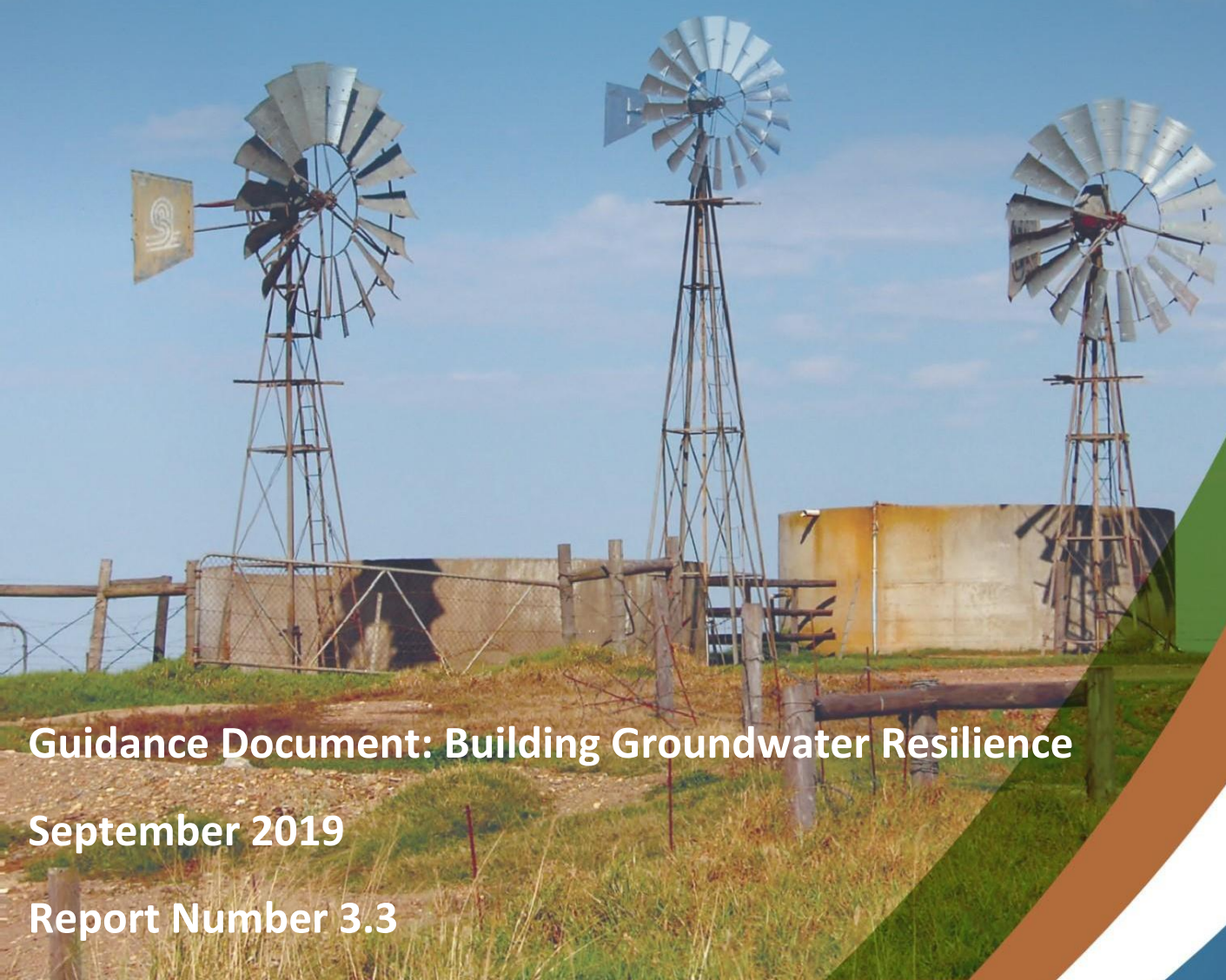


# Policy, Legal and Institutional Development for Groundwater Management in the SADC Member States (GMI-PLI)



**Guidance Document: Building Groundwater Resilience**

**September 2019**

**Report Number 3.3**





This report emanates from the project Policy, Legal and Institutional Development for Groundwater Management in the SADC Member States (GMI-PLI) commissioned by the Southern African Development Community Groundwater Management Institute (SADC-GMI), and executed by Pegasys.

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Citation: SADC-GMI, (2019). *Guidance Document: Building Groundwater Resilience*. SADC GMI report: Bloemfontein, South Africa.

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## FOREWORD

The Southern African Development Community (SADC) Member States, through the support of International Cooperating Partners have gone through a series of Water Sector Reforms which varied in terms of policy, legal and institutional development. The focus of the water sector reforms has been on Integrated Water Resources Management and aimed at achieving sustainable and equitable distribution of water resources in the respective Member States. To a large extent, the water sector reforms did not comprehensively address the sustainable management of groundwater resources, yet 70% of the population in the SADC region depend on it. Climate change continues to negatively affect the availability of surface water, placing significance reliance on the use of groundwater for both urban and rural supply throughout the region. Human wellbeing, livelihoods, food security, ecosystems, natural habitats, industries and urban centres growth throughout the SADC Region are increasingly becoming more reliant on groundwater. The SADC region in general has an abundance of groundwater resources. However, due to several factors which include the lack of an enabling policy, legal and institutional environment, only an estimated 1.5% of the available renewable groundwater resources are currently being utilised.

It is estimated that there are about 30 Transboundary Aquifers (TBAs) and 15 transboundary river systems and that these systems are central to the water security of the region. There is therefore a need for Members States to establish and strengthen existing policy, legal and institutional frameworks to achieve equitable and sustainable access to water resources through joint management of the transboundary resources. It is in view of the above and in response to the need to strengthen the sustainable use of groundwater resources conjunctively with surface water at both the national and regional level, that the Southern African Development Community – Groundwater Management Institute (SADC-GMI) was established by the SADC Secretariat, on behalf of the Member States.

The vision of the SADC-GMI is, “to be a Centre of Excellence in promoting equitable and sustainable groundwater management in the SADC region”. The key focus areas of SADC-GMI are to 1) advocate, raise awareness and provide technical support in SADC around sustainable management through the dissemination of information and knowledge; 2) create an enabling environment for groundwater management through policy, legal and regulatory frameworks; 3) promote action-oriented research; 4) promote impact-oriented capacity building and training for groundwater management in the region; 5) lead and promote regional coordination for groundwater management; and 6) support infrastructure development for groundwater management.

In pursuance of the focus area of creating an enabling environment, SADC-GMI implemented the project entitled “Policy, Legal and Institutional Development for Groundwater Management in the SADC Member States, (GMI-PLI)”. The methodology for said project included the development of the Desired Future State, conducting a baseline study of best practices, and description of policy, legal and institutional frameworks which promote sustainable groundwater management. Using an in-Country Experts model, a systematic analysis of the existing policy, legal and Institutional frameworks in comparison with the Desired Future State was conducted to identify gaps that required to be addressed in order to fulfil the SADC-GMI mandate – to achieve sustainable groundwater management in all 16 SADC Member States. The analytical assessment of the gaps identified at national level culminated in the production of 16 National Gap Analysis & Action Plan Reports and the higher-level Regional Gap Analysis Report. The latter summarises the findings across the SADC region.

This Guidance Document provides guidance to groundwater managers to understand and implement measures related to the role of groundwater in water resilience as the SADC region is prone to environmental, political, economic and social shocks and stresses. It is hoped that this Guidance Document will aid the SADC Member States to understand the importance of groundwater in water resilience and ultimately advance the groundwater narrative and bring it at par with surface water in terms of policy, legal and institutional frameworks which will no doubt enhance sustainable groundwater management at a national and regional level in the SADC Region.

James Sauramba  
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## ACKNOWLEDGEMENTS

The following individuals and organisations are thanked for their contributions to the project:

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### **Stakeholders Engaged**

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The project team would like to thank all those stakeholders that contributed to the project from Government, Private Sector, Civil Society and Academia and Research.

The authors also like to express sincere appreciation to members of the **SADC Sub-Committee on Hydrogeology** for identifying the need for this project, following on the numerous challenges that they experience in their respective countries. Without the dedicated facilitation and support from the members of the SADC Sub-Committee on Hydrogeology, who also serve as focal points for groundwater development in their respective countries, this exercise would not have been accomplished.

In this regard, special thanks are given to:

Mr Manuel Quintino, Angola; Mr Kedumetse Keetile, Botswana; Mr Cyrille Masamba, Democratic Republic of Congo; Mr Trevor Shongwe, Kingdom of eSwatini, Ms Christinah Makoe, Lesotho; Mr. Luciano Andriavelojaona, Madagascar; Ms Zione Uka, Malawi; Mr Pokhun Rajeshwar, Mauritius; Ms Ana Isabel Fotine, Mozambique; Ms Maria Amakali, Namibia; Mr Frankie Jose Dupres, Seychelles; Mr Zacharia Maswuma, South Africa; Ms Mwanamkuu Mwanyika, United Republic of Tanzania; Mr Frank Ngoma, Zambia; and Mr Robert Mutepfa, Zimbabwe.

Additionally, the authors thank all other professionals from the Member States who contributed to the project by providing ideas and feedback, in particular, professionals from various organisations who contributed to the over-all project, and senior officials from the Member States. The contribution of all institutions and individuals who supported the project through ideas and comments and may not have been credited by name, is greatly appreciated.

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## EXECUTIVE SUMMARY

### Groundwater resources - The road to water resilience

The South African Development Community (SADC) faces several risks to water security from extreme weather events, natural disasters and state collapse or crisis. Building resilience in groundwater resources provides an opportunity to improve water security by diversifying the water supply-mix.

The region has undergone severe droughts during the 2015/2016 and 2016/2017 rainy seasons and floods (2019) through tropical storms Idai and Kenneth which caused deaths and extensive damage in Mozambique, Malawi and Zimbabwe resulting in water crises and food shortages. Unplanned urban population growth in cities and informal settlements presents another major challenge for water security. Resilience system analysis is increasingly applied to water governance to understand socio-ecological systems ability to recover from imposed shocks such as extreme weather events. Guidelines are needed to support groundwater resource managers to implement measures in support of groundwater resilience in SADC.

#### What is groundwater resilience?

A risk is the likelihood of a negative event and its consequences. A shock occurs when a risk becomes reality (OECD 2014). A fundamental principle of resilience is being able to respond and adapt to shocks and stresses and to transform when conditions require it (Brown and Boltz 2016). Drivers that have a major bearing on groundwater, unfolding role and governance [in SADC], include widespread poverty and food insecurity in the region, the continuing need for a basic domestic water supply in both rural and informal urban areas, rapid urbanisation, and the need for drought security as part of all water provision (Braune and Adams 2013). Groundwater resilience refers to the ability of groundwater resources to recover from disturbances to its natural state or establish a new equilibrium in response to imposed shocks.

#### The natural absorptive capacity of groundwater resources

Absorptive capacity is the ability of a system to prepare for, mitigate or prevent negative impacts, using predetermined coping responses in order to preserve and restore essential basic structures and functions (OECD 2014). This includes coping mechanisms used during periods of shock. Examples of absorptive capacity for groundwater resources include groundwater storage availability, natural attenuation to pollution and is clearly related to the duration and magnitude of a perturbation.

Groundwater storage serves as a key buffer for achieving groundwater resilience under extreme climate events e.g. extended drought conditions. Using the groundwater resource strategically and sustainably means that it can be a crucial factor to bridge gaps between water resource availability and water demand. This requires careful consideration and includes: (i) setting a limit on how much water can be safely pumped to avoid irreversible subsidence caused when too much water is removed from the aquifer; (ii) defining a safety reserve to ensure an adequate water supply in a worst-case scenario,

such as a multi-year-interruption in surface water supplies; and (iii) defining a management level – a target groundwater level that allows use of the aquifer as a working reserve that can be used during dry times and refilled when adequate surface water supplies are available while protecting the safety reserve and while preventing exceedance of the irreversible subsidence limit.

The capacity of a groundwater system to recover from pollution is critical to the concept of resilience as natural disasters and extreme weather events undermine the effectiveness of remediation measures. Determining the natural attenuation capacity of groundwater systems at a local scale is complex as it requires detailed knowledge of: (i) the type and quantity of pollutants involved; (ii) the chemical and hydraulic characteristics of both unsaturated and saturated zones; and (iii) other factors controlling the spatial extent and persistence of pollutants. Because of the overall complexity (often unsuccessful) and costs of groundwater remediation the focus should be on prevention of pollution.

### **Interventions to support groundwater resilience**

There are several measures to support groundwater resilience such as conjunctive management of water resources; managed aquifer recharge (MAR); and groundwater reuse and recycling.

#### **Conjunctive management**

Conjunctive management in support of long-term groundwater (and surface water) resilience refers to management of the combined use of groundwater, surface water and other sources of water in a manner that prevents irreversible impacts (quantity and quality) on either of the resources. The benefits of coordinated management of the water sources should exceed the benefits obtained through their separate management. Benefits of conjunctive (planned) management are: (i) diversification of water supply mix; (ii) improved water supply security and security of water sources (prevention of over-exploitation, preparedness for extreme weather events); (iii) larger net water supply yield (efficient use of both water resources); and (iv) reduced environmental impact (prevents/limits over-exploitation of groundwater and surface water, water logging and salinisation). In rapidly expanding cities, conjunctive use of groundwater and surface water is often unplanned and includes 'traditional' groundwater sources (springheads or water wells) at the urban nucleus e.g. Lusaka, Zambia and immediate neighbouring surface watercourses either one of which subsequently become insufficient with urban growth.

#### **Managed aquifer recharge**

MAR is the replenishment of groundwater by planned subsurface infiltration which is recovered at a later stage. The main objective of MAR is to create additional storage in a controlled manner to meet future water needs, hence lessen the risk of over-exploitation. MAR usually forms part of a broader water management plan to ensure sustainable utilisation of the groundwater resource. Benefits of MAR other than storage enhancement includes flood and drought risk reduction, salinity improvement and ecosystem enhancement. In the case of Windhoek, the capital of Namibia, groundwater



contributes about 10% to the water supply (Christelis and Struckmeier 2011). A system of artificially recharging groundwater resources has been put in place (Murray et al. 2018). The aim is to make available up to 8 million cubic metre per annum ( $\text{Mm}^3/\text{annum}$ ) of groundwater for abstraction (Tredoux et al. 2009). The present Windhoek water demand is about 20  $\text{Mm}^3/\text{annum}$  (Christelis and Struckmeier 2011). MAR has contributed to water security in the Windhoek area.

### **Groundwater reuse and recycling**

Groundwater recharge with recycled water maximizes the reuse and should be an important component of water resource planning in major cities and towns of SADC. Indirect recycling of water at Atlantis near Cape Town, South Africa, started shortly after development of the town in the mid-1970s. The artificial groundwater recharge scheme of Atlantis stores and further purifies treated domestic wastewater and urban stormwater. The groundwater is abstracted at wellfields and re-used to augment the municipal water supplies for the town. It has alleviated the pressure on surface water resources in the region (Bugan et al. 2016).

The road to water resilience requires broadening the water supply mix to include urban stormwater, water harvesting, water reuse, recycled wastewater, desalinated water and groundwater.

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## LIST OF ACRONYMS

Acronym	Definition
<b>AWSS</b>	Atlantis Water Supply Scheme
<b>MAR</b>	Managed Aquifer Recharge
<b>NSC</b>	North-South Carrier
<b>SADC</b>	Southern African Development Community
<b>SADC-GMI</b>	Southern African Development Community Groundwater Management Institute
<b>mbgl</b>	Metres Below Ground Level
<b>mg/ ℓ</b>	Milligram Per Litre
<b>mm</b>	Millimetres
<b>Mm<sup>3</sup>/a</b>	Million Cubic Metre Per Annum
<b>t/ha</b>	Tons Per Hectare

## 1. INTRODUCTION

The purpose of the document is to provide guidance to groundwater managers to understand and implement measures related to the role of groundwater in water resilience (referred to hereafter as groundwater resilience) as the Southern African Development Community (SADC) region is prone to environmental, political, economic and social shocks and stresses (Box 1).

### Box 1: Resilience systems different type of shocks and stresses (OECD 2014)

Resilience systems analysis considers different types of risks, shocks and stresses:

- Infrequent events with an impact on almost everyone in the target group, such as violent conflict, volcanic eruptions or currency devaluations - **covariate shocks**
- Significant events that specifically affect individuals and families, such as the death of the main breadwinner or the loss of income-generating activity - **idiosyncratic shocks**
- **Seasonal shocks**, such as annual flooding linked to the rainy season, food market price changes, or **recurring shocks** such as frequent displacement or endemic cholera communities
- Long term trends, weakening the potential of a system and deepening the vulnerability of its actors, like increased pollution, deforestation, exchange rate fluctuations and electoral cycles - **stresses**

Examples of recent shocks and stresses in the region include:

- **Drought:** The SADC-region has undergone severe droughts during the 2015/2016 and 2016/2017 summer rainfall seasons (Blamey et al. 2018; Siderius et al. 2018; Archer 2019; Nhamo and Mabhaudhi 2019). In the past, droughts were driven by natural climate variability but with anthropogenic influences the characteristics of droughts are changing to include a type of drought that has a rapid onset and short duration (Yuan et al. 2018).
- **Flooding:** Widespread flooding over parts of Malawi, Mozambique, and Madagascar occurred in January 2015 resulting in huge damage to property, infrastructure, and agriculture over several regions in south-eastern Africa as well as significant loss of life (Rapolaki and Reason 2018). The flooding was associated with tropical storm Chedza which developed in the Mozambique Channel on 11 January 2015 (Rapolaki and Reason 2018), similar to tropical storm Idai and Kenneth (Box 2).
- **Disease:** Rieckmann et al. (2018) compared cholera outbreaks during droughts and floods with drought- and flood-free periods in 40 sub-Saharan African countries and found an increased incidence rate of cholera outbreaks during droughts and floods. In Zimbabwe, the most recent cholera outbreak began on 1 September 2018, in Harare. The Ministry of Health and Child Care reported approximately 2,000 suspected cholera cases, of which 58 (2.9%) were confirmed cases, and 24 (1.2%) resulted in death (WHO Regional Office for Africa 2018 in Ahmad et al. 2019).

### Box 2: Tropical storms Idai and Kenneth (Brackett and Wright 2019; Oxfam Education 2019).

Cyclone Idai made landfall in Mozambique on the night of 14 to 15 March 2019 - this weather system caused extensive damage in Mozambique, Malawi and Zimbabwe. Strong winds, a storm surge, heavy rains and widespread flooding had devastating impacts. More than 800 people died across the three countries, with many more still missing and millions of people left homeless without food or basic services.



The UN Secretary General declared this “one of the worst-weather related catastrophes in the history of Africa”. The cyclone that tore across southern Africa may have destroyed more than \$1 billion of infrastructure. Tropical storm Idai was quickly followed by tropical storm Kenneth – two major storms within two months. Tropical Cyclone Kenneth destroyed hundreds of homes and killed at least six people in Mozambique. The Category 4-equivalent storm brought flooding and landslides to the Indian Ocean archipelago nation of Comoros; local authorities reported at least three deaths. Ninety percent of homes 'flattened' on the Mozambique tourist island of Ibo.

Photo credit: Sergio Zimba/Oxfam

The capacity of social-ecological systems to deal with shocks, adapting to changing conditions and transforming in situations of crisis are fundamentally dependent on the functions of water to regulate the Earth's climate, support biomass production, and supply water resources for human societies (Falkenmark et al. 2019). Resilience systems analysis is increasingly applied to water governance to understand the socio-ecological systems ability to recover from shocks and stresses. Thresholds or tipping points are critical to understand as beyond these there is a point of no return. This document focusses on groundwater systems ability to cope and recover from disturbances and measures which can be put in place to support groundwater resilience. The guidance document has 8 Chapters ([Table 1](#)).



**Table 1: Structure of the Building Groundwater Resilience guidance document**

Chapter	Contents
1. Introduction	This chapter presents the introduction to the guidance document.
2. Groundwater resilience	In this chapter groundwater resilience is defined and the global environmental and societal risks discussed. Further information is provided about the groundwater risks related to droughts, floods, excessive groundwater pumping, pollution and sea-level rise.
3. Absorptive capacity for groundwater resilience	The natural absorptive capacity of groundwater resources is discussed in Chapter 3. Examples of absorptive capacity of groundwater resources include groundwater storage availability and natural attenuation to pollution. Absorptive capacity is clearly related to the duration and magnitude of any perturbation as discussed in Chapter 3.
4. Conjunctive management	Chapter 4 deals with conjunctive management of the combined use of groundwater, surface water and other sources of water in a manner that prevents irreversible impacts (quantity and quality) on either of the resources.
5. Managed aquifer recharge	Managed aquifer recharge (MAR) which is the replenishment of groundwater by planned subsurface infiltration recovered at a later stage is discussed in Chapter 5.
6. Groundwater reuse and recycling	Groundwater recharge with recycled water maximizes water reuse and should form an integral part of water resource planning in major cities and towns of SADC is discussed in Chapter 6.
7. Conclusions and recommendations	The conclusions and recommendations are presented in Chapter 7.
8. References	The references cited in the guidance document is presented in Chapter 8.

## 2. GROUNDWATER RESILIENCE

### 2.1. Defining resilience

A risk is the likelihood of a negative event and its consequences. A shock occurs when a risk becomes reality (OECD 2014). A fundamental principle of resilience is being able to respond and adapt to shocks and stresses and to transform when conditions require it (Brown and Boltz 2016). In the World Economic Forum (WEF) 2019 Global Risks Perception Survey, environmental risks have grown in prominence in recent years with the five most prominent types of risks in the environmental category (extreme weather events, natural disasters, failure of climate change mitigation and adaptation, man-made environmental disasters and biodiversity loss and ecosystem collapse) being ranked higher than average for both likelihood and impact over a 10-year horizon (WEF 2018; WEF 2019; Figure 1) compared to other risks. Water crises<sup>1</sup> have also been consistently ranked over the same time-period and defined as a societal global risk in terms of likelihood and impact (Figure 1).

