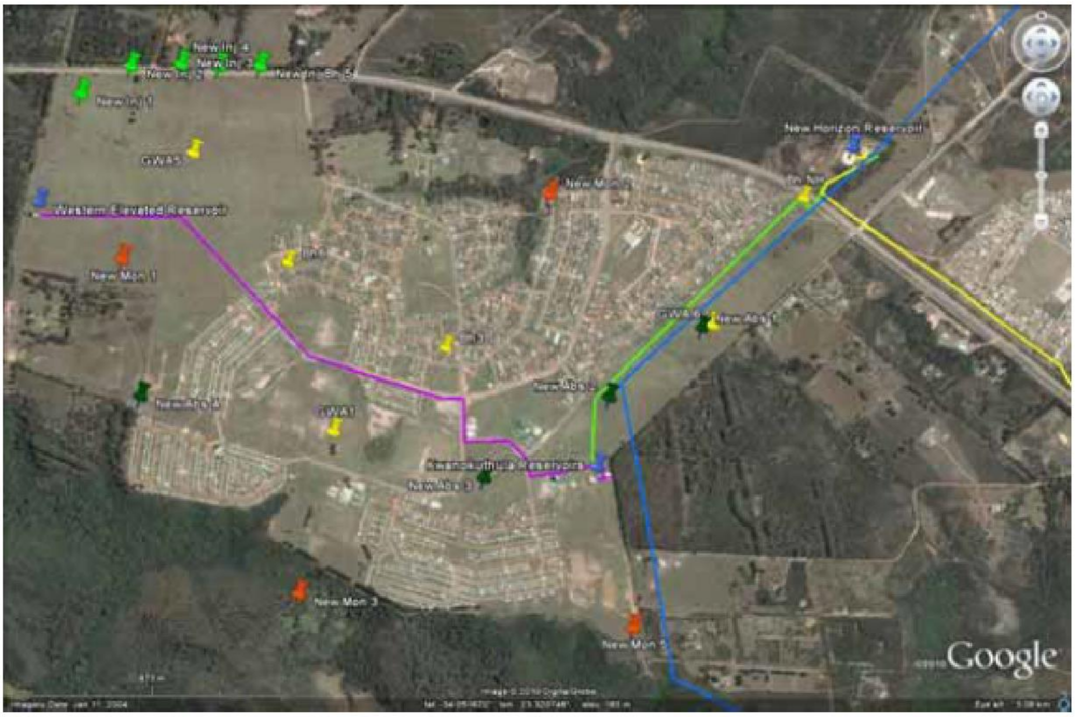


Figure 44 - Kwanokathula's existing and planned boreholes (Murray and Ravenscroft, 2010). Existing abstraction = yellow; planned abstraction = dark green; planned injection = bright green; planned monitoring = orange.

The study also indicated how peak demand could be met through incorporation of MAR into the Plettenberg Bay supply system (Table 11). Injection would take place July-September and abstraction November-March, with rest periods in between.

Table 11 - Existing and proposed water supply for Plettenberg Bay (after Murray and Ravenscroft, 2010).

Water supply	Source	Comment	(ml/day)
Existing water supply	Surface water (drought) Existing boreholes Roodefontein Dam	8.6 million liters/day (normal) (off-channel storage dam)	6.9 3.4 2.8
Existing water supply	Desalination (under construction – Nov. 2010)	(during peak demand periods)	2.0
Proposed water supply	Artificial recharge	(over the 5 peak demand months)	2.3
Total			17.4

MAR Cost Comparison with Desalination

The estimated cost of the proposed option is approximately US$ 1.8 million. It was proposed that the project be implemented in phases with the first phase targeted for completion in 2013. The MAR capital cost is about a third of the current cost of desalination plants, which would serve a similar application of being used only during the peak demand periods. The operational costs of artificial recharge are also expected to be considerably less than desalination (Murray and Ravenscroft, 2010).

8.6 Water Resource Management Environment

In South Africa, key players in water resource management and supply need to work together. On the national level, the Department of Water Affairs and Forestry is the overall custodian and regulator of water resources. On a regional level, Catchment Management Agencies (CMAs) undertake devolved management on behalf of national government at a regional (catchment) level and place water resource management into more manageable units. Implementation of CMAs has been challenging and has happened only in a few parts of the country so far because catchments are not natural political units.

Since 2000, municipalities have been given new responsibilities as water services providers and water services authorities. For example, Bitou Local Municipality, falls within Eden District Municipality, but is both the water services provider and water services authority for the Greater Plettenberg Bay area. Municipalities are expected to report to and be supported by the CMAs. Figure 45 summarizes the new water resource management framework.

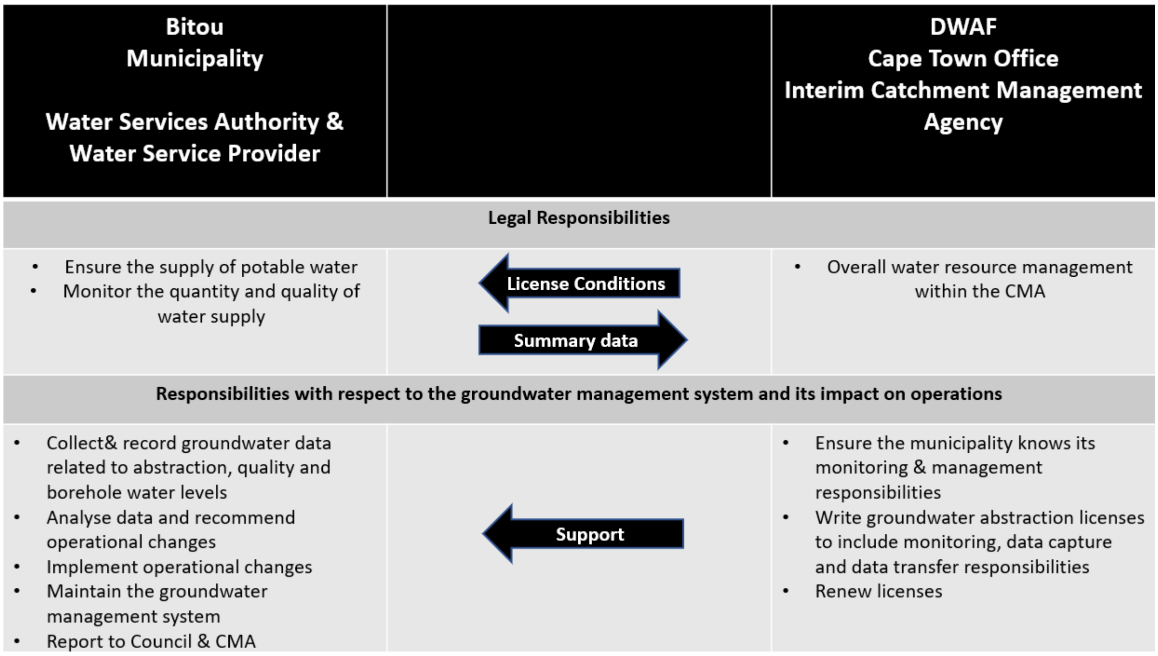


Figure 45 - Institutional framework for (ground)water management (Murray, 2007).

8.7 Evaluation and Way Forward

Despite an intensive internet search, no information could be found on implementation of the MAR proposal of 2007. Information on the roll-out of water supply augmentation since 2007 has been gathered from the last scientific study and various local news sources as shown on Table 12 (News24, 2009; Murray and Ravenscroft, 2010; EMG, 2011; Holloway et al., 2012; Bitou Municipality, 2017 and 2019).

Table 12 - Lack of groundwater resource planning and implementation focus by municipalities.

2007	MAR: pre-feasibility study undertaken. Borehole injection capacity was assessed in 2010.
2009	In January the Karatara River runs dry, leaving Sedgefield without water in peak holiday season. By April, Mossel Bay, George, Knysna and Bitou local municipalities introduce water restrictions; major dams at 60 percent; rainfall lowest in 132 years. By June, situational reports on water availability and storage capacity to Eden District Municipality reveal that municipalities are on the brink of crisis, as no municipalities have sufficient stored water, and there is no rainfall predicted for the near future; major dams at 45 percent. By August, first disaster management meeting, called by Eden District Municipality; major dams at 30 percent. By September the national Department of Water Affairs sets a consumption reduction target of 40 percent for affected municipalities. By November district and local municipalities are declared disaster areas and receive disaster relief money and begin to implement emergency water supply projects.
2009 - 2011	A total of US$ 70 million of the government drought response was directed to improving urban water supply infrastructure, of which National Treasury provided 58 percent, complemented by other sources and municipal co-funding. The majority of additional water supply projects did not come on-line until late 2010-2011, after the drought had broken. For the Bitou municipality, this included a 2 million liters/day desalination plant (Figure 46).
2017	The Western Cape Province was declared a national drought area. Bitou municipality again received drought disaster relief funding from the National Disaster Management Centre of US$ 1.6 million and a further US$ 0.25 million from Western Cape Provincial Government. Out of this money, groundwater also received a small portion for 2 boreholes drilled and equipped in KwaNokuthula for Plettenberg Bay supply. This must be seen against the estimated capital cost of US$ 0.8 million for the whole MAR scheme, which had still not been financed. Bitou commissioned further studies towards water resilience and less dependence on surface water; Wadrift Dam, an off-channel dam, filled from the Keurbooms River in times of high flow, is foreseen for 2022.

Figure 46 - Plettenberg Bay Desalination Plant – next to the town's iconic Beacon Isle Hotel (Veolia, 2019).

