Hydrogeology Journal (2019) 27:1099–1110
https://doi.org/10.1007/s10040-018-1892-1

PAPER

Review: Challenges and opportunities for sustainable groundwater management in Africa

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Received: 2 March 2018 / Accepted: 31 October 2018 / Published online: 29 November 2018

Abstract
Groundwater plays a fundamental yet often little appreciated role in supporting economic development and human well-being in both urban and rural environments, as well as supporting many aquatic ecosystems in Africa. Thus, groundwater has high relevance to the development and well-being of Africa, if adequately assessed and sustainably exploited. Whilst the potential for groundwater-resources development continues to be reported in the literature, a quantitative understanding of these issues remains poor. The objective of this paper is to highlight the main groundwater issues and problems in Africa and the current and expected opportunities for sustainable groundwater management. This will be done through the review of existing knowledge of groundwater resources and of ongoing and planned groundwater management programs and initiatives. Groundwater resources in Africa face increasing threat of pollution from urbanisation, industrial development, agricultural and mining activities, and from poor sanitation practices and over-exploitation due to increasing demand to meet human and agricultural needs. However, despite the existence of a number of groundwater management challenges, groundwater resources in Africa are still generally under-developed and can meet the various needs in a sustainable manner if better managed. Thus, strategies to ensure sustainable development and management of groundwater resources need to be put in place. These include establishment of groundwater monitoring systems, understanding of the groundwater–aquatic ecosystem relationships, management of transboundary aquifers, addressing climate-change impacts on groundwater, assessing the impact of increased pumping from various types of aquifers on sustainability of groundwater abstraction, and capacity building in groundwater management.

Keywords Groundwater management · Sustainability · Sub-Saharan Africa · Review

Introduction

The total water resources available in the world are estimated to be in the order of 46,000 km^3/year, including about 36,000 km^3/year of surface waters and 10,000 km^3/year of groundwater (Trenberth et al. 2007). These resources are distributed throughout the world according to the patchwork of climates and physiographic structures. At the continental level, America has the largest share of the world's total freshwater resources with 45%, followed by Asia with 28%, Europe with 15.5% and Africa with 9%. In terms of resources per inhabitant in each continent, America has 24,000 m^3/year, Europe 9,300 m^3/year, Africa 5,000 m^3/year and Asia 3,400.1 m^3/year (FAO 2003).

Groundwater is an essential part of the natural water cycle and is present nearly everywhere beneath our feet. As part of the water cycle, groundwater is a major contributor to flow in many streams and rivers and has a strong influence on river and wetland habitats for plants and animals. It forms the largest available store of fresh water on the Earth. About 23,400,000 km^3 of groundwater exist on Earth; 54% is saline and 46% (10,530,000 km^3) is freshwater (Gleick 1996).

Nevertheless, groundwater is a hidden asset, out of sight and all too often out of mind. Groundwater comes mostly from rainfall that has infiltrated into the ground. If not pumped out of the ground for different human uses, most groundwater eventually discharges into continental surface waters (~80%) or into the sea (~20%) where it supports river flows, and maintains ecosystems. Groundwater is therefore the primary

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source of water for rivers and lakes in summer or at times of drought.

Three-quarters of all the groundwater pumped from boreholes or taken from springs is used for water supply to the majority of the population in Africa. Groundwater use for irrigation is forecast to increase substantially to combat growing food insecurity on the continent. In some areas, groundwater wells are the only available drinking-water source, supplying nearly all those who do not have water mains. Groundwater is also used for bottling and food processing as well as other industrial activities. There are advantages in using groundwater for both public and private supplies, compared to surface water—tt is of relatively high quality and usually requires less treatment prior to use, even for drinking and other potable purposes (EA 2011).

The high socio-economic and ecological importance of groundwater and the fact that groundwater is an important strategic resource are recognised throughout Sub-Saharan Africa. However, data on groundwater systems are sparse and the current state of knowledge is low and this is a serious limitation for the sustainable development of the groundwater resources. Therefore, efforts to improve the situation have been made over the last decade through the publication of syntheses and reviews at the national, regional and continental levels.

Eberhard Braune and Yongxin Xu (Braune and Xu 2008) concluded from their work that in contrast to its strategic role as an essential resource to help achieve community development and poverty alleviation in the Southern African Development Community (SADC), groundwater has remained a poorly understood and managed resource. A key finding of this scoping study regarding the status of groundwater resources management in SADC region was that groundwater management links to the groundwater-dependent sectors like agriculture, rural development, health and environment are not well established in policy or in practice.

The GW·MATE (2011) report provides an overview of the major groundwater issues in Sub-Saharan Africa, with an assessment of their policy implications in terms of potential development and appropriate management. The GW·MATE report pointed out the fact that groundwater is the preferred source to meet most water-supply demands, despite hydrogeological complexity, natural constraints on water-well yields and quality, and institutional weaknesses. The report also concluded that many countries need to undertake strategic assessment of their groundwater and prioritize investment on institutional strengthening so as to facilitate appropriately managed groundwater development to meet the challenge of improving their urban water-supply security and expanding their irrigated agriculture. Above all, without effective use of available groundwater resources, improved livelihoods and climate-change adaptation will prove much more difficult to achieve.

Pavelic et al. (2012), in a review of the groundwater availability and use for 15 countries in Sub-Saharan Africa, confirmed the relative abundance of the groundwater resources in this part of the world and provided information to consolidate the existing knowledge on groundwater use and, to a certain point, some tools to support reasonable groundwater development and governance. They concluded that groundwater is a critically important resource for human survival and economic development across the vast drought-prone areas of Southern, eastern and Western Africa. However, the quantitative information on aquifer characteristics, groundwater recharge rates, flow regimes, quality controls and use is still rather patchy.

