Mar 16, 2020

Towards sustainable groundwater use in the African drylands

Contribution to addressing the issues highlighted in PBL's The Geography of Future Water Challenges

Final report

ACACIA WATER

Executive summary

Groundwater resources in African drylands are important sources of freshwater but are under increasing pressure due to population growth and climate change. As a result, it is increasingly important that groundwater resources are managed in a sustainable way. Here, sustainability strategies aimed at increasing water availability, decreasing water demand, and institutional arrangements are discussed and collected into sustainability pathways. The pathways are described for several landscape types representative of the African drylands which are based on a combination of hydrogeology, climate, and socio-economic conditions. Landscape-specific strategies include agricultural water-saving technologies accompanied by prioritization of water use in hyper-arid areas where large-scale irrigation is practiced. In rural landscapes with higher aquifer recharge, sustainability strategies include artificial aquifer recharge and groundwater protection mechanisms. In urban centers, tapping non-conventional water sources through desalinization and wastewater recycling and reduction of non-revenue water can contribute to more sustainable groundwater use. General strategies and requirements that are a condition for sustainable groundwater use are aquifer system understanding and monitoring; community participation and capacity building; and coordinated management and strong institutions.

Colophon

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1 Introduction

1.1 Background

Groundwater is an important source of water globally, accounting for more than 95% of the available freshwater resources. In Africa, it is estimated that more than 75% of the population depends on groundwater (Foster et al. 2006). This is especially true for arid and semi-arid regions, where surface water availability tends to be comparatively unreliable. There are several reasons for groundwater's prominence as a water source. When they are protected and properly managed, groundwater resources are less vulnerable to dry spells and drought periods, and groundwater quality is relatively stable compared to surface water resources. In addition, the natural storage is relatively high and the infrastructure is relatively affordable for poor communities (Adelana and MacDonald 2008). Finally, groundwater can easily be developed for small-scale uses compared to surface storage such as dams, which are generally more centralized and costlier (Pavelic 2012). Table 1 contains an overview of the benefits of groundwater resources.

Table 1. Summary of the benefits of groundwater (from AGW-Net 2014)

Characteristics	Explanation
Available where needed	Groundwater can be found almost everywhere (though not necessarily in the quantities desired)
Naturally protected	Groundwater is protected against direct pollution and evaporation and often provides potable water without treatment
Our largest reservoir	Global groundwater storage is vast, providing a water buffer that can be used to mitigate droughts and water scarcity
Untapped resource	There are many untapped aquifers that can provide water for future needs if managed sustainably. This is particularly true in Africa.
Stable temperature	Groundwater is becoming increasingly used as an important and safe source of renewable energy for heating and cooling, although this use is still minor in Africa
Environmental function	Dry season river baseflow is maintained by groundwater discharge. Groundwater dependent ecosystems such as wetlands provide vital environmental services.
Natural treatment	Soils and aquifers can improve water quality by degradation and sorption of biological and some chemical contaminants

The various benefits of groundwater resources, and especially the fact that groundwater quantity and quality are relatively stable, ensure that groundwater plays an important role in achieving the UN Sustainable Development Goals (SDGs). Groundwater is especially closely related to the goal for access to water and sanitation for all (goal 6) but is also indirectly related to many other SDGs. For example, the development of groundwater abstraction tends to reduce the time spent by women and children on water collection, allowing women to engage in more productive activities and children to go to school.

Despite this, groundwater is underrepresented in SDG targets and indicators (Guppy et al. 2018) – indeed only one target explicitly mentions groundwater - and sustainable management is often neglected.

Unsustainable use of groundwater resources can have a significant socio-economic and environmental impact. For example, lowering groundwater levels as a result of over-exploitation raise costs of abstraction and can cause wells to run dry. Water scarcity and unequal access to water resources can, in turn, be a cause for conflicts (van der Zaag 2007, Lecoutere et al. 2010, Snorek et al. 2014). In addition, groundwater often has an important role in ecosystem services provision, such as sustaining wetlands and other groundwater-dependent environments, as well as sustaining baseflow downstream.

Currently, groundwater resources worldwide and on the African continent are under pressure due to increasing populations and climate change. Rainfall patterns are expected to become more erratic and temperatures are projected to increase, potentially increasing crop stress and lowering crop yields. The population of Africa is expected to double between 2019 and 2050 (UN 2019a), resulting in higher water and food demand. Especially in Sub-Saharan Africa, groundwater irrigation is underutilized (Kadigi et al. 2013, MacDonald et al. 2012) and has a high potential to address the rising demand for food (Altchenko and Villholth 2015, Pavelic et al. 2013). However, despite potentially large groundwater storage in many aquifers within the African drylands, groundwater replenishment can be quite low and even negligible in hyper-arid environments. This means that aquifers in this region are vulnerable to over-exploitation. Therefore, there is a need to assess whether and how the groundwater resources of African drylands can be used more sustainably.

1.2 Aim and scope

Drylands and water-stressed areas were identified as one of four hotspot landscapes in The Geography of Future Water Challenges (Ligtvoet et al. 2018). Population growth, increased water stress, and crop yield gaps are potential drivers of migration and conflict, especially in African drylands. Groundwater development has the potential to meet rising demands for food and water in this region (Altchenko and Villholth 2015, Pavelic et al. 2013), as long as resources are used sustainably. The aim of this study is to assess whether groundwater resources in the drylands of Africa can be used and developed (more) sustainably in light of the increasing food and water demand and climate change, and how this can best be achieved.

The scope of the project is largely determined by the definition of two terms: drylands and sustainability.

In this project, ‘drylands’ assumes a broad definition, consisting of areas with seasonally or perennially dry climates. Specifically, the desert, semi-desert and dry savannah biomes defined by UNEP (2008) define the delineation of drylands. In practice, regions that experience medium to high water stress may also be treated as drylands. Water scarcity is defined by water availability related to water use and is especially likely where the population density is high. In this study, all water use is considered: water stored in the root zone of the soil (‘green water’) and water from surface and groundwater resources (‘blue water’). Several water stress indicators are available, including the WRI Aqueduct indicator relating domestic, industrial and agricultural water withdrawals to available renewable surface and groundwater resources (Hofste et al. 2019).

Box 1: Useful definitions

Non-renewable groundwater is groundwater from an aquifer which has a very low average annual recharge rate at human timescales.

Fossil groundwater is groundwater that infiltrated tens of thousands of years ago, often under climatic conditions that were different from the present and that has been stored underground since that time (sub-category of non-renewable groundwater).

Over-exploitation is the prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities that exceed its average annual replenishment, causing a persistent drop in groundwater levels and related socio-economic and environmental impacts.

Groundwater mining is the extraction of groundwater from an aquifer having predominantly non-renewable resources, which is often also fossil groundwater.

Non-conventional water sources are water resources that require treatment before use, and include water generated through desalinization, dilution, or wastewater recycling.

Sustainable groundwater use can be defined and evaluated by different metrics. From a physical or environmental perspective, sustainable groundwater use entails that groundwater abstractions are lower than the long-term average recharge into the aquifer. Under this definition, non-renewable groundwater can never be considered to be sustainable. However, the large storage of non-renewable aquifers in North Africa and the importance of water and food security in the region suggest that a more nuanced approach should be adopted.

An alternative approach is to include a social perspective based on a pre-determined time horizon. If the impact of abstraction of nonrenewable groundwater (groundwater mining) to the current and next generations, is low because the storage is very high, the abstraction may be considered to be socially acceptable. This approach assumes that in time, technological innovations and energy transitions will allow people to tap new sources of water that are currently not accessible or are inappropriate for consumption (use of non-conventional water). For example, if energy becomes cheaper or technologies become more efficient, then desalinization in coastal zones and areas with saline groundwater will become economically feasible for a wider range of uses that it is today.

However, when abstraction rates higher than the natural recharge rate are condoned for socio-economic reasons, it is crucial that guidelines for short-term and long-term use including maximum withdrawals for different users are developed. This should include an exit strategy stipulating which steps will be taken when groundwater levels fall below the maximum allowable level. Under this definition, groundwater mining for short-term use such as in emergencies is considered to be sustainable, but groundwater mining at multi-decadal time scales may not be. This approach combining an environmental perspective with a time horizon is considered to be more reasonable and achievable for the drylands of Africa and is therefore adopted in this study.

1.3 Outline

Groundwater use, including the physical context, extraction types and management are presented in chapter 2 and several landscape types that are representative for the African drylands are described. In chapter 3, general strategies towards more sustainable use are discussed. In chapter 4, case studies will be used to illustrate lessons learned in terms of sustainable groundwater use. A sustainability pathway will be presented for each of the representative landscape types in chapter 5. Finally, the main conclusions and the way forward are summarized in chapter 6.

2 Groundwater occurrence and use

Before it can be assessed how to use groundwater resources in a more sustainable way, it is necessary to understand groundwater as a concept and the current situation of groundwater in the African drylands. That is the focus of this chapter: to give some background, basic terms, and characteristics of groundwater, and current situation for groundwater in terms of biophysical context, use, management, and challenges. This elaboration will culminate in a classification of 'groundwater types', which will form the basis for the strategizing in the rest of the report.

The definition of drylands as stated in the scope of this study relates to climate type and water scarcity risk. Figure 1 shows the area described by desert, semi-desert, Mediterranean and dry savannah biomes (UNEP 2008), which are considered to be representative of seasonally and perennially dry climates in Africa. The area falling outside of the drylands consists of moist savannah and tropical rainforest. These areas form an approximate delineation of African drylands considered in this study. Areas where water scarcity is relatively high may face the same types of issues even when the climate is considerably wetter, but these are sparsely located outside the classification based on biomes are therefore not shown in the figure.

Figure 1. Approximate delineation of African drylands (yellow against a grey background) based on the desert, semi-desert and dry savannah biomes (UNEP 2008).

2.1 Physical context

Groundwater is everywhere but is not found everywhere equally. How much water is available where, how much can be abstracted and how easily it can be abstracted is determined by its physical context: historic and current climate, geology, topography, and more. Figure 2 (left) shows a map of the average annual rainfall in Africa. Almost all groundwater is derived from rainfall when precipitation infiltrates into the ground. The residence time of this infiltrated rainfall can vary from short time scales like weeks (especially for shallow groundwater where groundwater is directly replenished by surface water) to tens of thousands of years (i.e. fossil groundwater).

Even so, local/regional rainfall patterns are important to consider when working with groundwater, especially considering sustainability.

Even more important however is the (hydro)geology of the area (Figure 2). Geology determines the presence of aquifers: layers that can hold significant amounts of water and is related to a number of characteristics that determine the feasibility of its abstraction. How much water can be stored and abstracted is determined by what type of aquifers are present in the area, how thick those aquifer layers are and how they are connected.

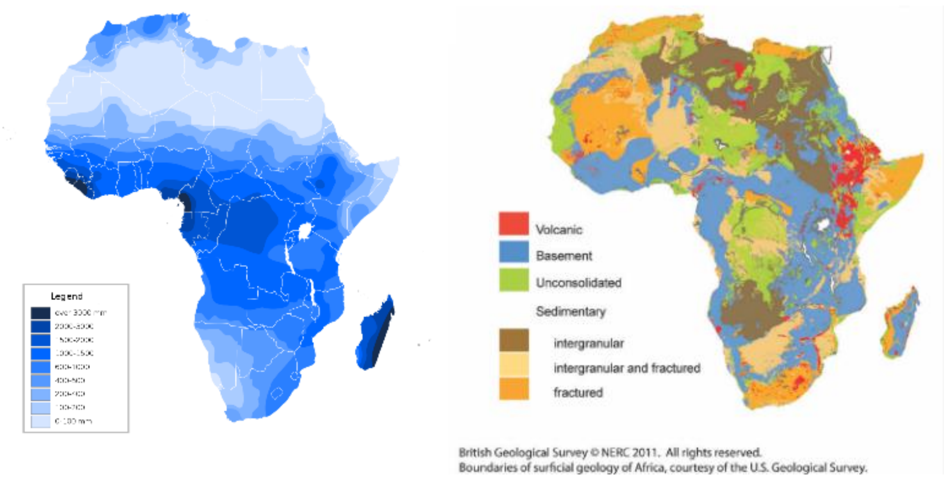

Figure 2. Precipitation (left) and hydrogeological environment (right) of the African continent (source: Wikimedia and BGS).

Note that the maps shown in this section give an impression of the variability in groundwater resources in the African continent as well as within the drylands. However, the drawback to these maps and many large-scale groundwater datasets in general is that they tend to treat groundwater as a two-dimensional phenomenon. In reality, there tend to be complex systems of aquifers where shallow, unconfined aquifers with high recharge overlie one or more semi-confined or confined aquifers with little to no recharge. This three-dimensional context is not visible in most datasets, and large-scale datasets of groundwater do not always clearly state which aquifer is represented by the data. The lack of data makes large-scale modeling of groundwater an extremely difficult task. Nevertheless, the maps provide insight into the regional variability of aquifer characteristics.

2.1.1 Aquifer characteristics

The availability of groundwater, the feasibility of cost-effective abstraction, the suitability of its use, and the risks of overexploitation are determined by the physical characteristics of an aquifer. These include storage, depth, productivity, quality, recharge, and vulnerability.

- **Storage**: how much water is stored within the aquifer?

Every aquifer is finite, and how much water it holds helps determine how vulnerable it is to over-exploitation. The storage largely depends on geology: loose sediments will hold much water while solid rock will hold little water. Figure 3 illustrates groundwater storage across Africa; from values below 1 meter of storage in for instance shallow alluvial aquifers to values over 50 meters in deep sedimentary rock aquifers, especially in North Africa.

Note that in North Africa, storage is very high (>50 meters of storage) while precipitation is very low (Figure 2). In this region, the water dates from thousands of years ago when the climate of the region was much wetter (fossil groundwater).

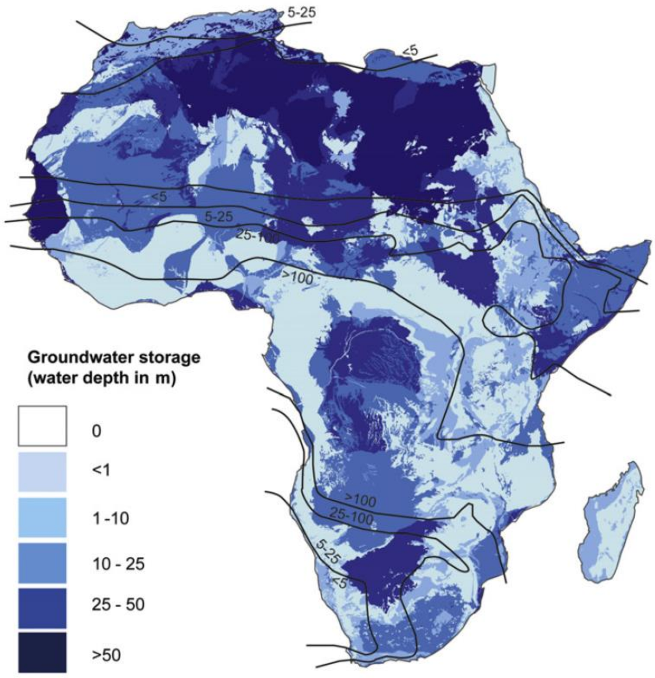

Figure 3. Aquifer storage and average annual recharge in Africa (from MacDonald et al. 2012); considering a population density of 45 people/km^2 (average for the whole of Africa), 5 mm/yr translates to about 300 l/person/day of recharge

- **Recharge**: how quickly is the aquifer replenished?

When an aquifer is not replenished, even small abstraction volumes will lead to groundwater level decline and ultimately deplete groundwater storage. How quickly this will impact users and the environment will depend on the storage properties of the aquifer. To ensure sustainability, there needs to be an understanding of where and how much recharge takes place in the area. Recharge (Figure 3) is closely related to rainfall, although it is also influenced by geology, topography, and human activity. Assuming an average population density of 25 people/km^2 in rural areas, 5 mm/yr translates to almost 550 l/person/day recharge. In cities, with an average population density close to 8,000 people/km^2 (Demographia 2015) this is less thn 2 l/person/day.

- **Productivity**: at what speed can water be abstracted? (Figure 4, right)

Even if there is a lot of water underground, it cannot be abstracted at high rates if it needs to travel through a dense medium. For instance, groundwater moves much more quickly through sandy layers, but if the mother material is clayey groundwater will travel very slowly. This phenomenon is referred to as productivity. The productivity of a well has a direct relation with the geology of the aquifer and its ability to transmit water. In other words, the productivity of an aquifer determines whether one or more wells are needed to extract a certain yield. Where productivity is low, the influence area of an abstraction is relatively large, and nearby wells are more likely to interfere with each other causing diminishing returns when increasing the number of boreholes.
Where well productivity is high, the influence area is relatively small and a single well may be able to meet the local demand for water. Water availability, however, is determined by aquifer storage and not by its productivity.

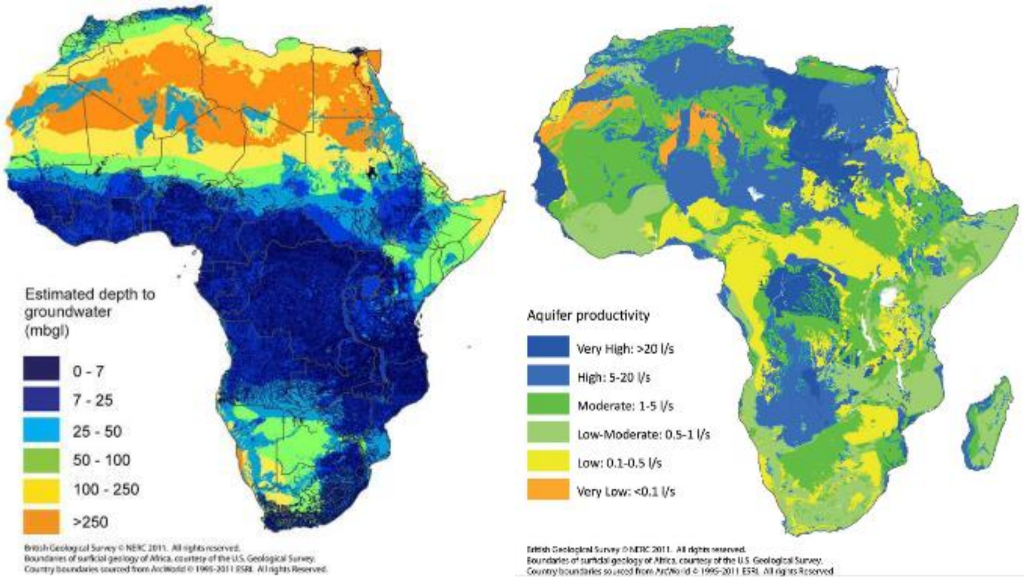

Figure 4. Estimated depth to groundwater level (left, from Bonsor and MacDonald 2011) and aquifer productivity (right, from MacDonald et al. 2012) for the entire African continent;

- **Depth**: how deep is the aquifer? (Figure 4)

Shallow groundwater is more easily abstracted than water hundreds of meters underground, assuming the same hydrogeological characteristics of the aquifer. Costs of extraction are usually directly proportional to the depth of groundwater (although productivity is also important for cost-effectiveness). Deeper groundwater also tends to be older water, which is more likely to have (very) low recharge rates than shallow groundwater. Depth to groundwater is affected by geology, climate, and topography.