A similar neglect of groundwater and MAR occurred from 2009 onwards in the neighboring Knysna municipality (Figure 39) in its water supply to Sedgefield. Recharge technology of dune infiltration had been proposed and a desk study undertaken. MAR would have provided a natural polishing of the seaside village wastewater that was creating a problem by partially discharging into the environmentally-sensitive Groenvlei area as shown on Figure 47 (Murray and Ravenscroft, 2010). Like at Bitou, drought relief funding was spent on a desalination plant. And, instead of implementing key elements of the 2009 MAR proposals, new plans emerged for constructing a second desalination plant. Because of problems with brine disposal, a second plant would likely have to be sited a few kilometers away. As a highly unlikely solution, a very costly, large-scale inter-basin water transfer from the Keurbooms River, which is the main water source for Plettenberg Bay, also came under discussion (Raynor, 2014).

Figure 47 - Sedgefield waste treatment works in the sand dunes, with Groenvlei in the foreground (Murray and Ravenscroft, 2010).

This situation is concerning, because the Sedgefield MAR project was seen as the forerunner in conjunctive water use in the southern Cape, paving the way for Mossel Bay, George, Knynsa and Plettenberg Bay to re-assess their available water sources. *"New Water is now mandatory in the water portfolios of the municipalities to limit the risk of complete water supply failure, should rivers run dry"* (IMESA, 2010).

Both Knysna and Bitou municipalities are known for excellent services. They were praised for having saved the day through impressive reductions in municipal water demand (41 percent) during the critical drought period. The efforts of municipal engineers were also praised for ensuring a remarkably rapid temporary expansion of local water supplies. On the other hand, an evaluation of the drought response during the 2009 through 2011 period highlighted serious gaps (Holloway et al., 2012) including:

- limited discernment of drought onset and impending water scarcity;
- lack of contingency plans for managing urban water shortages in areas exposed to erratic rainfall; and,
- serious shortcomings in the water sector, including aging municipal water distribution infrastructure, unaccounted-for water losses, and limited water management capability.

Above all, municipalities are political and not scientific institutions. They are able to distribute water, but not plan, finance, develop and operate water resources, let alone do it for poorly understood groundwater resources. This is not expected to change without detailed regulation of local water resource management by national government along with guidance and oversight from the CMAs, which are still not functional.

9 MAR as Part of Sustainable Groundwater Resource Development

9.1 Some Experience with MAR Success Factors

Overall, there has been very limited implementation of MAR in South Africa and in the wider region of Southern Africa. However, implementation experience indicates a generally good track record with the technical issues required for successful MAR implementation. This success can be measured against a set of success criteria developed in 2007 as shown on Table 13 (Murray, 2007). The relevance of these success factors was illustrated in the various case studies.

Table 13 - Ten questions to consider to ensure successful implementation of MAR, (Murray, 2007).

Aspect of MAR	Questions to consider
1. Need for artificial recharge scheme	Is artificial recharge really necessary – could you not increase your groundwater yield by expanding the wellfield or by managing the existing wellfield better?
2. Source water	What volume of water is available for recharge, and when is it available?
3. Aquifer hydraulics	Will the aquifer receive and hold the water in storage?
4. Water quality	Is the quality of the source water suitable for artificial recharge?
5. Engineering issues	How will the water be treated and transferred into the aquifer?
6. Environmental issues	What are the potential environmental benefits, risks and constraints?
7. Legal and regulatory issues	What type of authorization is required?
8. Economics	How much will the scheme cost, and what is the cost of supplied water per m^3?
9. Management and technical capacity	Are the skills available to operate the scheme?
10. Institutional arrangements	Who will be responsible for supplying the source water and ensuring its quality is suitable? Are there other users of the aquifer? Who will regulate use of the scheme?

Technical Issues Required for a Successful MAR Implementation

- *Motivation*: The need to make a detailed case for artificial recharge is crucial. Implementation involves costly infrastructure development in a non-scientific environment and implications of the development must be fully understood. The Windhoek and Plettenberg Bay case studies illustrate this.
- *Hydrogeology*: The Langebaan Road case study, which uses injection, demonstrates the importance of doing a thorough study of geology, groundwater flow, recharge and discharge. In this case, some of the injected water seeped away from the intended abstraction area and was lost in boreholes that became artesian far from the injection site, because the underlying geology had not been fully understood.
- *Water quality*: All case studies illustrate the need for clarity regarding the character of the source water and in particular on the large variety of water quality issues in the source water/aquifer combination. In the Atlantis case study, the importance of evaluating water quality at production wells in terms of clogging brought on by inherent properties of water and geology was highlighted. A case study of pilot implementation in Calvinia in the Northern Cape led to the discovery of arsenic containing minerals in the breccia, emphasizing the importance of considering source water-groundwater mixing as well as water-rock interactions.
- *Capacity*: Most cases illustrate the importance of determining the additional technical capacity required to successfully undertake MAR. A case study of water storage in sand dams in the Northern Cape found that scheme failure was a result of an inadequate technical capacity of the municipality. The Plettenberg Bay case study and the situation in neighboring Sedgefield illustrate lack of planning for MAR because of lack of technical capacity. The Langebaan Road case emphasizes the importance of involvement of all stakeholders – and more importantly, buy-in and ownership by stakeholders – and demonstrates how these were successfully engaged.

9.2 Roll-Out of the Artificial Recharge Strategy

The very limited implementation of MAR in South Africa indicates that there is more to successfully rolling out this technology than the technical capacity aspects mentioned above. An artificial recharge (AR) strategy for South Africa was developed in 2007, which included a focus on the wider issues of implementation. The AR strategy framework with its vision, themes and management objectives is shown in Table 14 (DWAF, 2007).

Table 14 - Artificial recharge: Vision, Themes and Management Objectives (DWAF, 2007).

Vision	
To use natural subsurface storage as part of integrated water resource management wherever technologically, economically, environmentally and socially feasible	
Artificial recharge themes	**Management objectives**
1 Knowledge Theme	To create awareness and provide education on artificial recharge
2 Legislation and regulation Theme	To enable water management and water services institutions to adopt and regulate artificial recharge as part of IWRM
3 Planning Theme	To facilitate the use of artificial recharge in achieving sustainable, efficient and cost-effective water resource use and management
4 Implementation Theme	To support water management and water services institutions in implementing artificial recharge
5 Management Theme	To optimize the management of artificial recharge schemes
6 Research Theme	To develop a body of knowledge that supports efficient and effective implementation and operation of artificial recharge schemes
7 Strategy Implementation Theme	To implement and update the artificial recharge strategy

As indicated before, it is clear that the knowledge and technical aspects of MAR (broadly themes 1, 5, 6, and 7 of Table 14) are not the bottleneck to implementation. Rather, the bottleneck is the slow progress in institutional development for the sustainable utilization and management of groundwater resources (broadly themes 2, 3, and 4 of Table 14). This is further highlighted below with particular reference to the National Groundwater Strategy (Department Water and Sanitation, 2017).

The major political changes of 1994 in South Africa resulted in a complete transformation of the water sector in terms of policy, legislation and institutions. In terms of the new National Water Act, 1998, groundwater had moved from a legal status of 'private water', in which there was little national interest, to a 'significant resource'. In terms of national importance, groundwater became the resource that enabled basic water service to be provided to more than 60 percent of communities that had never been served before in a matter of 15 to 20 years. However, despite its raised profile, groundwater has lacked the appropriate institutional development, because its unique characteristics have so far not been addressed in appropriate regulations and institutions within the overarching integrated water resource management approach that flowed out of the new policy and legislation.

A major purpose of the Act of 1998 was to achieve the establishment of suitable institutions for appropriate and participative management of water resources (a requirement for theme 4 of Table 14). This is particularly important for highly localized groundwater resources that cannot be physically managed centrally. The Act provides for three levels of management, namely national government, 19 Catchment Management Agencies (now consolidated into nine) at the regional management level and water user associations acting cooperatively at the local level.

For political reasons, with the advent of wall-to-wall municipal government and the introduction of local government in the former Black homelands in 2000, responsibility for managing thousands of groundwater schemes was transferred from the national Department of Water Affairs and community management structures to new municipal administrations. Since then, there have been many reports of scheme failure, starting with the much-publicized Dinokana disaster in 2004 (sudden groundwater supply failure from an excellent dolomitic aquifer after a complete lack of groundwater level monitoring).

Despite its higher profile on paper, experience on the ground indicates that many municipalities only turn to groundwater as a last resort or in emergencies. Groundwater is perceived as an unreliable and difficult source to manage. According to the Department of Water Affairs, *"more than 70 percent of municipalities do not want localized solutions and prefer regional schemes."* The Regional Bulk Infrastructure Grant puts financing under the control of municipalities, often resulting in a complete neglect of local groundwater sources. In some cases, very expensive options such as desalination are implemented as short- or medium-term solutions, without groundwater being given early, serious consideration (e.g., at the Sedgefield and Plettenberg Bay coastal towns in the Western Cape).

Groundwater specialists need to maintain an ongoing advocacy regarding the resource for which they possess the know-how, but they can only take it up to a point. Stakeholders at a National Dialogue in 2018 all agreed that groundwater development and the management framework presented there (Riemann et al., 2011) could become the overall framework within which joint actions at different management levels could be unpacked. However, the different institutions for various levels of water resource management forming the basis of this framework either do not yet exist or are not yet functioning with respect to groundwater resources.