In the SADC-region, the global environmental and societal risks are predicted to put further pressure on groundwater resources. The socio-economic drivers include (after Pegasys 2019):

- **Water crises:** SADC has about 280 million people of which 40% has no access to an adequate safe drinking water supply, whilst 60% has no access to adequate sanitation service (SADC 2016). Like the rest of Africa, urban population growth in SADC is outpacing economic, social and institutional development (Bello-Schünemann and Aucoin 2016). Unplanned urban population growth remains a serious threat to water security, especially in cities and informal settlements of sub-Saharan Africa (Dos Santos et al. 2017). Kinshasa (Democratic Republic of Congo – DRC) is already classed as a megacity with a population exceeding the 10 million mark with Johannesburg (South Africa), Dar es Salaam (Tanzania), and Luanda (Angola) emerging as megacities by 2030 (United Nations 2016; Van Niekerk and Le Roux 2017). The high rate of urbanisation is already putting strain on water infrastructure; poses problems for human and environmental health; and disparate socioeconomic development and access to water; all resulting from governance failure of water management institutions.

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<sup>1</sup> A significant decline in the available quality and quantity of fresh water, resulting in harmful effects on human health and/or economic activity (WEF 2018).

#### Top 5 Global Risks in Terms of Likelihood

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1	Asset price collapse	Asset price collapse	Storms and cyclones	Severe income disparity	Severe income disparity	Income disparity	Interstate conflict with regional consequences	Large-scale involuntary migration	Extreme weather events	Extreme weather events	Extreme weather events
2	Slowing Chinese economy (<6%)	Slowing Chinese economy (<6%)	Flooding	Chronic fiscal imbalances	Chronic fiscal imbalances	Extreme weather events	Extreme weather events	Extreme weather events	Large-scale involuntary migration	Natural disasters	Failure of climate-change mitigation and adaptation
3	Chronic disease	Chronic disease	Corruption	Rising greenhouse gas emissions	Rising greenhouse gas emissions	Unemployment and underemployment	Failure of national governance	Failure of climate-change mitigation and adaptation	Major natural catastrophe	Cyber-attacks	Natural disasters
4	Global governance gaps	Fiscal crisis	Biodiversity loss	Cyber-attacks	Water supply crises	Climate change	State collapse or crisis	Interstate conflict with regional consequences	Large-scale terrorist attacks	Data fraud or theft	Data fraud or theft
5	Retrenchment from globalization	Global governance gaps	Climate change	Water supply crises	Mismanagement of population	Cyber-attacks	High structural unemployment or underemployment	Major natural catastrophe	Massive incident of data fraud/theft	Failure of climate-change mitigation and adaptation	Cyber-attacks

#### Top 5 Global Risks in Terms of Impact

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1	Asset price collapse	Asset price collapse	Fiscal crises	Major systemic financial failure	Major systemic financial failure	Fiscal crises	Water crises	Failure of climate-change mitigation and adaptation	Weapons of mass destruction	Weapons of mass destruction	Weapons of mass destruction
2	Retrenchment from globalization (developed)	Retrenchment from globalization (developed)	Climate change	Water supply crises	Water supply crises	Climate change	Rapid and massive spread of infectious diseases	Weapons of mass destruction	Extreme weather events	Extreme weather events	Failure of climate-change mitigation and adaptation
3	Oil and gas price spike	Oil price spikes	Geopolitical conflict	Food shortage crises	Chronic fiscal imbalances	Water crises	Weapons of mass destruction	Water crises	Water crises	Natural disasters	Extreme weather events

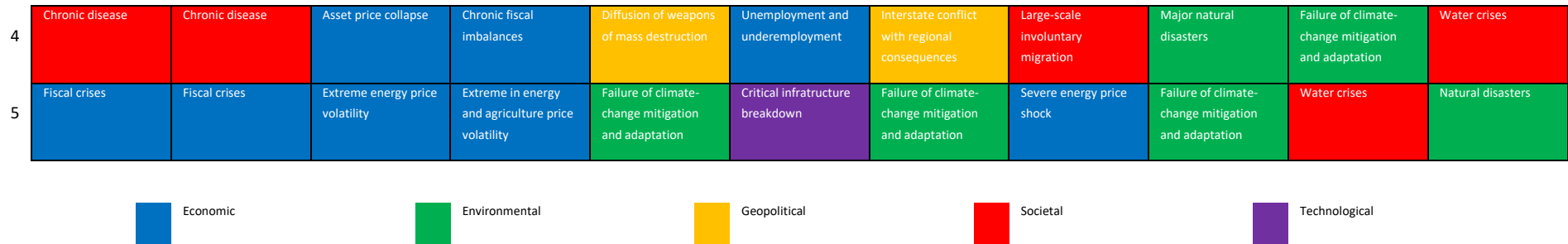


Figure 1: The evolving risk landscape, 2009–2019 (WEF 2019)



- **Food shortage crises:** Despite the urbanisation trends, a significant percentage of the SADC population is still rural. Most of the extreme poor in Southern Africa live in the rural areas and 85% of all poor people in the sub-region depend on agriculture for their livelihood (UNECA-SA 2012). Agriculture constitutes the primary source of subsistence, employment and income for 156 million people (55%) and accounts for close to 8% of its gross domestic product (UNECA-SA 2012).
- **State collapse or crises:** In countries that have undergone civil unrest (wars), investment in water infrastructure fell short which was further aggravated by the destruction of infrastructure and consequently regress of water supply. Significant investments are required to rebuild the infrastructure in these countries; in the case of the DRC an estimated \$2 billion is required for infrastructure projects (Partow 2011).
- **Failure of climate change mitigation and adaptation:** Water resources in the SADC Region will be impacted negatively by climate change. Therefore, issues related to climate change, climate variability and climate proofing need to be continuously addressed in the SADC water sector regional plans and programmes (SADC 2016). Namibia, for example, is expected to experience reduced rainfall of 10 to 30% relative to the present situation by 2050 and 2080 (Reid et al. 2007). Across the region there is an expectation of increased occurrence of extreme hydrological events, requiring the region to develop improved adaptive capacity to flood and drought events.

Increasing aridity and dwindling surface water supplies result in new opportunities for groundwater (Pegasys 2019). Drivers that have a major bearing on its unfolding role and governance [in SADC] include the widespread poverty and food insecurity in the region, the continuing need for a basic domestic water supply in both rural and informal urban areas, rapid urbanisation, and the need for drought security as part of all water provision (Braune and Adams 2013). Groundwater resilience refers to the ability of groundwater resources to recover from disturbances (shocks and stresses) to its natural state or new equilibrium.

## 2.2. Type of risks

### 2.2.1. Droughts

Groundwater drought is the sustained and extensive occurrence of periods below normal groundwater levels (Van Loon 2015). Groundwater drought is normally not incorporated in resilience planning as responses during drought conditions are reactive rather than proactive or strategic. Regulation of groundwater withdrawals during this time is generally absent and less applied than supply-side groundwater management strategies (Langridge et al. 2018). During such times groundwater is normally over-pumped. In California, the trend of increasing groundwater use amid cycles of drought has exacerbated groundwater depletion, water quality degradation, land subsidence, and depletion of interconnected surface water across the state (Babbitt et al. 2018).

Villholth et al. (2013) identified groundwater risk areas in SADC based on composite mapping analysis of region-wide gridded relative indices of meteorological drought risk, hydrogeological drought proneness and human groundwater drought vulnerability. The mapping results highlighted areas across the SADC with highest groundwater drought risk and populations in the order of 39 million at risk of groundwater drought at present with projected climate-model results suggesting a potentially significant negative impact of climate change on groundwater drought risk (Figure 1; Villholth et al. 2013).

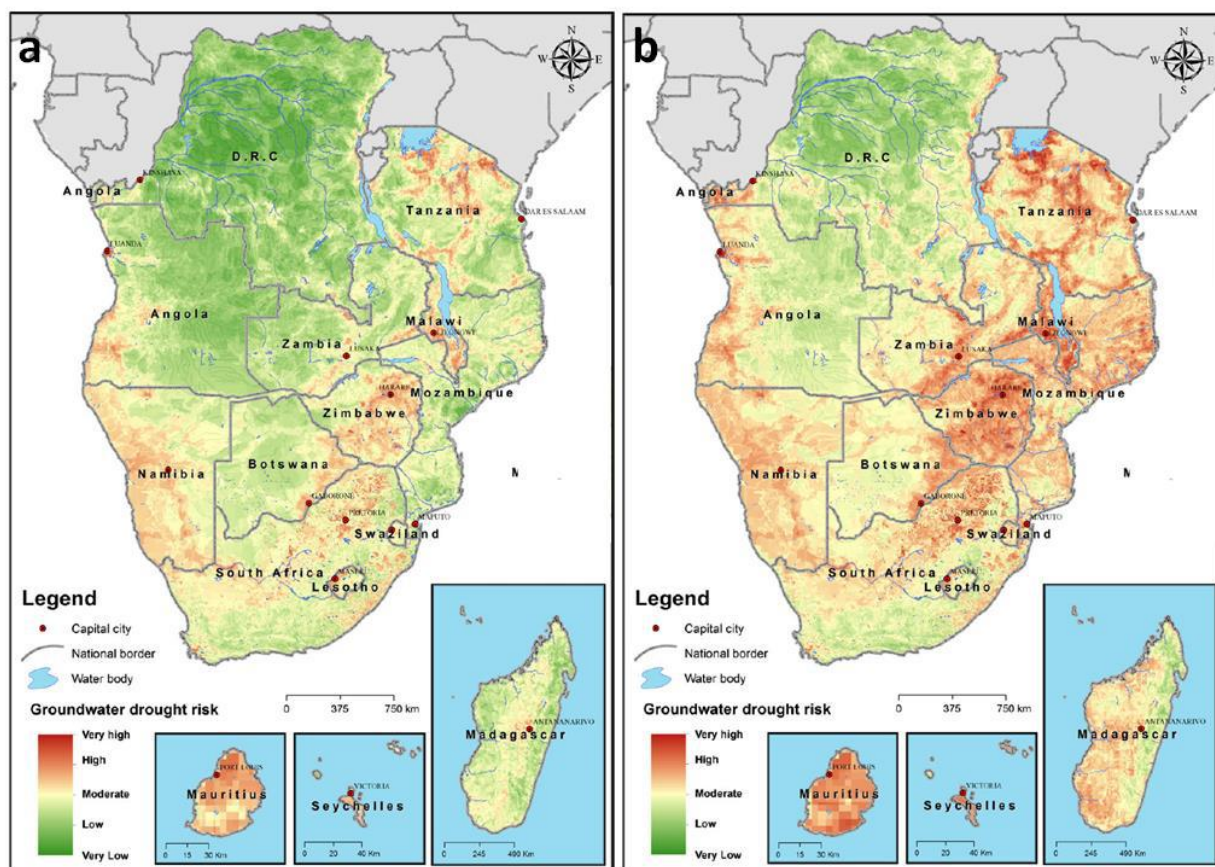


Figure 2: (a) Regional groundwater drought risk; and (b) future climate (based on IPCC SRES A1B) (Villholth et al. 2013)

Several problems are noted with drought planning (modified from Langridge et al. 2018):

- **Consumer resistance:** Resistance to (further) imposed water demand management by consumers can occur as a result of long-term conservation measures (outdoor use restrictions, rebate programs, and price structure changes) that make it difficult for utilities [or local authorities] to induce further reductions in water use during drought
- **Decreased revenue:** Most water utilities [or local authorities] receive their revenues from water consumption, so there can be a negative incentive to require conservation during non-drought periods
- **Inadequate drought planning:** Existing drought planning does not sufficiently include private borehole owners or small water systems serving disadvantaged communities
- **No pro-active planning:** Many drought projects focus on increasing storage for supply reliability, but projects do not necessarily specify whether and how water will be available for future droughts

### 2.2.2. Floods

High intensity and long-duration rainfall often result in rising groundwater levels and ultimately flooding at the surface. Three scenarios described for this type of flooding are (after Macdonald et al. 2008):

- a. **Long-lasting, often regionally extensive, flooding** caused by the water table in an unconfined aquifer rising above the land surface as a response to extreme rainfall (Figure 3), e.g. winter flooding on top of the Cape Flats aquifer
- b. **Rising groundwater levels** also occur in shallow unconsolidated sedimentary aquifers which overly aquitards (less permeable) when the storage capacity is limited, direct rainfall recharge is relatively high, and when there is a good hydraulic connection with adjacent rivers. Groundwater levels are often close to the ground surface during much of the year. Intense rainfall can cause a rapid response in groundwater levels due to rising river levels which creates increased heads that drive water into the aquifer
- c. Flooding occurs where there has been a **reduction in abstraction from large aquifers** underlying major urban centres due to a reduction in industrial or mining activities. This has allowed depressed groundwater levels to recover, thereby causing the risk of flooding to subsurface infrastructure, such as tunnels and basements of buildings, as well as changes in geotechnical and geochemical properties of the aquifer that could result in settlement and corrosion of deeply founded structures



Photo credit: Thembela Ntongana



Photo credit: Ashraf Hendricks

**Figure 3: Flooding of informal settlements due to high (rising) water table (GroundUp 2018)**

### 2.2.3. Excessive groundwater pumping

Groundwater overexploitation is a worldwide phenomenon with important consequences and only few effective solutions available (Molle et al. 2018). Groundwater depletion is primarily caused by sustained groundwater pumping with some of the negative effects being (Groundwater Foundation 2019):

- **Lowering of the water table:** Excessive pumping lowers the groundwater table, and cause wells to no longer be able to reach groundwater
- **Increased costs:** As the water table lowers, the water must be pumped from greater depths, thereby using more energy. In extreme cases, deepening a well and/or pumping from greater depth can be cost prohibitive
- **Reduced surface water supplies:** Groundwater and surface water are connected. When groundwater is overused, also water supply from lakes, streams, and rivers connected to groundwater is also reduced
- **Land subsidence:** Land subsidence occurs when there is a loss of support below ground. This is most often caused by human activities, mainly from the overuse of groundwater, when the soil collapses and/or compacts
- **Water quality concerns:** Excessive pumping in coastal areas can cause saltwater to move inland and upward, resulting in saltwater contamination of the water supply

Bonsor et al. (2018) using Gravity Recovery and Climate Experiment (GRACE) data to examine terrestrial water changes in 12 sedimentary aquifers (including Congo, North Kalahari, Kalahari and Karoo) found [at a regional scale] that there are no substantial continuous long-term decreasing trends in groundwater storage from 2002 to 2016 in any of the African basins.

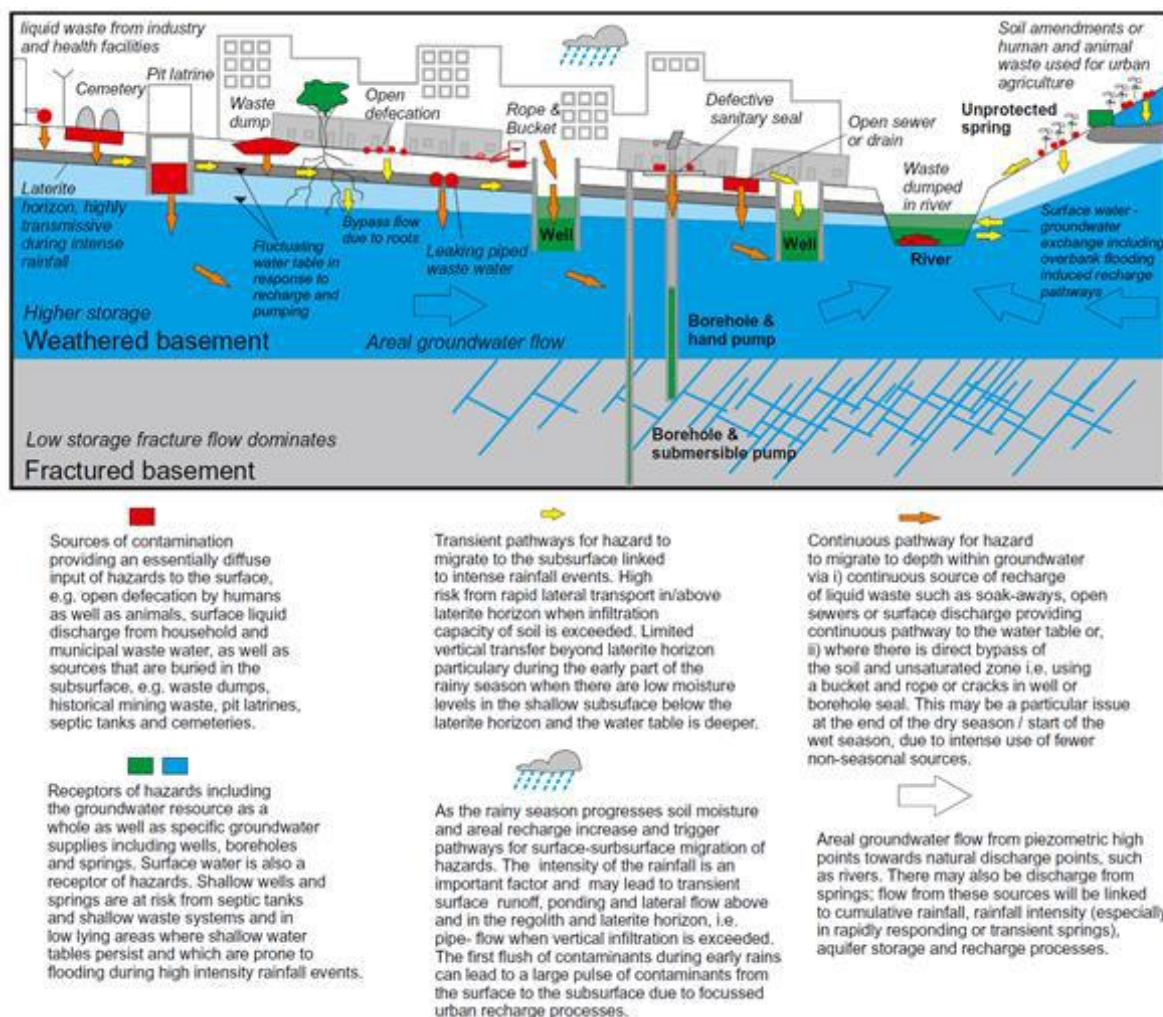
However, at local scale there has been groundwater depletion:



- The City of Windhoek, Namibia has been abstracting from the Windhoek aquifer since the 1950s with water levels dropping by about 40m in the micaceous quartzites which constitute the main wellfield areas; water levels were steadily declining in the pure quartzite areas (Murray et al. 2018)
- The Grootfontein groundwater aquifer is important for the water supply of the town Mahikeng in the North West Province of South Africa and for commercial agriculture in the Province. The water table, however, has fallen by up to 28m as a consequence of over-abstraction since the 1980s (Cobbing and de Wit 2018).
- Robins et al. (2013) postulated that the demand from weathered and fractured crystalline basement aquifers in Malawi in some places may exceed long-term resource potential and that this is also a cause of water point failure. The implications of long-term groundwater mining in parts of Malawi urgently require further investigation in order to develop and implement a sustainable remedial strategy to safeguard rural community livelihoods (Robins et al. 2013).

#### 2.2.4. Pollution

Pit latrines are the main form of sanitation in unplanned areas in many rapidly growing developing cities (Jenkins et al. 2015; Kayembe et al. 2018). In Maputo, the capital of Mozambique, nitrate concentrations above 250 milligram per litre (mg/l) in groundwater have been reported due to the widespread use of latrines and septic tanks that allow for constant infiltration of its content into the soil and eventually to groundwater resources (Arsénio et al. 2018). [Figure 4](#) summarises key pathways, shown by orange arrows, in high-risk settings such as fractured basement terrains with lateritic soil, including surface and subsurface pathways for migration of pollutants from sources to receptor areas (Lapworth et al. 2017).



**Figure 4: Key potential sources, pathways and receptors of faecal contamination in urban settings in Sub-Saharan Africa (Lapworth et al. 2017)**

Peri-urban agriculture impacts on groundwater resources through the use of fertilisers, either synthetic or manure, and pesticides and if irrigation is not managed adequately there can also be a risk of salinisation (Lapworth et al. 2017).

Organic contaminants are also becoming an issue. In Kabwe, Zambia, Sorensen et al. (2015) found the insect repellent N,N-Diethyl-m-toluamide (known as DEET) ubiquitous within groundwater with other compounds detected including bactericide triclosan, chlorination by-products trihalomethanes, and the surfactant 2,4,7,9-tetramethyl-5-decyne-4,7-diol. Emerging contaminants were most prevalent in shallow wells sited in low cost housing areas attributed to localised vulnerability associated with inadequate well protection, sanitation, and household waste disposal (Sorensen et al. 2015).

An increase in salinity of groundwater often occurs due to agricultural activities e.g. through irrigation return flow in semi-arid areas with high evapotranspiration. Significant salinisation has been reported in groundwater underlying the irrigated lands of the Great Fish- Sundays River basin (TDS increased from 2

000 to 3 400mg/ℓ) (Conrad et al. 1999). Studies of the influence of irrigation on groundwater at the Vaalharts Irrigation Scheme were conducted by Verwey et al. (2011). In 1971, salinisation became a problem as the water table had risen from 24 metres below ground level (mbgl) to 1.2 mbgl. Leakages from dams and soil furrows of the system were about 45 million m<sup>3</sup> per annum (Mm<sup>3</sup>/a). Salt deposited through irrigation water amounted to 4.65 tons per hectare (t/ha) per annum. The TDS averaged 1,005mg/ℓ in 1976 and 1,350mg/ℓ in 2004, an average increase per annum of 13mg/ℓ (Verwey and Vermeulen 2011). Irrigated salt deposits not drained build up in the soil at a rate of 0.8 t/ha per annum (Verwey and Vermeulen 2011).

#### 2.2.5. Sea-level rise

Coastal aquifers are influenced by various potential sources of salinity that determine the composition of water extracted from boreholes. Sappa et al. (2015) assessed the seasonal variations of water supply boreholes in the coastal areas of Dar Es Salaam City, Tanzania, and found that during the dry season the water quality was highly saline resulting mainly from seawater intrusion and agricultural activities. Salt water was found mostly in the area within 2 km of the Dar Es Salaam coastline, and the depth to the interface was ranging from 1.3 to 20m (Mtoni et al. 2015).