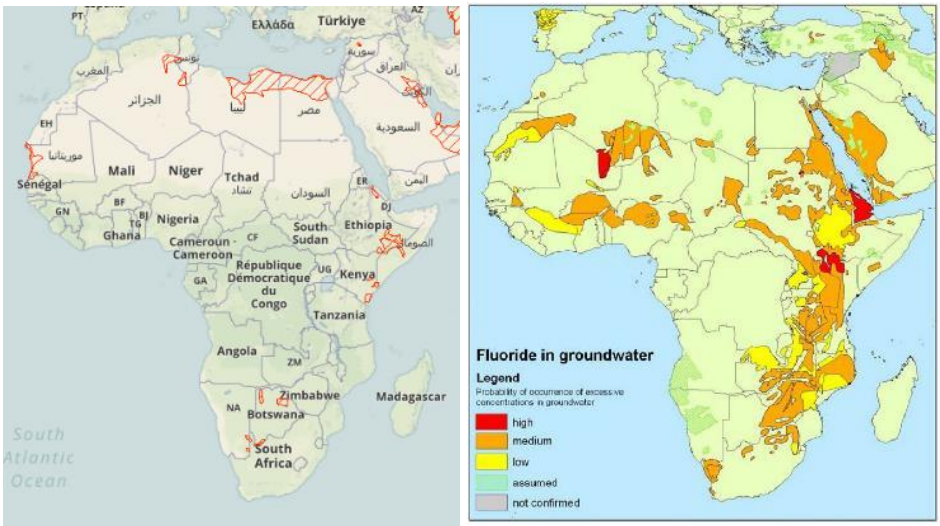

Figure 5. Groundwater salinity (left) and fluoride (right) in Africa (from Thole 2013).

- **Quality**: is the water suitable for its intended use?

While groundwater tends to be potable, some aquifers hold high amounts of salts or dangerous minerals. Both climate and geology (and its shared history) can affect salinity (Figure 5, left). Another quality risk for drinking water is fluoride (Figure 5, right). Groundwater quality is also affected by anthropogenic pollution, which will be discussed further under the groundwater vulnerability topic below and in chapter 2.4.

- **Vulnerability**: how vulnerable is an aquifer to pollution?

The vulnerability of an aquifer is mostly related to whether it is confined or unconfined. A confined aquifer is both underlain and overlain by an impermeable layer. The impermeable top layer makes it insusceptible to pollution from the surface. At the same time, aquifer recharge by infiltrating rainfall is very limited, though these aquifers can be recharged through regional groundwater flow. An unconfined aquifer, on the other hand, lacks an impermeable top layer, while it tends to be shallower and receive more direct recharge. This generally makes them more sustainable for prolonged periods of abstraction, but also more susceptible to pollution. Other characteristics that are related to vulnerability include the depth of the aquifer, hydrogeology, topography, and recharge. Figure 8 shows the vulnerability of aquifers for the African continent. The patterns in this figure are similar to the patterns of recharge (Figure 6) and depth to groundwater (Figure 7), with generally lower vulnerability where aquifers are deep and recharge is low, and higher vulnerability where aquifers are shallow and recharge is high.

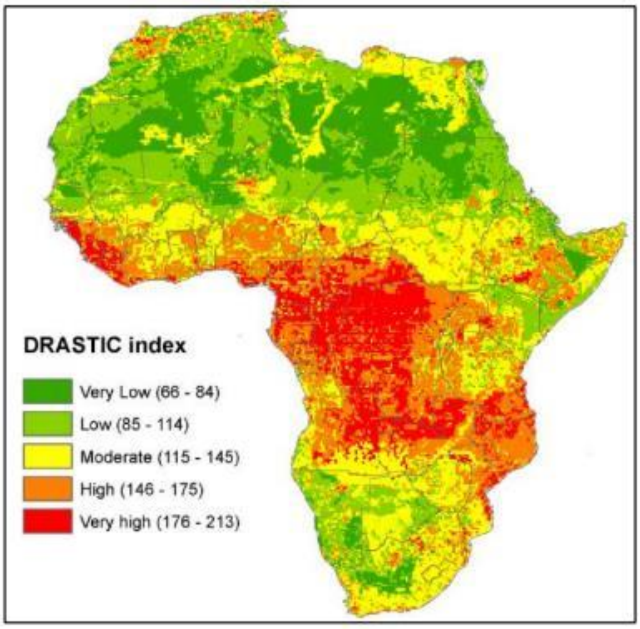

Figure 8. Natural vulnerability of aquifers based on the DRASTIC index (from Ouedraogo et al, 2016).

2.1.2 Surface water-groundwater interactions

Surface and groundwater resources are typically connected, and should, therefore, be considered as a single system. Though an elaborate analysis of surface water-groundwater interactions is outside the scope of this study, a few important implications will be highlighted here.

Firstly, groundwater is derived from rainfall, but the source areas may be located a large distance from where groundwater is abstracted for use. Changes to land cover and land use in the recharge zones can significantly impact the quality and quantity of the surface water-groundwater system, and should therefore be considered in groundwater management. The protection of recharge areas is a necessity towards more sustainable use of groundwater resources.

Secondly, groundwater can lose water to streams and rivers, or be replenished by surface water resources, depending on the season, location, and other system characteristics. Changes to groundwater levels in upstream locations, either as a result of changes in groundwater recharge, groundwater abstractions (de Graaf et al. 2019), or other influences, can therefore negatively impact baseflow in downstream locations. In the same way, groundwater-dependent ecosystems including wetlands can be impacted by changes in groundwater levels and flow. Where surface water recharges groundwater, changes to surface water regimes as a result of changing climate, land use, or flow regulation can impact groundwater recharge. In addition, an increase in impermeable or poorly permeable surfaces may negatively impact groundwater recharge. At the same time, slowing or storing surface water can positively impact groundwater availability.

The interactions between surface water and groundwater and the dependencies between source and abstraction areas imply that sustainable groundwater development must employ a system approach. In other words, management of the landscape, surface water resources, and groundwater resources must be integrated to achieve sustainable use of resources.

2.1.3 Groundwater in African drylands

Considering these aquifer characteristics, let's take a closer look at groundwater in the African drylands (Figure 1). Comparing the drylands with the geological map (Figure 2), it becomes clear that all kinds of geology exist in the drylands of Africa. The least prevalent geology type is volcanic. Basement rock and all kinds of sedimentary rock are the most abundant geology. And since many aquifer characteristics are related to the geology, the aquifer characteristics in African drylands are highly variable: aquifers with high and low storage, high productivity and low productivity can be found.

Clearer links can be established between depth to groundwater and recharge: groundwater tends to be deep and recharge low in drylands (both related to low amount of rainfall with high amount of evaporation). Also, the links with quality are clearer: all identified areas with salinity issues are located in drylands and are related to high evaporation rates in drylands and potential saline intrusion along coasts. Other types of quality issues tend to be more related to geology or human activity, however, and thus are not specific for drylands. The vulnerability index (Figure 8) shows that aquifers in drylands are relativity resilient. This is because of the low recharge rates and lower population densities.

2.2 Groundwater use

This chapter focuses on groundwater use: how can groundwater be made available for use (abstraction methods), and how is groundwater used in the African drylands. The amount of groundwater available for use depends on a number of factors, including the physical characteristics described in the previous section, but also potential interference of other existing wells nearby.

2.2.1 Abstraction methods

Except for springs, groundwater is never freely obtainable and usually infrastructure is needed to get to the water. The most important components are the type of well and the type of pump. Which well and pump are chosen depends on aquifer characteristics including geology, depth, costs, intended use, among others. Typical groundwater abstraction methods and use types for different types of groundwater resources are shown in Table 2.

Table 2. Overview of groundwater resources and use types in African drylands

Source type	Drinking	Livestock	Agriculture	Commercial
Springs	Yes	Yes	Limited for small-scale irrigation	Yes
Shallow groundwater	Dug wells, drilled wells and hand pumps	Yes	Small-scale irrigation	Yes
Deep groundwater	Drilled wells and motorized pumps	If only resource	If financially feasible	If financially feasible

Wells

Groundwater is obtained through a well, basically a vertical hole into the ground. There are two basic ways to create a well: digging (hand-dug wells) and drilling (boreholes). The costs of groundwater development are largely determined by the depth of the groundwater extraction. Shallow wells are less expensive to drill and require less sophisticated drilling technology. After installation, these types of wells are also cheaper to maintain and operate, especially when supplied with a hand pump.

Hand-dug wells

Hand-dug wells (Figure 9) are excavations, large enough in diameter to accommodate one or more people with shovels, dug down to below the water table. Until recent centuries, all wells were hand-dug, and many communities across Africa are still reliant on hand-dug wells.

Figure 9. A hand-dug well lined with crop residue and wooden poles

Advantages:

- Low-cost (only requires manual labor)
- Low-tech (only requires shovels and lining material)
- Almost always tapping into renewable groundwater resources (shallow groundwater)

Disadvantages:

- Not feasible everywhere (areas with shallow hard rock)
- Time-consuming
- Limited depth (typically <20m)
- Can only exploit shallow unconfined aquifers, thus liable to fluctuations and contamination

Boreholes

Boreholes (Figure 10) are long vertical or horizontal excavations of small diameter bored into the earth to obtain water and can be drilled manually or mechanically. These days, most wells across Africa are installed as drilled boreholes. The technology allows for much faster and deeper drilling. An overview of typical specifications for boreholes depending on the depth and scale of abstraction is shown in Table 3Advantages:

Figure 10. Drilling of a borehole

- Can go much deeper (typically 50-150m), and thus can tap a wider range of aquifers
- Relatively fast (how many days does it usually take to drill a borehole?)
- Possible in most areas

Disadvantages:

- Relatively expensive (costs vary considerably, depending on technology, depth, national/local economy, and more)
- Requires drilling equipment
- Requires hydrogeological understanding for proper siting
- Requires maintenance
- Depending on geology, the failure rate can be high (number of drilled boreholes that are dry will be higher in basement rock than sedimentary rock)

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- Requires maintenance
- Depending on geology, the failure rate can be high (number of drilled boreholes that are dry will be higher in basement rock than sedimentary rock)

Table 3. Overview of borehole types, typical characteristics, and costs. Costs of siting, land acquisition and unsuccessful drilling are not included (from Tuinhof et al. 2011)

Type of well	Depth, diameter and yield range	Construction detail	Total cost (USD)
Shallow boreholes for domestic and village water supply	• 20–50 m depth • 100–150 mm diameter • 0.1–0.5 l/s yield	• Plastic lining and part unlined • Hand pump	3,000–5,000
Deeper boreholes for village and small-town water supply or minor irrigation	• 50–150 m depth • 100–250 mm diameter • 1–10 l/s yield	• Pvc or steel lining • Electric or diesel-engined pump	15,000–25,000
Deep boreholes for urban water utilities (public), industrial use or large-scale irrigation (private)	• 150–250 m depth • 200–400 mm diameter • 20–100 l/s yield	• Purpose-designed • High capacity submersible pump	25,000–100,000+

Pump types

Water abstraction not only requires an excavation, but it also needs to be fitted with some sort of water delivery system (Figure 11). Except for an artesian well from which water flows under natural pressure without pumping. Generally, pumps are the most used water delivery system, although more primitive mechanisms exist and are used throughout Africa.

Scooping

The most straightforward way of getting water from a well is through scooping: manually obtaining the water. Mostly this can be done by wells with very high water tables (scoop holes) or in shallow wells with room for a person to descent. This technique is only used for hand-dug wells and is mostly used if there is no other technology available. Vulnerability to pollution is high, making groundwater protection surrounding the well essential.

Rope-and-bucket
As the name suggests, this technology revolves around a rope and a bucket: a bucket is attached to a rope, through which the bucket can be lowered into the well and be lifted out of the well filled with water. Ideally, the rope is attached to a small (wooden) structure built above well, holding the bucket in the middle of the well. While still liable to contamination, rope-and-bucket systems can be protected much better than scoop holes. Breakdowns are regular but are generally easily fixed.

Figure 11. From left to right: (1) Scoop hole; (2) Hand pump; (3) Motorized pump in hand-dug well.

Hand pump
A hand pump uses human power and mechanical advantage to pump up water. While it still requires manual labor, it is much more efficient than scooping or using a rope. The simplest type can pump up water from up to 7 meters, with a yield between 1-3 m^3/d. More advanced technology can go twice as deep or deeper and outputs up to 5 m^3/d. Hand pumps can be completely protected from contamination as well. Maintenance requires more parts and technical skills than scooping, but can easily be managed by the local community. Hand pumps typically cost a few hundred USD.

Motorized pump
With motorized pumps, the water delivery system is completely mechanical and makes use of a power source to pump water to the surface. In Africa, the most common motorized pump is the diesel pump. While they cost the most to install (typically 500-1,000 USD), they also produce much more water: fitted on a well-placed borehole, they can produce up to 300 m^3/d or more. Boreholes can only be operated by a motorized pump, but hand-dug wells can also be fitted with one. Operation and maintenance can be a major challenge for boreholes, however. Firstly, operation costs can be very high, depending on local prices of fuel. Secondly, when left managed by local communities they tend to fall into disuse after a breakdown due to lack of maintenance know-how.

Another type of motorized pump is a solar pump. While they are more costly than fuel-run pumps, they do not require any operating costs, making them often a better option in the long run when they are properly maintained. This type is becoming increasingly popular for shallow groundwater for small-scale irrigation. Another area of high potential is to use solar pumps to abstract deep groundwater where energy costs would otherwise inhibit its use.

2.2.2 Use in African drylands

Water is used for different purposes in different places, either for domestic use, agricultural use (irrigation), livestock or industrial use. When developed, agricultural use can account for the largest portion of water. At the same time, domestic use arguably has the highest priority. Conflicts can arise between users when water is scarce and/or when access to water is not equal. In this chapter, a closer look is taken at what groundwater is used for in the drylands of Africa.

Domestic

Most of the abstracted groundwater in Africa is used for domestic purposes; in fact, groundwater is the main source of domestic water for most people in Africa, especially in the dry season, especially for rural (see Table 4) but also for urban populations. Most groundwater is abstracted directly by users from low yielding, relatively shallow (usually less than 50 m deep) boreholes or hand-dug wells, usually with hand pumps. Deeper, higher-yielding boreholes are less common but are used in many urban areas to provide piped municipal water supplies, usually with electric (increasingly solar-powered) or hydrocarbon pumps (Earthwise, 2019).

Table 4. Population in rural/small towns served by groundwater in specific countries across the drylands of Africa (Pavelic et al. 2014)

Country	Population in rural/small towns served by groundwater (%)
Niger	92
Nigeria	70
Mali	55
Zambia	51
Zimbabwe	70
Mozambique	60
South Africa	60
Ethiopia	85
Kenya	50
Somalia	70
Tanzania	56

Irrigation

Agriculture is the largest user of water in Africa: 86% of all water withdrawals is used for agriculture (Frenken, 2005). Only about 1% of this land is irrigated using groundwater, however (and most of that restricted to North Africa, especially Egypt), compared to about 14% in Asia (Altchenko and Vilholth 2015). Some of these use fossil groundwater resources (such as in North Africa). However, across most of sub-Saharan Africa and the African drylands, the most common irrigation practice is small-scale and informal for only a few fields using relatively low-cost technologies (Earthwise, 2019).

In Figure 12, potential of groundwater for irrigation is illustrated for the African continent. As can be seen, even though the highest potential is in the humid regions, the potential for irrigation in the drylands is significant. The important exception is hyper-arid regions, which typically have high storage but very low recharge (Figure 3).

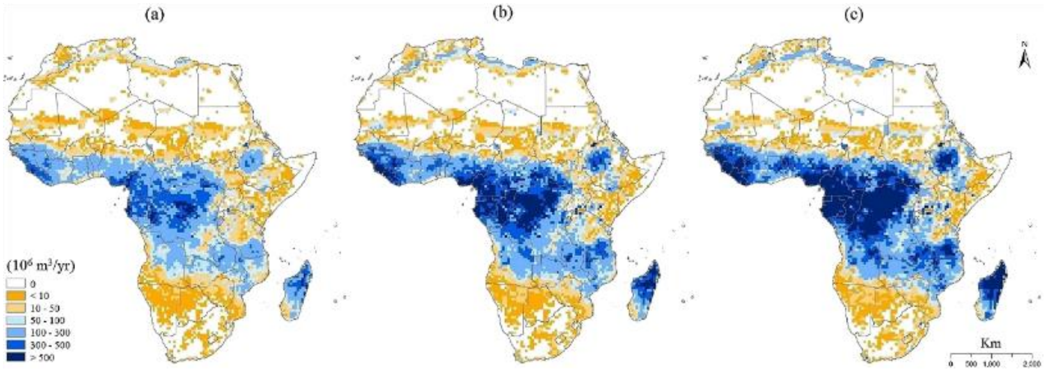


Figure 12. Potential of groundwater use for irrigation across Africa for various levels of environmental groundwater requirements as a percentage of recharge (a: 70%; b: 50%; c: 30%) (from Altchenko and Vilholth 2015).

Other uses

Next to domestic use and irrigation, the largest user of water in the drylands of Africa is livestock. In general, livestock watering is sourced from surface water. Cases of groundwater use for livestock are mostly limited to severe droughts, high-yield boreholes, or in seasonal aquifers (through scoop holes in sandy rivers).
As livestock is less affected by the generally lower quality of surface water than humans are and livestock is very mobile (unlike agriculture), groundwater use for livestock is generally recommended only when surface water is not available.

The fourth major use of water in Africa is industry. Industry is relatively underdeveloped in Africa and as such only uses a small proportion of the total water use, about 4% of total water withdrawals (Frenken, 2005). Of this 4%, over half takes place in Northern Africa. Again, this use is however mostly from surface water resources (especially the Nile, being the major source of water for Egypt and Egypt accounting for 73% of the water use in North Africa (Frenken, 2005). Though these numbers are somewhat dated and industry is generally on the rise in Africa, it can be safely assumed that even now only a minor portion of groundwater is used for industrial purposes.

2.3 Groundwater management

2.3.1 Management framework

As a hidden resource, groundwater management and governance are innately challenging. Indeed, while surface water management is increasingly common, groundwater management is easily and often forgotten or neglected. Even so, proper management is a key element in ensuring sustainable groundwater use.