Of particular concern is the weakness in the function of groundwater management in the national government at a time when new groundwater capacity has to be built at the regional level (i.e., in the new Catchment Management Agencies) and at the level of district and local municipalities, as well as local management institutions. Without a groundwater champion and a critical capacity of groundwater specialists in national government, the country will not be able to move meaningfully forward towards good groundwater governance. This critical requirement was clearly identified in the National Groundwater Strategy of 2017. It has also affected the national roll-out of the MAR strategy, for which the last website update was done in 2011.

In terms of legislation (theme 2 of Table 14), an important advance in the new water resource management environment is that all water uses, including groundwater use and MAR, have to be registered and authorized in terms of the National Water Act, 1998. A groundwater use registration drive was completed in 2000, providing the first national assessment of groundwater use. The most important mechanism to make groundwater fully operational within the 1998 National Water Act framework is the mechanism of water use authorization. In general, a water use must be licensed (unless it is listed as a Schedule 1 use in the Act), as an existing registered lawful use or be permissible under a general authorization. Authorization provides government the opportunity to state specific management requirements and guidance. This critical management measure has been slow to make a real impact, because the whole approach has been geared to surface water and does not cater to the unique characteristics and management requirements of groundwater.

In terms of planning (theme 3), national water planning has made advances in taking groundwater on board. One major step was groundwater becoming part of a nationwide program to develop water reconciliation strategies for Water Management Areas, towns and villages across the country, starting in 2008. These studies provide the potential for groundwater use in each municipality at a local scale and identify possible target aquifers in the vicinity. Also, various guidelines have been prepared, which address aspects of sustainable development and management of groundwater resources. An important supporting guideline has been a GIS assessment of areas countrywide where artificial recharge may be feasible and a list of possible areas where artificial recharge may be able to help mitigate water resource problems (DWAF, 2009). While planning has been well established at the national level, there are as yet (in 2021) no catchment management plans (regional level strategies) as foreseen in the National Water Act, 1998. At the municipal level, each municipality designated as Water Services Authority, must develop a Water Services Development Plan and must also take into account water supply sustainability. This level still suffers from a serious lack of technical capacity.

A key failure is the lack of monitoring and assessment of groundwater resources beyond the national level. This shortcoming is holding back most planning for local level implementation. Even the most basic water-level data are lacking at the local level, thus preventing the ability to assess whether MAR can be a viable option. This is related to inadequate capacity and resourcing for groundwater management at the lower levels.

Namibia, for which the OmDel and Windhoek MAR schemes were presented here as case studies, has a more stable institutional environment. Since 1997, development of water resources and their management has been undertaken by the Namibia Water Corporation (NamWater), a state-owned enterprise, which sells bulk water to local authorities. In the case of Windhoek, the city (municipality) also had its own boreholes and had many years of experience with the development and operation of the Windhoek Aquifer wellfield. In both cases, attention to monitoring and research informed decisions to continue to invest in MAR, allowing for proper planning and cost comparison with other alternatives.

A combination of several of the above groundwater governance institutional failings is apparent from the Plettenberg Bay case study. The lack of progress with MAR implementation in the Cape Flats, despite an obvious need for it and despite ongoing MAR advocacy and knowledge and technology development for more than 40 years, further illustrates (as discussed in Section 9.3) the importance of a water resource management environment in which groundwater resource development has been fully integrated and institutionalized.

9.3 Institutional Shortcomings: The Cape Flats Aquifer Case

Cape Town is a rapidly urbanizing coastal city of over 4 million people in the Western Cape region of the Republic of South Africa. The city receives about 98.5 percent of its water supply from surface water resources. Most of the rainfall in the Western Cape falls during the winter months (May to September), thus the runoff generated during this period needs to be stored to meet the water demands of the city for the whole year, in particular during peak demand during the hot dry summer. A network of major and minor dams that form the Western Cape Water Supply System are used to store winter runoff.

A Cape Flats Aquifer project was initiated in 1966 by the Cape Provincial Administration, triggered by foreseen water shortages for the Cape Town metropolitan area and environs. The Cape Flats Aquifer is made up of fluvial, marine, and aeolian sedimentary deposits, is predominantly unconfined and reaches thicknesses up to 55 m as shown on Figure 48. From 1973 to 1979, the Water Research Commission financed the project and extended its scope to accommodate various multi-disciplinary aspects (e.g., the feasibility of storing water from the Eerste River in the sand deposits adjacent to the False Bay coast and, in particular, the role the aquifer could play in terms of reclamation, infiltration, storage and abstraction of purified sewage effluents). For this, either infiltration basins or injection wells would be feasible. By 1980, a numerical model of the aquifer had been developed which could be used to delimit the potential of the Cape Flats and investigate scenarios of groundwater development. Concern was expressed that areas most suitable for recharge and abstraction were increasingly being used for high-density housing projects (Tredoux et al., 1980).

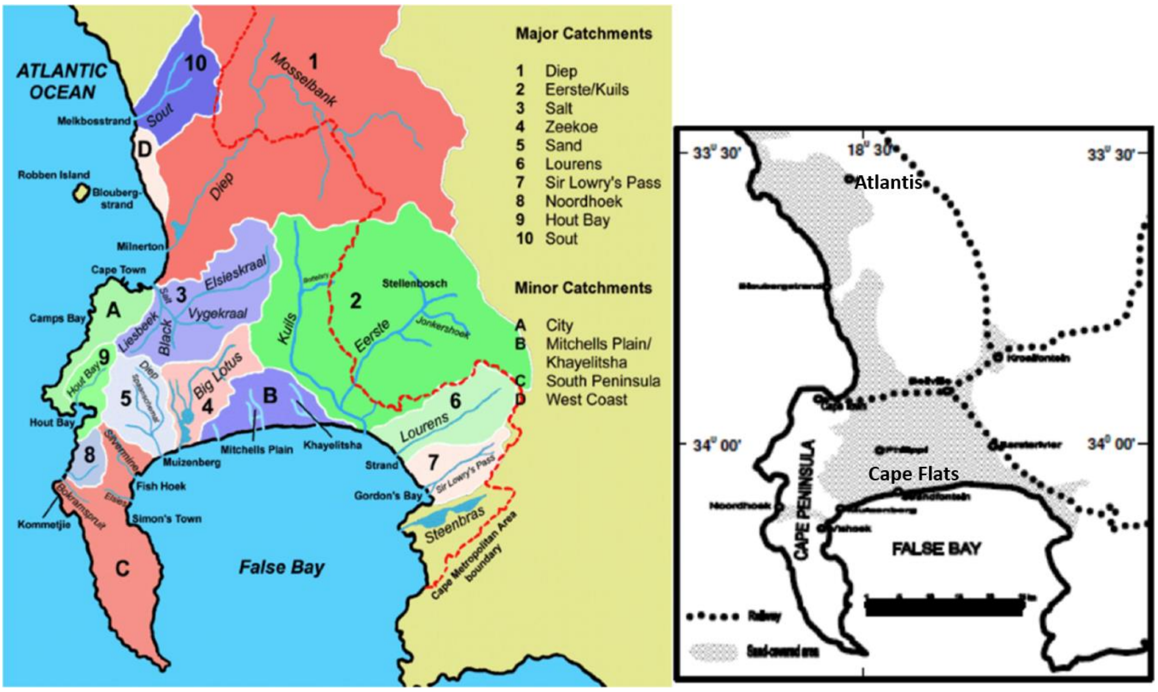


Figure 48 - The Cape Metropolitan Area with major catchments and settlements over Cape Flats sands (Adelana et al., 2014).

The Working Group for the above project proposed that groundwater development should begin in 1981. However, the City Council of Cape Town, the local authority responsible for the metropolitan water supply, decided not to develop the Cape Flats Aquifer. The City Council was known to prefer high quality surface water from the mountain catchments of the Western Cape above their own, poorer quality, groundwater resources. A further scheme, a major dam in the Berg River, was finally approved by the South African Cabinet in 2002, following considerable opposition from the environment sector and interested and affected parties, who all prioritized water demand and supply reconciliation options.

In 1996, the national Department of Water Affairs and Forestry, by way of its Western Cape Systems Analysis, provided a new target to have the Cape Flats scheme operational by 2005. It found that the Cape Flats Aquifer remained a viable resource because on the order of 15 to 20 Mm^3 could be abstracted annually at a very favorable unit cost of US$ 0.03/m^3 (Wright and Conrad, 1995). Again, there was no response from the City of Cape Town. By 2005, further studies found that the Cape Flats groundwater resource had deteriorated over the past decades and was now non-potable in certain areas, with varying degrees of contamination. The deterioration was due to a combination of pesticides and fertilizers from agricultural practices, wastewater treatment plants, numerous waste disposal sites, informal settlements, unlined or leaking canals and leaking sewer pipes. Removal of sand dunes and encroachment of urban development, in particular informal settlements, into low-lying wetland areas had resulted in flooding every winter, now enhanced by the urban recharge and elevated groundwater levels. Also, periodic phytoplankton blooms along the False Bay coastline had been worsening, impacting the marine and beach ecosystems (Adelana and Xu, 2006; Hay, et al., 2015; Mauck, 2017).