### 3. ABSORPTIVE CAPACITY FOR GROUNDWATER RESILIENCE

Absorptive capacity is the ability of a system to prepare for, mitigate or prevent negative impacts, using predetermined coping responses in order to preserve and restore essential basic structures and functions (OECD 2014). This includes coping mechanisms used during periods of shock. Examples of absorptive capacity of groundwater resources include groundwater storage availability and natural attenuation to pollution. Absorptive capacity is clearly related to the duration and magnitude of any perturbation.

#### 3.1. Groundwater storage availability

Groundwater storage represents a buffer for achieving groundwater resilience under extreme climate events e.g. extended drought conditions. Using the groundwater resource strategically and sustainably means that it can be a key component to bridge temporal (ranging from overnight to annual) gaps between water resource availability and water demand (van Steenberg and Tuinhof 2010). To manage the groundwater reserve requires careful consideration that includes (Figure 5; Albuquerque Bernalillo County Water Utility 2016):

- Setting a limit to how much water can be safely pumped to avoid irreversible subsidence caused when too much water is removed from the aquifer
- Defining a safety reserve to ensure an adequate water supply in a worst-case scenario, such as a multi-year-interruption in surface water supplies
- Defining a management level – a target groundwater level that allows use of the aquifer as a working reserve that can be drawn down during dry times and refilled when adequate surface water supplies are available while protecting the safety reserve and irreversible subsidence limit

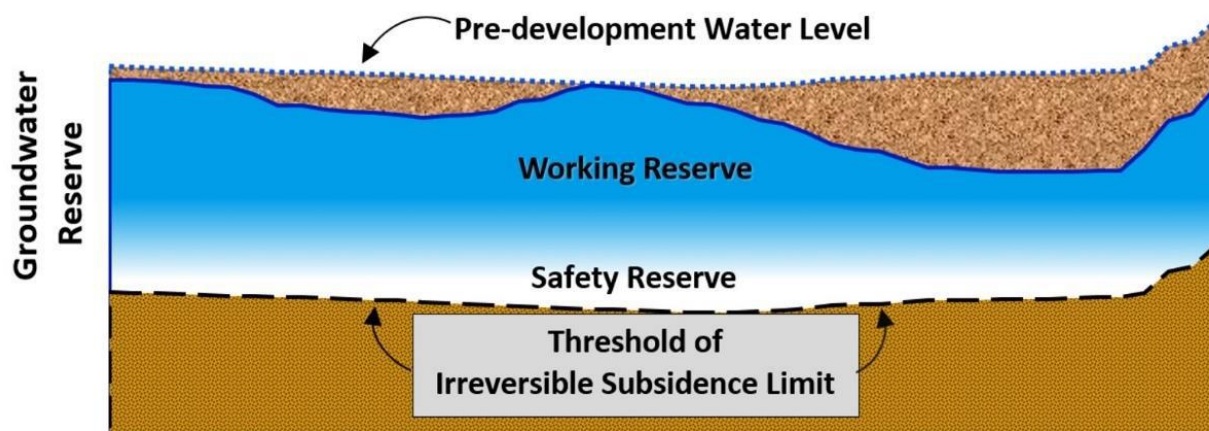
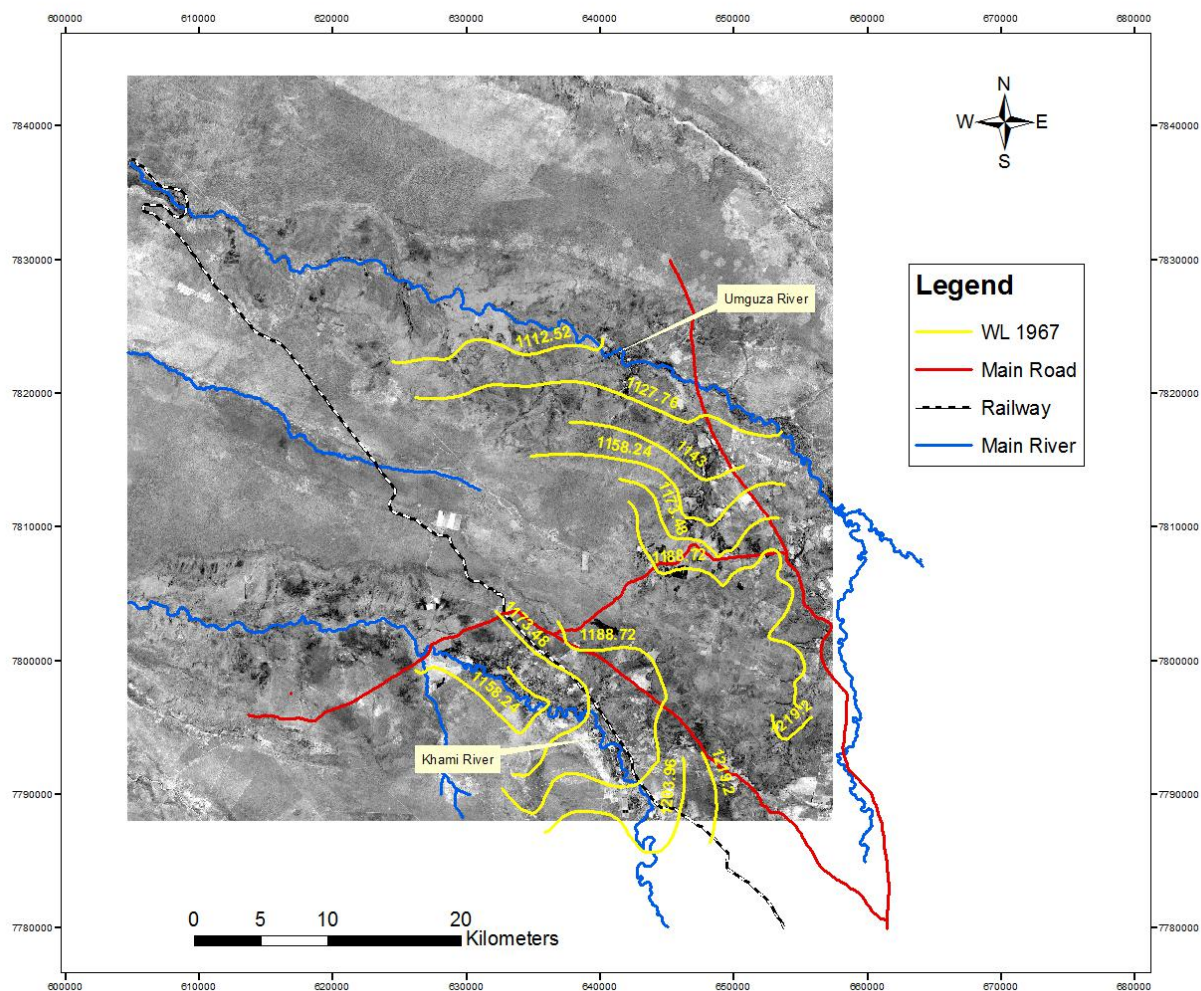


Figure 5: The groundwater reserve and its components (Albuquerque Bernalillo County Water Utility 2016)

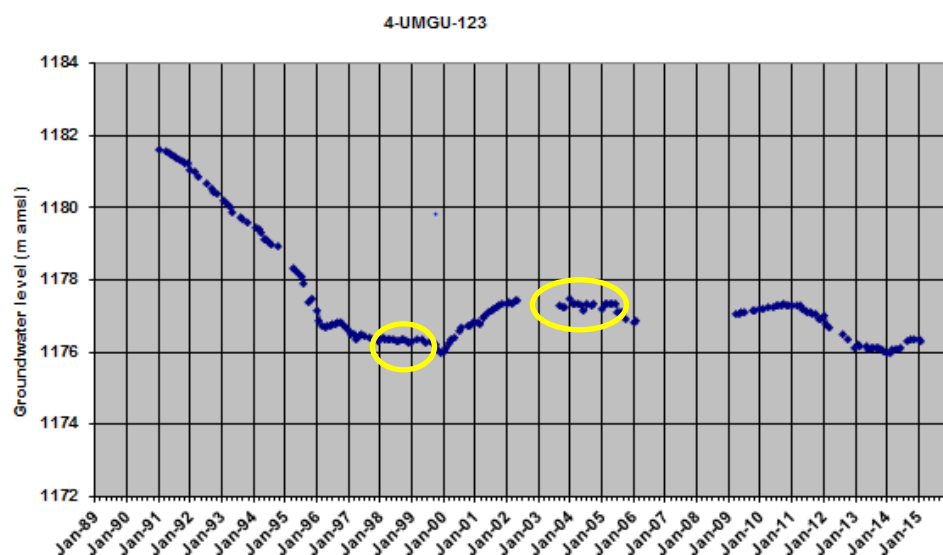


To manage the working reserve as illustrated in [Figure 5](#) it is highly recommended to construct a groundwater model (e.g. numerical model) to evaluate the (often complex) dynamics of the groundwater system. This is critical for analysing resilience. The Nyamandlovu area in the central part of the Upper Gwayi Sub-Catchment in western Zimbabwe ([Figure 6](#)) serves as an example of the above concept. The water demand of the City of Bulawayo is met from dams and from a wellfield in the Nyamandlovu area. [Figure 6](#) shows the groundwater level contours of the Umguzan area at the beginning of development of the Nyamandlovu aquifer and water level fluctuations of three boreholes from different parts of the wellfield are presented in [Figure 7](#) to show periods of steady state conditions within the timeframe of 1989 to 2015 (Beekman 2015):

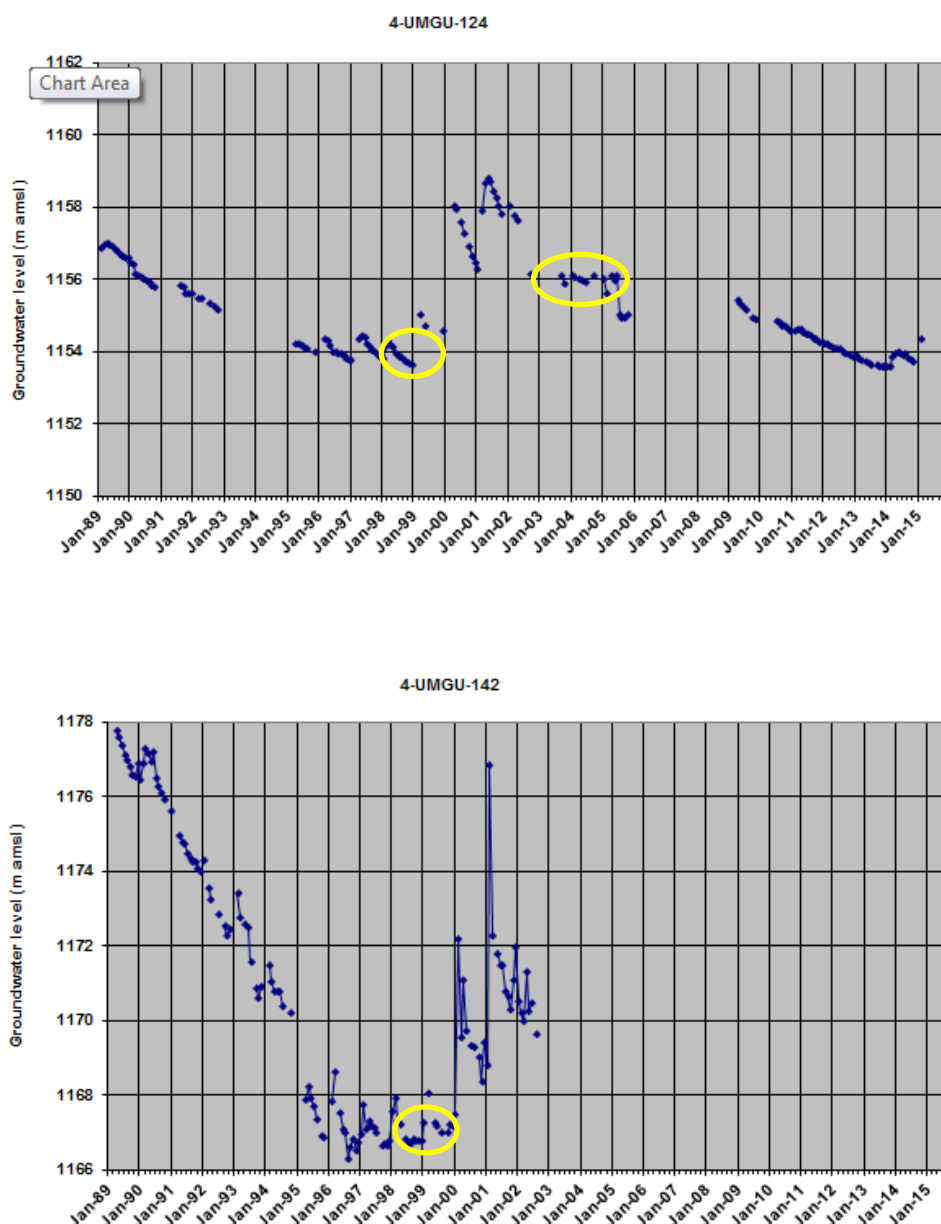
- Water levels in 1967 of the Umguzan area (northeastern part of the study area) were about the same as water levels in 1978; relatively higher average annual rainfall over this period of ~640 millimetres (mm) and subsequent higher recharge may have compensated for the (increased) abstraction for agricultural activities
- From 1978 to 1989, water levels (in the Umguzan area) declined by about 2m; despite lesser abstraction, the average annual rainfall of ~560mm over this period could not compensate for the abstractions
- From 1989 to 1998, when systematic monthly monitoring started over the whole Nyamandlovu area, water levels declined on average about 4m and in the wellfield which was established in 1992/93 even up to 12m; average annual rainfall of ~420mm (excluding 1997/98 for which there were no data) over this period could not compensate for the abstractions; clearly, drought conditions prevailed
- From 1998 to the end of 1999, water levels remained the same
- From 2000 to 2002, which includes increased rainfall from Cyclone Eline since 22<sup>nd</sup> February 2000, water levels increased ~2m on the average
- From 2002 to 2006, water levels remained the same
- From 2006 to 2015, water levels declined 2 to 3m; over the period of 2006 to 2009 there are no water level data available



**Figure 6: Groundwater levels of 1967 in the Nyamandlovu area (m amsl; after Beasley 1973 in Beekman 2015)**







**Figure 7: Water level fluctuations of BHs 123, 124 and 142 in the Nyamandhlovu aquifer (Beekman 2015)**

A first steady state period with constant water levels is identified as 1998 towards the end of 1999, representing a balance between inflow into the area (net recharge) and outflow (subsurface outflow and abstractions) from the area and a second period of steady state conditions was observed for 2002 to 2006 (Beekman 2015). The 1999 water levels represent the safety reserve (as the impact of further lowering of these water levels is unknown). The working reserve in this case is proposed to be the 2006 water levels which are about 3 m above the 1999 water levels.

Beekman (2015) recommended that predictions with regards to the change in water levels with changing abstraction and weather conditions should only be carried out once a transient state model is constructed and following calibration and validation of the model. Construction of a transient state model is therefore highly recommended by Beekman (2015) to:

- a. Validate the steady-state model results, especially with regards to determine the sustainable yield of the aquifer;
- b. Design optimum pumping scenarios for the wellfield;
- c. Act as an instrument for regulating drilling of boreholes and abstractions; and
- d. Provide a tool that contributes to the development of an early warning system, inter alia, in preventing or mitigating pollution and over-abstraction.

The above example also clearly demonstrates the critical need and value of long-term monitoring of rainfall, surface water, groundwater levels, abstraction rates and water chemistry.

### 3.2. Natural attenuation to pollution

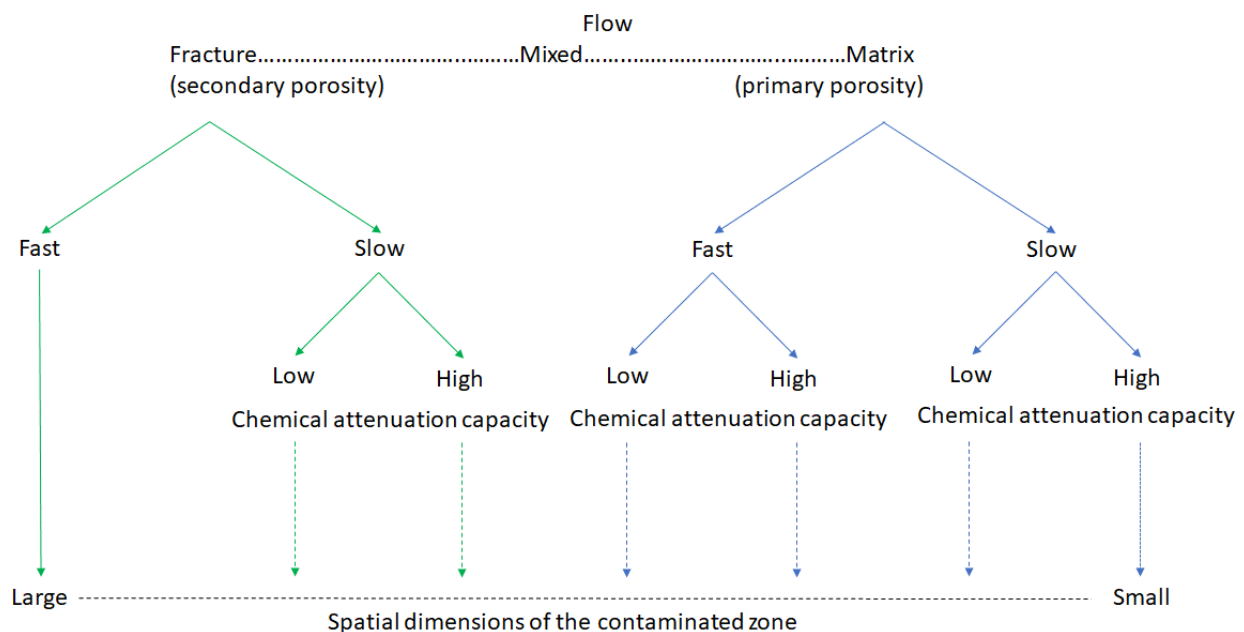
The capacity of a groundwater system to recover from pollution is critical to the concept of resilience as natural disasters and extreme weather events can undermine the effectiveness of site remediation, and can also affect contaminant toxicity, exposure, organism sensitivity, fate and transport, long-term operations, management, and stewardship of remediation sites (Maco et al. 2018). The natural attenuation processes include a variety of processes that reduce the mass, toxicity, mobility, volume or concentration of contaminants in soil and groundwater (City Chlor 2013). The in-situ processes can refer to physical, chemical or biological processes and include biodegradation, dispersion, dilution, sorption, volatilization, radioactive decay, chemical or biological stabilization, transformation and destruction of contaminants (City Chlor 2013).

There are three stages in evaluating natural attenuation capacity for decision-making (Saayman et al. 2007):

- **Stage I:** Screening and Scoping – to determine whether an assessment of groundwater contamination risk is required for decision making
- **Stage II:** Assessment – to determine the risk of groundwater contamination, which depends on the characteristics of the contaminant and the vulnerability of the aquifer to pollution
- **Stage III:** Decision-making – which integrates the outputs of the risk assessment into a cost benefit analysis, which the decision maker evaluates with consideration of relevant laws, regulations and guidelines and the principles and values of society.

Factors controlling the spatial extent of pollution are (Saayman et al. 2007):

- The dominance of in-fracture flow as opposed to diffuse/matrix (primary) flow (chemical attenuation is less for in-fracture flow)
- The faster groundwater moves, the further contaminated groundwater will move from its source in a given time period. Fracture-controlled flow will, by definition, constrain the contaminant's spread within the fracture network. Matrix flow will be constrained by spatial variations in hydraulic conductivity. Chemical diffusion is important at much lower flow rates. A conceptual framework of the factors controlling the spatial distribution of a contaminant in the saturated zone (aquifer) is depicted in Figure 8. The scales are relative and approximate, and the diagram describes the relative effects of the contributing factors over a fixed period

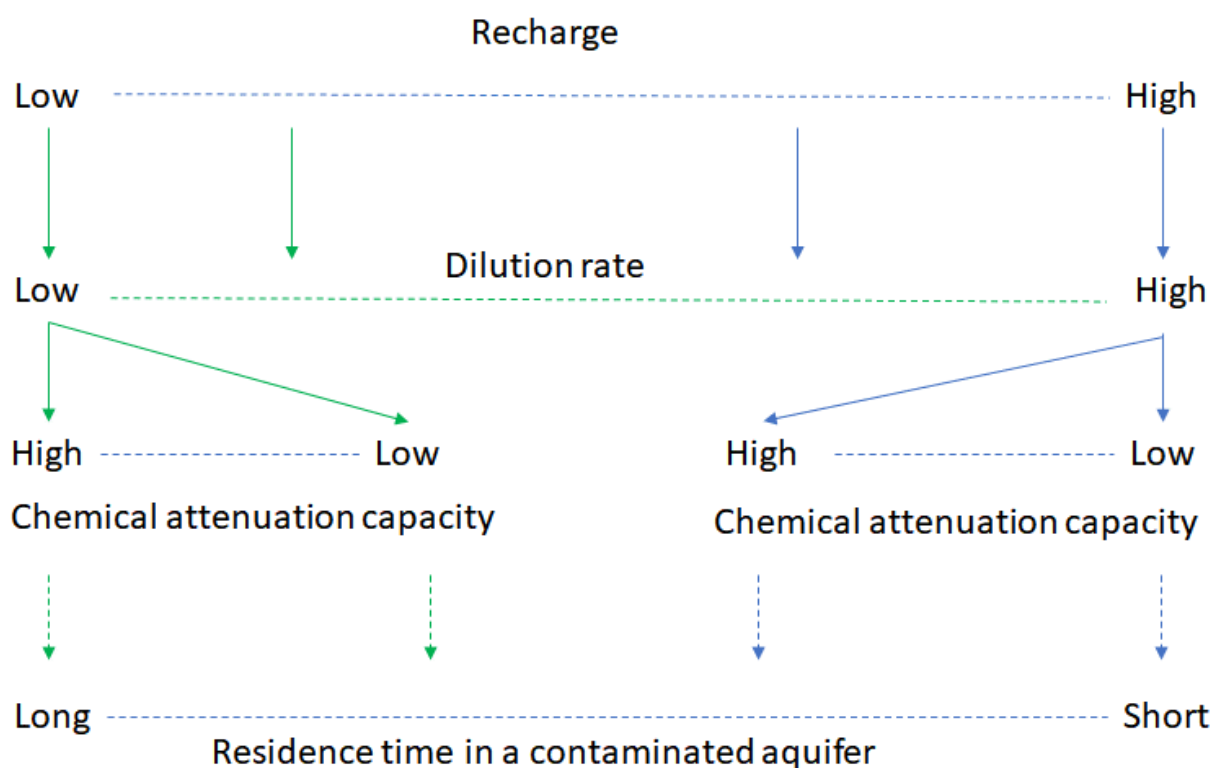


**Figure 8: Conceptual framework of the spatial dimension of saturated zone vulnerability (Saayman et al. 2007)**

Factors controlling the persistence of contamination are (Saayman et al. 2007):

- **Dilution** - the concentration of a contaminant is largely controlled by the rate at which dilution of a contaminant plume takes place in the aquifer. The main factor influencing dilution is the magnitude of recharge relative to the volume of the contaminated zone and recharge results in a change in the shape and extent of the contaminated zone. Faster flow velocities will also cause more dilution through dispersive processes. Conversely, low velocities result in less dispersion and, in extreme cases in fractured aquifers, contaminants may become trapped in the “dead-ends” of fracture networks with low interconnectivity. Dilution would then be driven by chemical diffusion and takes place very slowly

- Chemical attenuation** - Chemical attenuation is the capacity of aquifer solids to remove dissolved or suspended contaminants from groundwater and retain them. The residence time of a contaminant is controlled by dissolution/precipitation and de-sorption/sorption rates. A conceptual framework of the factors which influence the residence time of a contaminant in the saturated zone is shown in Figure 9



**Figure 9: Conceptual framework of the factors influencing residence time of a contaminant in an aquifer (Saayman et al. 2007).**

- Decay or decomposition** - Most organic compounds and other chemical species, for example nitrate, are consumed by reactions which reduce their concentration in aquifers. It is possible to assess the rate of these reactions and include this factor in a determination of residence time. Radioactive isotopes have limited life spans as a result of radioactive decay. The decay rate is a well-defined value which allows the maximum residence time of the radioactive isotope in an aquifer to be calculated
- Volatilisation and multi-phase partitioning:** Some contaminants may be either volatile, insoluble or partially soluble in water (multi-phase partitioning), including a non-aqueous phase liquid (NAPL) form. Partitioning coefficients are used to describe the partitioning of a chemical into these different phases. The fluxes of NAPL chemicals in liquid and non-liquid phase can be estimated from the relative permeability and proportion of air, water and NAPL saturation in porous media

Determining the natural attenuation capacity of groundwater systems at a local scale is complex and requires detailed knowledge of:

- The type and quantity of pollutants involved
- The chemical and hydraulic characteristics of both unsaturated and saturated zones
- The factors controlling the spatial extent and persistence of pollution as discussed above

Because of the overall complexity and costs of groundwater remediation (often unsuccessful) the focus should be on prevention of pollution.