It is widely considered the responsibility of the government to manage and protect water resources. Even so, other partners should be involved in the institutional framework, including non-governmental organizations and groundwater users. An example of a desirable institutional framework is shown in Figure 13.

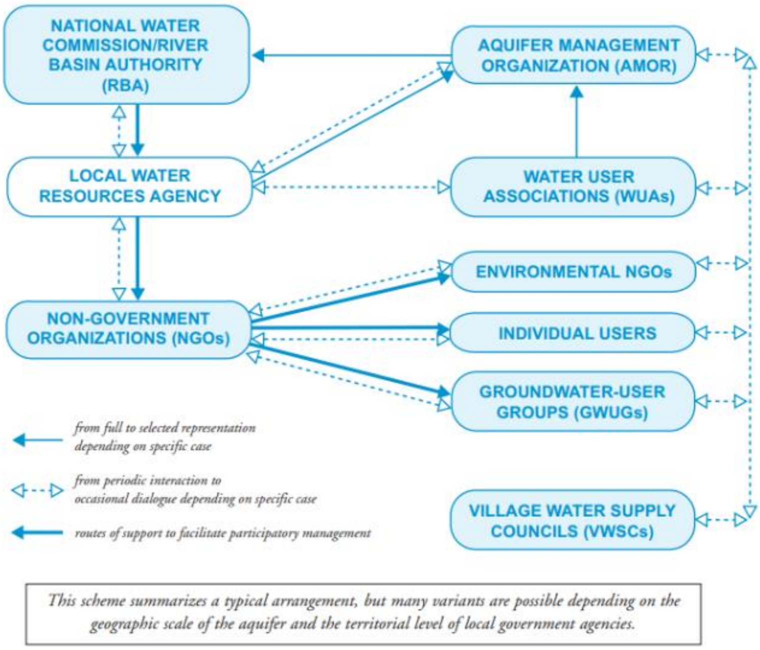


Figure 13. Example of a desirable institutional interaction in participatory groundwater resource management (from Garduño et al. 2010).

In Figure 13, a governmental authority ensures functionality at the national or regional level. Local water resource agencies as subsidiaries then ensure functionality on local (sub-catchment) level. Both of these institutions may focus on water resources in general. Additionally, where significant aquifers exist, a separate aquifer management organization may be more appropriate (especially in transboundary settings). Importantly, both the aquifer management organization and the local water resources agency interact with Water User Associations, which represent the users' interest. Only by having regular, direct dialogue with user groups and management organizations can all interests be safeguarded: this is called participatory water management.

However, in practice, there are also the so-called ‘fragile states' where no institutions are in place to access or manage groundwater resources. Often, and especially in rural areas, access is provided by NGOs and management by the communities. An example of this setting occurs in the Central Africa Republic, whereas NGOs work with local institutions to strengthen national objectives and generate adaptative service delivery models for access to water through groundwater abstraction. In other cases, groundwater is managed at local level by strong community values and norms without formalized groundwater user associations or the initiative of a water resource regulatory agency. Though there are cases where groundwater management in this manner is successful, in general, strong institutions are necessary to properly manage groundwater resources.

2.3.2 Groundwater monitoring

A vital part of groundwater management is monitoring the resource. Unlike surface water, the state of a groundwater resource is not directly visible. Without some measure of the state of your resource however, it will always be in danger of over-abstraction (see chapter 2.4.1). Therefore, monitoring boreholes should always be part of an aquifer management strategy. Monitoring boreholes are similar to regular boreholes, except they are not used for abstraction, they are purely used for monitoring the water levels in an aquifer. This way, over-abstraction can quickly be detected, groundwater use can be adjusted and depletion can be prevented.

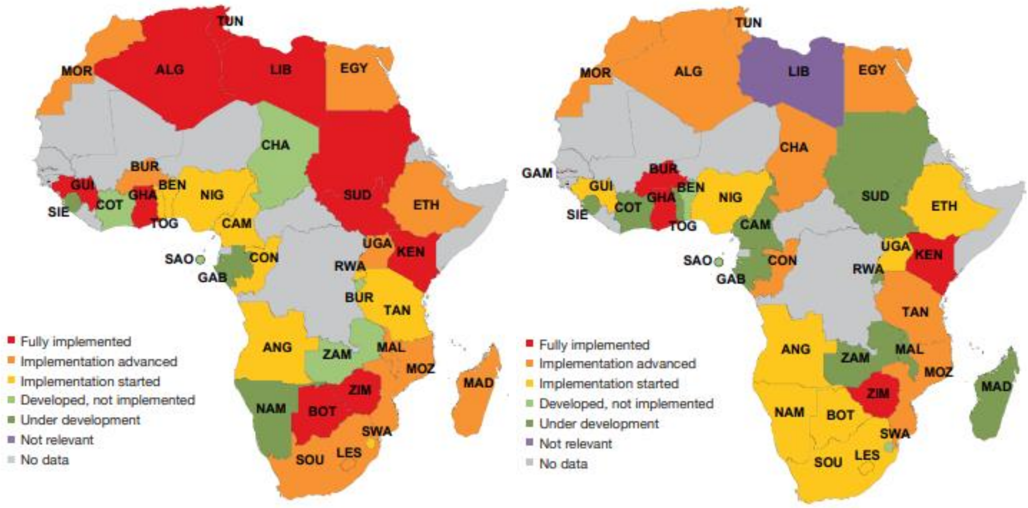


Figure 14. Water law development stage in Africa (left) and decentralized management of water resources (right; from AMCOW 2012).

2.3.3 Institutions and policies in African drylands

Most African countries have official institutions for water resource management with official policies. Figure 14 (left) shows a map of the development stage of water law in 2012, which indicates that the majority of countries were in an advanced stage of implementation or completed. However, such institutions, laws, and policies are generally more developed for surface water resources than groundwater. Moreover, while many countries are working on decentralized management of water resources, most still operate at a national level (Figure 14, right). Most groundwater resources are local and need local attention to be managed properly.

2.4 Threats and challenges

Groundwater resources face a number of challenges that threaten sustainable use of this resource now and in the future. The main challenges threatening groundwater resources are over-exploitation, anthropogenic pollution, population growth, climate change, a lack of understanding about the importance of groundwater, and institutional challenges. In the final sub-section, the three top challenges that must be overcome to achieve sustainable groundwater development are highlighted.

2.4.1 Over-abstraction and depletion

Over-abstraction occurs when groundwater abstraction rates are higher than average recharge rates. Depletion refers to the situation in which water resources dwindle to a fraction of their former volume as a result of a prolonged period of over-exploitation. At present, there are many aquifers in Africa where abstraction rates exceed recharge and are therefore considered to be over-exploited. Satellite data supports the anecdotal evidence and identifies other large aquifers where storage is steadily declining (Figure 15). Similarly, a study linking groundwater withdrawals to groundwater level drops and reductions in groundwater contribution to streamflow found that environmental flows have already been reached in some areas as a result of over-exploitation, and environmental flow in many more areas will be threatened by 2050 (Figure 15, de Graaf et al. 2019). The interaction between surface water and groundwater (paragraph 2.1.2) is important to understand the downstream effects of groundwater (over-)abstraction.

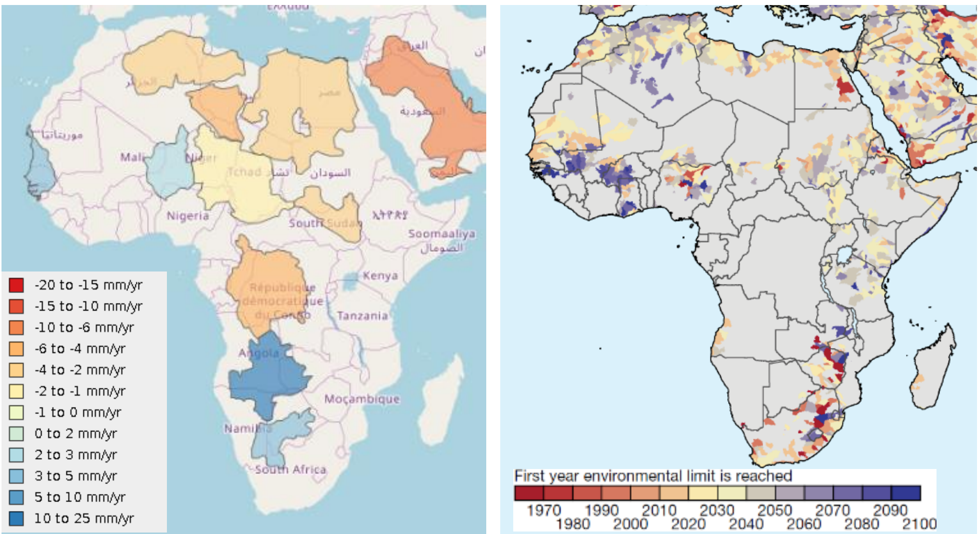


Figure 15. Over-exploitation based on satellite data (negative values in the left figure) and based on the year at which environmental flow limits have been or will be reached (right, from de Graaf et al. 2019).

Specifically for agriculture, over-abstraction is always a risk as abstraction tends to be maximized when used for irrigation. In Figure 12, the potential of groundwater use for irrigation was highlighted. In Figure 16, current groundwater use for irrigation is set against this potential. As can be seen, in many areas over-abstraction for irrigation is already taking place according to this analysis (Altchenko and Villholth 2015). The areas where over-abstraction is identified in the figure are generally similar to the over-abstraction of large aquifers measured by GRACE (Figure 15) and anecdotal evidence.

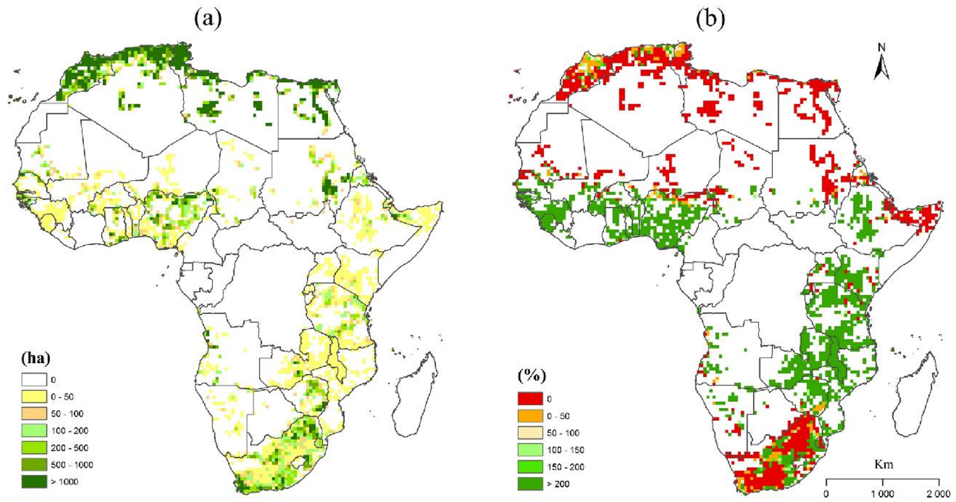


Figure 16. Area used for groundwater in ha per cell (a) and potential as a percentage of use where red colors depict over-abstraction (b) (from Altchenko & Villholth 2015).

2.4.2 Groundwater pollution

Increasingly, groundwater pollution is a threat to groundwater resources. In many cases, groundwater pollution is a result of human activity (though natural sources of pollution are also possible, for example, a volcanic eruption). Groundwater pollution from anthropogenic sources is related to all sectors of human activity. Industrial use can cause leaching of heavy metals into groundwater, agricultural activities can lead to high nitrate levels or salinization, poor sanitation infrastructure and insufficient waste management may cause biological contamination, et cetera. These contaminants can pose a health risk when water is not treated before use.

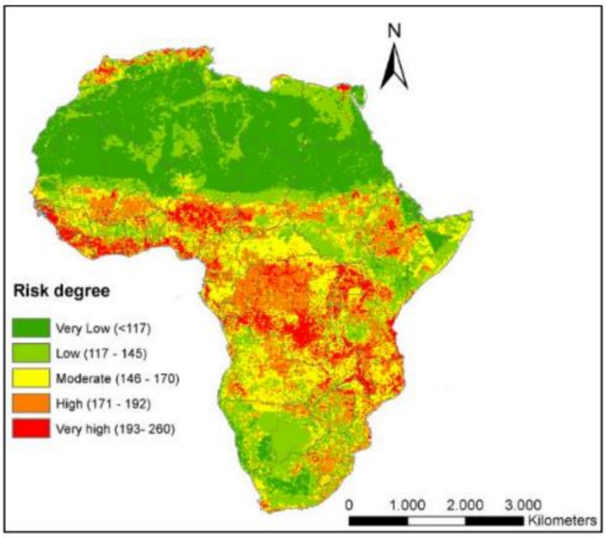


Figure 17. Risk of groundwater contamination for Africa (from Ouedraogo et al, 2016)

The risk of groundwater pollution is a combination of the vulnerability of the aquifer (see chapter 2.1.1) and human activity. Both aspects are combined into a groundwater contamination risk map for Africa in Figure 17.

2.4.3 Rapid population growth and economic development

The population is growing faster in Africa than anywhere else in the world, with predicted increases for certain countries of over 180% in the next 21 years (Figure 18). Such rapid population growth and further economic development result in higher water and food demand, increasing pressure on all water resources (both quantity and quality). Considering that groundwater is the main source of water for the majority of the population in the African drylands, groundwater resources are especially vulnerable, while many aquifers are already overexploited (see chapter 2.4.1). An indirect effect of population growth is an increased risk of contamination of groundwater resources as a result of poor sanitation infrastructure and insufficient waste management, adding to existing problems as mentioned in chapter 2.4.2.

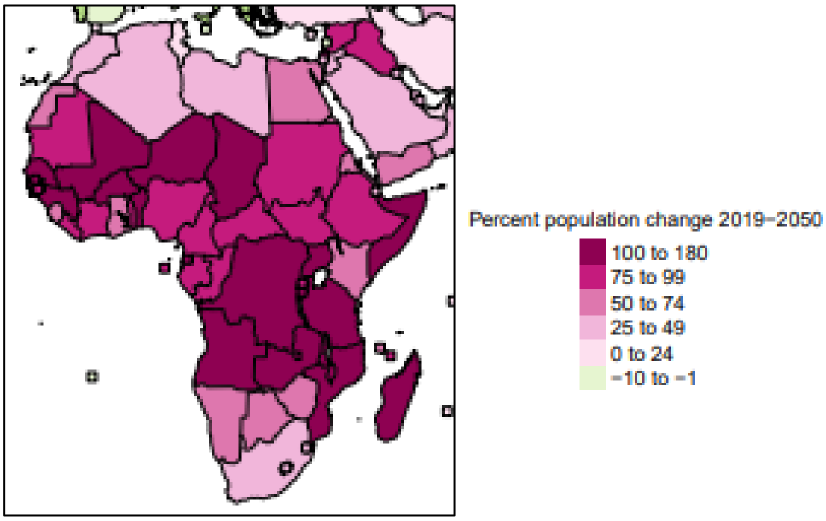


Figure 18. Population growth between 2019 and 2050 in African countries (source: UN 2019b).

2.4.4 Climate change

Climate change is complicating the picture even further. Figure 19 shows both observed and projected climate change figures from an ensemble simulation (CMIP5) for the whole of Africa (Niang et al, 2014). Over most of Africa, temperatures have increased by 0.5 ˚C or more during the last 50-100 years, with minimum temperatures warming more rapidly than maximum temperatures. Moreover, temperatures are predicted to increase further. Low estimates (RCP2.6) predict a mean temperature increase of 0.5-1 ˚C for the most of Africa in the 21st century, while high estimates (RCP8.5) predict mean temperatures to exceed 2 ˚C in the mid 21st century and exceed 4 ˚C in the late 21st century for most of Africa. An increase in average temperature will cause higher evaporation rates in surface water reservoirs and likely lower recharge rates to aquifers.

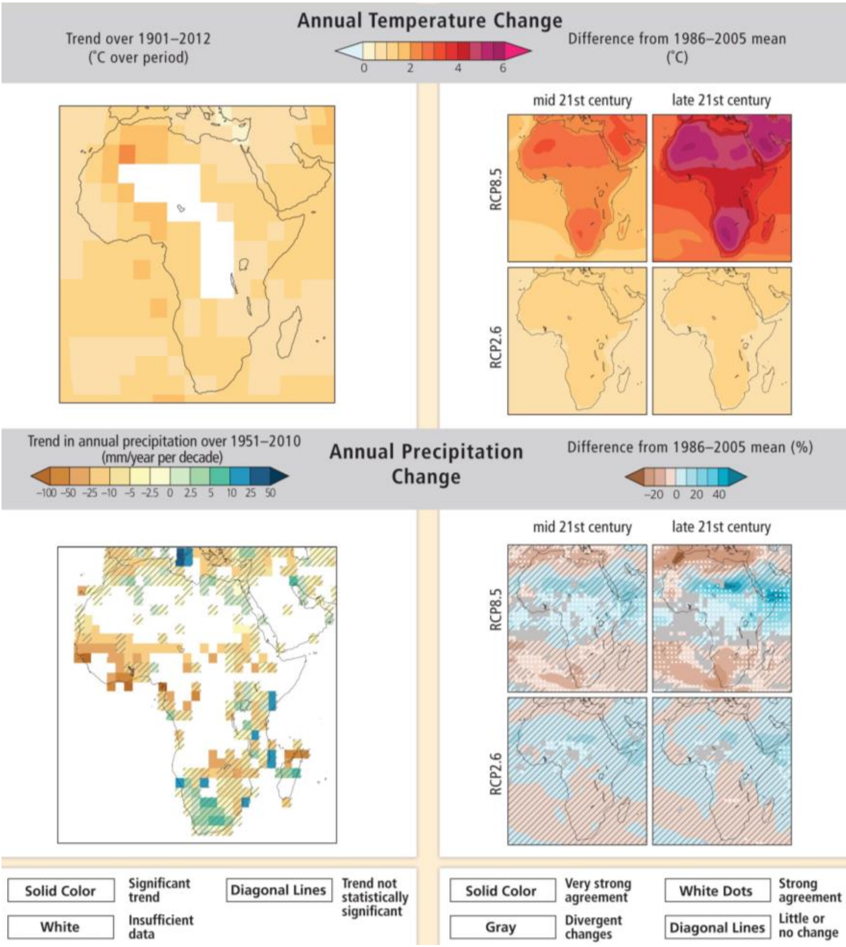


Figure 19. Observed and projected change in annual average temperature and precipitation from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble (Niang et al, 2014)

Based on available data, precipitation has decreased over the past century in the western and eastern Sahel, while it has increased over parts of eastern and southern Africa (Figure 19). The CMIP5 ensemble simulation meanwhile predicts precipitation to increase actoss central and eastern Africa and to decrease in southern Africa and coastal northern and western Africa. So precipitation will decrease and increase for different parts of Africa. An increase will most likely have positive effects on groundwater (more recharge), while a decrease in rainfall would cause a decrease in. The occurrence of extreme events, however, is predicted to increase for most of Africa (Niang et al, 2014). More extreme events will increase flooding risk, but also increase the frequency and severity of droughts. More frequent flooding increases risks to groundwater quality, as overflowing latrines and surface flows can transport contaminants to the groundwater. Higher drought frequency will result in lower surface water availability and may also lead to higher water demand, leading to higher groundwater withdrawals and increased aquifer stress.