A follow-on study commissioned by the Department of Water Affairs to develop an urban aquifer management approach for the City of Cape Town recommended a set of multiple solutions that could run simultaneously. In the short term, non-potable groundwater should be supplied to small scale users for irrigation such as schools, sports fields, parks and community gardens. While this would provide some benefit from the aquifer, the immediate solution was to systematically reduce and limit contamination to the aquifer. Bioremediation was seen as a potential method to remediate the aquifer by using natural or man-made wetlands and vleis (marshes) for this purpose. Large-scale bulk supply in the medium term could be accomplished by combining artificial recharge and abstraction. An additional benefit of artificial recharge and abstraction would be the remediation of the aquifer. By recharging the aquifer with good quality water, it would be circulated, ultimately diluting and cleaning the contaminated groundwater in the aquifer (Hay et al., 2015).

Practical steps from the City of Cape Town only resulted after Cape Town experienced an especially severe drought from 2017 to 2018 (the worst in over 100 years) after several years of low rainfall. To manage the drought, the city prioritized reducing demand for water and then rationed the remaining water stored in the supply system. It introduced increasingly strict water restrictions as the water shortage became progressively more acute. At the same time, water supply augmentation contingencies were assessed – a combination of groundwater abstraction, water reuse and desalination. Particular mention was made of the need to recharge the Cape Flats Aquifer with treated wastewater and stormwater. The city's recent Water Strategy aims to take a more holistic approach to water management and sets out five commitments, namely (City of Cape Town, 2019):

1. safe access to water and sanitation;
2. wise use;
3. sufficient, reliable water from diverse sources;
4. shared benefits from regional water resources; and,
5. a water sensitive city.

Under Strategy item 3, the city is committed to increasing the available supply by approximately 300 million liters/day over the next ten years from groundwater, water reuse and desalinated water, all aimed to cost-effectively and timeously increase resilience and substantially reduce the likelihood of severe water restrictions in future (City of Cape Town, 2019). This will require diversification of water sources and a much better understanding of the system, including environmental, physical, social, financial, economic and political aspects, and a new approach to managing the system beyond focusing on infrastructure (Parks et al., 2019; Ziervogel, 2019).

MAR and Increasing Urbanization

In terms of Strategy item 5, the City of Cape Town (2019) stated that:

> *"it will actively facilitate the transformation of Cape Town over time into a water sensitive city that makes optimal use of stormwater and urban waterways for the purposes of flood control, aquifer recharge, water reuse and recreation, and is based on sound ecological principles. This will be done through new incentives and regulatory mechanisms as well as through the way the city invests in new infrastructure."*

With intensification of land-use and increasing urbanization, the knowledge and institutional requirements for MAR have again increased significantly. It is timely that the Water Research Commission in South Africa, champion for groundwater resources and for artificial recharge for so many years, has taken up the challenge with a very relevant new project - Urban Groundwater Development and Management – allowing groundwater processes to be better understood in this environment and to fully feature in 'Water Sensitive Urban Design' (Seyler et al., 2019).

In terms of implementation, the city is currently in possession of licenses in terms of the National Water Act of 1998 for both the abstraction of groundwater and the practice of MAR. A monitoring protocol for a MAR system is currently being reviewed. During 2018, 159 boreholes were drilled into the Cape Flats Aquifer with a total yield of 41 million liters/day. Infrastructure for the treatment of water from the MAR scheme is already being constructed in the form of two reverse osmosis plants, as well as pipelines to the injection sites. The city has also explored implementation of MAR within the predominantly fractured rock setting of the Table Mountain Group Aquifer (Lasher-Scheepers, 2020).

While the Water Research Commission had actively pursued MAR knowledge and technology development for the Cape Flats Aquifer more than 40 years ago, it is the broader issue of sustainable groundwater resource development that still has not been fully addressed by the national government in South Africa. Had there been systematic development of regulations in terms of its National Water Act of 1998 to manage the unique aspects of groundwater resources, then important and vulnerable aquifer systems such as the Cape Flats would have been identified at an early stage. At that time, proactive measures could have been taken for their protection and development and adequate institutions could have been created for their local development and management.

10 Conclusion

Excellent progress has been made with all knowledge-related aspects and promotion of artificial recharge in South Africa. This has been driven by the Water Research Commission with its research and development programs for nearly 50 years. A tremendous opportunity was created when the Department of Water Affairs and Forestry, with support from the Water Research Commission, produced a detailed Artificial

Recharge Strategy to *"use natural sub-surface storage as part of Integrated Water Resource Management wherever technologically, economically, environmentally and socially feasible."*

The stumbling block to a systematic roll-out of this technology has been the lack of institutional development for the sustainable utilization and management of groundwater resources in South Africa – at the local (city) level, regional support level and at the national policy and support level.

Way Forward Towards Good Groundwater Governance

The way forward for this globally problematic stumbling block is best captured in a recent major global initiative: 'Groundwater Governance: A Global Framework for Action' (De Chaisemartin et al., 2017). Its vision underlines the important role of groundwater around the world, the dependency of humans and ecosystems on it and the existence of significant threats to groundwater resources. All these factors call for good groundwater governance, guided in particular by the following working principles:

- groundwater should not be managed in isolation, but conjunctively as appropriate with other water sources to improve water security and assure ecosystem health;
- groundwater quality and resources quantity should be co-managed, and therefore groundwater management needs to be harmonized with land management;
- effective groundwater governance requires co-governance of the subsurface space;
- vertical integration is required between national and local levels of resource management in the elaboration and implementation of groundwater management and protection plans; and,
- coordination should be established with the macro-policies of other sectors – such as agriculture, energy, health, urban and industrial development, and the environment.

The need for good groundwater governance is particularly important in urban areas due to the stress placed on water resources by unprecedented rates of population growth and urbanization, resulting in a *"widespread crisis of urban water governance, particularly in developing countries"* (Howard, 2015).

Groundwater specialists do not need to sit with folded hands because the groundwater institutional issue may appear out of their competency and responsibility. The National Groundwater Strategy (Department Water and Sanitation, 2017) puts special emphasis on ways forward in this regard, in which individuals and the profession as a whole can play a vital part.

Wise words were quoted in the introduction to a 1995 proposal to move ahead with development of the Cape Flats Aquifer venture as a team effort without further delay. It can only be hoped that 25 years on, this wisdom will finally prevail.

> *"Nothing will ever be attempted if all possible objections must first be overcome."*
> *(Samuel Johnson).*

11 Exercises

Exercise 1

Briefly describe what you understand about a) natural recharge and b) artificial recharge of an aquifer.

Describe why c) Managed Aquifer Recharge and d) Aquifer Storage and Recovery may be more appropriate terminology than artificial recharge for this practice. Use the internet to research and describe how a new over-arching term e) 'nature-based solutions', has been used in South Africa, and may add a further dimension to MAR terminology.

Click for solution to exercise 1⤵

Exercise 2

You are a consultant from Europe or the United States and have been called to a location in Southern Africa where groundwater levels in an aquifer for urban water supply are dropping, apparently unsustainably. Your client requires an investigation of the feasibility of MAR to deal with the problem. Briefly describe elements of the planning/investigation process you would follow before you would be able to advise to invest/or not in MAR at this location.

Click for solution to exercise 2⤵

Exercise 3

You have found MAR a feasible option in your planning process above. Describe at least 4 different MAR technologies and their appropriateness for different surface and underground environments you may be encountering in Southern Africa. As you would likely do if hired to make such an evaluation, use the knowledge you gained from this book along with the internet to research a) conditions in Southern Africa and b) MAR technologies, then c) present the possible technologies.

Click for solution to exercise 3⤵

12 References

Adelana, M. and Y., Xu, 2006, Contamination and protection of the Cape Flats aquifer, South Africa, *in* Groundwater Pollution in Africa, editors, Y. Xu and B. Usher. Taylor and Francis, pages 265-277. https://www.researchgate.net/publication/265728781_Contamination_and_protection_of_the_Cape_Flats_Aquifer_South_Africa↗.

Adelana, M., Y. Xu, and P. Vrbka, 2014, Hydrogeochemical characterization of the Cape Flats aquifer (South Africa): Constraints for water supply augmentation, *in* Groundwater: Hydrogeochemistry, Environmental Impacts and Management Practices, Chapter: 3, editor: S.M. Adelana. Nova Science Publishers Incorporated, New York, USA. https://www.researchgate.net/publication/266343087_Hydrogeochemical_characterization_of_the_Cape_Flats_aquifer_South_Africa_Constraints_for_water_supply_augmentation↗.

Amwele E., A.P. Ausiku, A.K. Lugambo, E. Toivo, H. Bernhardt, I. Fillemon, K. Israel, M. Rodrick, M. Moses, M. Mkwetu, N. Isaac, N. Ntandozenkosi, S.M. Ndahafa, S. Veronica, and T.D. Nandjamba, 2004, Water balance, use and management in the Omaruru Basin, *in* Occasional Paper XX, editors, E.S. Aitana, K. Ganeb, B. Hamilton, M. Lundgren, N. Manning, K, Nantanga, T. Parr, S. Pettersen, M. Seely and G. Van Langenhove. Desert Research Foundation of Namibia, http://the-eis.com/elibrary/search/11551↗.

Baumeler, H.P., 2017, Swakoppoort Dam, licensed under CC BY-SA 4.0↗.

Baumeler, H.P., 2018, Omaruru River, is licensed under CC BY-SA 4.0↗.

Beekman, H.E. and Y. Xu, 2003, Groundwater recharge estimation in Southern Africa. United Nations Educational, Scientific and Cultural Organization (UNESCO), International Hydrological Programme (IHP), series number 64, UNESCO Paris, https://unesdoc.unesco.org/ark:/48223/pf0000132404.locale=en↗.