MacDonald et al. (2012) produced the first quantitative maps of groundwater resources in Africa which reveals the magnitude and distribution of freshwater stored as groundwater. The volume of groundwater is estimated to be 0.66 million km^3, more than 100 times the annual renewable freshwater resources and 20 times the freshwater stored in African lakes.

The maps demonstrate the uneven distribution of groundwater across the continent and, in particular, the large groundwater volumes available in the sedimentary basins of northern Africa. The potential for boreholes yielding greater than 5 $L\ s^{-1}$ outside of large sedimentary basins is not widespread but limited to particular areas requiring careful exploration and development. Nevertheless, for many African countries, appropriately sited and constructed boreholes will support a hand pump (a yield of 0.1–0.3 $L\ s^{-1}$), and sufficient storage is available to sustain abstraction through interannual variations in recharge.

In 2012, the African Ministers' Council on Water published a status report on the application of integrated approaches to water resources management in Africa (AMCOW 2012). The report focused on the status of water resources management in Africa and identified some of the current barriers to progress, and made recommendations for future action. Furthermore, the report contributes to the establishment of a permanent monitoring and reporting framework to promote more sustainable development and management of freshwater resources, which is an agreed objective of African Water Ministers. In particular, the report indicated great promise for water and food security in Africa, as well as for reducing the vulnerability of many countries and peoples to climate variability and change. Major challenges still abound, particularly in mobilising the investment required to meet the targets of the Africa Water Vision 2025 for basic water supply and sanitation; for irrigated agriculture; and for supporting institutional development, capacity building, research, education, and information management. The report recommended to develop and/or strengthen programmes for the following: forecasting and early warning of water-related disasters; addressing climate change adaptation through water resources management, as well as enhancing disaster risk management and water storage capacity; learning through experience and country-to-country knowledge sharing; assuring transparency and efficiency in water allocation and use; defining the general principles, categorisation, and prioritisation of water uses; defining water quality objectives; and, sustainable funding. Also, developing appropriate tools and indicators for measuring the contribution of water to development is particularly important to provide a basis for highlighting the pivotal role of water resources as an essential ingredient in the advent of a green economy in Africa. The objective of this paper is therefore to highlight the main groundwater issues and problems in Africa and the current and expected opportunities for sustainable groundwater management. This will be done through the review of existing knowledge of groundwater resources on the continent and ongoing and planned groundwater management programs and initiatives.

Key groundwater management issues

Precipitation pattern

The distribution of precipitation follows a rather simple pattern in Africa. Maximum rainfall is observed in Equatorial regions, notably around the Gulf of Guinea and Mont Cameroon, where it can exceed 4 m annually. From there the precipitation decreases northward towards the Sahara and southward towards the Kalahari.

In the northern winter (Dec–Feb), the heaviest rainfall is in Central Africa from 0° to 10° S, where the centre of lowest pressure is located. This part of Africa receives both south-east trade winds from the Indian Ocean and monsoons from the Arabian Sea. The extreme north receives some rain from the Mediterranean, but the whole belt of the Sahara from the Atlantic to the Red Sea as far south as Lake Chad is almost rainless. At the same time, the coast of Guinea, as far south as the Congo, gets a moderate rainfall from the prevailing south-east winds drawn in by the lower pressure on the land. In South Africa, Natal, the coast of Cape Colony, and the Transvaal have their wet season, but the western regions, from Cape Town to the tropics, are dry, the winds being off-shore.

In the southern summer, there is a centre of high pressure over the cool southern plateau in Cape Colony and the Transvaal. This diminishes the force of the trade winds, and gives a dry season in Natal and along the east coast generally as far north as the equator. South-west Africa is now almost rainless, except for a small district around Cape Town, which at this season just comes within the zone of westerly winds, and therefore has a wet (winter) season, like the Mediterranean countries.

The zone of heaviest rainfall has now moved north with the sun and, in July, lies along the coast of Guinea and in the lower Niger basin. The whole continent from 0° to 15° N has a fairly heavy summer rainfall (least in Somaliland), but north of 20° there is virtually no rain, owing to the intense heat and the dryness of the north-east winds. The equatorial belt has no real dry season, but rather two distinct wet seasons (about March and September) separated by two less wet seasons.

Globally the rainfall is a strong function of altitude: it doubles on average every 2,000 m; therefore, the mountains and highlands (Fouta Djalon, Kilimanjaro, Mount Cameroon, Ethiopia) are the "water towers". Extremes of high temperatures in Africa do not occur in the equatorial belt, except near the southern margin of the Sahara. The average temperature for Timbuktu in May is about 46°.

Nearly the whole of Africa drains to the Atlantic basin. Only three major rivers flow elsewhere: the Zambezi and Limpopo flow to the Indian Ocean, and the Nile to the Mediterranean Sea. There is a wide range of hydrological situations in Africa and it could be divided into 24 major hydrological units or basin groups: 8 major river basins, draining to the sea (Senegal, Niger, Nile, Shebelle-Juba, Congo, Zambezi, Limpopo and Orange rivers); 9 coastal regions grouping several small rivers, also draining to the sea; 5 regions grouping several endorheic drainage basins (Lake Chad, Rift Valley, Okavango, South Interior and North Interior).