### **3.3. Perturbations and threshold metrics**

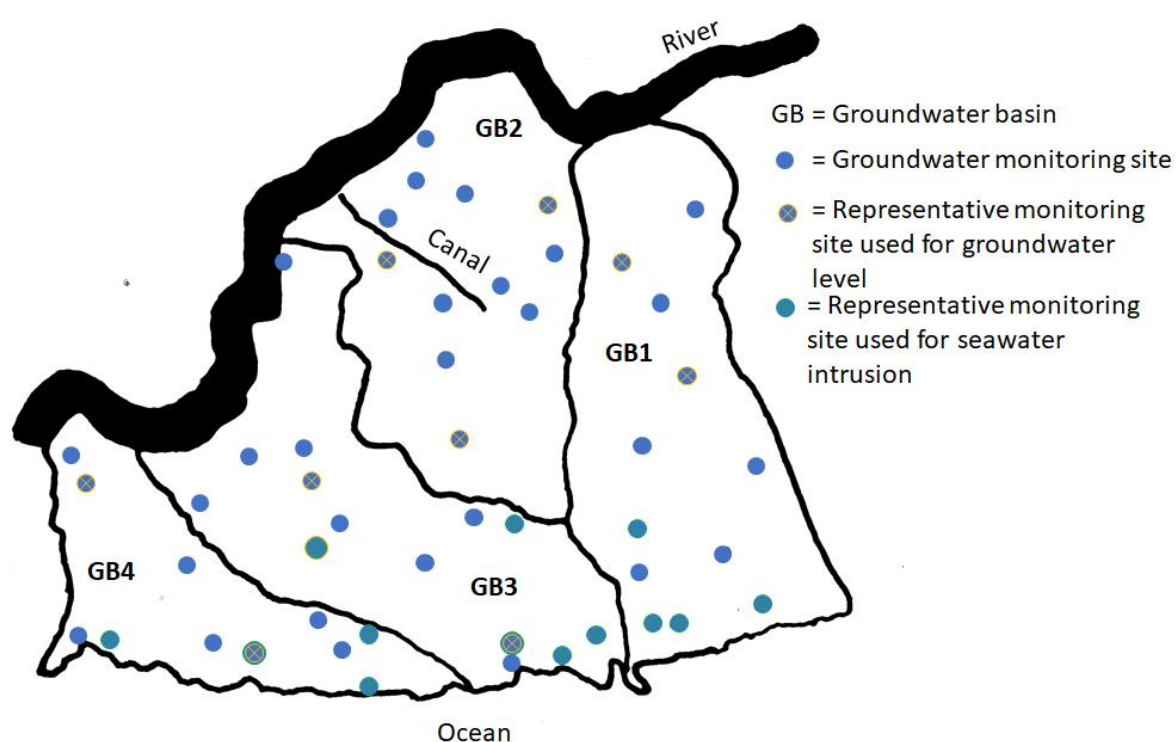
The concepts of stability and resilience with reference to ecological systems state that a natural system undergoes perturbations from an equilibrium state. The system is resilient when it can undergo a certain amount of disturbance without changing the equilibrium state. When damage is irreversible the following undesirable results occur in groundwater (DWR 2017):

- Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply
- Significant and unreasonable reduction of groundwater storage
- Significant and unreasonable seawater intrusion
- Significant and unreasonable degraded water quality, including the migration of contaminant plumes that impair water supplies
- Significant and unreasonable land subsidence that substantially interferes with surface land uses
- Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water

Minimum thresholds are the quantitative values that represent the groundwater conditions at a representative monitoring site that, when exceeded individually or in combination with minimum thresholds at other monitoring sites, may cause an undesirable result(s) in an aquifer system (CDWR 2017; Box 3):

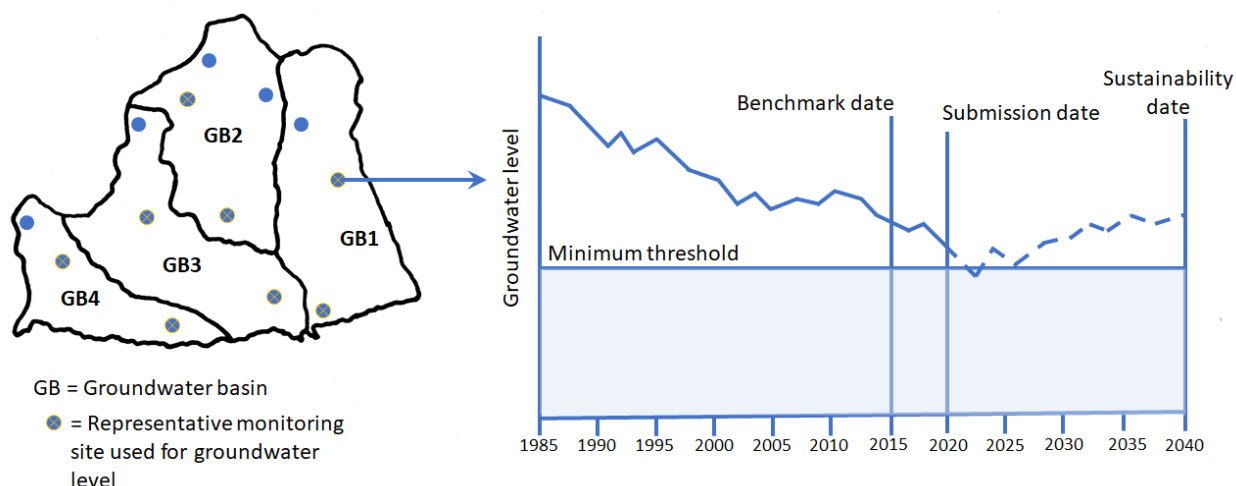
### Box 3: Representative monitoring sites and required minimum thresholds for each sustainability indicator (DWR 2017)

**Representative monitoring sites** are a subset of a basin's complete monitoring network, where minimum thresholds, measurable objectives, and interim milestones are set. Representative monitoring sites can be used for one sustainability indicator or multiple sustainability indicators. The figure below shows how different combinations of representative monitoring sites can be used to assess seawater intrusion and lowering of groundwater levels in a hypothetical groundwater basin.



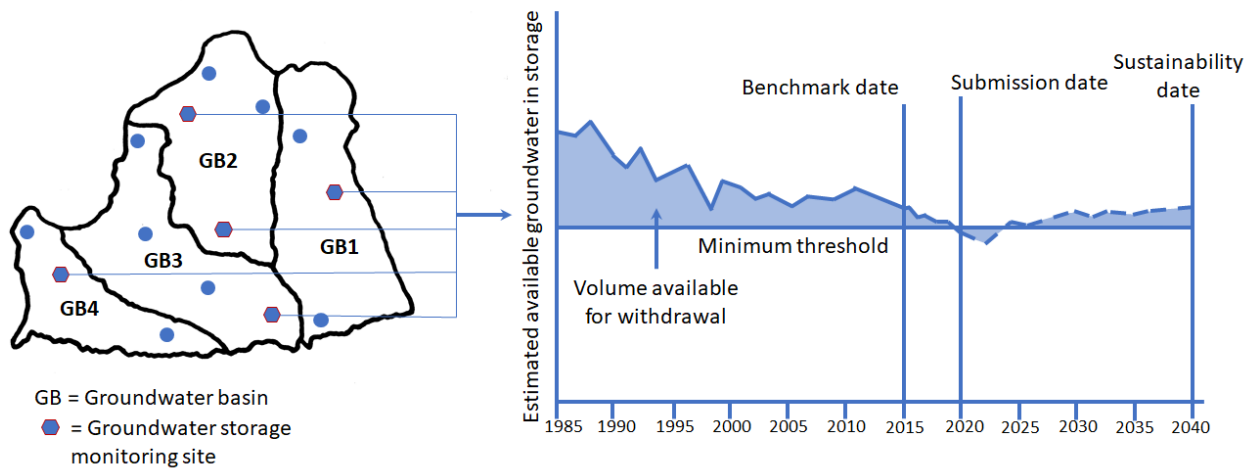
- The minimum threshold metric for the chronic lowering of the groundwater levels sustainability indicator shall be a groundwater elevation measured at the representative monitoring site (Box 3). Figure 10 illustrates a hypothetical groundwater level hydrograph and associated minimum threshold at a representative monitoring site. Considerations when establishing minimum thresholds for groundwater levels at a given representative monitoring site may include but are not limited to the historical groundwater conditions in the basin, the average, minimum, and maximum depths of municipal, agricultural, and domestic boreholes, and the potential impacts of changing groundwater levels on groundwater dependent ecosystems





**Figure 10: Groundwater level minimum threshold (DWR 2017)**

- The minimum threshold for reduction of groundwater storage is a volume of groundwater that can be withdrawn from a basin or management area, based on measurements from multiple representative monitoring sites, not leading to undesirable results. Contrary to the general rule for setting minimum thresholds, the reduction of groundwater storage minimum threshold is not set at individual monitoring sites. Rather, the minimum threshold is set for an aquifer system. [Figure 11](#) illustrates a hypothetical graph depicting the volume of groundwater available in storage through time, and the associated minimum threshold for the basin. Considerations when establishing the minimum threshold for groundwater storage may include but are not limited to the historical trends and projected water use in the basin, the groundwater reserves needed to withstand future droughts, and the effective storage of the basin.



**Figure 11: Groundwater storage minimum threshold (DWR 2017)**

- The minimum threshold metric for seawater [or saline] intrusion shall be the location of a chloride isocontour. Contrary to the general rule for setting minimum thresholds, the seawater [or saline] intrusion minimum threshold is not set at individual monitoring sites. Rather, the minimum threshold is set along an isocontour line in a basin or management area. [Figure 12](#) illustrates hypothetical chloride isoconcentration contours for two aquifers in a coastal basin. The isoconcentration contours are used as minimum thresholds for seawater intrusion. Considerations when establishing minimum thresholds for seawater intrusion at a given isocontour location may include but are not limited to the historical rate and extent of seawater intrusion in affected principal aquifers, the land uses in the basin sensitive to seawater intrusion, and the financial impacts of seawater intrusion on agricultural, municipal, and domestic wells.

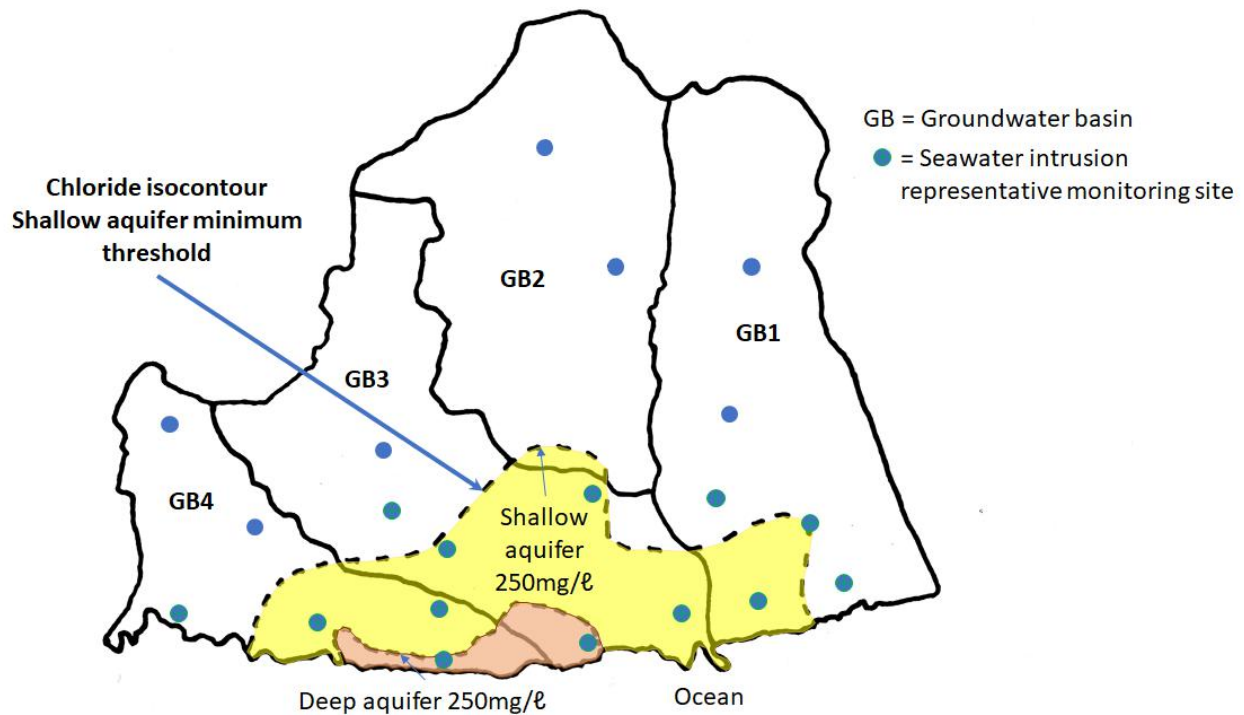
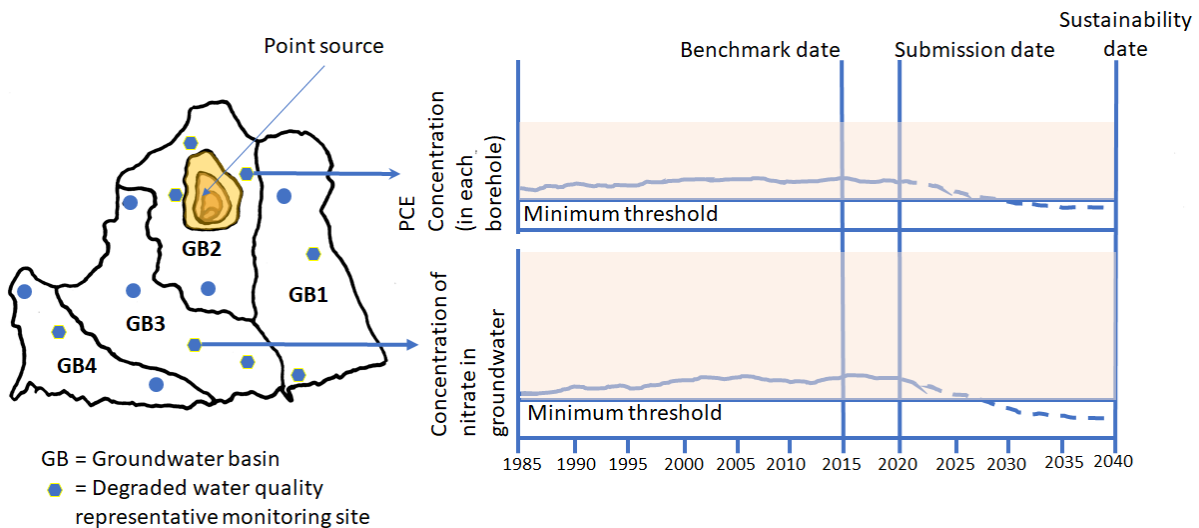


Figure 12: Seawater intrusion minimum threshold (DWR 2017)

- The minimum threshold metric for degraded water quality shall be water quality measurements that indicate degradation at the monitoring site. This can be based on migration of contaminant plumes, number of supply wells, volume of groundwater, or the location of a water quality isocontour within the basin. Depending on how the degraded water quality minimum threshold is defined, it can be defined at a site, along the isocontour line, or as a calculated volume. Figure 13 illustrates two hypothetical minimum thresholds for groundwater quality in a basin. The minimum threshold depicted in the upper graph is associated with point source contamination (e.g., tetrachloroethylene (PCE) released from a dry cleaner) and the minimum threshold depicted in the lower graph is associated with non-point source contamination (e.g., nitrate in groundwater from regional land use practices). Considerations when establishing minimum thresholds for water quality may include but are not limited to the historical and spatial water quality trends in the basin, the number of impacted supply wells, and whether the aquifers are primarily used for providing water supply



**Figure 13: Degraded water quality minimum threshold (DWR 2017)**

- The minimum threshold metric for land subsidence shall be a rate and the extent of land subsidence.