2.4.5 Lack of understanding and awareness

Despite the importance of groundwater, groundwater management is often neglected, especially in African drylands. Often, the population is fully dependent on (ground)water resources for their livelihood, but there is little awareness of the need for protection of recharge areas and (ground)water management. The core reason for this is a lack of understanding due to the invisibility of groundwater. For surface water, it is mostly clear where it comes from, where it may collect and where it flows towards.

More importantly, it is relatively easy to see how large the resource is, and it is directly noticeable when the resource quickly diminishes. With groundwater, the invisible water beneath our feet, this is not the case. With the naked eye, it is unclear where the water comes from, it is unknown how large the resource is, and depletion is not directly visible. Crucially, this lack of visibility and understanding does not result in more careful handling of the resource. Instead, the exact opposite tends to happen: people assume that there is plenty of groundwater available and extract without any consideration for sustainability. This makes groundwater management an often-underrated aspect of water management. Therefore, it is crucial to raise awareness with all stakeholders, including agricultural, domestic, industrial, and environmental land and water users.

Table 5. Groundwater and surface water dimensions for management (from Tuinhof and Heederik 2003)

Feature	Groundwater resources	Surface water resources
Hydrological Characteristics		
Storage Volumes	very large	small to moderate
Resource Areas	relatively unrestricted	restricted to water bodies
Flow Velocities	very low	moderate to high
Residence Times	generally decades/centuries	mainly weeks/months
Drought Propensity	generally low	generally high
Evaporation Losses	low and localized	high for reservoirs
Resource Evaluation	high cost and significant uncertainty	lower cost and often less uncertainty
Abstraction Impacts	delayed and dispersed	immediate
Natural Quality	generally (but not always) high	variable
Pollution Vulnerability	variable natural protection	largely unprotected
Pollution Persistence	often extreme	mainly transitory
Socio-Economic Factors		
Public Perception	mythical, unpredictable	aesthetic, predictable
Development Cost	generally modest	often high
Development Risk	less than often perceived	more than often assumed
Style of Development	mixed public and private	largely public

Groundwater management faces several challenges compared to surface water management due to differences in hydrological and socio-economic characteristics (**Fout! Verwijzingsbron niet gevonden.**). Surface water flows relatively rapidly, while groundwater moves through permeable strata at relatively slow rates. Tens, hundreds or even thousands of years may pass between initial recharge and abstraction or discharge. This means that groundwater is less vulnerable to droughts and floods, but also takes longer to recover from over-exploitation. This is just one example of the difference in dimensions of surface and groundwater, which also differ in evaporation rates, quality, pollution, perception, and development. This means that the management of groundwater requires a different approach from surface water. In order to properly manage groundwater, these dimensions need to be understood at least at a basic level. Despite the differences in the characteristics and therefore management approach of surface and groundwater, sustainable groundwater development is much more likely to

be successful if water resources are managed as a whole instead rather than as separate entities.
In groundwater management, it is essential to understand the aquifer system, how it interacts with the larger water system, and how abstraction can negatively impact both (like abstraction effects and recharge reduction effects). At the same time, monitoring is mostly still lacking in many areas despite the fact that it is a vital tool to develop the understanding needed for effective resource management. On the groundwater demand management side, it is also essential to realize that social development goals greatly influence water use, especially where agricultural irrigation and food production are concerned. Meanwhile, regulatory interventions (such as water rights or permits) and economic tools (such as abstraction tariffs and tradable water rights) are often more seen as a way for direct income instead of a means to regulate the resource.
Groundwater management can only be fully effective if cross-level and cross-sector coordination occurs.

A lack of expertise is not limited to groundwater management institutions but is also relevant for parties involved with the evaluation and development of groundwater, particularly in rural areas. Knowledge about proper siting and well development minimizes costs spent on constructing unsuccessful or unreliable wells, especially when deep groundwater is considered. In addition, water quality issues including well contamination can be avoided. Finally, groundwater development should evaluate which aquifer resources is best suited to the needs of water users. This is needed to avoid situations in which shallow groundwater wells tapping aquifers that are replenished regularly are shunned in favor of deep groundwater wells tapping aquifers that are replenished much more slowly, even though the water quality of the shallow aquifer is sufficient for the desired purpose.

2.4.6 Institutional challenges

Due to its lack of surface visibility (as discussed in the previous chapter), calls for groundwater management do not usually arise until a decline in well yields and/or quality affects one of the stakeholder groups. If further uncontrolled pumping is allowed, a 'vicious circle' may develop (Figure 20) and threaten the resource, for example through serious groundwater level decline, saline intrusion or land subsidence. To transform this 'vicious circle' into a 'virtuous circle' it is essential to recognize that managing groundwater is as much about managing people (water and land users) as it is about managing water (aquifer resources). Or, in other words, that the socio-economic dimension (demand-side management) is as important as the hydrogeological dimension (supply-side management) and integration of both is always required.

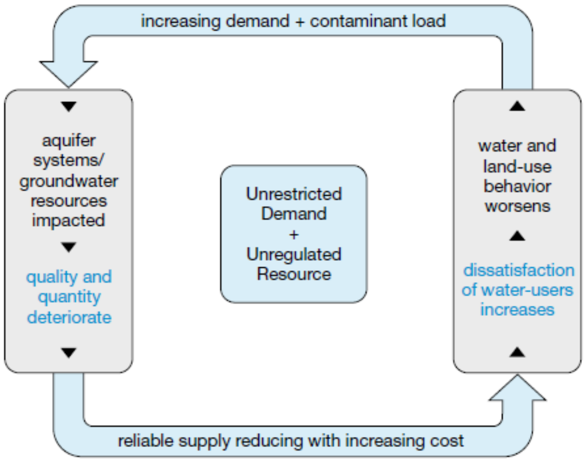


Figure 20. Supply-driven groundwater development - leading to a vicious cycle

Another institutional challenge is the limited scale (both temporal and spatial) in which groundwater managers and policymakers often think, especially at local level. For instance, district water officers typically think about the groundwater demand/availability in their 'zone of influence', often neglecting the fact that upstream has an impact on downstream. Comparable attitudes are prevalent in transboundary systems. The limited scale also applies to time, as short term benefits often overtake long term disadvantages because of the institutional system. Officials are often responsible for terms spanning a handful of years, during which the effect of certain actions in larger groundwater systems is often not visible.

Furthermore, weak law enforcement and low institutional capacity threaten the sustainable use of groundwater resources. Frequently, there is a lack of groundwater-specific legislation. Even when present, the lack of enforcement of existing policies and legislation increases the occurrence and thereby the impact of illegal overexploitation of groundwater resources and the degradation and pollution of recharge areas. Proper enforcement of existing laws is needed at all institutional levels, which extends to ensuring that international, national, and regional policies are accommodated at local level.

A final institutional challenge is inadequate funding opportunities for groundwater development and protection projects. Investments in groundwater resources are much smaller than for surface water resources, while groundwater accounts for most of the globally available freshwater. Though this is a common claim among groundwater experts, data about global or regional investments are scarce. Furthermore, funding for groundwater development and evaluation projects has not necessarily been increasing. In some countries, a trend towards block funding rather than financing specific water-related projects combined with the lack of awareness has even led to a reduction of funds for groundwater. Realizing funding for the small-scale types of measures that are especially effective in rural regions is further challenged by the fact that most funding organizations are biased towards large-scale projects.

Other observed issues with groundwater management across Africa include:

- Both hydrogeologic and socio-economic conditions tend to be quite location-specific. This makes comping up with a simple blueprint for integrated groundwater management impossible;

- The capacity to comply with all these considerations is severely lacking, both among water resource authorities and water users;
- Non-integrated management, which lacks comprehension of the relationship between groundwater and surface water, its limitations and strengths.

2.4.7 Main challenges towards groundwater development

Of the challenges and threats discussed in the previous sections, rapid population growth and economic development (chapter 2.4.1) and climate change (chapter 2.4.2) are the main pressures on groundwater resources, in terms of both quantity and quality. These exacerbate the issues of overexploitation of groundwater (chapter 0) and groundwater pollution (chapter 2.4.4). Three of the challenges mentioned in the previous sections are considered to be the main obstacles towards addressing or mitigating these threats, and thus the main challenges towards the sustainable development of groundwater resources.

The main challenges are:

- lack of knowledge about the groundwater system and awareness of its importance (see chapter 2.4.5),
- local lack of groundwater expertise (see chapter 2.4.5), and
- funding issues (see chapter 2.4.6).

2.5 Representative landscapes

The physical characteristics, abstraction infrastructure and groundwater use types are often interlinked. Therefore, these should be considered together when developing sustainability strategies for a particular location. African drylands have been categorized into landscape types to facilitate the development of sustainability strategies. The landscape types are primarily based on the hydrogeological environment and whether a rural or urban area is considered. Rural environments are further classified by the aquifer recharge rate and urban environments by population. Together, these distinctions form a classification with ten aquifer types (Table 6).

The African drylands have been classified into the representative landscape types in Figure 21. The hydrogeological environment is defined by aquifer productivity (MacDonald et al. 2012), where low productivities are assumed to be representative of basement rock environments and high productivities of sedimentary and volcanic rock environments. The area is further classified by recharge (MacDonald et al. 2012), with urban centers of different sizes overlying the map. Low recharge areas are found primarily in North African and southwestern Africa. High recharge environments are concentrated around central Africa, with intermediate recharge amounts between the two extremes. Low productivities are primarily located in eastern and southern Africa, though there are scattered pockets in northern Africa as well. The density of urban centers is relatively low in the low recharge environments compared to the high recharge environments, especially when considering the large urban centers with more than one million inhabitants.

Note that the classification as shown in Figure 21 is based on the bedrock type and other two-dimensional data, while aquifer systems are three-dimensional. This means that aquifers with different hydrogeological and recharge characteristics may be present on top of each other at the same location. For example, several sedimentary and volcanic rock aquifers can be present on top of the basement rock, and bedrock is usually overlain by a layer of unconsolidated (loose) sediments which may be up to hundreds of meters thick (for example in North Africa). If permeable, these unconsolidated sediments can form good aquifers, but generally are of shallow depth and limited extent. In fact, these aquifers can be very important for local water availability, especially for rural domestic and agricultural use. In other words, the mapping of the landscapes should be treated as an approximation of regionalization of landscapes only, and the local three-dimensional situation should always be considered in local project development.

2.5.1 Hydrogeological environment

The first classification by hydrogeological environment roughly divides basement rock environments, which typically have low aquifer productivity rates and low aquifer storage, from sedimentary and volcanic rock environments, which are typically characterized by moderate to high productivity rates and moderate to high aquifer storage. Though this relationship between rock type, productivity, and storage is generally true, it is not always clear-cut as represented here.

Nevertheless, this simplification supports a regionalization of groundwater in African drylands. The hydrogeological environment affects groundwater use, and thereby the potential for sustainable development and risk of over-exploitation.

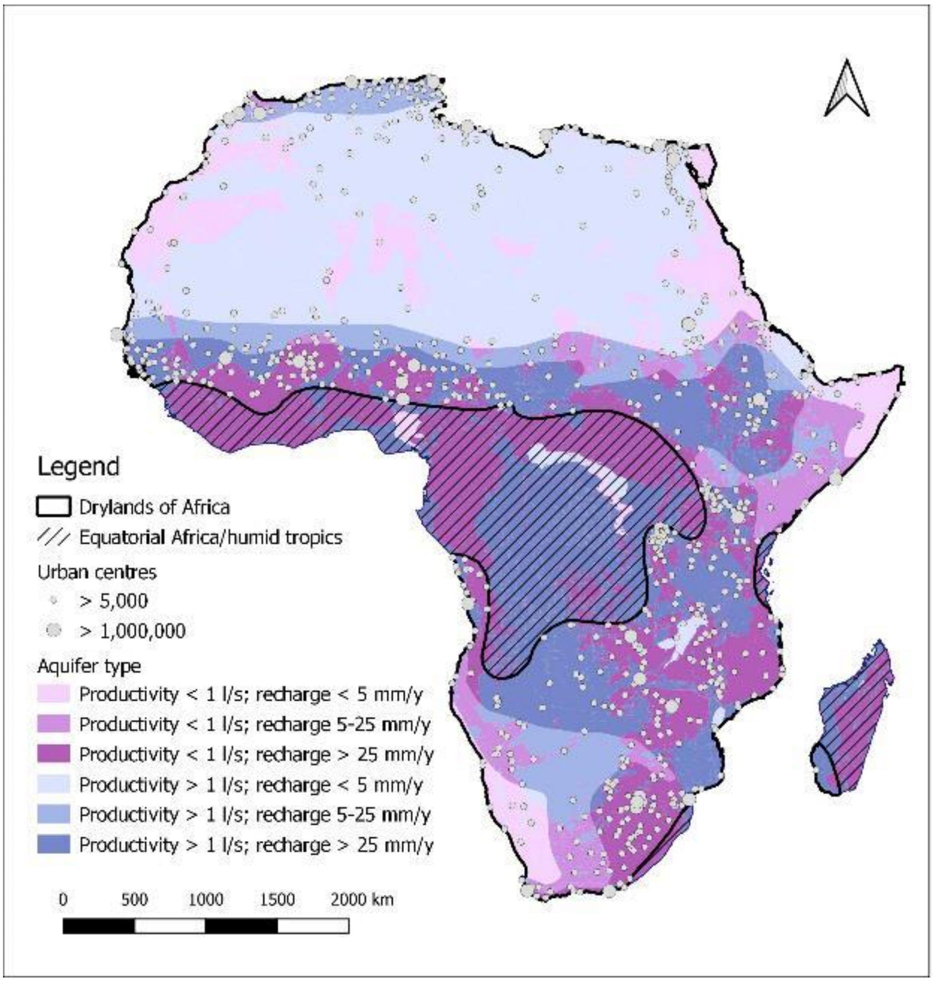


Figure 21. Map of the representative landscape types for the African drylands.

In aquifers with low productivity, a large number of wells is needed to abstract medium to high volumes of water. At the same time, wells need to be adequately spaced to avoid interference between wells, which would otherwise negatively impact well yield. These characteristics, along with relatively high well failure rates, have limitations for the potential scale of groundwater development. Irrigation is only possible at small scales and larger settlements may not be able to rely on groundwater alone as a water source. In basement rock environments, groundwater flow tends to be local and aquifers systems are small in scale. As a result, groundwater levels tend to drop significantly in dry years in areas where recharge is relatively low, meaning that wells in these areas are not very climate-resilient. On the other hand, the small scale of the aquifers also means that negative impacts of over-exploitation are generally local rather than regional.

In environments with high productivity and large storage, a single well can provide a large yield. This makes groundwater development at larger scales more feasible, providing water for more populous settlements and potentially for large-scale irrigation projects. At the same time, groundwater flow in these environments is generally regional, meaning that negative impacts of over-exploitation may be experienced in a larger region.

Table 6. Overview of landscape types based on hydrogeological environment, urban or rural setting, and recharge or population respectively. The overview includes the typical socio-economic conditions and main groundwater issues

Hydrogeol. Environm.	Urban/ rural	Recharge/ population	Socio-economic conditions	Groundwater Issues
Basement rocks Well productivity < 1 l/s Small stored volume	**Rural**	**Recharge < 5 mm/y**	• Hyper-arid • Population density ~0 people/km^2	• No issue
		Recharge 5–25 mm/y	• Population density < 25 people/km^2 • Mainly (agro)pastoral • Non-permanent villages (population 50–500) • Water supply (mainly for livestock) through reservoirs and deep wells	• Remote and low capacity wells • Low drilling success rates • Insufficient O&M facilities • Deep water levels • Wells not climate resilient • Decreasing baseflow of rivers
		Recharge 25–100 mm/y	• Population density > 25 people/km^2 • Mainly rainfed cereal/tuber growing • Permanent villages (population 250–3,000) • Water supply by wells fitted with handpumps	• Groundwater pollution in and around village • Insufficient O&M facilities • Risk of local overexploitation • Ephemeral rivers • Decreasing baseflow of rivers
	Urban	**Population >5,000**	• Piped water systems • Source is surface water or mixed surface/groundwater	• Groundwater pollution • Health risks because of informal wells in non-piped areas
		Population >1,000,000	• Piped water systems • Source is surface water	• Groundwater pollution • Health risks because of informal wells in non-piped areas • Large scale groundwater recovery is generally no option
Sedimentary and volcanic rocks; Well productivity > 1 l/s Large stored volume	**Rural**	**Recharge < 5 mm/y**	• Hyper-arid • Population density ~0 people/km^2 • In some areas high yielding wells possible	• Groundwater recovery is technically possible, but hydrologically not sustainable (mining) • Risk of poor groundwater quality due to high evaporation and saline soils or rock formations (evaporites)
		Recharge 5–25 mm/y	• Population density < 25 people/km2 • Mainly (agro)pastoral • Non-permanent villages (population 50–500)	• Groundwater pollution in and around village • Remote wells and insufficient number • Insufficient O&M facilities • Deep water levels
		Recharge 25–100 mm/y	• Population density > 25 people/km^2 • Mainly rainfed cereal/tuber growing • Permanent villages (population 250–3,000) • Water supply by wells fitted with handpumps	• Groundwater pollution • Insufficient O&M facilities • Risk of local overexploitation
	Urban	**Population >5,000**	• Groundwater supply by well fields	• Groundwater pollution • Health risks because of informal wells in non-piped areas • Risk of over-exploitation in expanding centers
		Population >1,000,000	• Piped water systems • Source is surface water and groundwater	• Groundwater pollution • Health risks because of informal wells in non-piped areas

Groundwater quality is also linked to the hydrogeological environment. Arsenic and fluoride are most common in volcanic rocks. Risk of poor groundwater quality due to saline soils and evaporites, on the other hand, are more common in sedimentary rock environments. In such areas, groundwater may not be suitable for use without treatment.

2.5.2 Rural landscapes

In rural areas, landscapes are further defined based on average annual recharge. The recharge is directly related to sustainability from a hydrological perspective, but also to the livelihoods of the local population and therefore the groundwater use type. The combination of physical and socio-economic characteristics determine the main challenges groundwater resources face.