Bitou Municipality, 2017, Effects of the drought disaster. Bitou Municipality News, media release on September 5, https://www.bitou.gov.za/effects-drought-disaster↗.

Bitou Municipality, 2019, Bitou municipality's disaster risk assessment: Summarised report, http://www.bitou.gov.za/download_document/3303↗.

Braune, E., 2007, Contributions of science and technology to water development and use in Southern Africa, *in* Our Water Our Culture, editor, L. van Vuuren. Water Research Commission (WRC), Pretoria, South Africa.

Braune, E., B. Hollingworth, Y. Xu, M. Nel, G. Mahed, and H. Solomon, 2008, Protocol for the assessment of the status of sustainable utilization and management of groundwater resources with special reference to Southern Africa. Water Research Commission, Pretoria, South Africa.

Braune, E. and Y. Xu, 2008, The role of ground water in Sub-Saharan Africa. Groundwater Journal, volume 48, issue 2, pages 229-238, doi: 10.1111/j.1745-6584.2009.00557.x↗.

Braune, E., S. Adams, and F. Fourie, 2014, Twenty years of groundwater research, development, and implementation in South Africa. Water Research Commission Report SP 78/14, South Africa, http://www.wrc.org.za/wp-content/uploads/mdocs/20%20years%20of%20groundwater.pdf↗.

Bugan, R.D.H., N. Jovanovic, S. Israel, G. Tredoux, B. Genthe, M. Steyn, D. Allpass, R. Bishop, and V. Marinus, 2016, Four decades of water recycling in Atlantis (Western Cape, South Africa): Past, present future. Water South Africa, volume 42, number 4, doi: 10.4314/wsa.v42i4.08↗.

Christelis, G. and W. Struckmeier (editors), 2001, Groundwater in Namibia - an explanation to the hydrogeological map, http://www.bgr.bund.de/EN/Themen/Wasser/Projekte/yearbgeschlossen/TZ/Namibia/groundwater_namibia.pdf?__blob=publicationFile↗.

Christelis, G., 2019, Field excursion Omdel aquifer, Managed Aquifer Recharge [MAR] of the Omdel aquifer in an arid environment, the Namibia example. China Africa Water Forum, number 7.

City of Cape Town, 2019, Cape Town water strategy – our shared water future. Draft for comment, version 1.6, January 2019.

CuveWaters, 2015, Integrated Water Resources Management in Northern Namibia, http://www.cuvewaters.net↗.

de Chaisemartin M. et al., 2017, Addressing the groundwater governance challenge *in* Freshwater Governance for the 21st Century, editor, E. Karar, Global Issues in Water Policy, volume 6, Springer, doi: 10.1007/978-3-319-43350-9_11↗.

DWAF, 1998, Department of Water Affairs and Forestry, Quality of domestic water supplies –Volume: I Assessment Guide, second edition. Water Research Commission, number: TT 101/98, ISBN No: 1-86845-416-9.

DWAF, 2007, Department of Water Affairs and Forestry, Artificial recharge strategy, version 1.3 *in* Strategy development: a national approach to implement artificial recharge as part of water resource planning, Pretoria, South Africa, http://www.artificialrecharge.co.za/strategydocument/yearRStrategySectD.pdf↗.

DWAF, 2008, Department of Water Affairs and Forestry, The Assessment of Water Availability in the Berg Catchment (WMA 19) by Means of Water Resource Related Models: Groundwater Model Report Volume 6–Langebaan Road and Elandsfontein Aquifer System Model. Prepared by Umvoto Africa (proprietary) limited in association with Ninham Shand (proprietary) limited on behalf of the Directorate. National Water Resource Planning, DWAF Report No. P WMA 19/000/00/0408.

DWAF, 2009, Department of Water Affairs and Forestry, Strategy and guideline development for national groundwater planning requirements. Potential Artificial Recharge Areas in South Africa, PRSA000/00/11609/1 - Activity 14 (AR04).

DWAF, 2010, Department of Water Affairs and Forestry, The Atlantis water resource management scheme: 30 years of artificial recharge, Strategy and guideline development for national groundwater planning requirements, Pretoria, South Africa. DWAF Report No. PRSA 000/00/11609/10 – Activity 17 (AR5.1).

DWS, 2016, Department of Water and Sanitation, South Africa, Development of Reconciliation Strategies for All Towns in the Southern Planning Region, Hopefield, Saldanha Bay Local Municipality, version 2.

Department of Water and Sanitation (DWS), 2017, National groundwater strategy. Pretoria, South Africa.

Dillon, P., P. Stuyfzand, T. Grischek, M. Lluria, R.D.G. Pyne, R.C. Jain, J. Bear, J. Schwarz, W. Wang, E. Fernandez, C. Stefan, M. Pettenati, J. van der Gun, C. Sprenger, G. Massmann, B.R. Scanlon, J. Xanke, P. Jokela, Y. Zheng, R. Rossetto, M. Shamrukh, P. Pavelic, E. Murray, A. Ross, J.P. Bonilla Valverde, A. Palma Nava, N. Ansems, K. Posavec, K. Ha, R. Martin, and M. Sapiano, 2019, Sixty years of global progress in managed aquifer recharge. Hydrogeology Journal volume 27, pages 1–30, doi: 10.1007/s10040-018-1841-z↗.

Drießen, C. and A. Jokisch, 2011, Technical report on historic pump storage dams (Stengel Dams) in central northern Namibia, doi: 10.13140/RG.2.2.35175.65446↗.

Du Pisanie, P., 2007, Windhoek Namibia: a case study in water supply in an arid environment. PowerPoint Presentation.

Du Plessis, J.A., 2009, Managing the unseen: Langebaan Road aquifer system. Water SA, volume 35, number 2, doi: 10.4314/wsa.v35i2.76730↗.

Earthwise contributors, 2019, Hydrogeology of Namibia. Africa Groundwater Atlas, Earthwise. http://earthwise.bgs.ac.uk/↗.

Ebrahim, G.Y., J.F. Lautze, and K.G. Villholth, 2020, Managed aquifer recharge in Africa: taking stock and looking forward. Water, volume 12, issue 7, page 1844, doi: 10.3390/w12071844↗.

EMG, 2011, Drought in Eden, An exploration of the 2009/10 drought in the southern Cape, Eden District Municipality, in terms of municipal responses, community impacts and lessons for water and climate change, Environmental Monitoring Group Water and climate change research series, report 4, prepared by Tarryn Pereira.

Engelbrecht, J.F.P., G. Tredoux, and L. Soltau, 2009, Langebaan Road aquifer artificial recharge study: pilot phase recharge. Report number CSIR/NRE/WR/ER/2009/0099/B submitted to Department of Water Affairs, Pretoria, South Africa.

Excellent, 2012, Sand Dams Will Transform Millions of Lives, https://en.calameo.com/read/00151136288482e7158dc↗.

Foster, S., A. Tuinhof, and F. van Steenbergen, 2012, Managed groundwater development for water-supply security in Sub-Saharan Africa: investment priorities. Water SA, volume 38, number 3, doi: 10.4314/wsa.v38i3.1↗.

Gale, I., 2005, Strategies for MAR in semi-arid areas. International Association of Hydrogeologists (IAH), Commission on Managed Aquifer Recharge, and United

Nations Educational, Scientific and Cultural Organization [UNESCO], https://unesdoc.unesco.org/yearrk:/48223/pf0000143819↗.

Geyh, M.A. and D. Ploethner, 1995, Groundwater isotope study in the Omaruru River delta aquifer, central Namib desert, Namibia. International Association of Hydrological Sciences, number 232, http://hydrologie.org/redbooks/year232/iahs_232_0163.pdf↗.

Global Water Partnership South Africa (GWP), 2009, Integrated Water Resources Management (IWRM) survey and status report: Namibia. Desert Research Foundation of Namibia (DRFN), https://www.gwp.org/globalassets/global/gwp-saf-files/namibia-iwrm-report.pdf↗.

Groundwater Africa, 2012, Managed Aquifer Recharge (MAR): Support to the Department of Water Affairs, Botswana. Final report, South Africa.

Hay, R., D. McGibbon, F. Botha, and K. Riemann, 2015, Cape Flats aquifer and False Bay – opportunities to change. Paper 16, Institute of Municipal Engineers (IMESA) Conference, Cape Town, South Africa, https://www.imesa.org.za/wp-content/uploads/2015/11/Paper-16-Cape-flats-aquifer-and-false-bay-Opportunities-to-change-Rowena-Hay.pdf↗.

Heyns, P.S., J. Montgomery, and M.K. Seely, 1998, Namibia's water, a decision maker's guide. Desert Research Foundation of Namibia and Department of Water Affairs, Windhoek, Namibia.

Holloway, A., G. Fortune, P. Zweig, L. Barrett, A. Benjamin, V. Chasi, and J. de Waal, 2012, Eden & Central Karoo drought disaster 2009-2011: "the scramble for water". University of Stellenbosch Report, reference number LG 10/2011/2012, doi: 10.13140/RG.2.1.3179.8009↗.

Howard, K.W.F., 2015, Urban rural tensions and opportunities for co-management. Thematic Paper 3: Groundwater Governance - A Global Framework for Action, http://www.zaragoza.es/contenidos/medioambiente/onu//newsletter15/968-eng-v3.pdf↗.

IMESA, 2010, Sedgefield water augmentation case study by N. Perring, K. Turner, and H. Erwee, paper 7, Conference and Exhibition 27-29 October 2010 East London, South Africa. https://www.imesa.org.za/wp-content/uploads/2015/08/7.pdf↗.