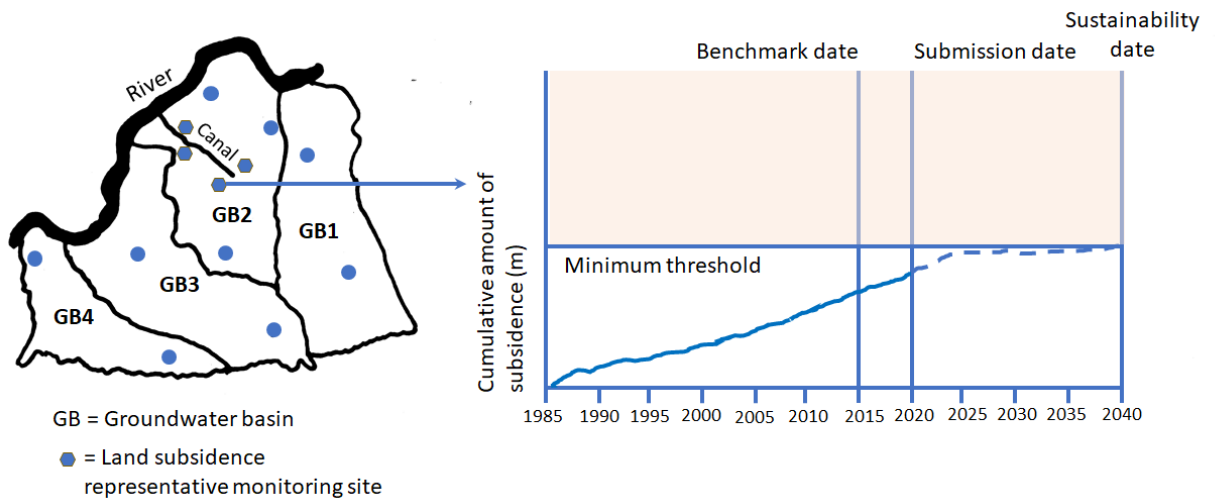
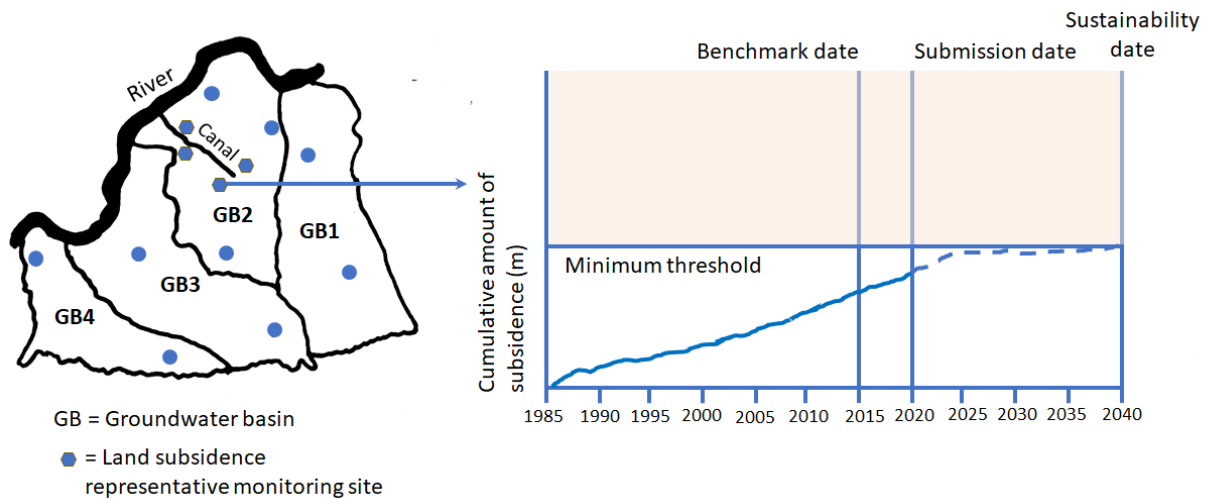
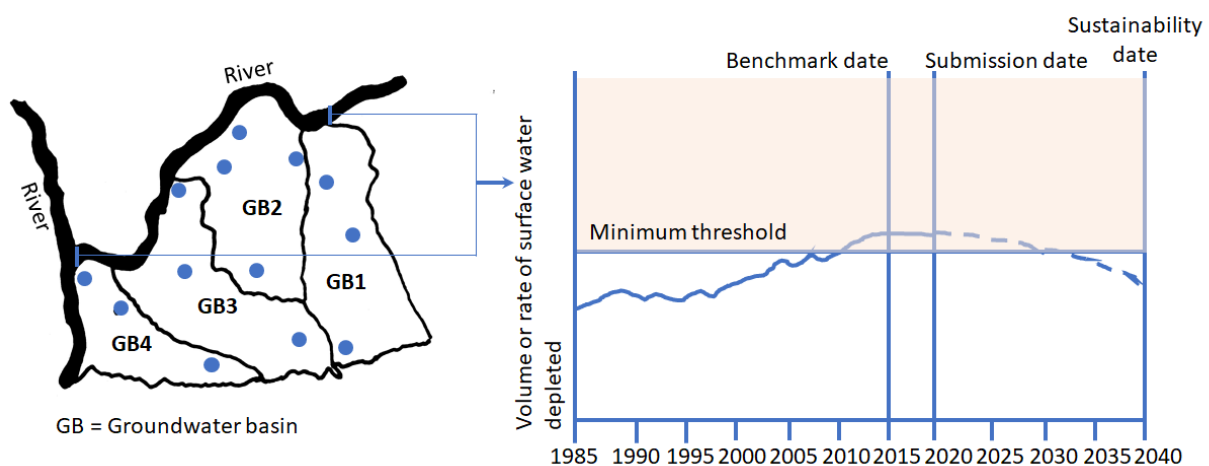


Figure 14 below illustrates a hypothetical minimum threshold for land subsidence in a basin. The minimum threshold depicts a cumulative amount of subsidence at a given point. Considerations when establishing minimum thresholds for land subsidence at a given representative monitoring site may include, but are not limited to the principal aquifers in the basin containing aquifer materials susceptible to subsidence, the historical, current, and projected groundwater levels, particularly the historical lows and the historical rates of subsidence



**Figure 14: Land subsidence minimum thresholds (DWR 2017)**

- The minimum threshold metric for depletion of interconnected surface waters shall be a rate or volume of surface water depletion. Figure 15 shows a hypothetical minimum threshold for depletion of interconnected surface waters. This example presents the potential stream depletion rate (or volume) due to groundwater pumping simulated by a basin's integrated hydrologic model. Considerations when establishing minimum thresholds for depletions of interconnected surface water may include but are not limited to the historical rates of stream depletion for different years, the uncertainty in streamflow depletion estimates from analytical and numerical tools, and the proximity of pumping to streams.



**Figure 15: Surface water minimum depletion threshold (DWR 2017)**

## 4. CONJUNCTIVE MANAGEMENT

Conjunctive management in support of long-term groundwater (and surface water) resilience refers to management of the combined use of groundwater, surface water and other sources of water in a manner that prevents irreversible impacts (quantity and quality) on either of the resources. The benefits of coordinated management of the water sources should exceed the benefits obtained through their separate management. Conjunctive water use is mostly done in large scale irrigation schemes with surface water shortage and in rapidly expanding cities where either one of the water sources become insufficient.

### 4.1. The benefits of conjunctive management

In order to achieve an optimal level of conjunctive management of surface water and groundwater, the distinct features of both resources must be accounted for (Table 2). For optimal conjunctive use, from a groundwater perspective, recovery and recharge of groundwater needs to be balanced (Dudley and Fulton 2005).

**Table 2: Distinct features of surface water and groundwater (modified after AGW-Net et al. 2015)**

Feature	Groundwater resources and aquifers	Surface water resources and reservoirs
<b>Hydrological characteristics</b>		
Storage	Very large	Small to moderate
Resource areas	Relatively unrestricted	Restricted to water bodies
Recharge	Restricted to unconfined aquifers	Takes place everywhere with rainfall
Response to changes	Very slow	Rapid
Flow velocities	Low	Moderate to high
Residence time	Generally decades / centuries	Mainly weeks / months
Drought vulnerability	Generally low	Generally high
Evaporation losses	Low and localised	High for reservoirs
Resource evaluation	High costs and significant uncertainty	Lower costs and often less uncertainty
Abstraction impacts	Delayed and dispersed	Immediate
Natural quality	Generally high	Variable
Pollution vulnerability	Variable natural protection	Largely unprotected
Pollution persistent	Often extreme	Mainly transitory
<b>Socio-economic factors</b>		
Public perception of the resource	Not visible, unreliable	Visible, reliable
Development cost	Modest - high	High
Development risk	Less than often perceived	More often than assumed





Feature	Groundwater resources and aquifers	Surface water resources and reservoirs
Style of development	Mixed public and private, often by individuals	Largely public

The benefits of conjunctive management are:

- Diversification of the water supply mix
- Improved water supply security and security of water sources (prevention of over-exploitation, preparedness for extreme weather events)
- Larger net water supply yield (efficient use of both water resources)
- Reduced environmental impact (prevents/limits over-exploitation of groundwater and surface water, water logging and salinisation)

#### 4.2. The need and opportunities for conjunctive management

Conjunctive management of surface water and groundwater is needed to secure water supply in times of water shortages of either resource, and when ecosystems are compromised, e.g. by reduced baseflow and salinization. There is also need for conjunctive management when there is (physical) interaction between surface water and groundwater (Box 4).

##### Box 4: Conjunctive management: surface water-groundwater interaction (AGW-Net et al. 2015)

- Groundwater recharge impacted by surface water use: damming rivers and abstracting water reduces downstream flow for indirect groundwater recharge through riverbed infiltration (e.g. in arid and semi-arid environments); irrigation excess and wastewater discharge are also sources of groundwater recharge.
- Groundwater use, particularly from shallow unconfined aquifers, delays the timing and reduces the amount of surface run-off in the rainy season and decreases baseflow in the dry season. Such baseflow may be of critical importance especially during periods of low flow and in semi-arid climates.
- Groundwater may provide perennial water to groundwater dependent ecosystems and the communities that survive from these resources.
- Interaction between surface and groundwater can cause pollution to be transferred from one to the other. Groundwater pollution can persist for centuries thereby reducing water resources availability for generations to come.

Opportunities for conjunctive management arise when (CapNet et al. 2010):

- Groundwater holds large volumes of water in storage, while surface water storage is moderate or small. Surface water could be allocated during the rainy season and groundwater use could be increased in the dry season. Groundwater volumes in storage can provide a buffer in times of drought and water scarcity.
- Managed aquifer recharge (MAR) of sandy aquifers may be done with surplus surface water during the wet season if there is excess flow (Chapter 0). Recharging aquifers in this way will not only provide additional dry season water resources but will also allow for natural purification of any bacterial contamination in the surface water.

- Groundwater may be developed where demand is dispersed and moderate, while development of surface water focuses on large-scale demand and irrigation development.
- Upstream and downstream interests: by considering the entire suite of water resources, both surface and groundwater, along the length of a catchment, managers are better able to provide for equitable upstream and downstream demands.

The potential for conjunctive use, e.g. in irrigated agriculture, varies with differing hydrogeological setting (Box 5). The implementation choice therefore needs to be adapted to the prevalent conditions. It is best implemented on the local level, as it is easier to identify the special needs and circumstances of the community and monitoring at local level is more easily carried out (Waelti and Spuhler 2019).

**Box 5: Variation of the dynamics and constraints of conjunctive use with hydrogeological setting (Foster et al. 2010)**

Hydrogeological typology	Examples	Dynamics of conjunctive use	Constraints on conjunctive use
Upstream humid or arid outwash Peneplain	Indian Punjab-Indus Peneplain,  Upper Oases Mendoza-Argentina,  Yaqui Valley,  Sonora-Mexico	deep groundwater table with major groundwater recharge from rivers and unlined canals, where river flow reduces seasonally groundwater use predominates	in more arid areas widespread natural soil salinity which can be mobilised to groundwater during irrigation development and requires careful management
Humid but drought-prone middle alluvial plain	Middle Gangetic Plain–India,  Middle Chao Phya Basin-Thailand	shallow groundwater table and surface water and groundwater resources generally freely available	excessive recharge in canal head-water sections can lead to serious soil waterlogging/salinity and poor canal-water service levels in tail-end sections causing excessive groundwater pumping
Hyper-arid middle alluvial plain	Middle Indus Plain-Pakistan,  Lower Ica Valley-Peru,  Tadla – Morocco,  Tihama - Yemen	major rivers and primary irrigation canals generate locally important fresh groundwater recharge/ lenses, in some cases further augmented by spate irrigation	conjunctive use of groundwater important to counter rising water-table problems, and concomitantly reach higher cropping intensity, but extreme care needed

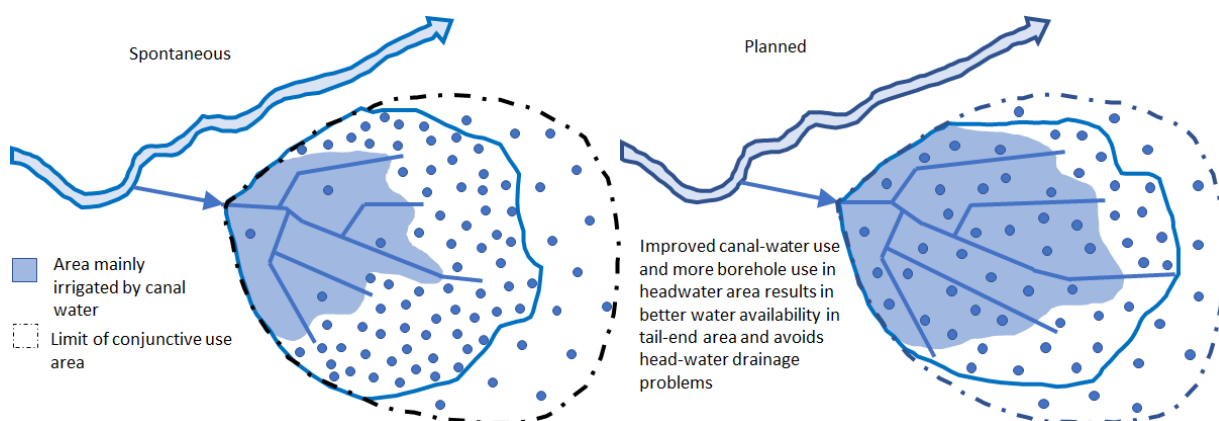
Hydrogeological typology	Examples	Dynamics of conjunctive use	Constraints on conjunctive use
			to avoid saline-water encroachment
Downstream alluvial plain or delta with confined groundwater	Ganges Delta-Bangladesh, Lower Oasis Mendoza-Argentina, Nile Delta-Egypt	irrigation predominantly from major rivers and associated canals but, where seasonal river flow reduction marked, supplementary groundwater irrigation can be important	alluvial aquifers often semiconfined by surficial clayey silts (also sometimes with saline phreatic groundwater) – thus water well use constrained by recharge limitation and sometimes by saline-water mobilisation

### 4.3. Irrigated agriculture

Conjunctive water management in shared water resources of the SADC region is steadily gaining ground, as the understanding of the benefits of coordinated use and management of surface and groundwater increases (Mukuyu 2018; SADC-GMI 2018). Changing climatic conditions and concerns around water scarcity in the region has made conjunctive management a viable option to mitigate water variability and food insecurity. From a groundwater perspective, groundwater storage of aquifers will act as a buffer to water supply variability (from surface water), groundwater salinisation and waterlogging for sustained agricultural production. Conjunctive management in SADC is not yet as advanced as in other parts of the world but lessons can be drawn from experiences elsewhere ([Box 6](#)).

### Box 6: Conjunctive use of groundwater and surface water in a canal command (Foster et al. 2010)

In a canal system for irrigation water supply, seepage losses (recharge to underlying aquifers) are generally the major cause of inequitable water distribution. Farmers located at the tail-end of the system usually get less canal water than the farmers located at the head reaches of the canal, hence a higher dependence on groundwater in tail areas. Unmanaged, or spontaneous (private initiative of farmers), conjunctive use of groundwater and surface water at the head ends of canals causes water tables to rise, resulting in waterlogging, whereas at the tail-ends salinity problems are usually increasing because of excessive use of poor-quality groundwater for irrigation. Also, the net income of tail-end farmers is generally less than those of the head-end farmers for the unmanaged situation, among others due to the relatively higher groundwater pumping costs and lesser agricultural productivity of the former. Planned conjunctive use comprises improved canal water distribution and more water well (groundwater) use in the head areas and aims for equitable access to water resources and improved agricultural productivity.



It therefore contributes to the alleviation of poverty. There are numerous tools available for evaluating sustainable conjunctive use options ranging from integrated numerical modelling of irrigation canal flows, groundwater use and aquifer response, soil water status and crop water use (Foster et al. 2010) to specific analytical and numerical models looking more at the sustainability of conjunctive use options at both local (farm) and basin scales with sustainability seen in the light of balancing water and salt (Alam 2014).

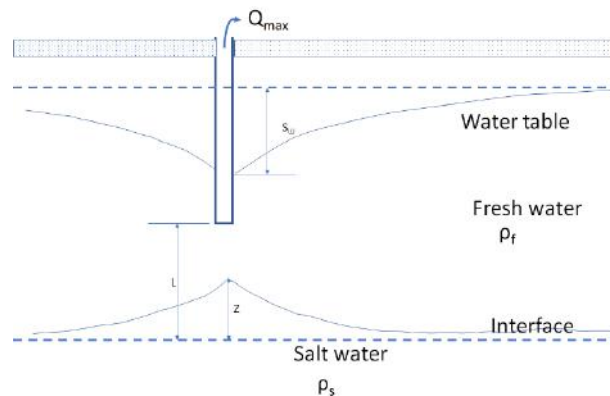
Irrigation with poor quality groundwater, in addition to surface water, adds salts to agricultural land and requires the farmer to deal with the salt balance below their field. The farmer should:

- Know the freshwater potential overlying the saline water to optimise pumping rates.
- Get to know the characteristics of the soils on their properties and familiarise with visual symptoms of crop damage on a regular basis.
- Ensure productive use of saline agricultural lands.
- Maintain sufficient irrigation return flow which depends on the efficiency of the irrigation method.
- Monitor groundwater salinity to detect changes over time to take remedial action as and when needed.



Leaching of salts from the root-zone, e.g. by flood MAR (Chapter 0), remains the most effective salt management measure from an agricultural perspective. Best leaching of salts from the topsoil occurs when the soil profile is near saturation and the water applied has little salt and water is applied slowly and evenly, either by rainfall or irrigation. **Box 7** presents a simple guideline for the calculation of a critical abstraction rate  $Q$  ( $\text{m}^3/\text{day}$ ) for a single borehole (with no interference from neighbouring boreholes) for homogeneous unconsolidated sediments beyond which there will be ingress of saline water into the borehole when only taking into account the density difference between fresh and saline water. The calculated critical abstraction rate should be considered a maximum rate as in reality dispersion characteristics of the porous medium will mostly determine, and lower, this rate. The guideline is useful for a first estimate of a maximum abstraction rate if there is a risk of up-coning or ingress of underlying saline water.

**Box 7: Up-coning of saline water – critical abstraction rate**

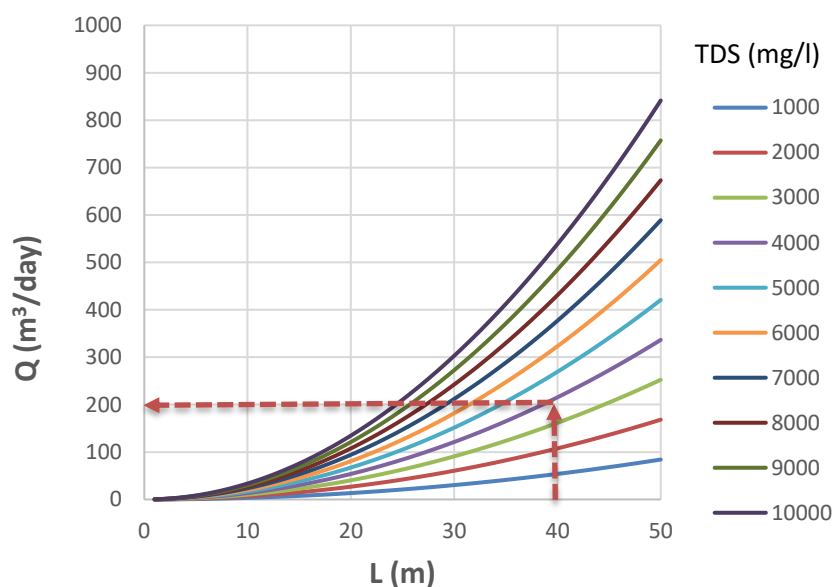


The critical abstraction rate  $Q_{\max}$  is a function of the horizontal hydraulic conductivity  $K_h$  ( $\text{m}/\text{day}$ ), the Total Dissolved Solids of the deeper and underlying salt water (TDS) and  $L$  the distance between the fresh-salt water interface and the bottom of the borehole:

$$Q_{\max} \sim 1.12 \times 10^{-6} K_h \text{ TDS}_{\text{saltwater}} L^2$$

- Steady horizontal flow of freshwater to the borehole
- No lateral movement of saltwater; sharp freshwater-saltwater interface;  $t$  (time) =  $\infty$  (infinite)
- $Q$  in  $\text{m}^3/\text{day}$ ;  $K_h$  in  $\text{m}/\text{day}$ ; TDS in  $\text{mg}/\text{L}$ ;  $Z = 0.25 L$  in  $\text{m}$

For a specific  $K_h$ , a graph can be constructed using the above equation to estimate  $Q_{\max}$  such as the graph below for  $K_h = 30 \text{ m}/\text{day}$  and for different TDS and  $L$ . If for example  $L = 40 \text{ m}$  and  $\text{TDS} = 4000 \text{ mg}/\text{L}$  ( $K_h = 30 \text{ m}/\text{day}$ ),  $Q_{\max} = 200 \text{ m}^3/\text{day}$  (follow the red dotted line and arrows in the graph).



Modified after Bear and Dagan, 1968 in Bouwer, 1978.