In hyperarid regions where recharge is very low (<5 mm/year), the population is negligible. In sedimentary and volcanic rock environments, however, large-scale groundwater development is possible, though this use is generally not sustainable from a hydrological perspective. In addition, the depth to groundwater is generally high, which has implications for the costs of groundwater development and abstraction. In basement rock environments where aquifer productivity and storage are low, groundwater development is severely limited by the hydrogeological conditions.

Rural areas with low recharge (5–25 mm/year) are characterized by low population densities. The population tends to be agropastoral and nomadic, meaning that water use is generally for domestic purposes and for livestock watering. The groundwater level tends to be deep, and wells are generally expensive and require more complex operation and maintenance.

The capacity for operation and maintenance can be insufficient in these areas, however. In basement rock environments with low productivity, a combination of wells and reservoirs has the highest potential. There is a higher risk of local overexploitation in these environments, which leads to decreased baseflow in rivers and can ultimately cause river flow to become intermittent. In sedimentary and volcanic rock, the well yield is typically sufficient for small-scale use and reservoirs are not necessary.

Where recharge is somewhat higher (25–100 mm/year), the landscape is typically characterized by permanent villages and the population density is higher. The population mainly cultivate rainfed cereals and tubers. The groundwater tends to be less deep, meaning that water supply by means of hand pumps is more feasible and also more common than in areas where recharge is lower. The higher population density and larger villages, which still may lack adequate sanitation facilities and waste management, make groundwater pollution a more serious threat. In basement rock environments where productivity is low, there is also a risk of local overexploitation as groundwater resources development increases.

2.5.3 Urban landscapes

In urban areas, water is typically distributed through piped systems. In areas with basement rock, a mix of surface and groundwater supply is used. In sedimentary and volcanic rock environments, the water source for smaller towns and cities may be largely groundwater, while large cities with a population over one million typically use a combination of surface and groundwater to supply their needs.

The main challenges in urban areas are groundwater pollution and health risks due to informal wells where the piped water supply has not been developed. The latter is particularly common in urban centers that are growing rapidly. Non-revenue water loss is another challenge in urban centers where water distribution systems are relatively old, typically in the large urban centers. While water leaking from pipes infiltrates into the soil and may replenish shallow groundwater resources, the pollution risk in urban centers makes it likely that the quality of the shallow groundwater renders it unsuitable for use. Overexploitation of groundwater resources is mainly relevant in smaller urban centers in sedimentary and volcanic rock environments that rely heavily on groundwater resources and which may expand rapidly in the future.

3 Sustainability strategies

Unsustainable groundwater use has far-reaching environmental and socio-economic impacts. One of the most important environmental impacts of unsustainable groundwater use is lower base flow. This can result in the loss of wetland and riparian areas, which are hotspots of biodiversity. In addition, it can cause changes in channel morphology, accelerate erosion and increase the risk of drought. Furthermore, unsustainable groundwater use can increase social inequality. Where groundwater levels drop, poorer water users may lose access to the water resources first as abstraction costs increase. Conflict may also arise when overexploitation of water resources by upstream users causes the flow of streams or springs in downstream areas to decrease. Ultimately this can result in intermittent flow or even cause streams and springs to run dry altogether. Finally, pumping groundwater from ever-lower depths costs more energy, which has economic consequences. To limit these effects or avoid them altogether, it is important to develop a sustainability pathway, consisting of a set of effective sustainability strategies.

In general, more sustainable water use from a hydrological point of view can be achieved by interventions from the supply perspective and from the use perspective. Some strategies aim to increase water availability, thereby decreasing pressure on groundwater resources. Others aim to reduce water demand, making water use more efficient, and thereby increasing sustainability from a quantitative hydrological perspective or allowing more needs to be met. Finally, there are institutional arrangements that do not directly impact water availability but are nevertheless crucial in determining whether groundwater is developed and used sustainably. Whether a specific strategy is effective in a particular location depends on the hydrogeology, how water is used, and other socio-economic conditions. While an exhaustive list of sustainability strategies is outside the scope of this study, strategies with high potential for the African drylands (listed in Table 7) are described in this chapter. The strategies described here and the hydrogeological and socio-economic conditions described in chapter 2 inform the sustainability pathways described in chapter 5.

Table 7. Overview of classes of sustainability strategies and selected examples of each type

Increase water availability	Reduce water demand	Institutional arrangements

• Artificial aquifer recharge and other small-scale infiltration measures (3R)
• Non-conventional water sources
  o Wastewater recycling
  o Dilution
  o Desalinization and improved water treatment
	• Agricultural water-saving
	• Crop selection
	• Water-saving in cities
	• Water tariffs
	• Education and awareness
		• Prioritize water use types
		• Regulation of abstractions
		• Rural subsidy reform
		• Water markets

3.1 Increase water availability

There are several strategies that can increase water availability. Some directly increase groundwater availability. Others involve the use of non-conventional water resources, for example by treating wastewater, which can reduce pressure on water resources in general. A brief overview of techniques that increase water availability is provided here.

3.1.1 Artificial aquifer recharge and other small-scale infiltration measures

In many regions, the population experiences water shortages even when there is enough precipitation on an annual basis. The precipitation in those areas is not divided evenly over the year, and during rainfall events, water is transported out of the area quickly through evaporation and surface runoff. Therefore, the rainfall does not get the chance to infiltrate into the soil. Infrastructure that slows or temporarily stores surface runoff encourages more water to enter the soil and potentially replenish shallow groundwater. In some cases, the stored water can then be extracted and used during the dry season or droughts. In other cases, stored water in the soil lowers water demand in agriculture. Besides improving groundwater availability and reducing the vulnerability to climate change and hydrological variability, artificial recharge can be applied to conserve excess surface water underground or to combat saline water intrusion. The most important requirements for this type of measure are sufficient surface water and/or rainfall and an underground storage medium.

Artificial recharge is a key component of the Recharge, Retain, and Reuse (3R) approach. This approach uses many smaller systems to store water in the landscape, whether that is in closed storage tanks, surface reservoirs, in the soil, or in the shallow aquifer. The water is then available for later use. In general, the potential of artificial recharge with 3R infrastructure is highest when multiple interventions are planned together in a landscape approach (Figure 22).

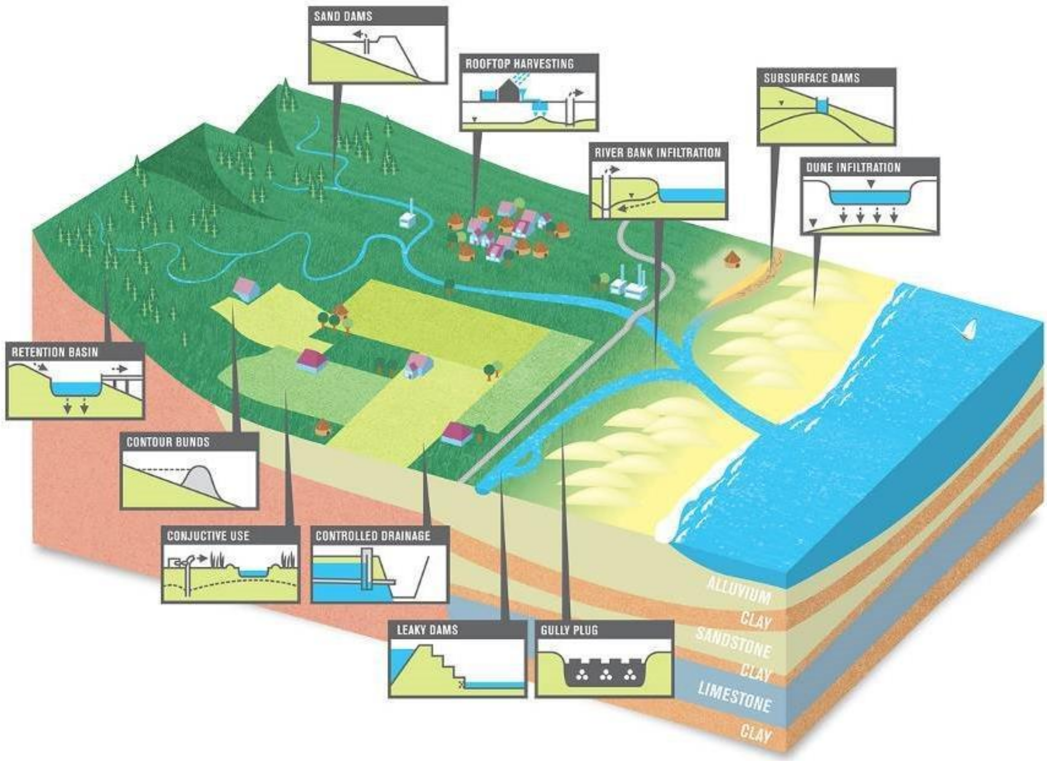


Figure 22. Overview of different 3R interventions distributed throughout the landscape.

Artificial recharge and infiltration measures to increase water availability can be categorized into three categories.

The first category consists of measures that increase infiltration. These are generally small-scale measures such as contour bunds, trenches, and infiltration galleries. Reforestation is a landscape management strategy that can also enhance natural recharge in African drylands, especially in future climates where intense rainfall events are expected to become more common (Bargués-Tobella et al. 2019).

The second category consists of infrastructure that stores water in river beds, such as sand dams, subsurface dams, and permeable dams. This type of simple infrastructure is capable of storing more water than the infiltration measures (Table 8) and is especially suited to rural areas as operation and maintenance (O&M) are relatively cheap and straightforward. Typically, these measures first store water in unconsolidated sediments overlying the bedrock. However, where the unconsolidated sediments are in contact with the bedrock aquifers, the recharge can replenish those aquifers as well.

The third and final category consists of measures that increase water storage in aquifers. These are typically large-scale managed aquifer recharge (MAR) techniques. These typically involve injection wells that pump excessive rainwater or surface water into aquifers when it is plentiful (rainy season) to be extracted for later use (dry season). This type of infrastructure can store larger volumes if local climatic and hydrogeological conditions allow. However, the infrastructure is typically more costly and complex. Therefore, this type of technology is more suited to urban centers, where O&M facilities are more readily available and costly infrastructure is more economically viable.

Table 8. Overview of approximate costs and benefits in water volumes of different measures that increase water availability

	Volume (1.000 m3/y)	Capital costs (1.000 USD)	Levelized costs (USD/m3)
Infiltration measures (earthen dams)	0.1 - 2	1 – 5	0.10
Small-scale aquifer recharge (sand dams)	1 – 5[a]	5 – 20	0.04[a]
Large-scale aquifer recharge (basin/riverbank infiltration)	10,000 – 50,000[b]	1,000 – 10,000[b]	0.20[b]
Large-scale aquifer recharge (well infiltration)	10,000 – 150,000[b]	10,000 – 100,000[b]	0.50[b]
Wastewater recycling	1,000 – 10,000[b]	10,000 – 100,000[b]	1.50[b]
Desalination	10,000 – 100,000	10,000 – 250,000	1.00[c]
Improved agricultural practices			0.04[d]

[a]RAIN (2011). [b]Ross and Hasnain (2018). [c]World Bank (2019). [d]2030 Water Resources Group (2009)

Riverbank filtration is an example of large-scale managed aquifer recharge that consists of production wells that extract water some distance away from a surface water body. As the production wells pump water from the aquifer, surface water flows underground to recharge it, while the subsurface sediments function as a natural filter that removes contaminants, producing higher quality water than the raw source water. In this way, overall water availability is increased.

The volumes of water made available through artificial recharge schemes and the costs involved vary widely with the design, scale, and construction and labor costs at the site. Approximate costs for different techniques are presented in Table 8, showing that small-scale aquifer recharge measures are relatively cost-effective compared to large-scale MAR. For large-scale MAR, costs are much higher for schemes using infiltration wells than those using basin (or bank) infiltration (Ross and Hasnain 2018).

3.1.2 Wastewater recycling

Urban and industrial wastewater quality varies widely, but the quantity may be substantial. The wastewater can often be reused directly for irrigation after treatment and should, therefore, be considered to be a valuable resource.

There are two main schemes of wastewater treatment, infiltration, and reuse assuming a sewerage system with effluent discharge downstream of the urban center (Figure 23). The first situation is an unplanned and uncontrolled situation where effluent is effectively dumped downstream. This type of system poses a serious risk to groundwater quality, though the natural treatment capacity of the soil can improve water quality compared to the raw effluent depending on the type of contaminant in question. In the second situation, interventions reduce groundwater pollution risk. A simple method is the installation of sewage ponds or lagoons, while sewage plants are a more expensive but also more effective method.

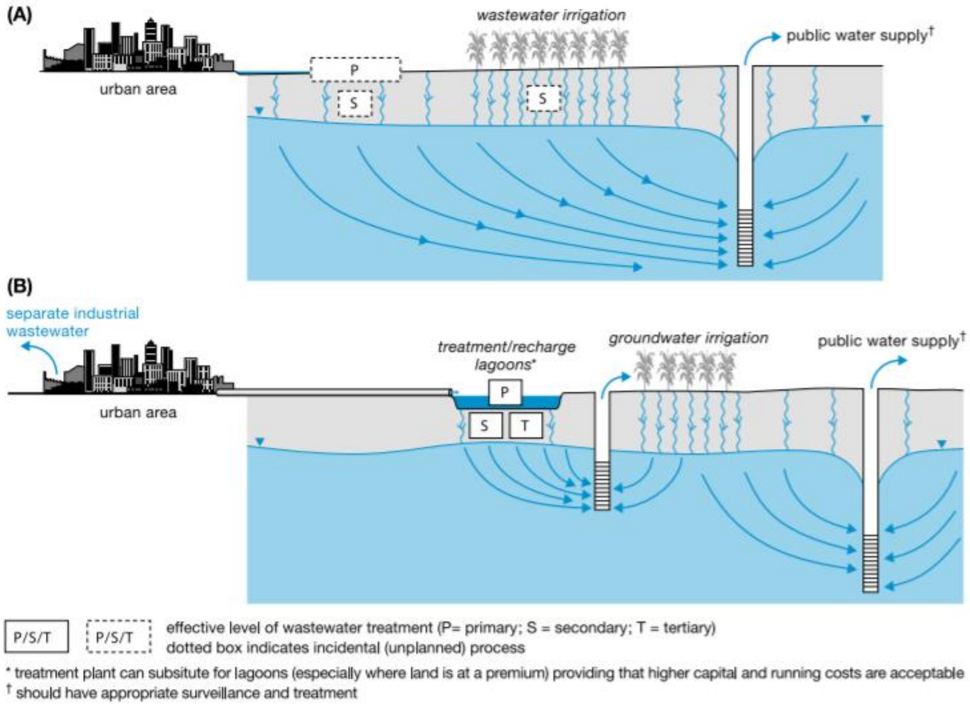


Figure 23. General schemes of wastewater generation, treatment, reuse, and infiltration to aquifers. A: commonly-occurring unplanned and uncontrolled situation. B: economical interventions aimed at reducing groundwater resource pollution risk (from Foster et al. 2005).

The potential risk that wastewater recycling poses for groundwater resources depends on a number of factors. First, the natural conditions determine the vulnerability of the aquifer to pollution (see chapter 2.4). Second are the conditions of groundwater use: the location of the well relative to the wastewater infiltration area, the depth of the groundwater abstraction, and the integrity of well construction.

There are several ways to reduce the impact of wastewater infiltration schemes on groundwater resources. First, by increasing the depth, constraining the use of private shallow wells, and improving the sanitary sealing of wells for drinking water. Second, by introducing groundwater protection zones around wells. Third, ensuring adequate monitoring of groundwater quality. This is needed to continually assess whether there are persistent threats to groundwater quality that should be addressed before infiltration. And finally, by using irrigation wells between the wastewater infiltration zone and drinking water wells. This final measure ensures that most of the wastewater will be abstracted for irrigation purposes, which has lower quality restraints than drinking water. Part of the water used for irrigation will infiltrate into the shallow aquifer and can therefore be reused.

Costs of artificial recharge schemes using wastewater as input are approximated in Table 8. The table shows that levelized costs are typically higher than schemes using natural water, and volumes are smaller.

3.1.3 Dilution

In areas where water is not suitable for use due to water quality issues, dilution is a way to increase overall water availability. In this approach, poor quality water is mixed with higher quality water, to produce a larger amount of water with acceptable water quality. Ideally, the mixing ratio would be based on the intended use. For example, water quality norms for domestic water tend to be lower than for agricultural use. In addition, crops have different salt tolerance levels. Dilution is naturally only possible when sufficient amounts of poor- and high-quality water are available.

This technique can be applied to both surface water and groundwater. There are two main scenarios where this practice contributes to more sustainable groundwater use. The first is when (renewable) groundwater with poor quality is not being used at all, meaning that dilution will increase water availability. The second situation is when high-quality groundwater is being extracted from a (nonrenewable) aquifer. In this case, the increasing water availability afforded by dilution will lower the pressure on groundwater resources.

3.1.4 Desalinization and improved water treatment

In some regions of the African drylands, substantial amounts of water are available, but not of sufficient quality for human use. Present and future technologies to treat this water have the potential to greatly increase water availability.

In water-scarce regions, desalinization is increasingly used to convert saline water into freshwater. Desalinization can be applied to water from saline surface water bodies, but also to water from saline aquifers (see Figure 5). Presently, this technique is generally used for drinking water production or industry due to the relatively high costs (DHV Water and BRL Ingénierie 2004, Table 8), though costs for desalinization of brackish aquifers can be substantially lower than desalinization of seawater (Qtaishat et al. 2017). In Africa, such schemes are already active in Algeria, Egypt, Tunisia, and Mozambique, among others. However, technological development and potentially decreasing energy costs may make desalinization more manageable and affordable, and therefore more widely applicable in the future. In any case, a proper and environmentally sustainable disposal plan for the large amounts of brine produced by desalinization is needed.

Elevated fluoride and arsenic levels are another water quality threat in certain regions of the African drylands (Figure 5). Technologies exist to treat this water, but they can be expensive. Nevertheless, future developments that reduce the cost of current treatment methods or the development of new technologies may improve the economic feasibility of using these aquifers as a water source.

3.2 Reduce water demand

It is also possible to make groundwater use more sustainable by reducing water demand, thereby decreasing pressure on water resources including groundwater. Most of the water use globally is for agriculture. Therefore, this sector has the highest potential to reduce water demand. While irrigation is underdeveloped in Sub-Saharan Africa (Kadigi et al. 2013), large-scale irrigation schemes using non-renewable groundwater resources are more common in North Africa, where many groundwater resources are non-renewable at human timescales. The potential for reducing water demand for domestic and industrial use in African drylands is mainly limited to major cities.