Jovanovic, N., G. Tredoux, R. Bugan, S. Israel, M. Steyn, and B. Genthe, 2014, Provision of professional services for Atlantis water supply scheme - Artificial recharge scientific and operational support. Report to Bulk Water Operations: Bulk Water Branch, Water and Sanitation Department, Utility Services Directorate, City of Cape Town, March 2014, South Africa.

Jovanovic, N., G. Tredoux, S. Israel, R. Bugan, T. Kanyerere, N. Vermaak, F. Fourie, C.W. Andries, M. Van der Schyff, and H. Zhang, 2019, Towards the sustainable exploitation of groundwater resources along the West Coast of South Africa, Deliverable 5 - Technical Report: Modeling Managed Aquifer Recharge. Water Research Commission, Report number K5/2744.

Kirchner, J., 1981, An updated evaluation of the Windhoek groundwater resources. Department of Water Affairs Technical Report, Windhoek.

Kirchner, J. and A. van Wyk, 2001, Overview of the Windhoek city water supply *in* Groundwater in Namibia - an explanation to the Hydrogeological Map, G. Christelis and Struckmeier, Department of Water Affairs, Namibia.

Lasher-Scheepers, C., 2020, Personal communication, principal professional officer: geohydrology, bulk water and infrastructure planning. Lecture notes prepared for the Department of Water Affairs and Forestry, Pretoria.

Lau, B., and C. Stern, 1990, Namibian water resources and their management: A preliminary history, including excepts from unpublished sources (Archeia), National Archives of Namibia, https://www.chapter1.co.za/product/4166915/Namibian-water-resources-and-their-management-A-preliminary-history-including-excepts-from-unpublished-sources-Archeia-Lau-Brigitte--Stern-Christel↗.

Lindhe, A., L. Rosén, P.O. Johansson, and T. Norberg, 2012, Increase of water supply safety by Managed Aquifer Recharge along the North-South carrier – a pre-feasibility study. Chalmers University of Technology, Sweden, https://publications.lib.chalmers.se/records/fulltext/208836/local_208836.pdf↗.

MacDonald, A.M., H.C. Bonsor, B. Dochartaigh, and R.G. Taylor, 2012, Quantitative maps of groundwater resources in Africa. Environmental Research Letters, volume 7, number 7, page 024009, doi: 10.1088/1748-9326/7/2/024009↗.

Mapani, B.S., 2005, Groundwater and urbanization, risks and mitigation: The case for the city of Windhoek, Namibia. Physics and Chemistry of the Earth, volume 30, pages 706–711, doi: 10.1016/j.pce.2005.08.011↗.

Mauck, B.A., 2017, The capacity of the Cape Flats aquifer and its role in water sensitive urban design in Cape Town. Doctor of Philosophy Dissertation Thesis, University of Cape Town, South Africa, http://hdl.handle.net/11427/27293↗.

Menges, W., 2020, Von Bach level nears 90%. The Namibian, News – National, published on February 27, 2020, https://www.namibian.com.na/198496/archive-read/Von-Bach-level-nears-90pct↗.

Mostert, A.C. and B.M. Matengu, 2019, Managed Aquifer Recharge of the Omdel aquifer in an arid environment – the Namibia example. China Africa Water Forum, number 7.

Murray, E.C. and G. Tredoux, 1998, Artificial recharge: a technology for sustainable water resource development. Water Research Commission Report, number 842/1/98, http://www.wrc.org.za/wp-content/uploads/mdocs/842-1-98.pdf↗.

Murray, E.C. and G. Tredoux, 2002, Pilot artificial recharge scheme: testing sustainable water resource development in fractured aquifers. Water Research Commission

Report, number 967/1/02, http://www.wrc.org.za/wp-content/uploads/mdocs/967-1-02.pdf↗.

Murray, E.C., 2002, The feasibility of artificial recharge to the Windhoek aquifer. Unpublished Doctor of Philosophy dissertation thesis, University of Free State, South Africa.

Murray, E.C., 2016, An overview of Managed Aquifer Recharge in Southern Africa. International Association of Hydrogeologists Newsletter, https://recharge.iah.org/files/2018/02/Southern-Africa-Murray_MAR-in-Southern-Africa-2016.pdf↗.

Murray, R., 2004, Wise water management for towns and cities. Water Research Commission, Report no. TT 219/03, Pretoria, South Africa, http://www.wrc.org.za/wp-content/uploads/mdocs/TT-219-03.pdf↗.

Murray, R., 2007, Bitou Municipality artificial recharge feasibility study. Groundwater Africa, https://www.artificialrecharge.co.za/casestudies/plettenberg.pdf↗.

Murray, R., 2008, Artificial Recharge: The intentional banking and treating of water in aquifers. Lecture notes prepared for the Department of Water Affairs and Forestry, Pretoria.

Murray, R., 2009, Artificial Recharge: The intentional banking and treating of water in aquifers. Lecture notes prepared for the Department of Water Affairs and Forestry, Pretoria.

Murray, R. and J. Harris, 2010, Water banking: a practical guide to using artificial groundwater recharge. Department of Water Affairs.

Murray, R. and P. Ravenscroft, 2010, Potential artificial recharge schemes – planning for implementation. Department of Water Affairs, Pretoria, South Africa.

Murray, R., 2017, Managed Aquifer Recharge: An introductory guide for the Southern African Development Community - Groundwater Management Institute [SADC-GMI] including the Windhoek case study. SADC-GMI, Bloemfontein, South Africa, https://sadc-gmi.org/2017/03/12/training-managed-aquifer-recharge-held-safari-court-hotel-windhoek-namibia-2-march-2017/↗.

Murray, R., D. Louw, B. van der Merwe, and I. Peters, 2018, Windhoek, Namibia: from conceptualizing to operating and expanding a MAR scheme in a fractured quartzite aquifer for the city's water security. Sustainable Water Resources Management, volume 4, pages 217–223, doi: 10.1007/s40899-018-0213-0↗.

National Research Council, 2008, Prospects for managed underground storage of recoverable water. The National Academies Press, http://www.nap.edu/catalog/12057.html↗.

News24, 2009, https://www.news24.com/news24/municipalities-warned-over-water-20090512↗, https://www.news24.com/news24/water-water-not-everywhere-20090113↗.

Nilsson, A., 1988, Groundwater dams for small-scale water supply. Practical Action Publishing, https://practicalactionpublishing.com/book/942/groundwater-dams-for-small-scale-water-supply↗.

Parks, R., M. McLaren, R. Toumi, and U. Rivett, 2019, Experiences and lessons in managing water from Cape Town. Grantham Institute Briefing, paper number 29, Imperial College, London, doi: 10.25561/67992↗.

Peters, I., 2014, personal communication regarding the Windhoek Managed Aquifer Recharge. Presentation - City of Windhoek.

Pietersen, K. and R. Parsons (editors), 2001, A synthesis of the hydrogeology of the Table Mountain group – formation of a research strategy. Water Research Commission Report number TT 158/01, Pretoria, South Africa, http://www.wrc.org.za/wp-content/uploads/mdocs/TT-158-01.pdf↗.

Postel, S., 1992, Last oasis-facing water scarcity. Routledge, https://www.routledge.com/The-Last-Oasis-Facing-Water-Scarcity/Postel/p/book/9781853831485↗.

Quayle, T., 2012, Atlantis, South Africa - Recycling wastewater to bolster ground water supply: the Atlantis story. ACCESSanitation Case Study, Council for Scientific and Industrial Research and City of Cape Town, South Africa, http://www.awasla.org/Docs/yearCCESS_Case_study_Atlantis_SA.pdf↗.

Raynor, L.J., 2014, An analysis of the impacts of Sedgefield's 2009/2010 drought response on water security, Mini-Dissertation (MOB791), Masters in Environmental Management, Faculty of Natural and Agricultural Sciences. University of the Free State, https://www.naturesvalleytrust.co.za/assets/Uploads/Raynor-2014.pdf↗.

Riemann, K., D. Louw, N. Chimboza and M. Fubesis, 2011, Groundwater management framework. Water Research Commission, Report number 1917/1/10, Pretoria, South Africa, http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/1917-1-101.pdf↗.

Robey, K. and G. Tredoux, 2013, In-Situ iron removal: Innovative option for preventing production borehole clogging, Groundwater Division Conference, Durban, 17-19 September 2013, https://www.researchgate.net/publication/271329117_IN-SITU_IRON_REMOVAL_INNOVATIVE_OPTION_FOR_PREVENTING_PRODUCTION_BOREHOLE_CLOGGING↗.

Rogers, J., 1980, First report on the Cenozoic sediments between Cape Town and Elandsbay. Open File Report 1980 – 0249, Pretoria: Geological Survey of South Africa.

Sauermann, H.B., 1966, Water storage in sand-filled dams. Council for Scientific and Industrial Research Report MEG 464, Pretoria, South Africa.

Seyler H., K. Witthüser, and M. Holland, 2016, The capture principle approach to sustainable groundwater use incorporating sustainability indictors and decision framework for sustainable groundwater use. Report to the Water Research Commission.

Seyler, H., K. Witthüser, and M. Sunaitis, 2019, Urban groundwater development and management. Water Research Commission Report, number 2741/1/19, http://www.wrc.org.za/wp-content/uploads/mdocs/2741_final.pdf↗.