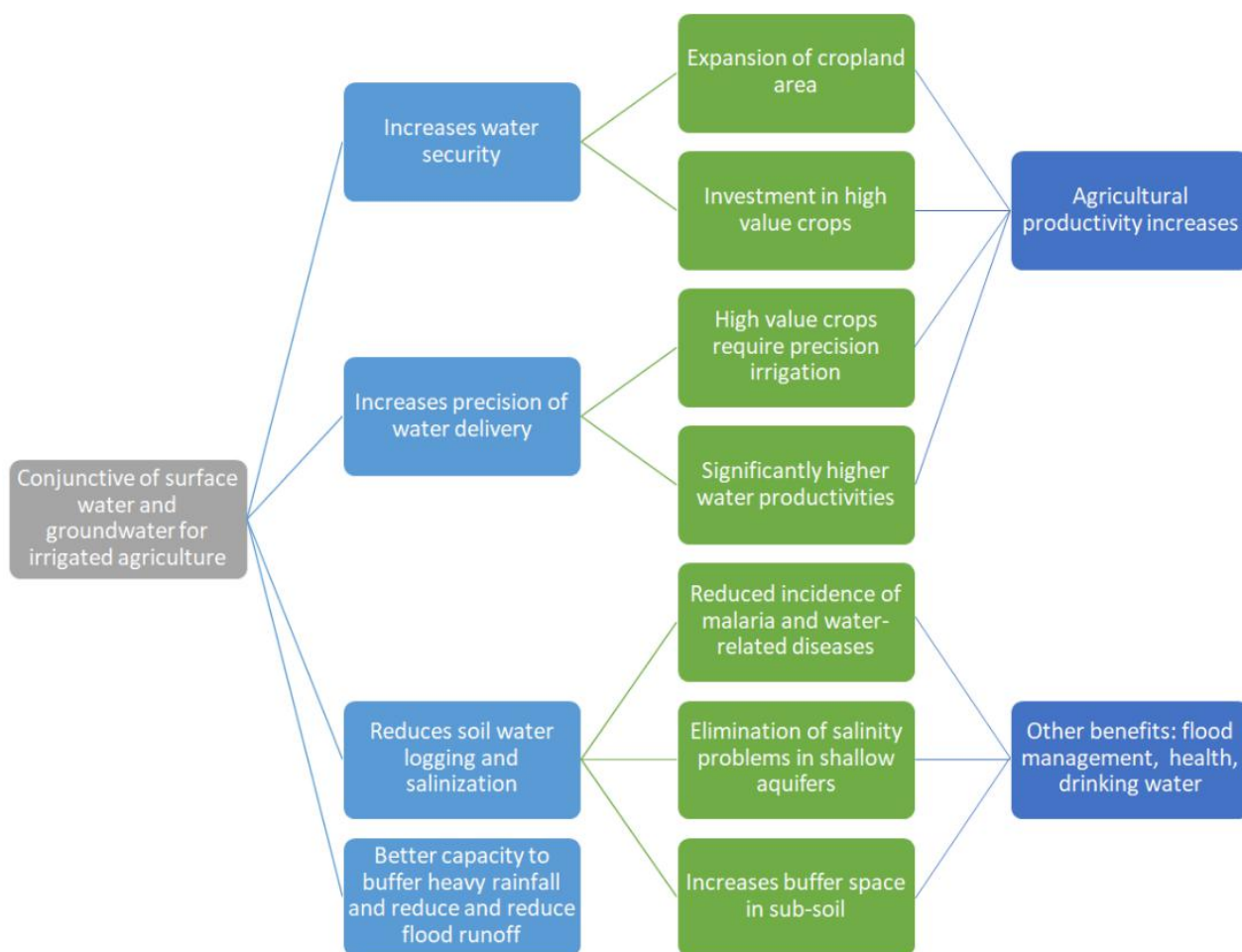
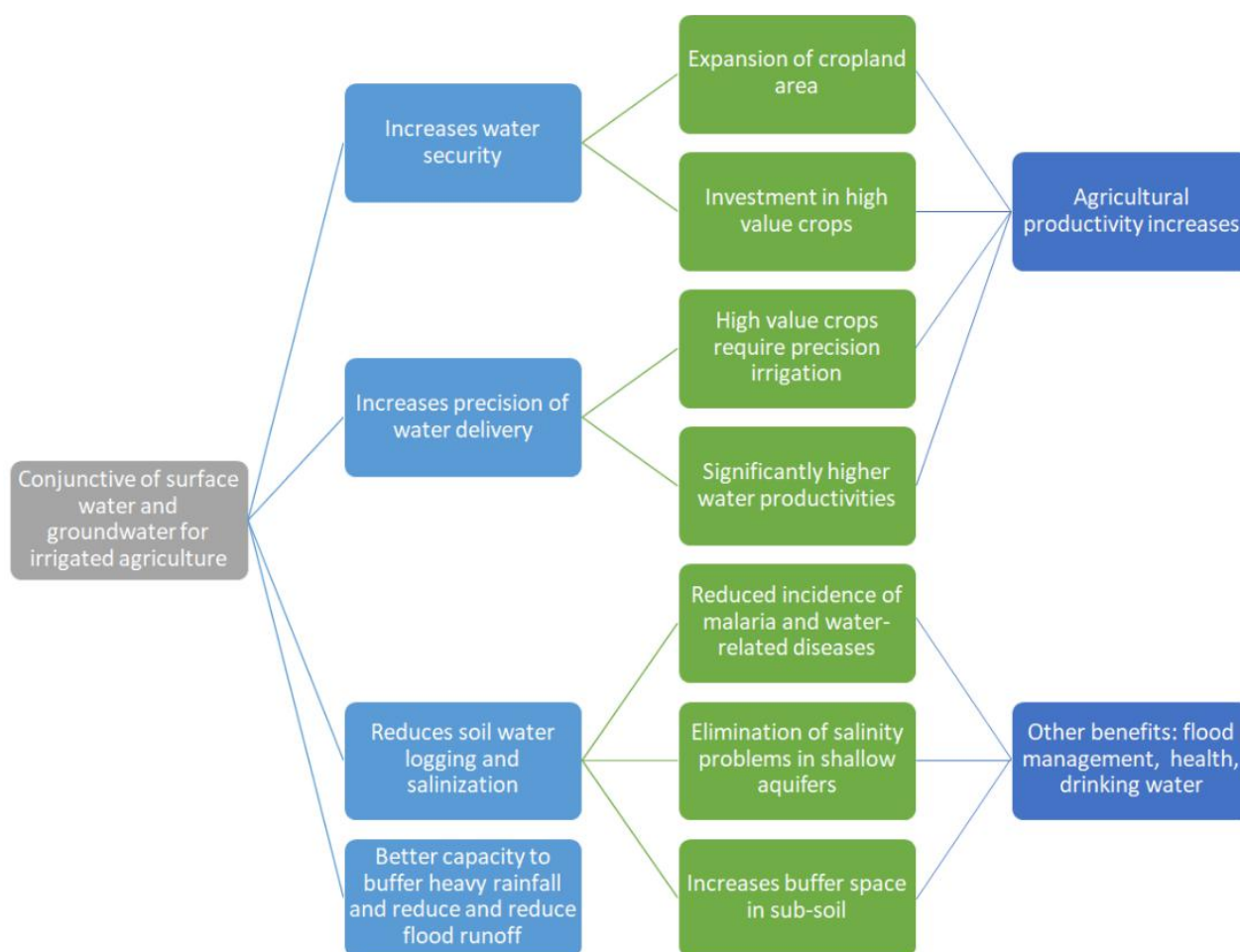


Figure 16 presents an overview of the benefits from improved planning and management of conjunctive water use for irrigated agriculture such as increased agricultural productivity, improved flood management, and improved drinking water quality. The benefits also vary with hydrogeological setting.



**Figure 16: Benefits of conjunctive use of groundwater and surface water for irrigated agriculture (modified from Foster et al. 2010)**

#### 4.4. Urban water supply

In rapidly-expanding cities, conjunctive use of groundwater and surface water is often unplanned and includes ‘traditional’ groundwater sources (springheads or water wells) at the urban nucleus and immediately neighbouring surface watercourses either one of which subsequently become insufficient with urban growth (Figure 17). Criteria on which a planned operational strategy of urban conjunctive use is normally based include (Foster et al. 2010; Figure 18):

- Abstract preferentially from the river whilst its flow-level is above the minimum required for ‘downstream’ wastewater assimilation and dilution and/or ecological interests (except where river water is periodically not treatable because of high suspended solids and/or pollution)

- Use water wells at other times, especially during extended drought when surface-water availability is limited – whenever possible ensuring that the impact of water well abstraction is mainly delayed until higher river flow periods.

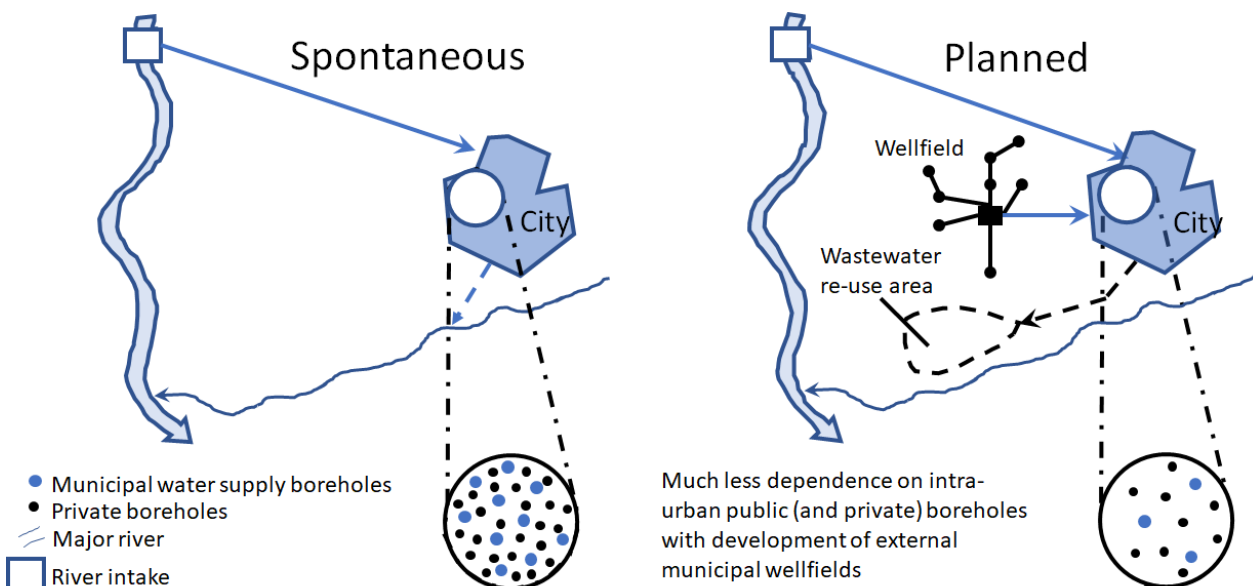


Figure 17: Conjunctive use of groundwater and surface water for urban water supply (Foster et al. 2010)

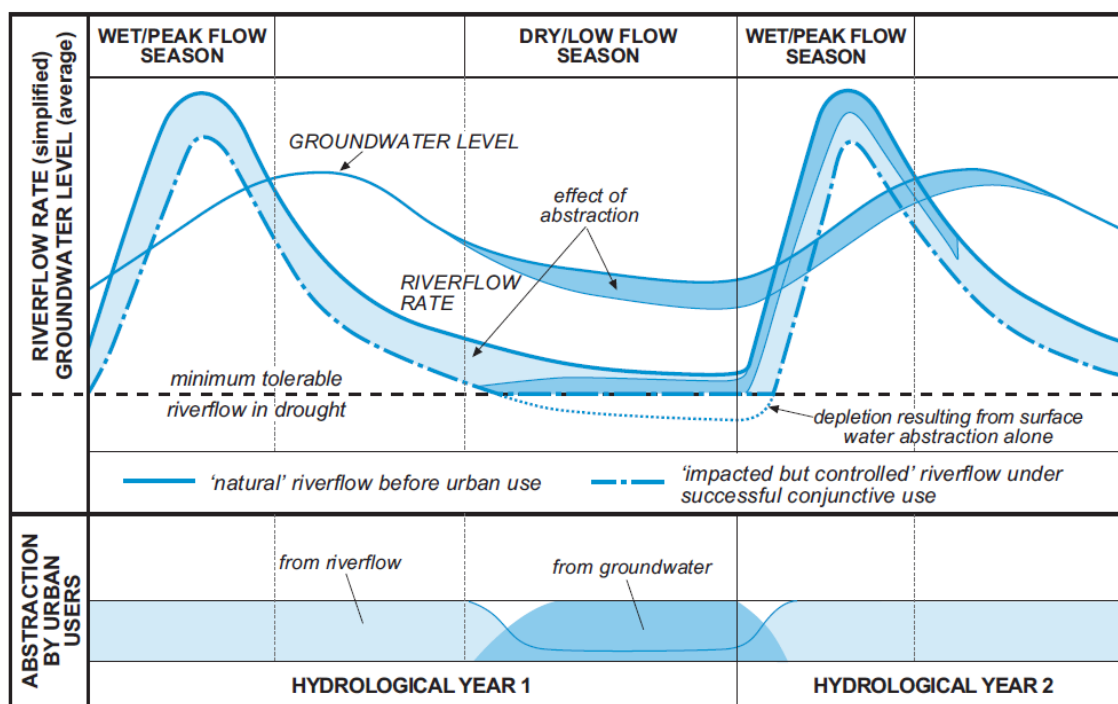


Figure 18: Typical hydrological modifications caused by successful conjunctive use of groundwater and surface-water resources for urban water-supply (Foster et al., 2010)

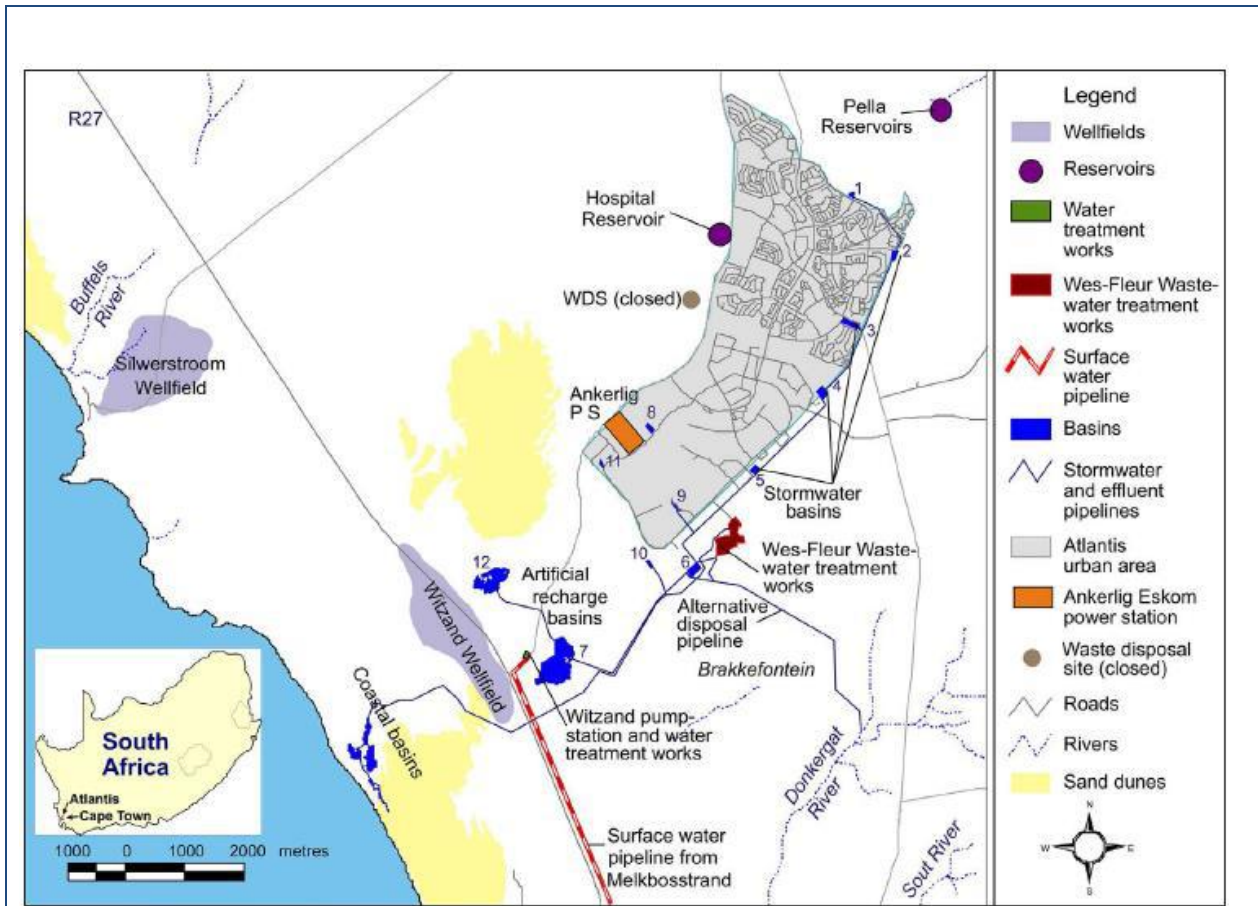
Only in a few cases, the use of groundwater has evolved as part of planned urban water-supply development (e.g. Atlantis – South Africa, [Box 8](#)), but more often it has occurred in response to water shortage or service deficiency, and often through private initiative (e.g. Lusaka, Dar-es-Salaam, Cape Town, Windhoek and Gaborone and probably elsewhere). An example of conjunctive use is the North-South Carrier (NSC), which is a bulk water supply system running from north to south in eastern Botswana, connecting a number of surface water dams, groundwater aquifers and water treatment facilities (Lindhe et al. 2014). The NSC system includes:

- 6 surface water dams
- 8 wellfields
- 7 water works
- 18 demand centres

**Box 8: Atlantis planned urban water supply (Buchan et al., 2016)**

The primary aquifer at Atlantis (Western Cape, South Africa) is ideally suited for water supply and the indirect recycling of urban stormwater runoff and treated domestic wastewater for potable purposes. The relatively thin, sloping aquifer requires careful management of artificial recharge and abstraction for balancing water levels. Water quality management is a further key issue at Atlantis for ensuring the highest quality potable water. Groundwater quality varies from point to point in the aquifer, while urban runoff and wastewater qualities vary greatly. The layout of the town allows for the separation of stormwater from the residential and industrial areas as well as separate treatment of domestic and industrial wastewater. This permits safe artificial recharge of the various water quality portions at different points in the aquifer, either for recycling or for preventing seawater intrusion. Lessons learnt from the Atlantis experience can be transferred to other potential sites for establishment of similar systems in arid and semi-arid areas of Southern Africa.





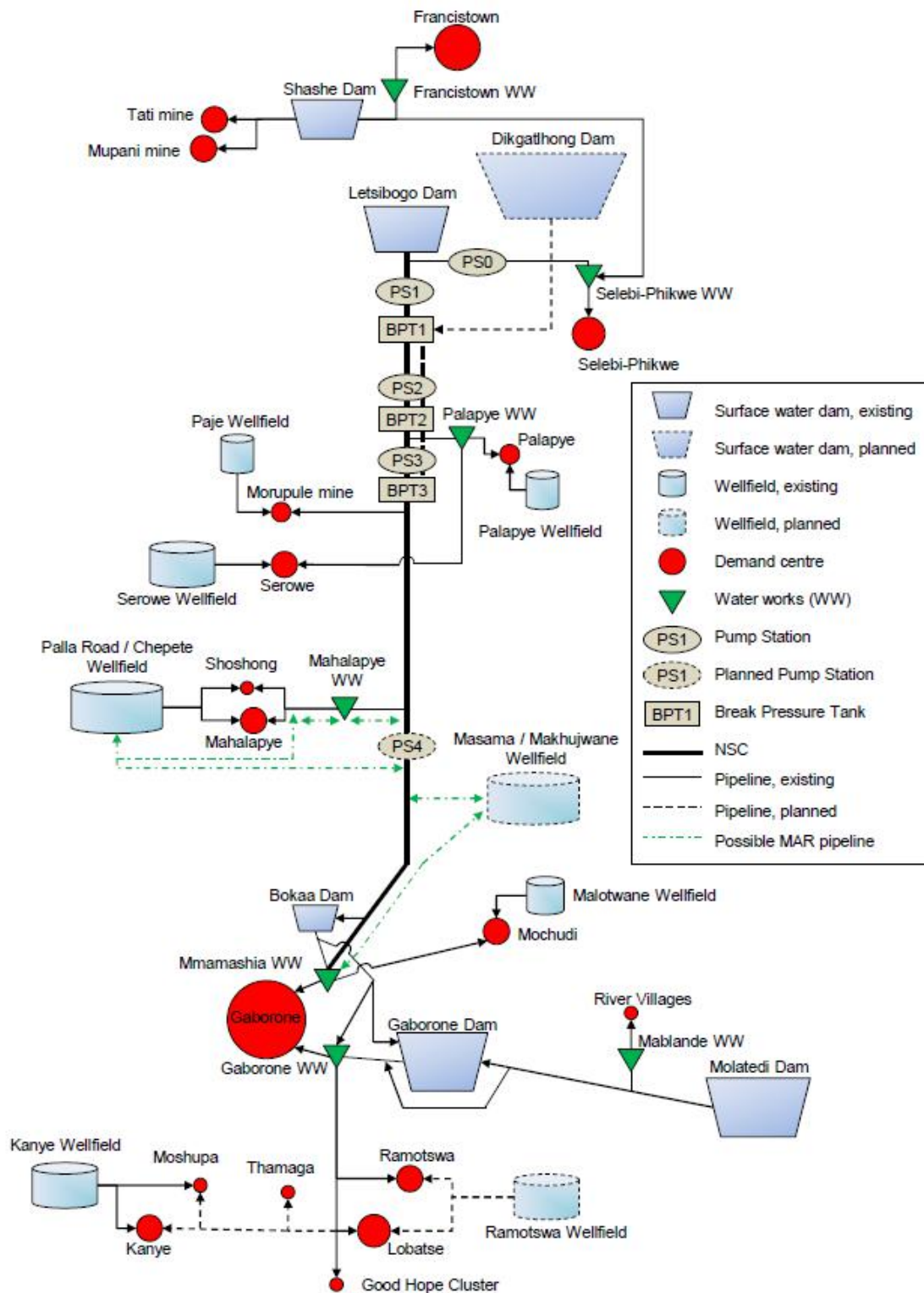


Figure 19: Schematic illustration of the water supply system linked to the NSC (Lindhe et al. 2014)

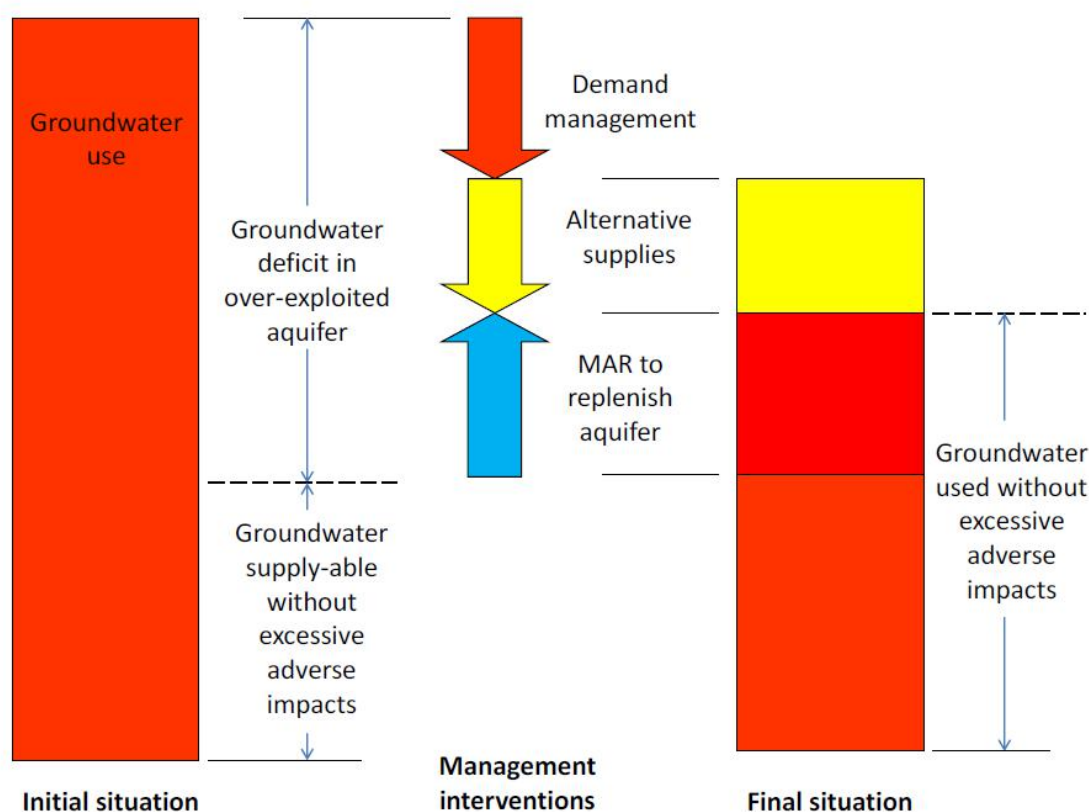
#### **4.5. Requirements for conjunctive management**

Conjunctive water management requires:

- A proper institutional framework comprising a regulatory body to control water distribution, groundwater use and groundwater abstraction. The institutional framework should focus on water agencies at local and provincial levels capable of implementing Integrated Water Resources Management, and water user associations representing the stakeholders
- Minimum standards for sustainable conjunctive use of groundwater and surface water.
- Public awareness raising on the beneficial concept of conjunctive water use
- Capacity building of stakeholders to manage groundwater resources
- Implementation of solutions for sustainable groundwater use and groundwater abstraction

## 5. MANAGED AQUIFER RECHARGE

Managed aquifer recharge (MAR) is the replenishment of groundwater by planned subsurface infiltration which is recovered at a later stage. The main objective of MAR is to create additional storage in a controlled manner to meet future water needs, hence lessen the risk of over-exploitation. MAR usually forms part of a broader water management plan to ensure sustainable utilisation of the groundwater resource (Figure 20).