3.2.1 Agricultural water-saving measures

More water-efficient irrigation technologies have a high potential to reduce water demand. Note that the term water-efficiency can lead to misconceptions, as it is generally based on water withdrawals. In reality, a portion of the water extracted for irrigation returns to the soil and may replenish shallow groundwater. This portion remains available for irrigation or other water use, assuming that water quality is sufficient. This is known as the paradox of irrigation efficiency. The only water that is lost from the local system is that which is transpired by the crop or evaporated, either during transportation or from the soil or plant surface. Nevertheless, studies have shown that water-saving measures can reduce non-beneficial evapotranspiration by 50 to 80 mm/y when using surface or groundwater resources, respectively (Foster and Garduño 2004). Three types of measures can be distinguished: engineering measures, management measures, and agronomic measures.

Engineering measures include the use of more efficient irrigation techniques. Drip or micro-sprinkler irrigation systems are more efficient than pivot or flood irrigation. Locally, ensuring that spate irrigation is applied to its full potential can lower pressure on water resources. Spate irrigation is an ancient irrigation technique that harnesses seasonal floods of rivers and streams to fill irrigation channels and is especially common in arid and semi-arid regions. Another example of an engineering measure is a shift from conveyance through canals to piped systems. This lowers the evaporation losses during conveyance, though a drawback is that piped and pressurized systems increase energy demand. Therefore, this technique is more suited to large-scale irrigation schemes than individual farmers.

Management measures that can result in water savings include improved water forecasting and water scheduling. The purpose of water scheduling is to optimize the timing and amount of irrigation, which can lead to water conservation. Improved weather forecasts can support decisions about when and how much irrigation is needed and tends to lower water use. Also, crop sowing dates can have a large impact on water demand. Combining these management measures, where possible combined with field data, have a high potential for water savings. This has already spurred the development of mobile apps that combine weather data, crop sowing dates, and local information to advise farmers on irrigation scheduling and other agricultural management operations.

The extent to which this kind of optimization is possible will depend on the scale and investment potential of the farmers.

Finally, agronomic measures that result in water savings include deep plowing and mulching, which lower non-beneficial evapotranspiration losses. In addition, the use of improved seeds or varieties that are for example more drought-resistant can lower the amount of irrigation needed to still ensure optimal crop growth. While improved seeds or varieties may not be readily available, mulching is a more accessible technique for all kinds of farmers.

Which measure is most effective depends on the socio-economic situation. Large-scale irrigation schemes such as those in Northern Africa have the means to implement relatively expensive measures such as piped conveyance and more efficient irrigation technology. These technologies are not realistic for small-scale and subsistence farms, where inexpensive measures such as mulching are more appropriate. The use of improved seeds or varieties will similarly not only depend on the investment potential, but also on availability.

3.2.2 Crop selection

In addition, agricultural water use can be reduced by cultivating crops that are less water-intensive. Ideally, crop scheduling should be based on optimizing water use on the one hand and impact on food security on the other hand. For African drylands, the cultivation of water-intensive crops that are not used for human consumption, such as energy crops, is arguably the least sustainable agricultural pathway.

The nutritional water productivity is a measure quantifying the nutritional value (such as energy, protein or calcium) per unit water input. In general, animal food products have lower nutritional water productivity than vegetal crops. In terms of energy and protein, potatoes, maize and soybean have relatively high values for this metric (Wenhold et al. 2012). Onions score well in terms of the nutritional water productivity in terms of calcium, and carrots and sweet potatoes in terms of vitamin A (Renault and Wallender 1999). It is not realistic nor desirable to blindly substitute local crops with those mentioned here, but this type of metric can be used to explore whether there are more sustainable alternatives for water-intensive crops in irrigated agriculture.

Food security can also be improved while ensuring more sustainable groundwater use by replacing water-intensive crops with low value, for example, cereal crops, by less water-intensive, higher-value crops. One way to achieve this could be through greenhouse cultivation, which has the added benefit of reducing the land area needed for cultivation. However, there may be market, transport and storage limitations related to this type of cultivation. As a result, it is more feasible near urban areas.

In a similar way, food security can be improved while ensuring more sustainable groundwater use by introducing salt-tolerant agriculture. By introducing varieties of well-known crops that do grow on salt-affected land, degraded soil becomes productive again and part of non-conventional groundwater (too brackish) becomes available as irrigation water again.

3.2.3 Water-saving measures in cities

In cities, water supply is generally through piped systems. When these systems are relatively old, corroded or leaky pipes can result in a low water distribution efficiency.

Renewing and improving the water distribution system is the first way to increase efficiency and therefore decrease total water demand in cities. Besides reducing the physical water losses, other steps towards reducing Non-Revenue Water (NRW) include reducing the apparent losses, such as unfunctional water meters, and reducing commercial losses, consisting of unbilled unauthorized consumption (bypasses / illegal tapping) and unbilled authorized consumption. Making consumers pay for previously unpaid water may be a very cost-effective method to incentivize improvements in water-efficiency and lower water demand.

Also, though the majority of the population in Africa uses less than 50 liters of water per day and many have access to less than 20 liters per day, water use in urban areas can be considerably higher. Reducing water use in the home, at work, and in public spaces can be especially important where population density and local pressure on water resources are high. Inside, whether at home or at work, water-saving technologies include water-saving showers, faucets, and toilets. Reducing irrigation of plants and grassy areas or replacing water-intensive plants with drought-resistant species in gardens and public spaces can also contribute to water conservation. In addition to water-saving technologies, increasing awareness of more efficient water use by closing the tap while brushing teeth to watering plants early in the morning or at the end of the afternoon can reduce the water use of the population.

Industry is another important water user in cities. Measures that contribute to more sustainable use can include measures to improve water efficiency or to use poorer-quality water resources where possible, for example for cooling.

3.2.4 Water tariffs

Imposing fees to abstract groundwater may be the most effective method to incentivize improvements in water-efficiency, ultimately lowering water demand. Large-scale agricultural or industrial users could be the main target for water tariffs, while small-scale domestic use can be subsidized to ensure access to safe drinking water. However, implementing water tariffs is not straightforward (Hellegers and Perry 2004), facing challenges including long-standing conditions of the system and potential unintended consequences of the pricing scheme (Davidson et al. 2019). As a result, the effectiveness of water tariffs in irrigation is debated and they are not widely practiced. In the African context, in particular, an additional challenge is that the monitoring of abstractions and proper enforcement are crucial to ensure this measure is successful, but institutional authority can be lacking in some African countries (see chapter 0).

3.3 Institutional arrangements

A broad range of institutional and management-related strategies are harder to quantify in terms of decreased pressure on water resources but are crucial to ensure that a sustainability pathway is successful. A selection of strategies that are institutional in nature is outlined in this section.

3.3.1 Prioritize water allocation

The main types of water use can be prioritized according to the following scheme:

1. Domestic use
2. Agricultural use
3. Industrial use

However, prioritization is also needed within these categories, especially when it comes to agricultural use.

In regions where water is scarce during the dry season, agricultural water should be prioritized in terms of water-intensiveness and contribution to local food security. Water-intensive crops like sugar cane and paddy rice should be replaced by less water-intensive crops like maize or potatoes. This is especially important when water-intensive crops are grown for international export, which in effect is exporting groundwater. Crops for fodder, commonly alfalfa and maize, and biofuel production should receive lower priority than crops for human consumption. Crops that are not used for food and which are also water-intensive, such as qat, should have the lowest priority.

3.3.2 Education and awareness

One of the main reasons groundwater management is neglected is a lack of knowledge. Education campaigns and awareness-raising are needed to ensure all stakeholders, from the local population to policymakers, understand groundwater resources, especially where they differ from surface water resources. Important topics for education and awareness-raising include that groundwater resources are not infinite, any relevant groundwater quality issues, and the potential impacts of overexploitation and inadequate protection of groundwater resources. Ultimately, improved understanding of the context of groundwater resources will increase motivation for and participation in sustainable groundwater resources management.

Local contractors can receive training in improved siting techniques, including geophysical measurements, more appropriate drilling techniques and filter placement and design. These topics contribute to lower well failure rates and longer lifespans of the wells. Though this may not directly improve the hydrological sustainability of groundwater use, it does promote more efficient use of resources and can lower the cost of groundwater development.

3.3.3 Regulation of abstractions

In order to protect groundwater resources against over-exploitation, especially in stressed aquifers, regulation of abstractions is essential. Indeed, for water-saving technologies to lead to more sustainable groundwater use, it is essential that they are combined with regulation of abstractions. For agricultural use, the reduction of irrigated areas is also an option to ensure water-saving measures truly lead to a reduction in groundwater abstractions and are not for larger areas of irrigated cropland or the expansion of industrial use. This is especially important considering that increased supply, whether domestic, industrial or agricultural, tends to lead to higher water demand. Proper regulation, however, requires monitoring and enforcement of the regulations, assessment of the sustainable production from aquifers and legislation and planning.

3.3.4 Rural subsidy reform

If resource prices of for example electricity and fuel are distorted and not aligned with sustainability goals and farmers' needs, farmers may make suboptimal choices. In the past, some countries have used energy subsidies to promote agricultural production. In fact, energy subsidies are wide-spread in African drylands. However, energy subsidies in rural areas may have the unintended consequence that farmers are less affected by increasing energy consumption that accompanies dropping water levels. This can result in higher groundwater abstraction and lower incentive to invest in water-saving techniques. Instead of rural energy subsidies, there may be other ways to support farmers that promote higher water use efficiency. One approach may be to provide farmers with a lump sum at the start of the season.

3.3.5 Water markets

Establishing water markets can ensure that high-value uses are allocated more water without leaving small-scale water uses behind. In order to create a successful water market, it is essential to monitor groundwater use and establish water rights for each user. Once this step is achieved, water can be traded between users. Water markets alone will not result in more sustainable water use. However, when combined with regulation of abstraction rates they can form an incentive to increase water-efficiency, as any water savings can be traded on the water market.

3.3.6 Protection of water resources

Sustainable groundwater use is not only dependent on groundwater availability, but also on its quality. Therefore, the protection of groundwater resources against pollution is crucial, especially where population densities are high. This protection can be achieved by different methods. First, groundwater protection zones can be implemented limiting activities with a risk of contamination within a specified distance of wells and springs used for public drinking water supply. Typically, several zones are defined with increasing limitations with decreasing distance from groundwater abstraction. Another way to protect groundwater resources is to improve waste management and upgrade or renew outdated or leaky sewage systems. This is especially relevant in urban areas with high population densities, but is also common in large villages and smaller cities as solid and liquid waste management facilities are frequently lacking.

4 Case studies

The extent that groundwater is used sustainably in African drylands and the potential of sustainability strategies is best illustrated through case studies. Here, examples of groundwater use spanning different landscape types defined in Chapter **2** are presented. These give insight into the potential of different measures and the main lessons learned in terms of groundwater sustainability.

4.1 Great man-made river project, Libya

The Great man-made river project consists of a network of pipelines transporting fossil groundwater to the Libyan coast. The water was intended to supply domestic and industrial water to the cities along the Mediterranean coast, but the largest portion (around 80%) was intended to supply water for small- and large-scale irrigation schemes. The project was initiated in the 1980s and was designed to have five phases. The first two phases were completed in the 1990s and the third phase was completed in 2011.

The wells tap aquifers with high storage containing water that is tens of thousands of years old. The water is pumped from a depth of about 500 m and transported from the wellfields to the coast, a distance of up to 1,600 km, by underground pipelines. Near the coast, water is stored in reservoirs near the main endpoints of the pipeline network to accommodate short-term variations in supply and demand and longer-scale fluctuations due to dry seasons and drought. With all phases built, the planned total capacity of the project will be 6.5 million cubic meters per day, transported by 4,000 km of pipelines (Aqeil et al. 2012). The estimated cost of the entire project is 25 billion USD, or about 10 times higher than the cost of desalinated water (Aqeil et al. 2012). Currently, the project supplies almost 2.5 million cubic meters, providing 70% of all freshwater used in Libya.

The project aimed to allow small farmers to grow crops for the local market, while large farmers would grow crops to reduce imports. Indeed, the irrigated area has increased dramatically since the pipeline has been completed. In addition, the cultivation of water-intensive crops including cabbage, corn, peanuts, and fruits including oranges and grapes has increased.

Lessons learned:

- Fossil, non-renewable groundwater resources with large storage have great potential to meet water and food demand in arid areas.
- It has been argued that the large storage contained within the aquifers will be able to meet water demand for thousands of years.
- Critics have argued that in reality, the water supply may not last until 2100.

4.2 SEKEM Initiative, Egypt

The SEKEM Initiative was founded in 1977 and aims to achieve sustainable development through a holistic approach.

The project started by developing an area of 70 hectares in the Egyptian desert and promotes biodynamic agriculture as a solution for environmental, social and food security challenges. Today, the organization contains multiple companies and NGOs, has a network of farmers throughout Egypt and has links to projects in other countries including India, Palestine, and Turkey.

The initiative uses a Sustainability balance card to keep track of sustainability indicators related to the four dimensions: ecology, economy, societal and cultural life. Targets are set for the various indicators and progress is evaluated at regular intervals. Indicators include "water usage" for agricultural and company use, "share of wastewater recycled" and "energy savings". Indeed, one of the main aims of the SEKEM vision is to optimize water consumption through innovative concepts and technologies (SEKEM 2018).

SEKEM uses water from the Nile River, municipal sources, and groundwater from wells. In 2018, the contribution of fossil groundwater to the total water supply was just under 30%, a decrease from 35% in 2017. This was largely achieved by a change in the cropping plan, shifting towards less water-intensive crops. From a groundwater point of view, there are several advantages to the SEKEM approach. First, biodynamic agriculture reduces the risk to groundwater quality since pesticides and artificial fertilizers are not used. Second, the reuse of wastewater not only reduces the risk of groundwater pollution, but it also lowers pressure on water resources. Third, groundwater levels are monitored to promote sustainable withdrawals.

<u>Lessons learned:</u>

- Indicators of different dimensions of sustainability can be used to track progress on sustainability goals at local scales.
- Data and monitoring are necessary to be able to quantify these indicators.
- Combining different measures with the same overall goal can be effective in reaching sustainability targets.

4.3 Water harvesting, Kenya

One technique to increase groundwater availability is to build sand storage dams in seasonal riverbeds. Typically, the dams are constructed in concrete and have a width of 15–25 m and stand 3–5 m high. An average sand dam can provide between 5.300 and 8,100 cubic meters of water per year. A study suggests that only a small portion (<5%) of the water is retained behind the dam, indicating that the impact on downstream water users is limited.

In Kitui, Kenya, 500 of such sand dams were built, costing 8.000–12.000 USD each. Each dam provides water for 150–200 people, including their domestic water use, livestock watering, and rural industry. A comparison of a village where a sand dam was constructed with a nearby village without a sand dam showed that irrigation was more common and household income higher than in the village without sand dams (Table 9). In addition, the dams ensured that the distance to drinking water in the dry season was considerably smaller, meaning that water collection for domestic and livestock was considerably shorter. Finally, the number of people exposed to droughts was minimalized after dam construction compared to the nearby village.

This concept was similarly tested in southern Ethiopia, where the scheme was less successful. The lower success of sand dams in Ethiopia compared to Kenya was attributed to ownership.

In Kenya, part of the construction cost was provided by the community, improving the sense of ownership and the commitment to maintain the dams. In Ethiopia, sand dams were not maintained by the neighboring communities due to a lack of know-how and sense of ownership, reducing the effectiveness of the project.

Table 9. Effects of sand dam construction in a Kenyan village compared to a village where no sand dam was constructed (from Tuinhof et al. 2011)

Indicator	Kiindu (village with dam)		Koma (village without dam)	
	1995	2005	1995	2005
Access to drinking water in dry season	3 km	1 km	4 km	3 km
People exposed to droughts	420	0	600	600
Households with irrigated crops	37%	68%	38%	38%
Agricultural water consumption	220 l/d	440 l/d	160 l/d	110 l/d
Household income (USD/y)	180	290	180	180

Lessons learned:

- Artificial recharge schemes can improve water availability in the dry season and reduce vulnerability to drought.
- Improved water availability has socio-economic benefits for the local population, including higher income.
- A sense of ownership and an effective maintenance plan are crucial to ensure the success of infrastructure schemes.

4.4 Aquifer contracts, Morocco

Since 2006, the Moroccan government has used aquifer contracts in a bid to control groundwater abstraction and improve groundwater management in the Souss Massa-Draa Basin. In this basin, groundwater is overexploited, as agricultural withdrawals are more than 50% higher than the recharge. The technical and financial contracts are signed by stakeholders and the government. Negotiating these contracts together with stakeholders provides the opportunity to define a common problem and develop solution strategies at a local level. The contracts include water fees and the restriction of cropland area, as well as action plans and financing needed to achieve the objectives laid out within the contract.

However, the main obstacle preventing the achievement of the aims of the contract is that the contract is not binding and voluntary in nature. The payment of groundwater fees is low and not obligatory. In addition, not all stakeholders are equally involved in the contract and its negotiation, and smallholder farmers, in particular, are not adequately represented.

Several measures have been proposed to increase the effectiveness of the aquifer contract. First, the negotiation and implementation of the contract should include all stakeholders. Second, there is a need to introduce binding measures and enforce controls on well drilling, abstraction, and cultivated area. Third, more data is needed to better understand the groundwater resources and support better groundwater management. Finally, inconsistencies in various agricultural and environmental policies should be addressed.

Lessons learned:

- Regulation of groundwater use that is supported by all stakeholders is a key strategy to address over-exploitation.
- Binding measures and enforcement of rules and regulations are crucial to ensure management aims are achieved.
- Groundwater data and monitoring are necessary to support groundwater management.
- Agricultural and environmental policies should be aligned for effective groundwater management.

4.5 Desalinization in Turkana, Kenya

Turkana is one of the driest regions in Kenya. The discovery of the Lotikipi aquifer, located 300m below the surface and with an estimated storage of 200 billion cubic meters of water, lead to global headlines in 2013 which suggested that the local population could be provided with enough water for decades. However, the salinity levels are too high for human consumption, though experts maintain that there may still be pockets of freshwater in the aquifer. In the meantime, the Kenyan authorities are discussing the construction of a desalinization plant with a Saudi investor to make the water suitable. The business plan includes the privatization of water, selling water to the private sector while subsidizing water for the local population.

Lessons learned:

- Understanding of the groundwater system is not complete, and potentially large new fresh groundwater storage can still be discovered through groundwater mapping and geophysical investigations.
- Desalinization is a technique that can make groundwater resources that are naturally too saline suitable for human consumption, though it is costly.