Smith, M., 2006, Prediction, control and rehabilitation of iron encrustation in water supply boreholes, Western Cape, South Africa: a geochemical approach. Doctor of Philosophy Dissertation Thesis, University of Cape Town, Faculty of Science, Department of Geological Sciences, http://hdl.handle.net/11427/4223↗.

South African National Standards (SANS), 2011, Drinking Water, Part 1: Microbiological, Physical, Aesthetical, Chemical Determinants, SANS241-1:2011. South African Bureau of Standards, Pretoria, South Africa.

Southern African Development Community (SADC), 2007, Regional Water Strategy. Gaborone, Botswana.

Southern African Development Community (SADC), 2009, Explanatory brochure for the Southern African Development Community hydrogeological map and atlas, https://sadc-gip.org/documents/96/download↗.

Stengel, H.W., 1963, Water affairs in South West Africa. Windhoek, Namibia.

Stengel, H.W., 1966, The rivers of the Namib and their discharge into the Atlantic. Part II: Omaruru and Ugab. Scientific Papers of the Namib Desert Research Station, number 30.

Timmerman, L.R.A., 1985, Preliminary report on the Geohydrology of the Grootwater Primary aquifer unit between Yzerfontein and the Modder River. Geotechnical Report GH3372, Directorate of Geohydrology, Department of Water Affairs, Cape Town, South Africa.

Timmerman, L.R.A., 1988, Regional hydrogeological study of the lower Berg River area, Cape Province – South Africa. Faculty of Science, Ghent University, http://hdl.handle.net/1854/LU-8544626↗.

Travel Guide, 2020, Namaqualand: the blooming desert of South Africa. www.travelguide-en.org↗.

Tredoux, G., W.R. Ross, and A. Gerber, 1980, The potential of the Cape Flats Aquifer for the storage and abstraction of reclaimed effluents (South Africa), doi: 10.1127/zdgg%2F131%2F1980%2F23↗.

Tredoux, G., 1987, The role of artificial recharge in groundwater management at Atlantis. Paper presented at the Biennial Conference and Exhibition, Institute of Water Pollution Control, South Africa Branch, Port Elizabeth, South Africa, 12-15 May 1987.

Tredoux, G. and L. Cavé, 1997, Atlantis Groundwater Management Review 1996/97. Report number ENV/S-C97114, Council for Scientific and Industrial Research, Stellenbosch, South Africa.

Tredoux, G., P.B. King, and L.C. Cavé, 1999, Managing urban wastewater for maximizing water resource utilization, Water Science and Technology, volume 39, issues 10-11, 353-356, doi: 10.1016/S0273-1223(99)00309-1↗.

Tredoux, G. and L. Cavé, 2002, Atlantis aquifer: a status report on 20 years of groundwater management at Atlantis. Report submitted to the City of Cape Town, South Africa, Council for Scientific and Industrial Research report number ENV-S-C 200269.

Tredoux, G., E.C. Murray, and L. Cave, 2002, Infiltration systems and other recharge systems in Southern Africa, *in* Management of aquifer recharge and subsurface storage, editors, A. Tuinhof and Heederik, Netherlands National Committee of the International Association of Hydrogeologists [NNC-IAH], publication number 4, https://www.hydrology.nl/images/docs/iah/publications/4_Management_of_Aquifer_Recharge_and_Subsurface_Storage.pdf↗.

Tredoux, G., 2007, Down-the-hole hydrogeochemical logging of boreholes for artificial groundwater recharge pilot study at Plettenberg Bay. Report for Groundwater Africa. Council for Scientific and Industrial Research, Natural Resources and Environment Unit, Stellenbosch, South Africa.

Tredoux, G. and J.F.P. Engelbrecht, 2009, Langebaan Road aquifer artificial recharge study, Pilot phase recharge final report. Report prepared for Department of Environmental Affairs (DEA), number CSIR/NRE/WR/ER/2009/0099/B.

Tredoux, G., B. Genthe, M. Steyn, J.F.P.Engelbrecht, J. Wilsenacht, and N. Jovanovic, 2009a, An assessment of the Atlantis artificial recharge water supply scheme (Western Cape, South Africa), volume 127, pages 403-413, doi: 10.2495/RAV090351↗.

Tredoux, G., N. Jovanovic, B. Genthe, M. Steyn, and K. Le Corre, 2009b, Reclaim water, a specific targeted research project under the thematic priority 'Global Change and Ecosystems'. Deliverable D4.3, Mass balance-based sustainability analysis for the Atlantis recharge site, European Commission, Brussels, Belgium.

Tredoux, G. and A.S. Talma, 2009, Langebaan Road aquifer: Environmental isotope and hydro chemical sampling, analysis, and interpretation of samples collected in 2008. Report submitted to West Coast District Municipality, Moorreesburg, South Africa.

Tredoux, G.; B. Van der Merwe, and I. Peters, 2009c, Artificial recharge of the Windhoek aquifer, Namibia: Water quality considerations. Boletín Geológico y Minero, volume 120, number 2, pages 269-278, http://yearsgmi.igme.es/Boletin/2009/120_2_2009/269-278.pdf↗.

Tuinhof, A., S. Foster, F. van Steenbergen, A. Talbi, and M. Wishart, 2011, Appropriate groundwater management policy for Sub-Saharan Africa: in face of demographic pressure and climatic variability. World Bank, Washington, D.C., http://hdl.handle.net/10986/27363↗.

Van der Merwe, A.J., 1983, Exploration, exploitation and evaluation of groundwater in sand deposits in the Atlantis area for water supply to the Atlantis Growth Point (in Afrikaans). Master of Science thesis, University of Free State, Bloemfontein, South Africa.

Van Rensburg, F., 2006, Urban Water Security in the City of Windhoek. https://www.sustainabilityinstitute.net/↗.

Van Steenbergen, F. and A. Tuinhof, 2009, Managing the water buffer for development and climate change adaptation – groundwater recharge, retention, reuse and rainwater. United Nations Educational, Scientific and Cultural Organization, International Hydrological Programme [UNESCO-IHP], 91 pages, https://www.ircwash.org/resources/managing-water-buffer-development-and-climate-change-adaptation-groundwater-recharge↗.

Veolia, 2019, News&Media. Case Studies: Bitou Municipality (Plettenberg Bay), Western Cape, South Africa.

Water Scarcity Solutions, 2015, Groundwater recharge Omdel Dam, Namibia. Industrial case studies, https://www.waterscarcitysolutions.org/wp-content/uploads/2015/07/Groundwater-recharge-Omdel-Dam-Namibia.pdf↗.

Water Wheel, 2003, Artificial recharge schemes – a novel method to "bank water". The Water Wheel, May/June 2003, http://www.wrc.org.za/wp-content/uploads/mdocs/WaterWheel_Archive_ww-may-jun%2003.pdf↗.

Weidlich, B., 2019, Namibia plans future water supply, https://namibian.org/news/nature-and-environment/water-supply↗.

West Coast District Municipality, 2005, Assessment of the response of the Langebaan Road aquifer system to a 3-month shutdown of the municipal Wellfield. SRK Consulting Engineers, draft report number 335975.

West Coast District Municipality, 2009, Investigation into alternative water sources for the West Coast District Municipality. Water Study Report, Final, volume 2, Optimization of Existing Sources, compiled by Element Consulting Engineers, project number 07076.

Wikipedia, 2016, Water supply and sanitation in Namibia. https://en.wikipedia.org/↗.

Wikipedia, 2021, Swakoppoort Dam. Accessed on June 18, 2021, https://en.wikipedia.org/wiki/Swakoppoort_Dam↗.

Wipplinger, O., 1953, The storage of water in sand: an investigation of the properties of natural and artificial sand reservoirs and of methods of developing such reservoirs. Doctor of Science Thesis, Stellenbosch University, http://hdl.handle.net/10019.1/54014↗.

Woodford, A.C. and M. Fortuin, 2003, Assessment of the development potential of groundwater resources for the West Coast District Municipality. Specialist geohydrological report for Kwezi-V3 Consulting Engineers, as part of the 155 project: Pre-feasibility study of potential water sources for the area served by the West Coast District Municipality, completed by SRK Consulting Engineers and Scientists for Kwezi-V3.

Wright, A., 1991, The artificial recharge of urban storm water runoff in the Atlantis coastal aquifer. Unpublished Master of Science thesis. Rhodes University, Grahamstown, South Africa, 188 pages, http://hdl.handle.net/10962/d1005491↗.

Wright, A. and R. Parsons, 1994, Artificial recharge of urban wastewater, the key component in the development of an industrial town on the arid West Coast of South Africa, https://search.informit.org/doi/10.3316/informit.753963955739309↗.

Wright, A. and J. Conrad, 1995, The Cape Flats Aquifer – current status. Watertek, Council for Scientific and Industrial Research, Stellenbosch, South Africa.

Xu, Y. and B. Usher (editors), 2006, Groundwater pollution in Africa (first edition), Chemical Rubber Company Press, doi: 10.1201/9780203963548↗.

Xu, Y. and H.E. Beekman, 2019, Review: Groundwater recharge estimation in arid and semi-arid southern Africa. Hydrogeology Journal, volume 27, pages 929–943, doi: 10.1007/s10040-018-1898-8↗.

Zeelie, S., 2004, Omdel (Namibia): Capturing and infiltrating flood runoff in the desert, http://www.artificialrecharge.co.za/05casestudies.html↗.

Zhang, H., Y. Xu, and T. Kanyerere, 2019, Site assessment for MAR through GIS and modeling in West Coast, South Africa. Water, volume 11, issue 8, page 1646, doi: 10.3390/w11081646↗.