**Figure 20: Management interventions for sustainable groundwater use (Dillon et al. 2012)**

### 5.1. Storage enhancement

Storage enhancement can be realized by various approaches that include injection wells (ASR), infiltration ponds, managed releases of water through natural (river) channels or man-made canals, intentional flooding of agricultural lands to increase seepage into underlying aquifers, etc. (Figure 21).

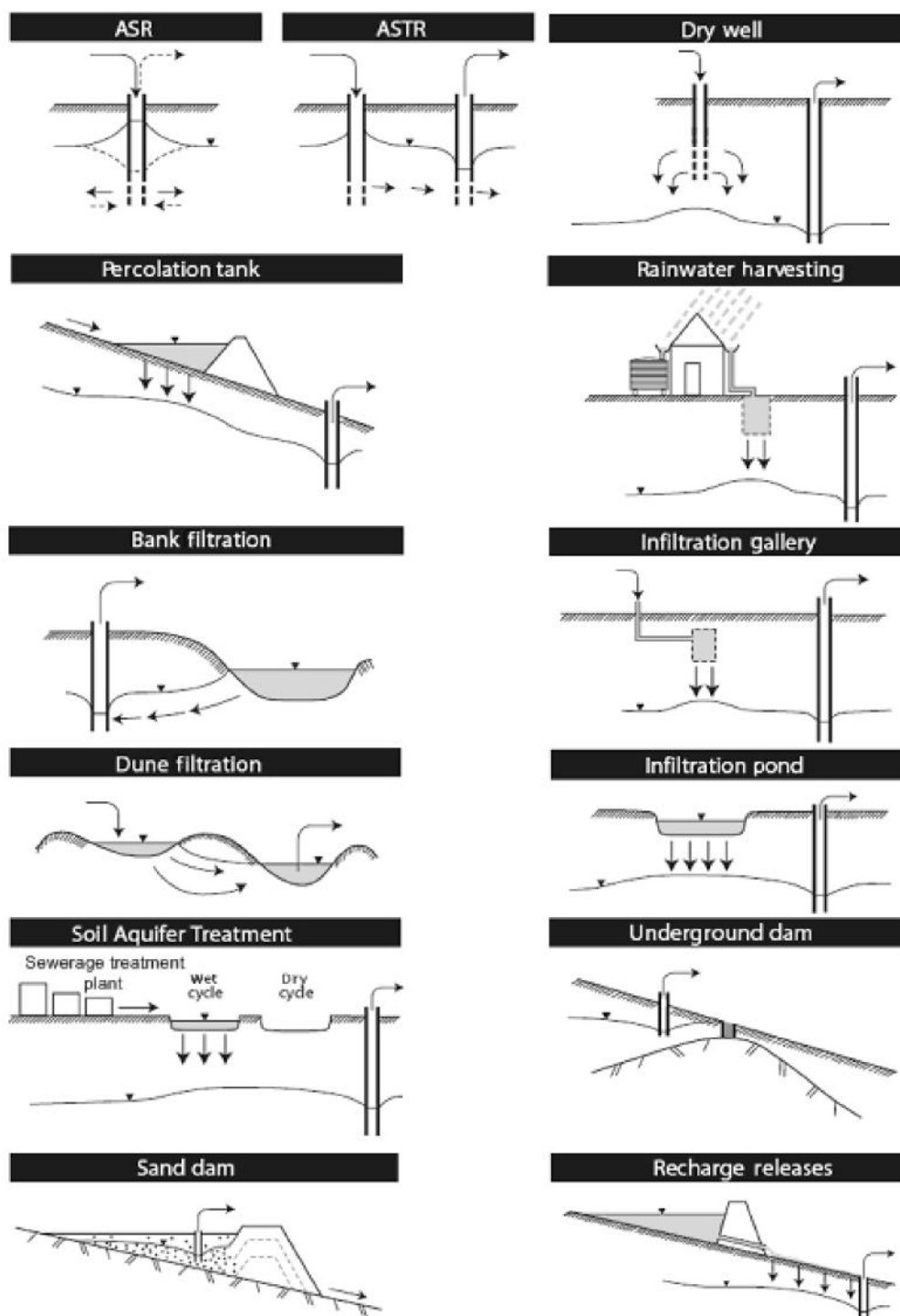


Figure 21: Schematic of types of managed aquifer recharge ( adapted from Dillon 2005 as cited by Dillon et al., 2012)

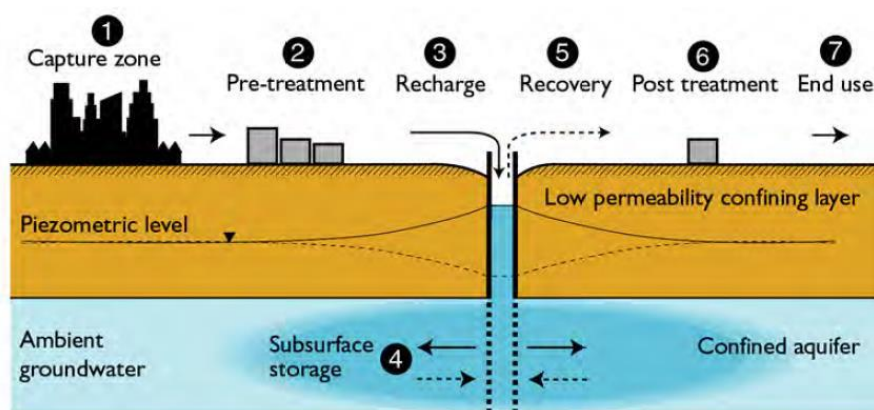
Groundwater replenishment can also occur indirectly as a secondary benefit of specific actions, including deep percolation from applied irrigation water and water placed into unlined conveyance canals.



In the light of climate change and population growth there is an increasing need to secure city water supplies, especially cities that are affected to a large extent by seasonal variations in water sources in addition to inter-annual variability (Dillon et al. 2009). Cities with prolonged dry periods or with low ratio of mean annual rainfall to evaporation have a greater need for water storage, than wetter cities with more uniform rainfall. A 25% reduction in rainfall near Perth, Australia, resulted in more than 50% reduction in stormwater runoff from rural water supply catchments. In urban catchments, annual runoff is expected to decline by the same proportion as rainfall, hence the relative efficiency of urban catchments to rural catchments will increase as water supplies become more stressed, and MAR could play a role in averting the need to augment urban stormwater systems.

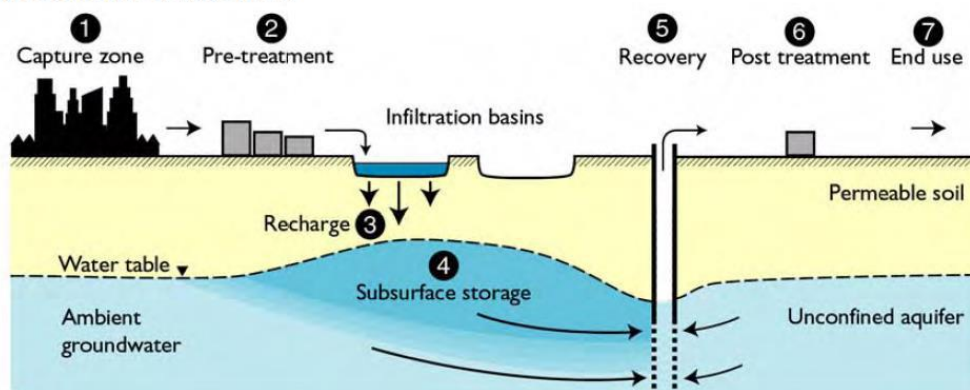
Figure 22 shows two examples of MAR systems under different hydrogeological settings near an urban area.

#### CONFINED AQUIFER



(a)

#### UNCONFINED AQUIFER



(b)

**Figure 22: Aquifer Storage and Recovery (a) and Soil Aquifer Treatment (b) (Dillon et al., 2009)**

The seven elements common to all types of MAR projects depicted in Figure 22 are explained in Figure 23.



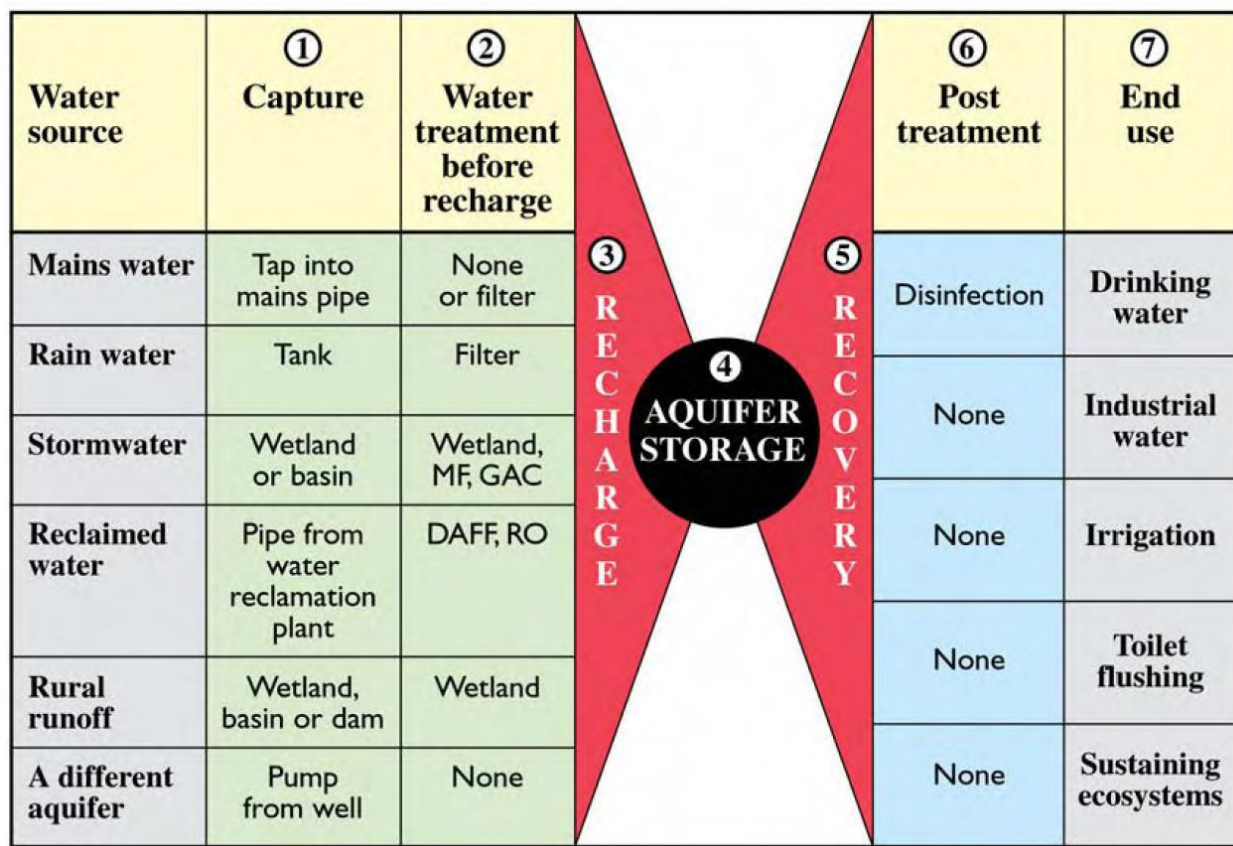


Figure 23: Sources of water, methods of capture and treatment for MAR (Dillon et al. 2009)

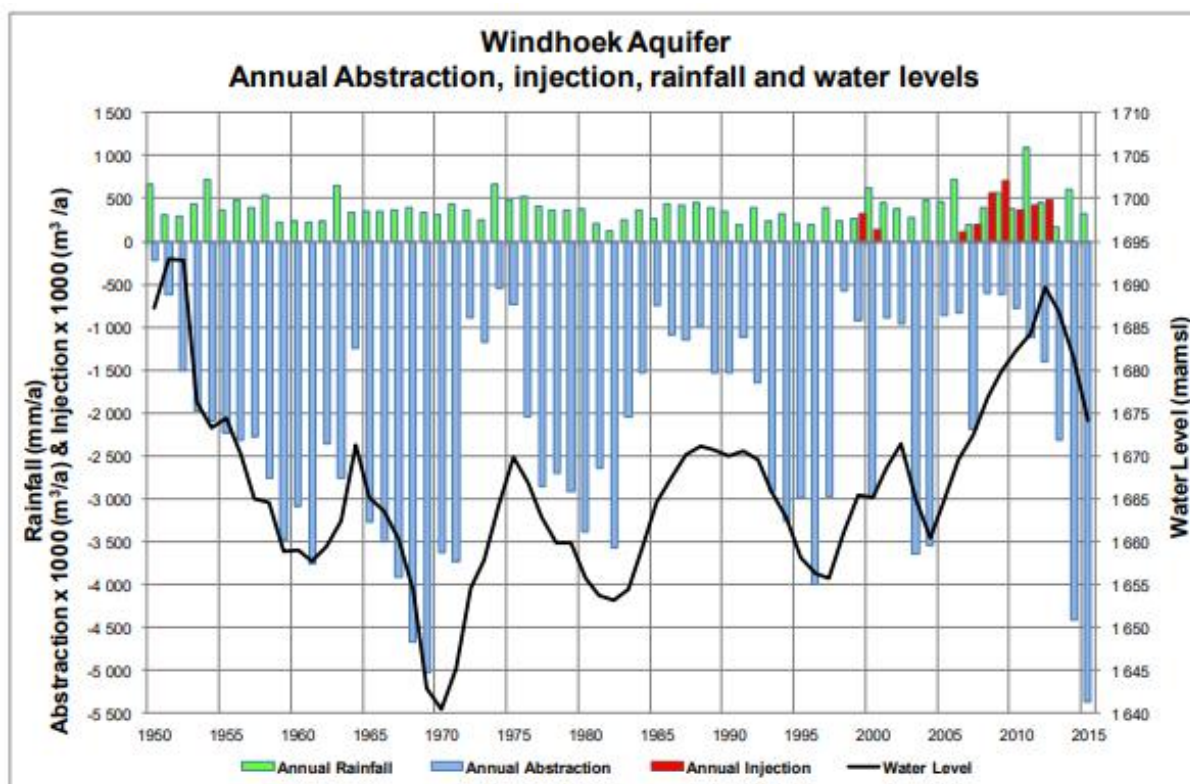
MAR projects typically provide intermediate scale supplies and are generally cost effective at sizes above 50 to 100 Mℓ/yr. Capital costs per unit storage volume of infiltration projects that store water in unconfined aquifers are significantly lower than for any other form of water storage. Near urban areas, ASR has the potential to have the least total capital costs per unit of water storage mainly due to the often-high land value (Dillon et al. 2009). MAR projects in Southern Africa are discussed in [Box 9](#).

### Box 9: MAR in Southern Africa (Murray 2016; Murray et al. 2018)

In the early to mid-1900s sand storage dams were constructed in stages in Namibia for the storage of water in “artificial” aquifers and in South Africa the Atlantis scheme near Cape Town started infiltrating storm run-off and treated wastewater in 1979. In addition to these, farmers over the years have built numerous earth dams for the purpose of enhancing groundwater recharge. In recent times a major borehole injection scheme for the City of Windhoek, Namibia was constructed, and the South African government developed and rolled-out its national MAR strategy.

The Windhoek’s MAR scheme involves large-scale borehole injection and recovery in a highly complex, fractured quartzite aquifer. The first injection boreholes were commissioned in 2005. Its current injection capacity is 420 m<sup>3</sup>/hr and with the new boreholes that have been drilled, this will increase to over 1 000 m<sup>3</sup>/hr.

Besides the larger schemes of Windhoek and Atlantis mentioned above, a few small-medium scale MAR schemes have been implemented in South Africa (mostly borehole injection), and several feasibility studies have been conducted with the intention of implementation in the near future. In addition to these a major feasibility study was undertaken for the Botswana government with the aim of assessing the value of MAR for the more industrious eastern part of the country. In most cases, the main purpose of MAR in Southern Africa is to augment water



supplies and to enhance water security.

Basin infiltration is a more cost-effective MAR approach for irrigated agriculture in rural areas. The farmer must first consider access to recharge water and conveyance to the recharge area. Farms that are adjacent to rivers and irrigation canals<sup>2</sup> are more fortunate than areas lacking surface water conveyance facilities which may constrain MAR implementation. There are several factors that determine the feasibility of MAR on agricultural land (Geen et al. 2015):

- Deep percolation: Soils must be readily able to transmit water beyond the root zone.
- Root zone residence time: The duration of saturated/near saturated conditions after water application must be acceptable for the crops grown on lands under consideration for MAR for the entire crop root zone.
- Topography: Slopes that negatively influence the even distribution of water will be more difficult to manage.
- Chemical limitations: High soil salinity and sodicity may result in saline leachate (poor water quality) that must be avoided to protect and sustain good groundwater quality.
- Soil surface condition: Certain soils may be susceptible to compaction and erosion if large volumes of water are applied. Surface horizons with high sodium are prone to crusting that may contribute to decreased surface infiltration rates.

The following actions are proposed that farmers can take to enhance fresh groundwater storage:

- Review suitability of crops and farming practices for on-farm groundwater recharge by flood/streamflow retention and aquifer storage and recovery techniques.
- Consider differentiated use of groundwater and surface water to optimise water quantity and quality

Murray (2017) furthermore formulated key questions related to a wide range of topics from engineering/environmental to legal/institutional/socio-economic perspectives that need to be addressed prior to embarking on a MAR project (Table 3).

**Table 3: Key questions to be addressed for MAR projects (Murray 2017)**

Topic	Some key questions
1. The need for the scheme	<ul style="list-style-type: none"> <li>• Is artificial recharge really necessary?</li> <li>• Could you not increase your groundwater yield by expanding the wellfield or by managing existing wellfields better?</li> </ul>

<sup>2</sup> There may be a governance issue at play – as surface water is a public good but groundwater considered private water.

Topic	Some key questions
2. The source water	<ul style="list-style-type: none"> <li>What volume of water is available for recharge, and when is it available?</li> </ul>
3. Aquifer hydraulics	<ul style="list-style-type: none"> <li>Will the aquifer receive and store the water?</li> </ul>
4. Water quality	<ul style="list-style-type: none"> <li>Is the quality of the source water suitable for artificial recharge?</li> </ul>
5. Engineering issues	<ul style="list-style-type: none"> <li>How will the water be transferred into the aquifer?</li> </ul>
6. Environmental issues	<ul style="list-style-type: none"> <li>What are the potential environmental benefits, risks and constraints?</li> </ul>
7. Legal and regulatory issues	<ul style="list-style-type: none"> <li>What type of authorisation is required?</li> </ul>
8. Economics	<ul style="list-style-type: none"> <li>How much will the scheme cost, how much will it cost to operate it, and what will the cost of supplied water per m<sup>3</sup> be?</li> </ul>
9. Management and technical capacity	<ul style="list-style-type: none"> <li>What skills are required to operate the scheme, and are they available?</li> </ul>
10. Institutional arrangements	<ul style="list-style-type: none"> <li>Who will be responsible for supplying the source water and ensuring its quality is suitable for recharge?</li> <li>Are there other users of the aquifer?</li> <li>Who will regulate the use of the scheme?</li> </ul>

## 5.2. Flood mitigation (Green infrastructure)

Urban stormwater, rainwater that runs off urban surfaces such as roofs, pavements, car parks, and roads, flows into storm water drains, creeks and rivers and forms part of the fresh water that ultimately flows to estuaries and the ocean.

Stormwater in urban areas is usually abundant but may require treatment and storage before reuse (Page et al. 2018). The primary limitation to storm water harvesting and reuse in urban areas is the ability to store the water from runoff events in the wet season for subsequent use when water is in demand, typically during the dry season. MAR can provide an economical method of storing and treating stormwater in urban areas. Common uses of stormwater recycled via an aquifer include the irrigation of parks and gardens, ovals and golf courses, other municipal and commercial purposes, and drinking water.

With increasing adoption of MAR, green infrastructure<sup>3</sup> and water-sensitive urban design practices, the quality of urban stormwater and the quantity of harvestable should improve, and with tightening requirements on urban (coastal) water quality, investments in wastewater, will make more water available for use and for storage. These practices also contribute to mitigating floods and flood damage.

In the context of irrigated agriculture, flood MAR (including spate irrigation; see Latif 2015) purposefully captures water from flood events and spread over land using diversion structures. Kocis and Dahlke (2017) studied the magnitude, frequency, duration, and timing of high-magnitude flow (i.e. flow above the 90th percentile) in the Central Valley, California, in order to assess the physical availability of surface water for groundwater banking and found that these flows could provide enough water to balance more than two times the annual groundwater overdraft. Similarly, wet years can provide over four times the average annual groundwater overdraft.

In [Box 10](#) groundwater based natural infrastructure (GBNI) solutions are presented to increase water storage, water retention, water quality and environmental functions or services.