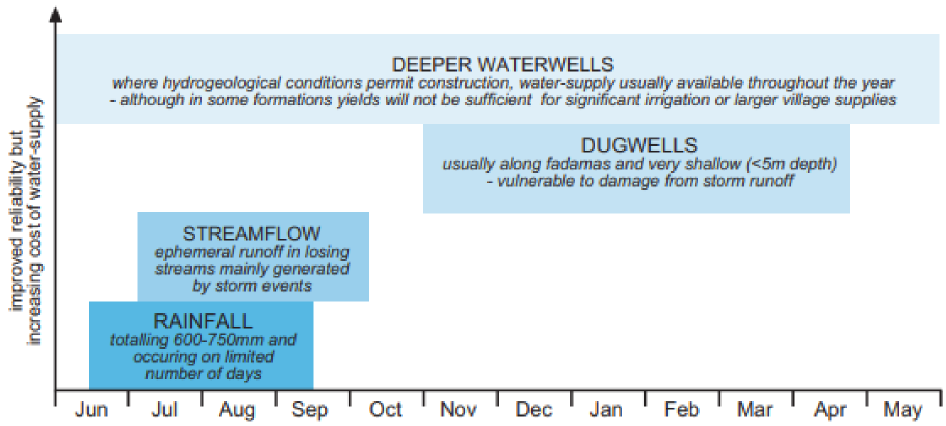


Figure 24. Reliability and relative costs of different water sources in the fadamas of Nigeria (from Tuinhof et al. 2011).

4.6 'Fadama' development, Nigeria

A 'fadama' is a local term in the Sahel for land that is seasonally inundated or waterlogged and is therefore considered to be capable of being irrigated. This term can refer to local shallow depressions in the landscape as well as major floodplains. The local population has dug dugwells into fadamas for thousands of years to provide water for human consumption and livestock watering. However, the dugwells are frequently damaged as a result of flooding during the short rain season typical of the semi-arid climate (see Figure 24). The dugwells then need to be repaired during the dry season.

Deeper tubewells are more reliable and provide water over a longer period, but the installation and operating costs are substantially higher than those of dugwells.
A series of 'fadama development projects' has provided grants aimed at expanding irrigated crop production in Nigeria through grants for agricultural infrastructure. As a part of this, over 40,000 shallow tubewells have been constructed and equipped with motorized pumps. These investments stimulated irrigated vegetable cultivation and have raised crop productivity by over 75% (Tuinhof et al. 2011). At the same time, there has been increasing social tension between farmers and nomadic pastoralists concerning access to grazing land and the loss of shallow water points. Furthermore, water wells were traditionally used for irrigation in the morning and livestock watering in the afternoon. Longer groundwater level recovery times associated with heavier use have put this arrangement under pressure.

Lessons learned:

- Crop productivity can be substantially raised through more reliable groundwater supply.
- Heavier water use can result in longer water-level recovery periods.
- Social tensions can arise between farmers and nomadic pastoralists concerning grazing land, loss of shallow water points, and disruption of traditional water scheduling.

4.7 Addis Ababa urban water supply

Addis Ababa is one of the fastest-growing urban centers on the African continent. Early this century, the Addis Ababa Water & Sewerage Authority faced a production shortage as a result of increasing water demand and limited availability of water resources. At the time, surface water supplied more than 80% of the city water, with the remainder sourced from a wellfield in the Upper Basalt Aquifer with a thickness of 150–250 m. The aquifer is locally recharged, limiting the potential for further sustainable development.

The 2006 discovery of the deeper Scoraceous Basalt Aquifer provided an alternative water source. The aquifer has a thickness of 300–500 m and is recharged from the elevated Abbay plateau at much higher rates than the shallower aquifer. The groundwater resources, therefore, have a higher potential for sustainable abstraction and can be tapped to meet the increasing water demand in Addis Ababa as well as nearby towns and planned irrigation projects. However, groundwater development requires wells of around 500 m depth. This type of well is very expensive and capacity and experience in drilling to such depths are limited in the region.

Lessons learned:

- Different aquifers in the same area can have drastically different characteristics.
- Extensive groundwater mapping is needed to characterize aquifer systems and rate potential for sustainable use.
- Though deep groundwater is typically considered to have low recharge rates, there are locations where recharge of deep groundwater is (much) higher than shallow groundwater and therefore has a higher hydrologically sustainable yield.

5 Sustainability pathways for landscape types

Sustainability pathways for the African drylands describe potential sets of sustainability strategies that can be effective in moving towards sustainable groundwater resources development and use. Here, several pathways are defined building on the current status of groundwater resources, the defined representative landscape types, and potential sustainability strategies discussed in the previous chapters. In addition, general requirements and conditions for sustainability pathways are described.

A summary of landscape-specific and general strategies or requirements for sustainable groundwater use are presented in Table 10 and Table 11. Table 10 focuses on the first hydrogeological environment including basement rock environments and Table 11 focuses on the second hydrogeological environment including sedimentary and volcanic rock environments. The tables show that the issues and strategies of the landscape types are not distinct and some strategies have potential in multiple landscapes. Nevertheless, the combination of strategies into sustainability pathways differs between landscapes. Here, we first discuss the landscape-specific sustainability pathways and then the general strategies and conditions for sustainable groundwater use.

Note that while these sustainability pathways provide insight into regional differences within the African drylands, they cannot be used at local scales. A thorough assessment of the socio-economic conditions and the physical context is needed to evaluate which set of sustainability strategies is most effective for a particular location.

5.1 Landscape-specific sustainability pathways

The hydrogeological and socio-economic setting of the landscape types determines the main groundwater issues of the landscape and the potential sustainability strategies. Sustainable groundwater use is arguably more likely to be achieved through a combination of such strategies and not by deploying only one of them. In chapter 3, sustainability strategies were divided into (i) those that increase water availability, (ii) those that decrease water demand, and (iii) those that are institutional arrangements. In some landscapes, all three types of measures may be equally relevant. In others, one type may be more relevant than the other. Here, sustainability pathways of each of the landscape types are discussed. The landscape types are discussed according to whether they are urban or rural landscape types since the socio-economic conditions - which largely determine the risks and scale of possible measures - are most clearly defined by this category.

Table 10. Overview of basement rock landscape types, their typical socio-economic conditions, groundwater issues, and landscape-specific and general sustainability strategies

Hydrgeol. Environ.	Urban/ rural	Recharge/ population	Socio-economic conditions	Groundwater Issues	Strategies			
Basement rocks **Well productivity < 1 l/s** **Small stored volume**	**Rural**	**Recharge < 5 mm/y**	• Hyper-arid • Population density ~0 people/km²	• No issue	• No strategies	Groundwater system understanding and monitoring	Community participation and capacity building	Coordinated management and strengthening institutions
		Recharge 5–25 mm/y	• Population density < 25 people/km² • Mainly (agro)pastoral • Non-permanent villages (population 50–500) • Water supply (mainly for livestock) through reservoirs and deep wells	• Remote and low capacity wells • Low drilling success rates • Insufficient O&M facilities • Deep water levels • Wells not climate resilient • Decreasing baseflow of rivers	• Separate solar-powered wells combined with small reservoirs for pastoral use • Artificial aquifer recharge and other small-scale infiltration measures (3R)			
		Recharge 25–100 mm/y	• Population density > 25 people/km² • Mainly rainfed cereal/tuber growing • Permanent villages (population 250–3,000) • Water supply by wells fitted with handpumps	• Groundwater pollution in and around village • Insufficient O&M facilities • Risk of local overexploitation • Ephemeral rivers • Decreasing baseflow of rivers	• Exploration of wells outside polluted zone, but < 500 m from village • Artificial aquifer recharge and other small-scale infiltration measures (3R) • Rural subsidy reform • Groundwater protection zones • Agricultural water-saving measures and crop selection (under future development of groundwater irrigation)			
	Urban	**Population >5,000**	• Piped water systems • Source is surface water or mixed surface/groundwater	• Groundwater pollution • Health risks because of informal wells in non-piped areas	• Exploration of large well fields, possibly remote • Bank infiltration wells along reservoirs and wadis (MAR) • Wastewater recycling • Non-conventional water sources (desalinization, dilution, and wastewater recycling, if economic and technological developments allow) • Groundwater protection zones • Improve waste management and sewage systems			
		Population >1,000,000	• Piped water systems • Source is surface water	• Groundwater pollution • Health risks because of informal wells in non-piped areas • Large scale groundwater recovery is generally no option	• Non-conventional water sources (desalinization, dilution, wastewater recycling) • Water-saving measures in cities (where applicable) • Reduction of non-revenue water • Groundwater protection zones • Improve waste management and update sewage systems			

Table 11. Overview of sedimentary and volcanic rock landscape types, their typical socio-economic conditions, groundwater issues, and landscape-specific and general sustainability strategies

Hydrgeol. Environ.	Urban/ rural	Recharge/ population	Socio-economic conditions	Groundwater Issues	Strategies			
Sedimentary and volcanic rocks **Well productivity > 1 l/s** **Large stored volume**	**Rural**	**Recharge < 5 mm/y**	• Hyper-arid • Population density ~0 people/km² • In some areas high yielding wells possible	• Groundwater recovery is technically possible, but hydrologically not sustainable (mining) • Risk of poor groundwater quality due to high evaporation and saline soils	• With large investments irrigation or industrial development is possible. If so, socio-economic criteria needed for groundwater mining, including an exit strategy. • Prioritize water allocation • Agricultural water-saving measures and crop selection • Regulation of abstractions	Groundwater system understanding and monitoring	Community participation and capacity building	Coordinated management and strengthening institutions
		Recharge 5–25 mm/y	• Population density < 25 people/km² • Mainly (agro)pastoral • Non-permanent villages (population 50–500)	• Groundwater pollution in and around village • Remote wells and insufficient number • Insufficient O&M facilities • Deep water levels	• Separate solar-powered wells for pastoral use • Artificial aquifer recharge and other small-scale infiltration measures (3R)			
		Recharge 25–100 mm/y	• Population density > 25 people/km² • Mainly rainfed cereal/tuber growing • Permanent villages (population 250–3,000) • Water supply by wells fitted with handpumps	• Groundwater pollution • Insufficient O&M facilities • Risk of local overexploitation	• Exploration of multi-village schemes with high capacity wells and piped supply for larger villages (population > 1500) • Artificial aquifer recharge and other small-scale infiltration measures (3R) • Rural subsidy reform • Groundwater protection zones • Agricultural water-saving measures and crop selection (under future development of groundwater irrigation)			
	Urban	**Population >5,000**	• Groundwater supply by well fields	• Groundwater pollution • Health risks because of informal wells in non-piped areas • Risk of over-exploitation in expanding centers	• Exploration of large well fields around urban center • Artificial recharge through MAR or RBF systems • Non-conventional water sources (desalinization, dilution, and wastewater recycling, if economic and technological developments allow) • Groundwater protection zones • Improve waste management and sewage systems			
		Population >1,000,000	• Piped water systems • Source is surface water and groundwater	• Groundwater pollution • Health risks because of informal wells in non-piped areas	• Groundwater recovery in combination with large-scale MAR systems • Non-conventional water sources (desalinization, dilution, wastewater recycling) • Water-saving measures in cities (where applicable) • Reduction of non-revenue water • Groundwater protection zones • Improve waste management and update sewage systems			

5.1.1 Rural environments

In rural areas, the sustainability pathways are closely related to the socio-economic conditions, including the livelihood and typical water use of the population. Low population densities are generally related to lower risks for sustainable groundwater use, but also limit the potential strategies that can be implemented due to economic and capacity constraints.

While the basement rock environments in areas with very low recharge and storage are not conducive to groundwater development, groundwater resources in aquifers with very little recharge in sedimentary and volcanic rock environments have among the highest risk of unsustainable use in the African drylands. The high aquifer productivity and storage in these sedimentary and volcanic rock environments allow potentially large-scale groundwater development, though abstracting water from the deep aquifers is costly. From a hydrological (quantity) perspective, sustainable groundwater use of these aquifers is nearly impossible: demand is often higher than replenishment. Instead, a groundwater management plan based on the resources availability and socio-economic criteria must be developed, which may include prioritization of water allocation. An important part of the management plan in areas where groundwater use is not hydrologically sustainable is an appropriate exit strategy for when the aquifer becomes depleted. Opportunities to increase water availability are severely limited due to low precipitation, high evapotranspiration, and low surface water availability. However, decreasing water demand has high potential, especially in the agricultural sector. This can be achieved through engineering, management, and agronomic measures and crop selection. Socio-economic criteria can be used to determine whether realized water savings should result in lower abstractions, or increased crop production to improve food security.

In rural environments with slightly higher recharge rates (5–25 mm/y), artificial recharge techniques are more feasible. Due to the low population density, inexpensive, small-scale, and simple interventions such as sand dams and contour bunds have the highest potential. Basement rock environments with low productivity are less suited for (deep) aquifer recharge methods with underground storage than sedimentary and volcanic rock environments. However, in most basement rock landscapes suitable locations for small-scale aquifer recharge interventions can be found. The bedrock is typically overlain by unconsolidated sediments, which may be up to several hundreds of meters thick but are usually of shallow depth. If permeable, these unconsolidated sediments are more conducive to infiltration and artificial recharge measures. Surface storage can be used as an alternative when the distance between suitable locations and settlements is too large, especially when required volumes are relatively small. Such small-scale infiltration and aquifer recharge methods can increase (ground)water availability and improve and sustain baseflow.

Water demand is mainly for domestic use, small-scale agriculture, and livestock watering and is on average very low in rural environments with medium recharge rates. Therefore, water-saving measures are generally not applicable. However, separate wells for pastoralists may reduce social tension between permanent settlements and nomadic pastoralists. In areas with low productivity, installing reservoirs near the wells for livestock watering can improve water availability. Solar-powered wells have high potential in this landscape as infrastructure tends to be less developed. In sedimentary and volcanic rock environments where well productivity tends to be higher this is not necessary.

Where recharge rates are relatively high for the African drylands, the population tends to depend on rainfed crop cultivation. Despite relatively low average water demand, there is a risk of local over-exploitation in larger settlements. In these landscapes, there is a relatively high potential for aquifer recharge techniques, though these should still be inexpensive and simple to ensure that construction and maintenance can be carried out by the local population. Water-saving techniques under the current situation are limited, though this would change under future development of groundwater irrigation to stimulate crop production. In that case, agricultural water-saving measures and crop selection would be important strategies to mitigate local over-exploitation risk. Farmer uptake of these types of measures may benefit from rural subsidy reform.

Higher population densities, especially in expanding rural centers, raise the risk of groundwater pollution and therefore the need for groundwater protection zones and investments in sanitation and waste management. This is especially relevant as shallow groundwater is more readily available in these landscapes compared to the low recharge landscapes and therefore more frequently utilized.

5.1.2 Urban environments

In urban centers, costlier technologies that require more operation and management facilities are more feasible. The sustainability pathways for urban environments are more similar than was the case for rural environments, though there are differences depending on the hydrogeological environment and the size of the urban center.

Increasing water availability can be achieved through various methods. Non-conventional water resources such as dilution, desalinization, and improved water treatment, and wastewater recycling have high potential here. Currently, desalinization may only be possible in the larger urban centers due to the high associated costs, but if technological developments reduce costs it may become relevant for the smaller urban centers as well. In sedimentary and volcanic rock environments with high aquifer productivity, large-scale MAR systems can be installed to store excess water in the wet season for use in the dry season. In basement rock environments with low productivity and storage, this is not feasible. However, bank infiltration schemes along reservoirs and wadis have potential in smaller urban centers.

Water demand is higher in cities than in rural areas, meaning that water-saving measures may become relevant. Maintenance and renewal of the water distribution system is an important way to minimize non-revenue water and increase the efficiency of piped systems, especially where the water distribution system is relatively old and leaky. Water-saving measures in homes and workplaces may contribute to more sustainable water use, but only in developed cities where water use is relatively high. Even then, the savings achieved in this way is likely to be limited.

Groundwater pollution is a serious threat in urban centers, especially as there are generally large numbers of informal wells that lack adequate protection and where water quality is not monitored. Additional threats are industrial activities and poor sanitation facilities. One of the most important ways to prevent groundwater pollution is to maintain and renew sewage systems and improve waste management. This can be complemented by groundwater protection zones near the abstraction wells, though this needs to be properly enforced.

5.2 Priority landscapes

Of the representative landscape types, three are considered to have high potential in terms of making steps towards sustainable groundwater use. These are:

- rural areas with medium recharge rates,
- rural areas with very low recharge and high aquifer productivity and storage, and
- smaller urban centers.

Rural areas with medium recharge rates (both in sedimentary and volcanic rock environments as well as basement rock environments) are considered to be high priority landscapes because the potential impact of artificial aquifer recharge and groundwater irrigation is high. Small-scale and inexpensive technologies have great potential to decrease vulnerability to drought and increase household income in these regions. While the artificial aquifer recharge and agricultural sustainability strategies can be applied in the landscapes with lower recharge rates, these measures are less suited to the mainly pastoral population and non-permanent settlements in those landscapes, limiting their potential overall impact.

The second priority landscape consists of rural areas with very low recharge, but high aquifer productivity and storage. Expansive irrigation schemes in these areas mean that water withdrawals are much higher than the natural recharge (groundwater mining) despite the low population density. As a result, aquifers are more likely to be over-exploited. In light of the reported evidence of over-abstraction (Figure 15), it is critical to develop and implement local sustainability pathways including an exit strategy for when aquifers become depleted.

The third and final priority landscape is smaller urban centers (both in sedimentary and volcanic rock environments as well as basement rock environments). As a result of urbanization and rapid population growth, these centers are often facing transitions in the provision of services including water and waste management. For example, in smaller settlements, a single well may suffice for water supply, but as populations increase, this must be supplemented by piped water delivery systems. In contrast, larger cities tend to be older and more established. The transitions in water supply and management require a lot of energy and resources and are ideal opportunities to ensure that sustainability is taken into account in further groundwater development.

5.3 General strategies and requirements

There are several organizational and institutional strategies and requirements that can make a sustainability pathway more effective. These can loosely be divided into three main types: (i) groundwater system understanding and monitoring, (ii) community participation and (iii) capacity building, and coordinated management and strong institutions.

5.3.1 Aquifer system understanding and monitoring

The basis of sustainable development and use is knowledge about the groundwater and the larger water system as a whole. This includes the understanding of groundwater availability, the recharge mechanisms, the impact of groundwater abstraction, the interaction with surface water, related or dependent ecosystems including wetlands, and potential changes in groundwater quality.

Groundwater mapping, which provides insight into the location and extension of aquifers, their recharge rate, storage, and productivity, is needed to determine which abstraction rate can be balanced by the natural recharge. Ideally, the abstraction rate will be lower than the recharge to build resilience to droughts in extremely dry years. However, when high abstraction is socially acceptable, it is imperative to understand how long the (planned) abstraction rate can be maintained, in terms of the economic viability of groundwater use and environmental effects on dependent ecosystems. The risk of current and future water quality, including saltwater intrusion and pollution from the surface, must also be taken into account.

Once a socially acceptable abstraction rate has been decided upon, monitoring of groundwater levels and abstraction rates is crucial. Even the best available maps and hydrogeological models are simplifications of reality, and the response of groundwater levels to abstraction may be different from what was expected. This makes long-term monitoring important, as it is the only way to signal that additional sustainability measures must be taken before the impacts of over-exploitation are noticeable. Ideally, this monitoring should even start before abstractions so the impact of (increased) abstraction can be quantified. Monitoring of the baseline situation can also provide insight into recharge events and processes, which are an important building block for groundwater management plans. The monitoring data should be the basis of regular reporting, and both should be available for all users.