Geological and hydrogeological setting

The availability of groundwater depends primarily on the geology. Groundwater is stored within pore spaces and fractures in rocks. Where the pores or fractures are interconnected, groundwater can flow easily and the rocks are said to be permeable. Fractured or porous rocks such as sandstones and limestones, therefore have a high potential for groundwater development. The availability of groundwater also depends to a certain extent on the volume and intensity of rainfall. The hydrogeology of Africa has been classified according to geological environment (Fig. 1).

Reviews of the regional hydrogeology are available in the literature (UNESCO 1991; Guiraud 1988; MacDonald and Davies 2000; MacDonald et al. 2011, 2012). Guiraud (1988), on the basis of their geological and stratigraphical features, has identified about 12 principal aquifers ranging from the crystalline and metamorphic rocks of Precambrian age in most of West Africa to the Post-Hercynian volcanic formations in East Africa, providing the most complete description of the aquifers in Africa. However, what is used here is the simplified classification given by MacDonald and Davies (2000), who have identified, mainly based on their geological characteristics, four provinces represented by the Precambrian "basement" rocks; volcanic rocks; unconsolidated sediments; and consolidated sedimentary rocks.

Precambrian crystalline basement rocks occupy 34% of the land surface of Africa and are found in West Africa, Eastern

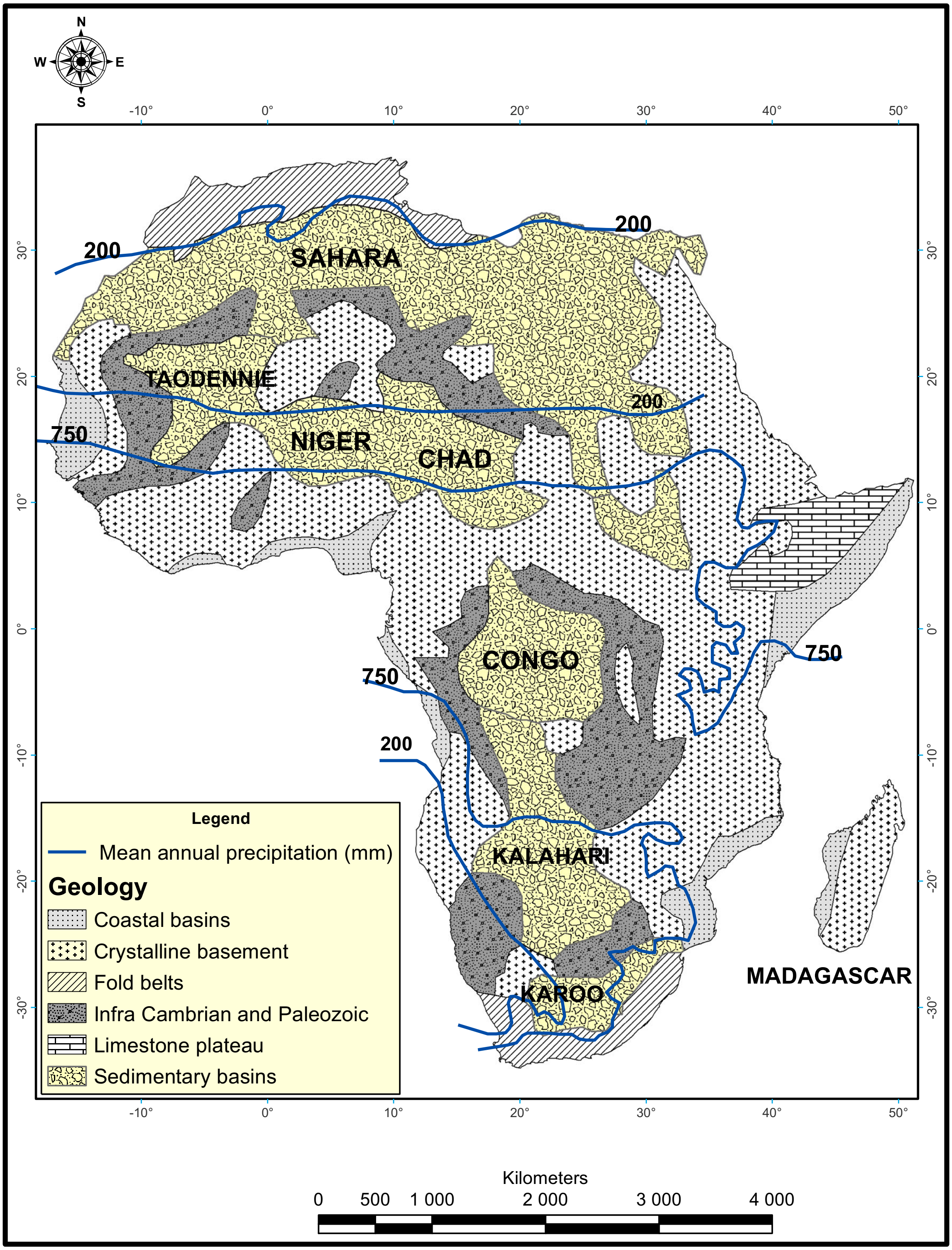

Fig. 1 Groundwater regions of Africa (after Dijon-Les Eaux Souterraines de l'Afrique in Wright 1992, reproduced by Gaye)

Africa (Uganda, Tanzania) and Southern Africa (Malawi, much of Zimbabwe, northern Mozambique and northern South Africa). They comprise crystalline rocks with very little primary permeability or porosity (MacDonald et al. 2012). Basement aquifers are developed within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin which are mainly of Precambrian age. Sedimentary cover rocks, even when consolidated and of comparable age, usually differ in certain key aspects, most notably in mineralogy with a preponderance of components of lower susceptibility to chemical weathering (quartz sands and clays). Unmetamorphosed volcanic rocks can also be distinguished since they may have significant primary porosity and layering along with associated sedimentary intercalations. Additionally, recent volcanic rocks occur mainly in upland areas where any weathering products tend to be rapidly eroded. Yields of properly sited boreholes in Precambrian basement rocks are commonly 0.1–1 L/s, but can occasionally be as high as 10 L/s.