Ziervogel, G., 2019, Unpacking the Cape Town drought: lessons learned. Report for Cities Support Programme, African Centre for Cities, University of Cape Town, South Africa.

13 Exercise Solutions

Solution Exercise 1

a) Groundwater is recharged from rain that falls on the surface of the earth, infiltrates through the soil and then into the pores, cracks and fissures of geologic formations until these interstices become saturated. This is natural recharge. Much rainfall runs off over the surface or evaporates back into the atmosphere, thus there are limits to the magnitude of natural recharge.

b) Artificial recharge is the practice of increasing the amount of water that enters an aquifer through human-controlled means. For example, groundwater can be artificially recharged by redirecting water across the land surface through canals, infiltration basins, or ponds from which water seeps into the subsurface; creating irrigation furrows to allow infiltration of excess irrigation water; using sprinkler systems to irrigate with surface water, some of which infiltrates beyond plant roots; or injecting water directly into the subsurface through wells.

c) The term 'Artificial' does not capture the process of humans enhancing natural recharge in a systematic manner. These deficiencies in the term "Artificial Recharge" have been overcome by the now generally accepted term "Managed Aquifer Recharge" (MAR).

d) The term "Aquifer Storage and Recovery" is mainly used in the United States and Australia. It describes well injection of surface water supplies such as potable water, reclaimed wastewater, harvested rainwater, stormwater, or river water into an aquifer for later recovery and use. This term explicitly describes that the managed aquifer recharge is a matter of placing water into aquifer storage and retrieving it for later use.

e) In South Africa a number of new small schemes, similar in local importance to the Kharkams case study, have been reported. Mr. Fanus Fourie of the Department of Water and Sanitation, a champion of MAR, calls them 'nature-based solutions' to emphasize the need for holistic management of locally available water resources for small towns and communities. The only natural resources these small communities have are water, soil and vegetation. Before expecting pipelines to come their way, these communities need to manage their local environment in an integrated and sustainable way. A further dimension is added in the community-driven, multiple use water services (MUS) approach - as a critically important alternative to urbanized models of water supply – i.e., water supply, livelihood and health addressed holistically and with community participation.

Return to Exercise 1↥

Solution Exercise 2

Groundwater occurrence and aquifer characteristics are highly variable from location to location and depend on a number of factors, in particular the hydrogeological make-up of the aquifer and the natural recharge environment of the location. Thus, Managed Aquifer Recharge is not equally feasible at every location.

A groundwater professional will need the following information and needs to determine how much of this information can be gleaned from published sources and what information needs to be determined through site investigation.

- Clarify the objective for artificial recharge with the client - artificial recharge to groundwater is normally done with some or all of the following objectives in mind:
    - enhancing the sustainable yield in areas where over-development has depleted the aquifer;
    - conserving and storing excess surface water for future need, because needs vary with season and may periodically depend on other factors such as development;
    - improving the quality of existing groundwater through dilution;
    - removing bacteriological and other impurities from sewage and wastewater so that water is suitable for re-use; and,
    - restoring water supply to aquifers depleted due to excessive groundwater development.
- Develop an understanding of the socio-political influence that would facilitate or prevent some of the potential technical options for MAR
- Identify potential recharge areas where water could infiltrate and reach the aquifer, or be injected
- Identify potential source waters and determine their quality both with regard to suspended and dissolved constituents
- Evaluate the potential for the aquifer to receive artificial recharge water both physically (to allow the water to flow readily from the recharge site out into the aquifer) and chemically (that clogging diminishes the potential for water to enter the aquifer will not occur)

Return to Exercise 2↥

Solution Exercise 3

a) There are a number of different surface and underground environments one may encounter in Africa. The natural recharge of groundwater is related to climatic conditions such as average temperatures and evapotranspiration, and geological factors such as porosity and infiltration rates. The potential for natural recharge is relatively low across much of Southern Africa, improving to the north, due primarily to increased precipitation.

Approximately 55 percent of the region is covered by low permeability formations. These are largely basement rocks with aquifer systems developed in the weathered overburden and in the fractured bedrock. The aquifers developed in these areas are unconfined, not spatially extensive and locally developed. In general, only modest groundwater supplies can be abstracted sustainably from these aquifers and large-scale groundwater well fields are not feasible. Fissured aquifer systems are associated particularly with the Karoo formations (interlayered shales and sandstones) found extensively throughout southern Africa. The formations are normally low yielding, but where the rocks have been subjected to deformation and intrusion of dolerites, a secondary permeability resulting in good aquifers may be found.

The unconsolidated intergranular aquifer systems occur as large inland basins, such as the Kalahari and Congo basins, in coastal aquifers and in alluvial aquifers in river channels, banks and flood plains.

Karst aquifers are not wide-spread in the region, but constitute some of the most productive aquifers in Namibia, Botswana, Zimbabwe and South Africa. They occur in highly soluble rock, most notably limestone and dolomite. Groundwater flow is concentrated along secondarily enlarged fractures and fissures and other connected openings, where the chemical dissolving action of slightly acidic (rain) water can take place.

b) Similar to the variations in the hydrogeological conditions, the artificial recharge techniques also vary widely. The artificial recharge techniques can be broadly categorized as follows:

Table Exercise 3-1 - Categorized artificial recharge techniques.

Direct surface techniques	• Flooding • Basins or percolation tanks • Stream augmentation • Ditch and furrow system • Over-irrigation
Direct subsurface techniques	• Injection wells or recharge wells • Recharge pits and shafts • Dug well recharge • Bore hole flooding • Natural openings, cavity fillings
Combination surface – subsurface techniques	• Basin or percolation tanks with pit shaft or wells.
Indirect Techniques	• Induced recharge from surface water source • Aquifer modification

c) In the Southern Africa region, MAR started in the coastal aquifers, therefore the emphasis was on direct surface techniques and this is one possibility for the potential project. So, (1) the traditional 'sand dams on alluvial aquifers' are a possible approach. For the more challenging hard-rock environments, (2) injection wells are a more likely solution. For either environment, if agriculture is a major water user, (3) over irrigation is a possible option. In the less likely scenario in which the aquifer has natural openings, (4) treated wastewater could be introduced.

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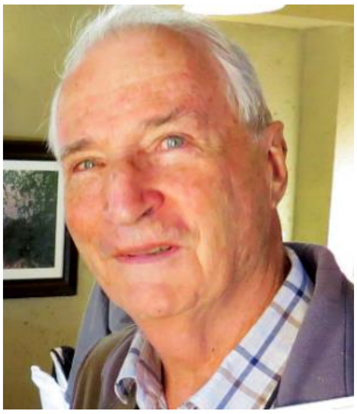
14 About the Authors



Eberhard Braune has had a 42-year career with the Department of Water Affairs, initially in South West Africa and then at the Head Office in South Africa, among others as Director of the Department's Hydrological Research Institute and of the Directorate Geohydrology. There, he led the production of the first national hydrogeological map series for South Africa and published extensively for the Water Research Commission of South Africa. He holds a Master of Science degree (Engineering Hydrology) from Imperial College, London and a Doctorate degree (Science, Honoris Causa) from the University of the Western Cape. After retiring he joined the University of the Western Cape as an Associate Professor. His teaching focus in the Department of Environment and Water Science of the university has been Integrated Water Resources Management. Together with Professor Yongxin Xu, he served as specialist consultant to the United Nations Environment Program (UNEP) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) in regard to groundwater resources management in Africa, with transboundary groundwater resources governance as his special interest. He recently helped with drafting a National Groundwater Strategy for South Africa. He has served for many years as chair of the South African chapter of the International Association of Hydrological Sciences and received Life Honorary Membership of the Groundwater Division of the Geological Society of South Africa.

Sumaya Israel is a Senior Lecturer in the Environmental and Water Science section of the Earth Science department at the University of the Western Cape (UWC), where she teaches and conducts research related to groundwater quality. Her undergraduate studies in Geology took place at UWC, while her Master (2007) and her Doctorate (2015) degrees were obtained from Stellenbosch University with a focus in groundwater remediation. She has about 20 years of experience working in industry where her research spanned a number of topics including, reserve determination, classification of groundwater resources, water quality assessments, monitoring network design, water quality monitoring, managed aquifer recharge research, characterization of aquifers, site assessment for groundwater remediation, implementation of groundwater remediation, the spatial distribution and concentrations of various chemical constituents of groundwater in the environment (including nitrate in Southern Africa, fluoride in South Africa, and pharmaceuticals in the Western Cape), and remediation of nitrate in groundwater. She has worked with PHREEQC as well as Aquachem database management software as data analysis tools and to simulate groundwater systems. Her passion lies in understanding chemical processes linked to water rock interactions in various geological settings, as well as the influence of anthropogenic activities on these natural systems. She manages a number of research projects related to these topics. Dr. Israel also serves as a reviewer for a number of peer reviewed journals, and as the chairperson of the groundwater division of South Africa's Western Cape branch.

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Modifications from Original Release

page vi, Added the book DOI.

page vi, moved copyright page to before the Table of Contents to be consistent with standard GW-Project book layout.

page 80, reference to Department of Water Affairs and Forestry (DWAF), 2009 was reformatted

page 81, reference to Department of Water Affairs and Forestry (DWAF), 2010 was reformatted and enhanced with additional information

page 84, reference for Murray 2008 was added

page 85, reference to Peters 2014 was revised, the website is no longer available

page 89, the reference to Ziervogel 2019 was revised, the website is no longer available