Water quality should be monitored as well. Groundwater quality in shallow phreatic aquifers can vary seasonally and interannually as a result of fluctuations. Population growth may increase the risk of groundwater pollution if sanitation services and waste management are not developed accordingly. And finally, over-exploitation can increase the risk of saline intrusion. Monitoring is needed to ensure that a groundwater quality risk is detected in a timely fashion.

The importance of a transparent and open monitoring scheme accepted by all users cannot be overemphasized, as it forms the basis for the understanding of the current status of groundwater resources and informs discussions about how these may change in the future depending on changes in use scenarios.

5.3.2 Community participation and capacity building

A sustainability pathway has a higher chance of success if all stakeholders are involved in groundwater management. Effective community participation starts with raising awareness and capacity building, ensuring all users understand groundwater issues and their context. This includes agricultural, domestic, industrial, and environmental users. In order for capacity building to be successful and continuous, it is imperative that all users have access to groundwater data, including storage, yields, water quality data, and the boundaries of the aquifer. This means that institutional arrangements must be made about how and where data is stored, and how it is processed, interpreted, and disseminated.

Proper understanding forms the basis for dialogue and support for and cooperation in water demand management and water conservation. A good way to make data available to all users is to develop a dashboard that is accessible to all users where all data and information are presented in a clear and organized fashion.

The next step in making community participation more successful is to facilitate the adoption of water conservation strategies. This facilitation can be achieved through the design of the organizational structure, financing management, and a proactive government role. Additional capacity building may also be necessary to implement new water conservation strategies and increase groundwater management capacity at all levels.

Community participation in management is essential, but there are other forms of participation that should be considered. Long-term and effective use of infrastructure is more likely when the community is involved in and preferably responsible for operation and maintenance. Citizen science is another approach in which groundwater users are motivated to take measurements, giving them a sense of ownership of the acquired data and a higher understanding of the relevant processes.

5.3.3 Coordinated management and strong institutions

Management of groundwater should be coordinated between relevant institutions and actors, but also between surface and groundwater resources. This coordination is needed between government institutions at all levels, non-governmental organizations, community representatives (as discussed in the previous section), and other agencies that can influence groundwater availability and quality (e.g. NGOs from the WASH sector). The first step towards coordinated management is to ensure that policies and legislation are consistent between ministries, but also between levels of government. However, communication and cooperation about visions and strategies related to the quantity and quality of water resources and groundwater, in particular, needs to be continuous. Such measures need to be set according to national water policies.

Regulation and management of groundwater resources can only be successful when supported by strong institutions. Institutions play an important role in strategic management planning, and therefore shaping and incentivizing stakeholder behavior, as well as promoting a sense of ownership. In a general sense, evidence has shown that strong institutions promote poverty reduction (Leftwich 2000) and are related to economic growth (Aron 2000). Related to groundwater resources in particular, farmer-led management systems are more effective when well-defined institutions exist that support the assignment of property rights to land and water and provide avenues for conflict resolution concerning those rights (Hanemann 2014). Besides the planning aspect, it is crucial that the institutions are trusted and that they enact and enforce rules and regulations. Therefore, strengthening institutions at all levels is imperative to ensure sustainable groundwater management.

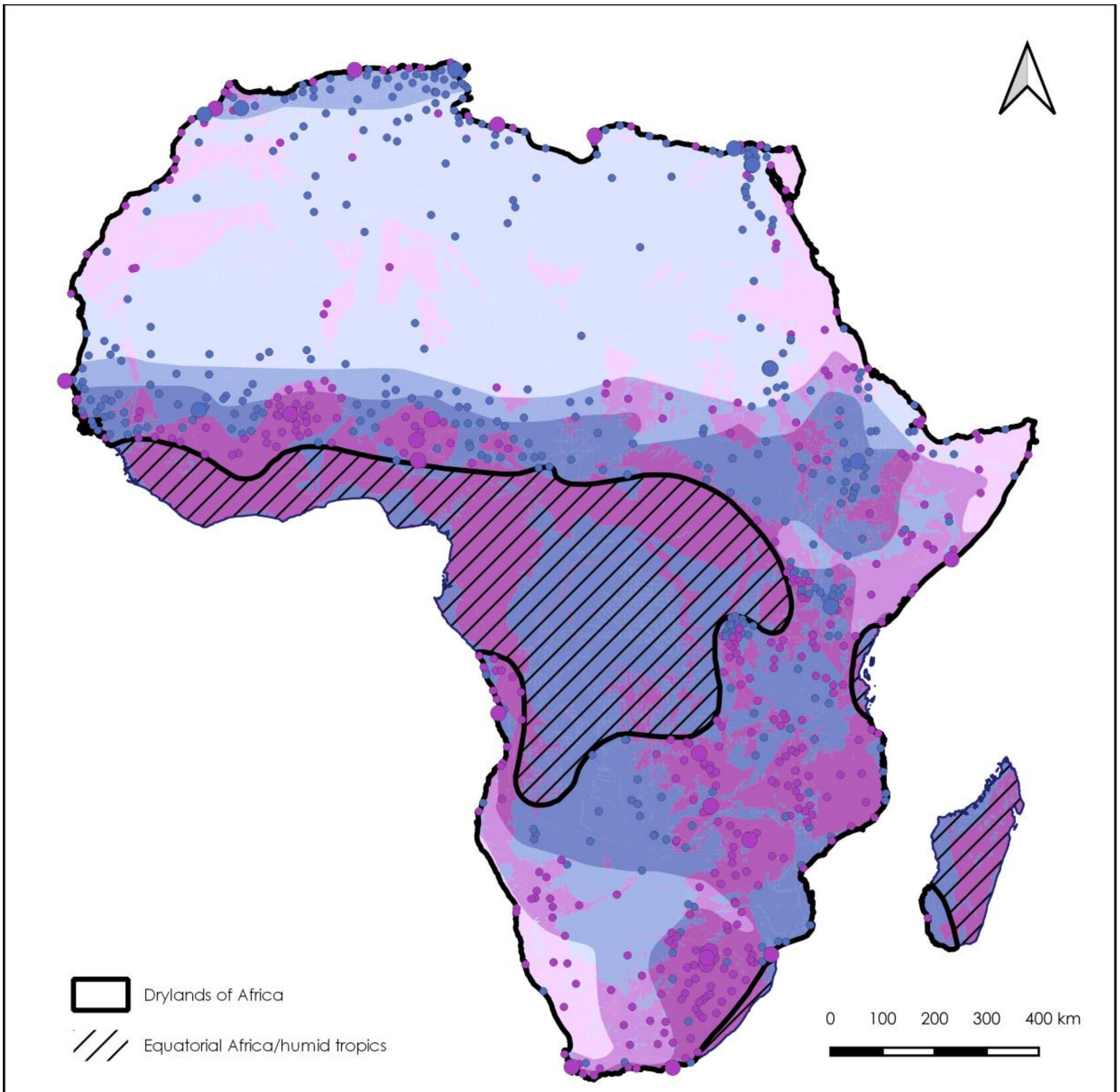
Many large-scale aquifers are transboundary, whether between countries or between provinces or counties of a single country. In these cases, a joint technical group and a high-level steering committee should be appointed. In addition, there should be extra attention to creating a common groundwater database, establishing a joint monitoring strategy, ensuring policies and legislation are harmonized, and setting up joint conflict prevention and resolution strategies.

6 Conclusions

Groundwater resources are an important freshwater resource globally, and in the African drylands in particular. They are critical for supplying drinking water, ensuring food security, adapting to climate variability, supporting biodiversity, and sustaining surface water bodies. However, groundwater resources are under pressure due to climate change and increasing population pressure, and groundwater is increasingly depleted or polluted in the African drylands. Such non-sustainable use of groundwater can have severe environmental and socio-economic impacts. Falling groundwater tables hamper socio-economic development, threaten water and food supplies, and be a cause of conflict when access to the resource becomes unequal. In addition, decreased baseflow from groundwater can cause river flow to decrease and wetlands to shrink, potentially impacting biodiversity. At the same time, groundwater has the potential to address increasing food demand (Altchenko and Villholth 2015, Pavelic et al. 2013) and support the achievement of various Sustainable Development Goals. Therefore, it is crucial to ensure groundwater resources are used as sustainably as possible to support current and future generations.

In the African drylands, a strict hydrological approach to sustainability in which groundwater abstractions must not be higher than the natural recharge rate is not realistic. In light of the importance of water and food security in the region, it is recommended to evaluate the impact of abstractions on the current and next generations, a time period of around 50 years. If this effect is limited, than abstractions higher than the natural recharge rate may be socially acceptable. This approach assumes that in the future technological innovations and energy transitions will allow people to tap (ground)water resources that are currently unavailable or economically unfeasible. In the African drylands, regions with largely untapped aquifers (mainly in Sub-Saharan Africa) could expand groundwater use to contribute to achieving the Sustainable Development Goals, while in highly-stressed aquifers in arid regions (such as North Africa), socially-accepted groundwater depletion may be the highest achievable goal.

In this study, pathways towards (more) sustainable groundwater development and use have been described. The sustainability pathways presented here provide insight at the regional scale, but do not necessarily reflect the local situation. Before putting a sustainability pathway into practice for a particular location, a detailed hydrogeological and socio-economic analysis should be performed that takes all available water resources (including surface water), all users and stakeholders and expected climatic, environmental, and socio-economic changes into account. Even after putting a specific pathway into practice, regular monitoring is needed to signal whether adjustments may be necessary as a result of changing conditions. This is, therefore, an iterative process. Nevertheless, the pathways described here provide first steps towards sustainable groundwater use in different landscapes.



Hydrogeol. Envir.	Urban/rural	Recharge/population	Legend	Strategies
Basement rocks Well productivity < 1 l/s Small stored volume	Rural	Recharge < 5 mm/y		• No strategies
		Recharge 5–25 mm/y		• Solar powered wells and surface reservoirs • Small-scale MAR
		Recharge 25–100 mm/y		• Well (fields) just outside village • Small-scale MAR • Agricultural water-saving and crop selection
	Urban	Population >5,000		• Bank infiltration in wadis and reservoirs • Non-conventional water sources
		Population >1,000,000		• Non-conventional water sources • Reduction of non-revenue water
Sedimentary and volcanic rocks Well productivity > 1 l/s Large stored volume	Rural	Recharge < 5 mm/y		• Prioritize water allocation • Agricultural water-saving and crop selection • Regulation of abstractions and exit strategy
		Recharge 5–25 mm/y		• Solar powered wells • Small-scale MAR
		Recharge 25–100 mm/y		• Multi-village, high-capacity wells • Small-scale MAR • Agricultural water-saving and crop selection
	Urban	Population >5,000		• Large-scale MAR • Non-conventional water sources
		Population >1,000,000		• Large-scale MAR • Non-conventional water sources • Reduction of non-revenue water

Figure 25. Overview of landscape types and a selection of strategies towards sustainable groundwater use.

6.1 Sustainability pathways for representative landscape types

Groundwater use in African drylands is highly variable and depends on physical and social dimensions. Natural recharge of groundwater resources can be quite low, yet storage and water availability can be very high (Figure 3). Groundwater abstraction infrastructure is closely linked to the hydrogeology on the one hand and the intended use on the other. Therefore, there is no single sustainable use pathway that can be applied to the area as a whole. Instead, pathways to promote sustainable groundwater development have been developed for a set of landscape types (chapter 5).

6.1.1 Profiling opportunities: landscape types

In this study, the African drylands have been divided into ten representative landscape types based on the hydrogeological environment, whether the area is rural or urban, and the aquifer recharge rate or population. Each landscape type is characterized by typical socio-economic conditions and specific groundwater issues (chapter 2.5 and Table 6). A rough indication of the location of different landscape types is shown in Figure 25.

The hydrogeological environment is described by basement rock landscapes with typically low aquifer productivity and storage and sedimentary and volcanic rock landscapes with typically high aquifer productivity and storage. Large-scale well development in basement rock landscapes (covering about 35% of the African drylands) is not possible. Instead, a large number of wells with small yields may be necessary to meet water demand. As a result of the low yields, groundwater use in these regions is mainly limited to household use and small-scale irrigation, even when the number of wells is increased. In sedimentary and volcanic rock environments with high aquifer productivity and storage (covering about 65% of the African drylands), however, groundwater development for domestic and agricultural use is possible, though costly at times. The possibility of groundwater development renders them more sensitive to over-exploitation, especially where recharge is very low. These environments with very low recharge but typically high aquifer productivity and storage and cover approximately 35% of the African drylands and are areas where evidence of overexploitation has already been observed (Figure 15). Urban landscapes are generally more vulnerable to groundwater pollution and health risks resulting from the use of informal wells, inappropriate sanitation facilities, and industrial activities.

Note that Figure 25 shows a two-dimensional representation of a three-dimensional phenomenon. Aquifers with different hydrogeological and recharge characteristics may be present on top of each other at the same location. For example, several sedimentary and volcanic rock aquifers can be present on top of the basement rock, and bedrock is usually overlain by a layer of unconsolidated (loose) sediments. In the same way, recharge of different layers of aquifers can vary considerably depending on which aquifer is considered. The relative areas mentioned in the previous paragraph are thus an only an indication of relative occurrence.

6.1.2 Sustainability pathways and priority landscapes

A sustainability pathway was developed for each of the representative landscape types (see summary in Figure 25 and full overview in Table 10 and Table 11). These sustainability pathways consist of three main categories of sustainability strategies:

- measures that increase (ground)water availability,
- measures that reduce water demand, and
- institutional arrangements that affect (ground)water use.

An overview of different measures falling under each category can be found in Table 7.

Quantifying the effectiveness of the respective measures and their costs is not straightforward as these can vary with the location and design of the measure. This is especially true for water-saving measures, which are generally only effective when combined with regulation of abstractions or irrigated area, and institutional measures. An approximation of the effectiveness and costs of a selection of measures increasing water availability is presented in Table 8. This shows that small-scale measures are generally more cost-effective than large-scale measures. At the same time, large-scale measures are capable of providing very large volumes of water and are therefore a viable option in urban areas where such large investments are more economically feasible.

Of the representative landscape types, the following are considered to have the highest potential in terms of making steps towards sustainable groundwater use and are therefore considered to be priority areas:

- rural areas with medium recharge rates,
- rural areas with very low recharge and high aquifer productivity and storage, and
- smaller urban centers.

In rural areas with medium recharge rates, inexpensive, small-scale measures are most feasible and effective. Small-scale artificial aquifer recharge infrastructure, such as sand dams, has the potential to increase water availability, decrease vulnerability to drought, and increase household income. Where groundwater irrigation is currently practiced, or where it will be developed in the future, simple and inexpensive agricultural water-saving (such as tillage methods and mulching) and crop selection strategies (using less water-intensive, higher-value crops or more salt-tolerant crops) have high potential to reduce water demand and thereby contribute to more sustainable use.

The second priority landscape consists of rural areas with very low recharge, but high aquifer productivity and storage. This landscape is considered a priority because significant over-exploitation is already observed (Figure 15), mainly as a result of large-scale irrigation schemes. Here, more expensive and large-scale agricultural water-saving measures are feasible to reduce water demand. This includes transitioning towards more efficient irrigation methods (such as drip irrigation rather than pivot irrigation) and piped water conveyance rather than open canals, but also crop selection. However, these types of measures will only lead to water savings if accompanied by institutional arrangements such as prioritization of water use and the regulation of abstractions and/or irrigated area.

Smaller urban centers are the third priority landscape. As a result of rapid urbanization, economic development, and population growth, these centers are often facing transitions in the provision of services including water and waste management that provide ideal opportunities to ensure that sustainability is taken into account in further groundwater development. Here, large-scale and relatively expensive technologies are feasible and have higher potential than small-scale interventions. Non-conventional water sources are the most effective method to increase water availability, including wastewater recycling, dilution, desalinization in coastal zones and areas where groundwater is saline (Figure 5 and chapter 4.5), and improved water treatment. The potential and feasibility of such non-conventional water resources are expected to increase in the future as a result of research and technological development. Reduction of water demand can be achieved by upgrading existing systems and reducing non-revenue water, as well as encouraging water-saving measures in industry, and households.

A more in-depth analysis (for a particular location or region) could map (future) water demand by sector, making use of data about urbanization, population growth, and irrigation potential. Such an investigation could form the basis of a more quantitative analysis of sustainability pathways.

6.2 The way forward: acknowledging groundwater importance and overcoming funding challenges

Groundwater is a critical resource from socio-economic and environmental perspectives, but it faces increasing pressure and groundwater management is often neglected. This study presents the first steps towards increased but at the same time more sustainable groundwater use in African drylands. However, there are three main challenges that need to be overcome when putting the sustainability pathways into practice:

- lack of understanding of the groundwater system and awareness of its importance,
- local lack of groundwater expertise, and
- funding issues.

Currently, the low profile of groundwater resources contributes to inadequate management and monitoring of the resource (chapter 2.4.5). One way to increase the visibility and perceived importance of groundwater resources would be to incorporate groundwater more specifically into all SDG pathways related to food security, water, and energy. The first step towards achieving this would be to describe the relationships and interlinkages between groundwater and each of the SDG pathways. This would not only increase awareness of groundwater resources and their importance but also contribute to an integrated sustainability strategy for groundwater resources balancing environmental and socio-economic aspects.

The step from awareness to putting sustainable groundwater development into practice further requires groundwater expertise (chapter 2.4.6). Expertise on how to evaluate and develop groundwater, including groundwater monitoring. Management capacity is needed to develop groundwater management plans that carefully weigh hydrological sustainability and socio-economic factors, with a vision for short-term and long-term use. The development of this expertise is best achieved through capacity building, which is also mentioned above as one of the requirements for sustainable groundwater use.

Last, but certainly not least, is the challenge of funding for groundwater development and protection projects (chapter 2.4.6), particularly considering that small-scale projects are more effective in rural areas. A first approach to address this issue is to bundle a number of small-scale projects together. A similar tactic has been applied within the Reducing emissions from deforestation and forest degradation (REDD) project. By bundling smaller projects, it is not only easier to apply for larger funding bodies, but funds will likely also be used more effectively by cutting costs that would be related to a large number of individual projects. Another approach is to supply a lump sum for groundwater-related projects at national or regional level and assign a managing body to distribute the amount over small projects. The managing body would ideally consist of one or more experts without local interests who are responsible for controlling the quality and effectiveness of the expenditures and local administrators to supply the local context and delineate priority areas.

Addressing these challenges is crucial to ensure the sustainability pathways described here are implemented effectively and that their maximum potential is achieved, thereby contributing to more sustainable groundwater use in African drylands.

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