Consolidated Proterozoic and Palaeozoic sedimentary rocks occupy 37% of the land area of Africa. Four major categories of aquifers are hosted by these formations. The aquifers within fractured thick sandstone formations such as the consolidated sandstones of the Upper Proterozoic and those of the Cambro-Ordovician, contain considerable volumes of groundwater and support high-yield boreholes of 10–50 L/s. The springs flowing from the bottom of the Assaba cliffs (Mauritania) and the Banfora cliffs (Burkina Faso) are outlets of these aquifers. The fractured aquifers in schisto-pelitic formations are often unproductive or only support yields of less than 0.5 L/s. Karstic aquifers are found in thick carbonaceous intercalations and where the dolomitic limestones drain water contained in fractured sandstones. Boreholes in the region of Kiffa (Mauritania) and north of Burkina Faso have provided high-yield fractures (100 m^3/h for the Christine borehole). Aquifers of this kind are encountered among others in Democratic Republic of Congo RDC, Zambia, Angola, Namibia (Etosha Basin), Transvaal and Algeria. Aquifers are also found in the loosely cemented sandstones and conglomerates of Upper Palaeozoic around the region of Agades in Niger, the Karoo basin in South Africa, Madagascar and East Africa. The Karoo series often correspond to multilayered aquifers with very variable yields. Volcanic rocks are also present and can contribute as drains. The largest groundwater volumes are found in the large Saharan sedimentary aquifers (North Western Sahara Aquifer, Nubian Sandstone Aquifer System, Senegalo Mauritanian Aquifer). These aquifers contain fossil water that infiltrated up to a million years ago and have very little present-day recharge (Guendouz and Michelot 2006; Guendouz et al. 2003; Sturchio et al. 2004).

Unconsolidated sediments are probably the more productive aquifers in Africa and occur in southern Mozambique, central Democratic Republic of Congo, and across much of the Sahel. Unconsolidated sediments are also found along major and minor rivers and in coastal areas, but are often fine textured and therefore of low permeability. Groundwater is associated with sediments, which vary from coarse gravel and sand to silt and clay. They are easy to drill and hand drilling is possible where aquifers are shallow.

Volcanic rocks can be important aquifers but the complexity of the geology leads to a high variability in groundwater potential which is related to the presence of fractures. These aquifers are mainly located in the Ethiopian and Kenyan highlands and Southern Africa.

Role of groundwater

Groundwater is important for drinking water, livestock water, and irrigation in Africa. It is of vital importance in meeting the sustainable development goals (SDGs), specifically SDG6 on water, as most of rural Africa and a considerable part of urban Africa are supplied by groundwater. Groundwater also plays a major role in improving food security through expansion of irrigation supplied by shallow and deep wells. Thus, groundwater has high relevance to the development and well-being of Africa, if adequately assessed and sustainably exploited. Whilst the potential for groundwater resources development continues to be reported in the literature, a quantitative understanding of these issues remains poor. MacDonald et al. (2012) have estimated the total groundwater storage in Africa to be within a range of 0.36–1.75 million km^3. In most cases the groundwater resources are of excellent quality microbiologically and of generally adequate chemical quality for most uses. Health problems are associated with elevated concentrations of arsenic and fluoride, or the deficiency of iodine, whilst in some places, the total salt content of the water is high and makes the water unsuitable for drinking.

Current groundwater use in Africa

Whereas groundwater development in Africa has been ongoing since the 1930s mainly for rural water supply through deep boreholes and springs (Adelana and MacDonald 2008), the current levels of groundwater resource development in Africa are low, except in localised areas and around some major towns and cities. Most of Sub-Saharan Africa is experiencing 'economic water scarcity' due to lack of infrastructure investment, rather than 'water resource scarcity' as reflected by average rainfall and population density (GW·MATE 2011). The classic problems associated with major and excessive groundwater development are, for the moment, very localised, and the priority must be more effective planning and sustainable implementation of groundwater development (often in minor aquifers) to help meet critical social welfare targets and livelihood opportunities. Managed groundwater development, to meet a variety of demands, will be vital in the overall future development process, but priorities and rates of implementation will vary considerably with differing national socio-economic trajectories (GW·MATE 2011). An issue which has generally impeded groundwater development in Sub-Saharan Africa is the high cost of water-well construction compared, for example, to that elsewhere (most notably in India). The cause is complex; however, one factor which can easily be remedied is inappropriate well design and construction, with excessive drilling depth in some ground conditions, and insufficient use of low-cost technology options.

There has however been an increase in intensive groundwater abstraction mainly for town water supply since the early 1990s, due to the need to have piped water supply systems that can easily be operated and managed by the users (Tindimugaya 2008). In addition, groundwater normally has good quality and requires little or no treatment unlike surface water. This therefore makes investment and operational costs of groundwater-based systems much lower than those of surface-water based systems. Boreholes with yields greater than 3 m^3/h are thus normally considered for installation with motorised pumps for piped water supply (Tindimugaya 2000). The recent drilling of high-yield boreholes (>20 m^3/h) for town water supply has been made in former river channels in various parts of the continent.