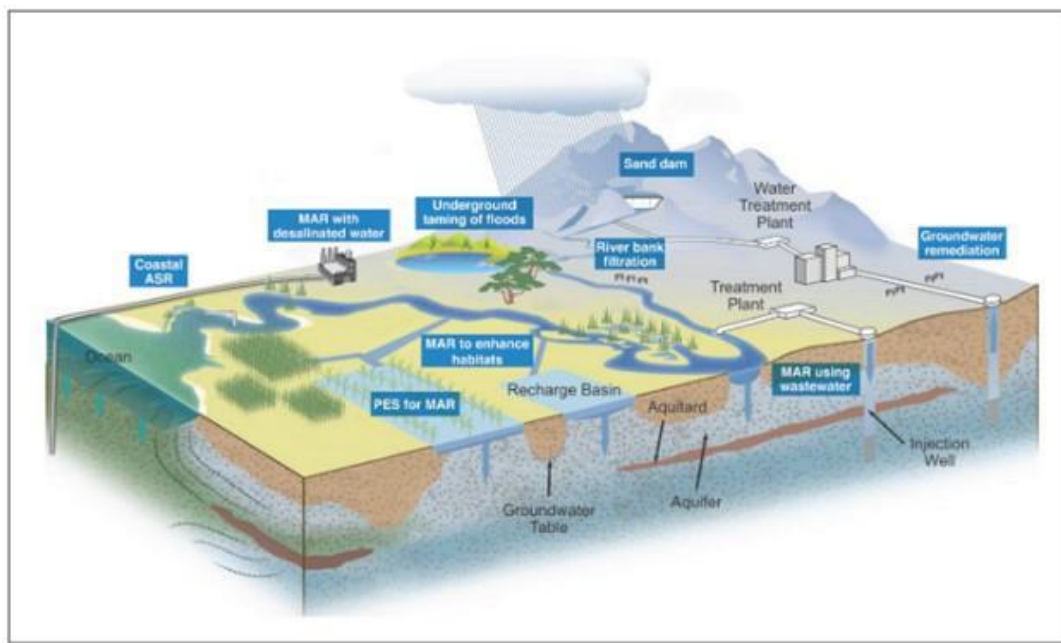
#### **Box 10: Examples of GBNI solutions**

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<sup>3</sup> Green infrastructure uses vegetation, soils, and other elements and practices to restore some of the natural processes required to manage water and create healthier urban environments. At the city scale, green infrastructure is a patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water. <https://www.epa.gov/green-infrastructure/what-green-infrastructure>



In the diagram below, IWMI (modified after Maven's notebook) gives examples of groundwater based natural infrastructure (GBNI) solutions that utilize and manage groundwater and subsurface systems and processes in order to increase water storage, water retention, water quality and environmental functions or services for the overall benefit of water security, human resilience, and environmental sustainability.



One such an example is the underground taming of floods (for irrigation), which forms part of a guide for GBNI solutions and is being practiced in India.

Source: <http://gripp.iwmi.org/natural-infrastructure/overview-on-groundwater-based-natural-infrastructure/>

### 5.3. Drought mitigation

Storage of additional water in the underground can provide a buffer for water shortage during drier periods. With the increasing demand and the threat to water supply security posed by droughts, MAR may turn out to be the most favourable augmentation option in the SADC. A good example is the MAR scheme in Windhoek, Namibia, where since 2004 injection and recovery BHs were drilled into the Windhoek Aquifer (comprising faulted and fractured quartzite and schist rocks; Murray 2017). Since the onset of the MAR scheme, groundwater levels recovered and the water supply security of the City improved; the recent drought of 2015/16 was mitigated due to the additional groundwater available through the MAR scheme. Other examples of artificial recharge in SADC to overcome water shortages include check dams, sand dams and subsurface dams to capture and store water from ephemeral flows (Box 11).



### Box 11: MAR with check dams – Gaborone, Botswana (Mathias et al. 2018)

Gaborone, the capital city of Botswana, with a semi-arid climate, relies on the reservoir storage behind the Gaborone Dam of the Notwane River. Unfortunately, expansion of reservoir storage in Botswana is limited by the availability of suitable topographical sites. Furthermore, conventional surface water storage from dams often provides more environmental impacts than benefits. The Department of Earth Sciences, Durham University in partnership with the Centre of Ecology and Hydrology (UK) and the University of Botswana



have started a project to improve the knowledge of how MAR with check dams (CD) could potentially improve water and food security for the Gaborone region of Botswana. Improving water availability is in turn hoped to increase arable agricultural productivity and food security in the area. A check dam (also called gully plug; see example of a loose stone dam in East Africa above) is a small, temporary or permanent dam constructed across a drainage ditch, swale, or channel to lower the speed of concentrated flows for a certain design range of storm events. A check dam can be built from wood logs, stone, pea gravel-filled sandbags or bricks and cement. By slowing the flow of river water check dams enable much greater infiltration, which leads to increased groundwater recharge and storage. Infiltrated water can be recovered during dry periods from bankside groundwater wells. Two significant advantages of MAR-CD are: (i) reduced evaporative losses and (ii) improved water quality from bankside filtration. Another important advantage is that because the upstream riverbed completely dries out following infiltration, sediment build-up behind the check dams can be easily removed by simple excavation methods and can be redistributed locally to partially reverse soil erosion.

## 6. GROUNDWATER REUSE AND RECYCLING

Groundwater recharge with recycled water maximizes water reuse and should form an integral part of water resource planning in major cities and towns of SADC. Indirect recycling of water at Atlantis near Cape Town, South Africa, started shortly after the town was established in the mid-1970s. The artificial groundwater recharge scheme of Atlantis stores and purifies treated domestic wastewater and urban stormwater. The groundwater is abstracted by wellfields and re-used to augment the municipal water supplies to the town (Atlantis Water Supply Scheme – AWSS). It has alleviated the pressure on surface water resources in the region (Bugan et al. 2016).

### 6.1. Recovery of reclaimed water through ASR

ASR can be used to recover reclaimed (Figure 24) water that has been injected into a subsurface formation for storage (Chapter 0). ASR can be an effective management tool to minimize seasonal fluctuations in supply and demand, by storage during the wet season when demand is low and recovery of water during dry periods when demand is high (EPA 2012; Bloetscher et al. 2014). There are, however, a number of concerns (EPA 2018):

- Pathogens may enter the aquifer if water is not disinfected prior to injection. In the case of injection of raw water and treated effluent, the fate of microbes and viruses in an aquifer is a critical factor to consider.
- Disinfection by-products can form in the aquifer if water is disinfected prior to injection. Soluble organic carbon should be removed from the injectate before disinfection. If not, chlorinated disinfectants may react with the carbon to form contaminating compounds. Contaminants include trihalomethanes and haloacetic acids.
- Metals and radionuclides may be mobilized from the rock depending on the chemistry of the injected water and the aquifer. Differences in pH and reduction-oxidation processes between the injected water and aquifer may cause arsenic, iron, manganese, or radionuclides that are present in the rock to dissolve.
- Carbonate precipitation in carbonate aquifers can clog wells when the injectate is not sufficiently acidic.

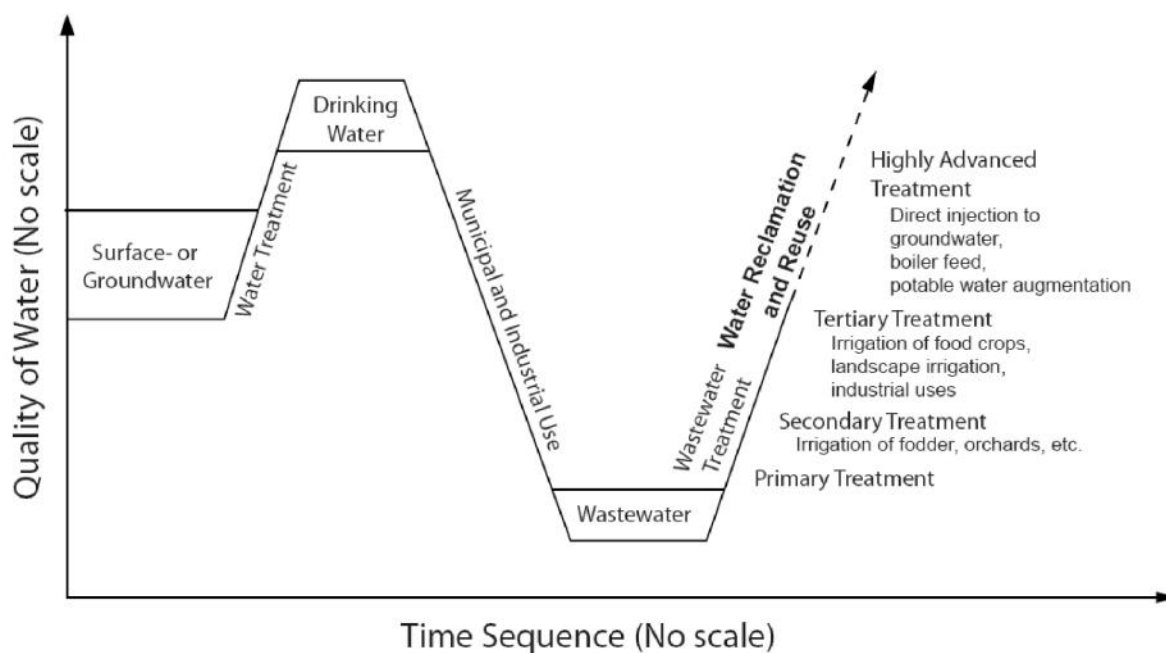


Figure 24: Quality change of water in water/wastewater systems (Esposito et al. 2005)

Some of the factors to be considered when recharging an aquifer for the purpose of human consumption are discussed below (Aertgeerts and Angelakis 2003):

- Primary treatment and disinfection, plus soil aquifer treatment, handling of dry and wet cycles as well as hydraulic and mass charges to avoid soil clogging, if suspended solids are mostly minerals.
- Advanced treatment and disinfection, plus handling of dry and wet cycles as well as hydraulic and mass charges to avoid soil clogging, if suspended solids are mostly minerals.
- Secondary treatment and disinfection with a well operated soil aquifer treatment.
- Possibly advanced treatment based on site-specific conditions.
- Meet drinking-water standards after percolation.
- Monitoring for coliforms, pH, chlorine residual, and drinking-water standards plus site-specific parameters.
- Distance to point of extraction or dependent on site-specific factors.

As human contact with reclaimed water increases, further treatment such as chemical coagulation, sedimentation, and filtration with higher levels of disinfection is required as illustrated in Figure 24 (Esposito et al. 2005).

## 6.2. Aquifer reclamation

Aquifer reclamation involves the injection of large quantities of higher-quality water into a compromised aquifer. One application is the injection of freshwater into aquifer zones that have been compromised by

brackish water (water containing 1,000 to 10,000 ppm of total dissolved solids) intruding into the formation (USEPA 2002). The freshwater serves to stabilize the water quality at a given chloride concentration or forces the brackish water to retreat toward the source—typically the ocean, but also lower formations where up-coning is a problem (AWWA 2015).

There are several techniques available for the sustainable abstraction of fresh groundwater whilst preventing up-coning and/or intrusion of saline water in fresh aquifers, however each of the techniques coming at a high cost.

A 'balanced scavenger well system' consisting of a production well and a so-called scavenging well some 20-30 meters deeper was proposed as a solution to solve long-term salinization problems in the Punjab in Pakistan (Alam 2014). The dual pump system taps both the shallow fresh water and the deeper saline water zones. The wells pump fresh and saline waters from the same site simultaneously without mixing, through two separate discharge systems. The brackish water is disposed of, while the fresh water is used for irrigation.

Zuurbier et al. (2017) proposed new technologies to counteract salinisation of well fields by interception and desalination of up-coning brackish groundwater. The so-called 'Freshkeeper' aims to safeguard the water supply from abstraction wells at risk of salinisation. The concept follows a three-step approach (Figure 25):

- a. Intercept up-coning brackish groundwater by abstracting fresh water from the top of the aquifer, while pumping intruding brackish water from the lower part of the aquifer;
- b. Use the intercepted brackish water as an additional water source by desalination through reverse osmosis (RO); and
- c. Dispose of the RO membrane concentrates by deep-well injection into a confined, more saline aquifer.

At a pilot field site, Zuurbier et al. (2017) observed that the abstracted fresh water as well as the brackish abstraction water freshened upon dual zone Freshkeeper abstraction. Chloride concentrations of the abstracted fresh and brackish water decreased in the first months of the pilot, from 45 to 35 and 1000 to 600 mg/l, respectively. Freshening not only occurred in the near surrounding of the abstracting well screens, but also in observation wells at greater distance (Zuurbier et al. 2017).

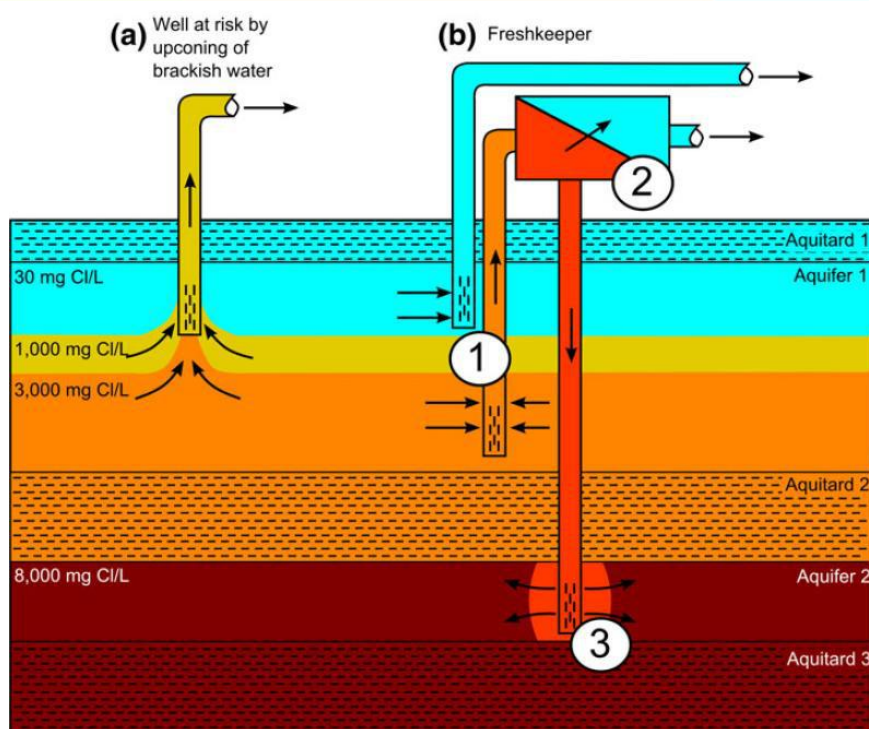


Figure 25: Water well prone to (a) salinisation and (b) Freshkeeper solution (Zuurbier et al. 2017)

Monitoring water quality for potential problems associated with salinity and sodicity will indicate if there is any deterioration in the quality of water supply. With the appropriate institutional set-up and management, interventions could be implemented if potential problems with water quality are evident.



## 7. CONCLUSION AND RECOMMENDATIONS

The road to water resilience requires broadening the water supply mix to include urban stormwater, water harvesting, water reuse, recycled wastewater, desalinated water and groundwater.

Groundwater storage serves as a key buffer for achieving groundwater resilience under extreme climate events e.g. extended drought conditions. Using the groundwater resource strategically and sustainably means that it can be a crucial factor to bridge gaps between water resource availability and water demand. This requires careful consideration and includes: (i) setting a limit on how much water can be safely pumped to avoid irreversible subsidence caused when too much water is removed from the aquifer; (ii) defining a safety reserve to ensure an adequate water supply in a worst-case scenario, such as a multi-year-interruption in surface water supplies; and (iii) defining a management level – a target groundwater level that allows use of the aquifer as a working reserve that can be used during dry times and refilled when adequate surface water supplies are available while protecting the safety reserve and while preventing exceedance of the irreversible subsidence limit.

The capacity of a groundwater system to recover from pollution is critical to the concept of resilience as natural disasters and extreme weather events undermine the effectiveness of remediation measures. Determining the natural attenuation capacity of groundwater systems at a local scale is complex as it requires detailed knowledge of: (i) the type and quantity of pollutants involved; (ii) the chemical and hydraulic characteristics of both unsaturated and saturated zones; and (iii) other factors controlling the spatial extent and persistence of pollutants. Because of the overall complexity and costs of groundwater remediation (often unsuccessful), the focus should be on prevention of pollution.

There are several measures to support groundwater resilience such as conjunctive management of water resources; managed aquifer recharge; and groundwater reuse and recycling.

Conjunctive management in support of long-term groundwater (and surface water) resilience refers to management of the combined use of groundwater, surface water and other sources of water in a manner that prevents irreversible impacts (quantity and quality) on either of the resources. The benefits of coordinated management of the water sources should exceed the benefits obtained through their separate management. Benefits of conjunctive (planned) management are: (i) diversification of the water supply mix; (ii) improved water supply security and security of water sources (prevention of over-exploitation, preparedness for extreme weather events); (iii) larger net water supply yield (efficient use of both water resources); and (iv) reduced environmental impact (prevents/limits over-exploitation of groundwater and surface water, water logging and salinisation). In rapidly expanding cities, conjunctive use of groundwater and surface water is often unplanned and includes 'traditional' groundwater sources (springheads or water wells) at the urban nucleus e.g. Lusaka, Zambia, and immediate neighbouring surface watercourses either one of which subsequently become insufficient with urban growth.



Managed aquifer recharge (MAR) is the replenishment of groundwater by planned subsurface infiltration which is recovered at a later stage. The main objective of MAR is to create additional storage in a controlled manner to meet future water needs, hence lessen the risk of over-exploitation. MAR usually forms part of a broader water management plan to ensure sustainable utilisation of the groundwater resource. Benefits of MAR other than storage enhancement includes flood and drought risk reduction, salinity improvement and ecosystem enhancement. In the case of Windhoek, the capital of Namibia, groundwater contributes about 10% to the water supply (Christelis and Struckmeier 2011). A system of artificially recharging groundwater resources has been put in place (Murray et al. 2018). The aim is to make available up to 8 million cubic metre per annum ( $\text{Mm}^3/\text{annum}$ ) of groundwater for abstraction (Tredoux et al. 2009). The present Windhoek water demand is about 20  $\text{Mm}^3/\text{annum}$  (Christelis and Struckmeier 2011). MAR has significantly contributed to water security in the Windhoek area and has a great potential for the SADC.

Groundwater recharge with recycled water maximizes the reuse and should be an important component of water resource planning in major cities and towns of SADC. Indirect recycling of water at Atlantis near Cape Town, South Africa, started shortly after development of the town in the mid-1970s. The artificial groundwater recharge scheme of Atlantis stores and further purifies treated domestic wastewater and urban stormwater. The groundwater is abstracted at wellfields and re-used to augment the municipal water supplies for the town. It has alleviated the pressure on surface water resources in the region (Bugan et al. 2016).

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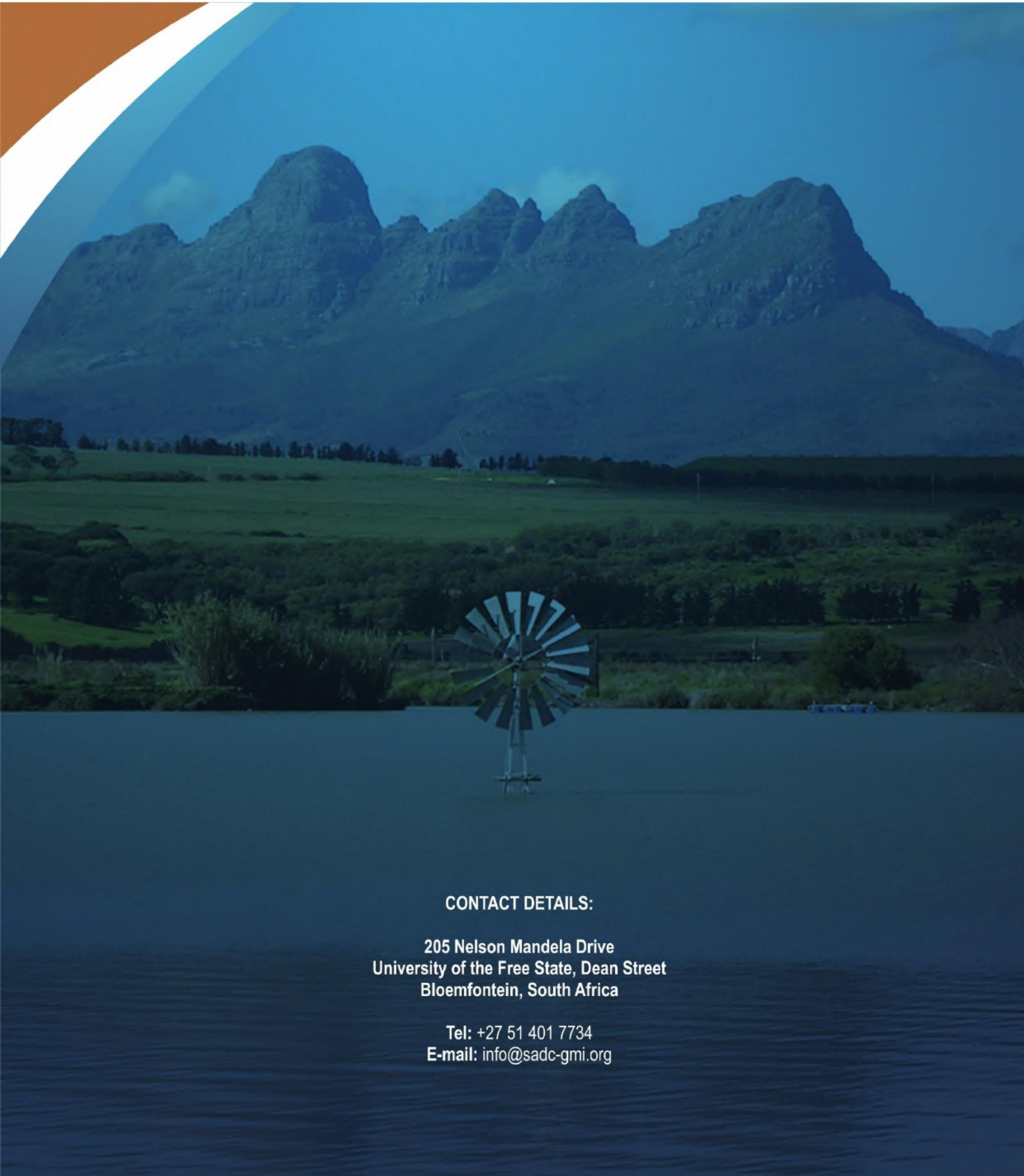
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