Pavelic et al. (2012) provide useful information on water use for the different subregions. In West Africa, a major use of groundwater is drinking water for both rural and urban populations. Drinking water supplies sourced from groundwater for rural/small towns serve 33% of Ghana, 92% of Niger, 70% of Nigeria and 55% of Mali. Burkina Faso uses groundwater as the principal source of supply in small towns and rural areas. Groundwater is accessed by various means such as hand-dug wells, bore water extracted using hand pumps, motorised pumps, government/private network supply, etc. Whilst groundwater use for irrigation is largely limited, the scenario is expected to change in many cases as the development of groundwater to sustain agriculture is expected to grow in the short or mid-term.

For Southern African countries, groundwater is mostly used for rural water supply and for mining in isolated areas. Drinking water supplies sourced from groundwater for rural/small towns serve 51% of Zambia, 70% of Zimbabwe, 65% of Malawi, 60% of Mozambique and 60% of South Africa. Irrigation demand for groundwater is expanding, although where surface water is abundant, this appears to be preferred. South Africa and Zimbabwe use the largest amounts of groundwater for irrigation. A good number of commercial farmers such as around the Lusaka area in Zambia, use groundwater from boreholes for their irrigation and livestock production, whilst shallow wells are used mostly for rural water supply, and recently very shallow wells (< 9 m deep) in floodplain areas have come into use for treadle pump and bucket irrigation.

In East Africa, groundwater is the most important water source for a great majority of the population, whilst the available data indicate limited irrigation use. In some arid and semi-arid regions it is the only source of water. Drinking water supplies sourced from groundwater for rural/small towns serve 85% of Ethiopia, 50% of Kenya, 70% of Somalia, 56% of Tanzania and 70% of Uganda. Groundwater in Kenya is used for many different purposes including human consumption, livestock watering, wildlife watering and crop production with substantial scope for expansion.

Groundwater pollution

In Africa, on average 65% of the population depends upon in-situ sanitation (mainly the basic pit latrine) and around 10% have no sanitation system whatsoever, whilst 25% of the population is reported as having a 'flush toilet' (Adelana and MacDonald 2008; GW·MATE 2011). Some of the population is connected to septic tanks, and it is only in the larger cities of middle-income countries (and a few exceptions) that water-borne sewerage systems exist, and even there, not all dwellings in the nominal area of coverage are connected. In urban areas, only a minor proportion of pit latrines are emptied (and contrary to operational guidelines sometime after construction most are connected to supplementary pits). This information implies a very large subsurface contaminant load and threat of groundwater pollution, especially in situations of highly populated peri-urban areas underlain by shallow aquifers. Thus, the main groundwater pollution problems are high nitrate concentrations (coupled with other types of chemical contamination) and the hazard of faecal contamination from pit latrines. The pollution load from unsewered sanitation in some places is variously augmented by industrial effluent disposal, hydrocarbon spillage/leakage and leachates from solid-waste tipping. The risk of faecal pollution of groundwater, however, should be limited to the most vulnerable hydrogeological conditions; however, it currently remains a much more widespread problem because of inappropriate in-situ-sanitation-unit design/operation and inadequate water-well-sanitary completion, including the definition of a protective zone (or perimeter) around each water supply well, where pit-latrines or any polluting activity should be prohibited.

Groundwater management challenges

Intensive groundwater development for domestic water supplies in Africa began in the twentieth century in association with urbanisation. Groundwater is a common low-cost alternative to surface water for urban water supplies as it is widely distributed and generally of potable quality. Despite growing dependency upon groundwater for urban water supplies, however (Taylor et al. 2004), concerns remain over the sustainability of these supplies not only in terms of the magnitude of abstraction but also its quality. Sub-Saharan Africa is the most rapidly urbanising region in the world (320% from 2000 to 2050, United Nations 2007). This rate of growth presents major challenges to the provision of not only safe water supplies but also sanitation. First, few reliable groundwater data exist upon which abstraction policies can be based (MacDonald et al. 2001). Indeed, there has been comparatively limited investment in monitoring infrastructure for groundwater resources relative to surface-water resources. Recent research from Uganda highlights the importance of aquifer storage at the borehole catchment scale in determining the sustainability of intensive abstraction for town water supplies (Tindimugaya 2008). Second, inadequate community hygiene in many rapidly urbanising centres makes urban water supplies derived from shallow groundwater vulnerable to contamination (Howard et al. 2003).

At national to regional scales, limited technical and institutional capacities constrain sustainable groundwater development and management in Africa. Since major gaps exist in current knowledge of groundwater resources in Africa and their relationship to climate variability and change, major investments are required in programmes of applied, interdisciplinary research in groundwater and climate. As demand for expertise in hydrogeology and climatology rises with the inevitable increase in groundwater use in Africa, similar investment is also required in training and capacity building in hydrogeology, climatology and allied fields in water policy and management. Such efforts need to recognise that considerable time lags can occur between changes in groundwater resources and their impact on surface-water resources and these complicate integrated water resources management, including issues around 'cause and effect'.

Furthermore, the development of effective institutions to manage transboundary groundwater resources in Africa is an added challenge. A recent review by Nijsten et al. (2018) indicates that 72 transboundary aquifers (TBAs) have been mapped in Africa. These TBAs underlie 40% of the continental area, mostly in arid and semi-arid regions and are the source of water supplies for about 33% of the population. The degree of knowledge on transboundary aquifers still remains low, even though good progress has been made in their inventory over the last 20 years (BGR and UNESCO 2006; CGIAR Research Program on Water, Land and Ecosystems (WLE) 2014). So far, only 11 TBAs have been subjected to detailed studies and cooperation arrangements have been formalised for 7 TBAs, with most of these TBAs being in North Africa, the Sahel and Southern Africa. Availability of data at national level is low, hampering regional assessment. Reports on agreements scoping TBA management, indicate that this may be dealt with within international river/lake agreements, but reported inconsistencies between TBA-sharing countries also indicate that implementation is limited. Increasing awareness and support for joint TBA management is noticeable amongst international organisations; however, such cooperation requires long-term commitment to produce impacts at the local level. Thus, specific groundwater management challenges in Africa include: inadequate information on groundwater resources, groundwater pollution, the implications of complex geology, inadequate technical capacity, the impact of climate change on groundwater resources, and the management of transboundary aquifers.

Inadequate groundwater information

One of the challenges to sustainable groundwater resources management and development in Africa is inadequate data and information to guide the planning process—for example, it is unclear how far production boreholes should be sited from one another to prevent competitive abstraction and how far potential sources of pollution should be from groundwater abstraction points. There are thus key practical questions concerning the protection and development of groundwater resources for water supplies which need to be addressed namely:

- What area around wells and springs must be restricted from competitive abstraction by other wells under different pumping conditions so that either overdevelopment of the resource or undesirable reduction in the pumping water level does not occur?
- How many wells can be constructed in one area (i.e., a well-field) without reducing pumping water levels to unacceptably low levels through competitive pumping?

Groundwater pollution

There are increasing incidences of reported outbreaks of water-borne diseases resulting from the consumption of contaminated groundwater in both urban and rural areas. This is attributed to the poor location of sanitary facilities, especially pit latrines, whose contents infiltrate and mix in with groundwater. Pollution of groundwater in urban areas is also attributed to dilapidated sewerage systems and solid waste disposal sites whose contents and leachates easily infiltrate and mix in with groundwater.

Complex geology

Groundwater in about 30% of Africa occurs in fractures and weathered zones found in complex geological formations. The complex geology makes understanding of the nature of groundwater occurrence and movement very difficult. This, in turn, presents a serious challenge to sustainable groundwater management and development.

Inadequate technical capacity

Technical capacity for sustainable groundwater development in Africa is limited. The number of hydrogeologists is not only small but also their expertise is low in most countries due to the nature of training they receive with most undergraduate education being in geology with only limited courses in hydrogeology. This state of affairs inevitably results in poor quality professional work and, hence, unsustainable groundwater development.

Climate change impacts on groundwater

Current assessments of the impacts of climate variability and change on water resources commonly exclude groundwater. This omission is of particular concern in Africa where current usage and future adaptations, in response to climate change and rapid population growth, place considerable reliance upon groundwater to meet domestic, agricultural, and industrial water demands. Climate change and variability have already been observed in Africa and are projected to increase considerably over the course of this century (Taylor and Tindimugaya 2009). Rainfall intensities in most parts of Sub-Saharan Africa are projected to increase as a result of global warming and will give rise to more variable (but not necessarily less) river discharge and soil moisture (Taylor and Tindimugaya 2009, 2011). The former will exacerbate intra-annual freshwater shortages and the risk of flooding, whereas the latter threatens food security through reduced crop yields (Taylor and Tindimugaya 2009). However, current evidence suggests that the shift toward more intensive precipitation enhances groundwater recharge. As a result, groundwater in Africa could play a strategic role in the adaptation to changing freshwater availability and improving food production and security through groundwater-fed irrigation. Since small-scale farming accounts for 70% of agricultural production in Sub-Saharan Africa (UNESCO 2001), discrete low-yielding aquifers in weathered crystalline rock and fluvial aquifers in river beds may prove fit for purpose as they are self-regulating, naturally solving the age-old problem of allocation and restricting the impacts of local overdevelopment. There is a long history of low-intensity groundwater development (e.g. hand pump abstraction) for domestic water supplies in Africa. Low recharge fluxes (<10 mm year^{-1}) required to sustain such development (Taylor and Howard 1996) are expected to occur because rainfall in most of Sub-Saharan Africa exceeds 200 mm year^{-1}. There is little evidence of water-level decline from such low-intensity abstraction; localised depletion is often due to anomalous geological conditions or faulty infrastructure rather than broad-scale resource depletion. Due to the noted variability in Africa's hydrological systems, inter- and intra-annual contributions of freshwater from storage are critical to the sustainability of water supplies and maintenance of aquatic ecosystems (Taylor and Tindimugaya 2009). Considerable inter-annual variability in recharge fluxes has been estimated and observed in Africa (Taylor and Howard 1999). From a water management perspective, balancing highly variable and episodic recharge with groundwater withdrawals over decadal rather than annual timescales would likely prove more instructive; however, there are currently few long-term studies of recharge in Africa to inform such an approach. A quantitative understanding of the relationship not only between climate and groundwater, but also the impact of abstraction, is severely constrained by the near-absence of very few reliable estimates of groundwater storage in Africa.

Management of transboundary groundwater resources

Most of the 72 identified transboundary aquifer systems are managed unilaterally by individual countries. This problem is made worse by the fact that groundwater is often not included in river basin management programs, yet it may contribute substantial amounts of water to river flows as is the case in the Lake Chad Basin. Thus, uncoordinated management and development of transboundary groundwater resources will certainly result in conflict over groundwater use in situations where the aquifer is transboundary or where groundwater abstraction affects base flow to shared river courses.

Opportunities for improving groundwater management in Africa

There are many ongoing groundwater-related initiatives in Africa that provide opportunities for improving groundwater management. These can be categorised in terms of institutional coordination and stakeholder participation frameworks, information management programs and capacity building programs.

Groundwater institutional coordination and stakeholder participation frameworks in Africa

A number of institutional coordination and stakeholder participating frameworks exist at continental, regional, river basin, national and local levels in Africa that are key in sustainable groundwater management. These include the African Union (AU), African Ministers' Council on Water (AMCOW) with its specialised Africa Groundwater Commission, Regional Economic Communities (RECs), river basin organisations (RBOs), member states (ministries responsible for water), and sub-national (basins, counties/districts, and local communities).

Specifically, the African Groundwater Commission (AGWC) was established under the jurisdiction of AMCOW to pay greater attention to the management of groundwater in Africa. AGWC aims to support AMCOW to promote sustainable groundwater governance in Africa as a whole and at national and local levels. AGWC is currently not very active and the process of its reactivation is ongoing. AMCOW plans to work with partners to fully operationalise the AGWC and bring value to the groundwater sector in Africa. The institutional coordination and stakeholder participating frameworks, most specifically AGWC, provide a good opportunity to promote groundwater management in Africa.

Groundwater information management programs in Africa

A number of groundwater information management programs do exist at the various levels in Africa namely continental, regional, river basin, national and local levels. These provide information on the distribution, quantity and response of groundwater resources to human and climate impacts. These programs provide opportunities for sustainable groundwater management as elaborated in the following.

Mapping and management of transboundary aquifers

Substantial amounts of groundwater resources occur in transboundary aquifers shared by two or more countries. Most of the existing river basin organisations have started integrating groundwater in their programs. There are a number of transboundary groundwater resources management programs in Africa implemented within the framework of river basin organisations that are aimed at mapping and management of transboundary aquifers (Nijsten et al. 2018). These programs provide opportunities for sustainable management of groundwater resources in Africa.

The Nubian Sandstone Aquifer System (NSAS) forms one of the largest aquifers in the world underlying some 2,500,000 km^2 of Egypt, Libya, Chad and Sudan, dominated by desert and arid to semi-arid climate (CEDARE 2001). The NSAS states cooperate through agreements made from 1992 to date. These agreements confirm increased cooperation, with the aquifer states being prepared to engage at increased levels and intensity of cooperation (Quadri 2017). The agreement of the Joint Authority for the Study and Development (joint authority) of the NSAS, signed in 1992, was the first step in the process of cooperation.

The Irhazer-Iullemeden Basin shared by Algeria, Mali, Niger and Nigeria has an agreement on joint policy implementation through a joint legal and institutional consultative mechanism adopted by the aquifer states (Tujchneider and van der Gun 2012).

The SADC region is an example of a regional economic community (REC) which has relatively advanced TBA management. The SADC Protocol on Shared Watercourses (SADC 1995, 2000) was instrumental in getting groundwater added into the programme of activities of the African Network of Basin Organizations (ANBO) in 2008. Some of the river basin organisations in the SADC region are starting to play a role in transboundary groundwater management. The Orange-Senqu River Commission (ORASECOM) was the first river basin commission in SADC to establish a groundwater hydrology committee in 2007 to facilitate dialogue between the basin states on TBA management. The ORASECOM agreement (ORASECOM 2000) specifically mentions "hydrogeological" data among the data that the countries are obligated to exchange. ORASECOM was one of the parties suggesting to pilot TBA management principles in SADC focussing on the Stampriet transboundary aquifer system (ORASECOM 2017). This became a case study in the UNESCO-IHP-executed project on 'Governance of Groundwater Resources Governance in Transboundary Aquifers' (UNESCO-IHP and IGRAC 2016).

Groundwater monitoring

Groundwater monitoring is done at transboundary and national levels with the prime objective of understanding how water levels in aquifers respond to climatic changes and to groundwater abstraction in order to provide quantitative information for effective water resources management. A few countries in Africa have groundwater-monitoring stations, whilst most countries lack groundwater monitoring stations and this limits understanding of the response of groundwater to human and natural conditions. Countries with groundwater-monitoring stations have a good basis for decision-making regarding sustainable development of groundwater resources—for example, Uganda has a groundwater monitoring network comprising 30 wells that was established in 1999 from which data are collected monthly and stored in a database. Such monitoring networks and the resultant data sets can be used to raise awareness about the benefits and importance of groundwater monitoring.

In addition to long-term monitoring networks that assess long-term changes due to natural and man-made changes, specific monitoring is done as part of groundwater abstraction licensing. In most countries, the water laws require monitoring at all abstraction points based on powered pumps (flow, total pumped volumes and levels) and if well done, these would help to assess the impacts of intensive groundwater abstraction, therefore providing guidance on the most effective means of developing groundwater resources. Improvement in the monitoring of groundwater abstractions in pumping wells is however needed.

In addition to groundwater quantity monitoring, groundwater quality also needs to be monitored. Groundwater quality monitoring is aimed at determining the physical, chemical and microbiological properties of groundwater that determine its fitness for use; thus, the existing groundwater-monitoring programs at transboundary and national levels in a few areas in Africa provide an opportunity for sustainable groundwater management.

The Chronicles is an international consortium of scientists from across Africa and beyond, collating and analysing multi-decadal records of groundwater levels, representing long-term aquifer dynamics, in order to assess the impacts of groundwater use, climate variability and change, and land-use change on groundwater storage across Africa.

The Global Groundwater Monitoring Network (GGMN) is a participative, web-based network of networks, set up to improve quality and accessibility of groundwater monitoring information and subsequently knowledge on the state of groundwater resources. GGMN is a UNESCO programme, implemented by IGRAC and supported by many global and regional partners (IGRAC 2013). The GGMN portal gives insights on the availability of groundwater monitoring data through space and time. Groundwater level data and changes occurring in groundwater levels can be displayed on a regional scale. Additional data layers and information are available to understand the monitoring data in a broader water-related context.

Groundwater assessment

In general, the knowledge of groundwater resources on the African continent is limited, although the situation is getting better with improvements in assessment techniques and capacity. There are a number of groundwater assessment programs, both regional and national, which can provide useful information on availability and development potential of groundwater. Some countries in Africa such as Uganda, Kenya, Tanzania, South Africa, Ghana, are carrying out national groundwater resources assessments aimed at quantifying groundwater resources availability and demand, assessing the quality of groundwater resources, identifying hotspot areas vulnerable to droughts, assessing the economic value of groundwater resources and preparing a strategy for sustainable development of groundwater resources to meet the current and future water demands (Tindimugaya 2004). Such studies have resulted in a better understanding of groundwater resources in specific areas; moreover, current initiatives aimed at improving the situation are being developed. These include the Africa Groundwater Atlas, which is a new online resource that provides an introduction to the groundwater resources of 51 African countries, and aims to address the problem of access to good quality existing information about groundwater in Africa, providing a gateway to further information. It was developed by the British Geology Survey (BGS) in collaboration with the International Association of Hydrogeologists (IAH) Burdon Groundwater Network for Developing Countries. More than 50 groundwater scientists across Africa co-authored country summaries. The Atlas, and the accompanying Africa Groundwater Literature Archive, is a platform to publicise expert knowledge about African groundwater (BGS 2017).

Capacity-building programs in groundwater management in Africa

Capacity for groundwater management in Africa is fairly limited. A number of groundwater-related capacity-building institutions and networks however exist in Africa, contributing greatly to the improvement of the human capacity to manage and develop the continent's resources. These include Africa Groundwater Network (AGW-Net), Southern Africa Development Community (SADC) Capacity Building Center on Integrated Water Resources Management (WaterNet), Capacity Building Network for Integrated Water Resources Management (Cap-Net), Western Africa Capacity Building Network (WA-Net), Capacity Building Network for Integrated Water Resources Management in the Nile Basin (Nile IWRM-Net), Global Water Partnership-Southern Africa (GWP-SA) and the new SADC Groundwater Management Centre.

Africa Groundwater Network (AGW-Net) inaugurated in 2008 is aimed at creating a network of groundwater professionals on the continent to exchange experiences and expertise through training programs and joint research. Similarly, Cap-Net, with its affiliated networks (WA-Net, Nile IWRM –Net, WaterNet), has a component on capacity-building on groundwater among its programs. Global Water Partnership-Southern Sahara (GWP-SA) also has a component on capacity building regarding groundwater within its IWRM program.

The new SADC Groundwater Management Centre was established in 2017 to build groundwater capacity in the SADC region. The existing capacity-building programs through networks and institutions provide opportunities for sustainable groundwater management and development in Africa.

The UNESCO Chair in Hydrogeology established at the University of Western Cap (South Africa) in 2001, mainly focuses on groundwater-related education, research and outreach in Sub-Saharan Africa and the developing world. It aims to assist with implementation of national and regional water policies through the capacity building of the groundwater industry. The UNESCO Chair in Hydrogeology is strategically positioned to provide advice to the AMCOW via the Africa Groundwater Commission.

Conclusions and recommendations

Although groundwater systems respond to human and climatic changes slowly (relative to surface-water systems), climate change still could affect groundwater significantly through changes in groundwater recharge as well as groundwater storage and utilisation. These changes result from changes in temperature and precipitation or from changes in land use/land cover, and increased demand.

Despite the importance of small-scale farming in Africa, there is little information on the present and potential role of groundwater in agriculture. In contrast to its socioeconomic and ecological importance, groundwater has remained a poorly understood and managed resource. Widespread contamination of groundwater resources is occurring, and the important environmental services of groundwater are neglected. There appear to be critical shortcomings in the organisational framework and the building of institutional capacity for groundwater. Addressing this challenge will require a much clearer understanding and articulation of the role of groundwater's contribution to national and regional development objectives and an integrated management framework, with top-down facilitation of local actions.

There is therefore a need for sustainable management of groundwater resources in Africa through putting in place institutional coordination and stakeholder participation frameworks, information management programs and capacity-building programs. These include groundwater-monitoring systems for better understanding of the role of groundwater storage and groundwater discharges in sustaining aquatic ecosystems, groundwater assessments for understanding the interactions between various aquifers (including transboundary aquifers) and assessing the impact of increased pumping from various aquifer systems on the sustainability of groundwater abstraction. The ongoing groundwater-related initiatives in Africa, in the form of institutional coordination and stakeholder participation frameworks, information management programs and capacity-building programs, provide opportunities for sustainable groundwater management in Africa.

Acknowledgements Revision of an earlier version of the manuscript by G. de Marsily is gratefully acknowledged.

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