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The potential impacts of climate change on groundwater management in west Africa

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Abstract

Climate change is probably going to affect groundwater resources, in Sub-Saharan ccountries (SSA) in Africa either directly, by means of changing precipitation patterns, or indirectly through the combination of changing precipitation patterns with evolving land-use practices and water request. West Africa has, over the past few decades, experienced a sharp decline in rainfall and average annual flow of watercourses. A break in the rainfall pattern was observed around 1968-1972. 1970 is considered as the turning point after which the decline in average rainfall worsened from minus 15% to minus 30% depending on the zone. This situation led to the drifting of isohyets by about 200 km to the south. A 1°C increment in temperature could change overflow by 10%, expecting that precipitation levels stay consistent. Any reduction in groundwater recharge will intensify the impact of sea-level rise in coastal aquifers. For various reasons and at various levels, West African countries are dependent on one another. Over the past few decades, this interdependence has not only generated tension, but has also led to a dialogue and cooperation process. Only one country (Burkina Faso) are below the international standard for water scarcity (1,700 m^3 of renewable fresh water per year per person); On the other hand, there are major problems in terms of availability at the desired time and place. According to the Global Water Partnership, the withdrawal level of renewable water resources in West Africa (excluding Cameroon and Chad) is currently at 11 billion m^3 per year for an available 1,300 billion m^3, which is less than 1%. Agriculture uses 75% of these withdrawals, domestic consumption 17%, and industry 7%. Although it is by far the highest in proportion, agricultural use of water resources is low. Out of the 75.5 million hectares of arable land in West Africa, only 1.2% (917,000 ha) is developed for irrigation, and 0.8% (635,000 ha) is used effectively.

Keywords: Groundwater Management; Rainfall Pattern; Sustainability; Water Resources

INTRODUCTION

groundwater resources are finite and are only sustainable as long as annual depletion, particularly during the dry season, does not exceed replenishment during the subsequent rainy season or two. Depletion of groundwater over long periods is very difficult to reverse and will threaten all activities that depend on its use. Climate variability looks at changes that occur within smaller timeframes, such as a month, a season or a year, and climate change considers the changes that occur over a longer period of time, typically over decades or longer (Al-Gamal, 2020).

In Africa, there are three crucial clarifications behind groundwater's growing prominence as a water source: 1) the normal storing limit is high; 2) the water quality is routinely worthy; and 3) establishment is more sensible to defenseless organizations (Adelana and MacDonald, 2008). Hence, the term “West Africa” here refers to the region covering the Economic Community of West African States, Cameroon, Chad and Mauritania. These 18 countries cover an area of 7,800,000 km2 and had a total population of 290 million inhabitants in 2005 (Fig. 1)

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(Goulden *et al*., 2008). Groundwater framework for five chosen West African *Sub-Saharan African* Countries (SSA) exemplified by Burkina Faso, Ghana, Mali, Niger and Nigeria in the critical zones of Sub-Saharan African (SSA) will be considered in the present study (Fig. 1).

AIM OF THE PRESENT STUDY AND RELATED METHODOLOGY

Climate change predictions of increased temperatures as well as more erratic and variable rainfall during the present century are likely to lead to a decrease in recharge, as more water will be lost to transpiration and evaporation. Areas with basement complex geology and lower rainfall are the most vulnerable to declining aquifer discharge. An analysis of these regional climatic data and its impact on water availability is the main issue addressed in this study. It is by developing this linkage that the region will be better prepared for the future in which many people believe water will be one of the major stakes. For various reasons and at various levels, West African countries are dependent on one another. Over the past few decades, this interdependence has not only generated tension, but has also led to a dialogue and cooperation process. The case studies considered in the present study have included five African Sub-Saharan countries (SSA) (Burkina Faso, Ghana, Mali, Niger and Mozambique (Fig. 1), to develop an understanding of groundwater availability in relation to climate change. Any reduction in groundwater level will enforce sea-water intrusion to expand and prompt the salinization of shallow aquifers.

Climate Change and Availability of Freshwater

The ultimate effects of climate change on the distribution of water in West Africa are highly uncertain but potentially of great significance for some parts of West Africa, such as the coastal areas. Climate models are still unable to provide a reliable estimate of the intensity and frequency of extreme events. The recent International Panel on Climate Change (IPCC) report underlines that West Africa is a region in which the uncertainty of the climate scenarios is large, (Goulden *et al*., 2008), where some authors have predicted the increase of rainfall by 2021 while the others predict a lasting and more intense drought. Regardless, climate change is expected to affect the groundwater quantitatively and qualitatively on both spatial and temporal scales .This problem of availability is mainly regional considering most of the water resources come from the transboundary river basins and aquifers Only two countries (Cape Verde and Burkina Faso) are below the international standard for water scarcity (1,700 m3 of renewable freshwater per year per person) (Fig. 2). Groundwater cannot be managed independently of surface water. The two are connected hydrologically. Groundwater levels relate more firmly with precipitation than with temperature, yet temperature turns out to be more significant for shallow aquifers and in warm periods. All groundwater levels show reactions to precipitation as increments, however hydrogeologic site uniqueness and spatio-fleeting variety of precipitation (both are examined in more detail later) lead to variety in the sum and timing of reaction (Fig. 3).

Diminishing Surface Water Resources West Africa has, over the past few decades, experienced a sharp decline in rainfall and average annual flow of watercourses. A break in the rainfall pattern was observed around 1968-1972. 1970 is considered as the turning point after which the decline in average rainfall worsened from minus 15% to minus 30% depending on the zone (Wolf *et al*., 2003). This situation led to the drifting of isohyets by about 200 km to the south. An accompanying variation in annual average flows was observed for most of the rivers. In a number of cases, the decline in flows was even greater than that of rainfall; going down to minus 30% for the Senegal River and minus 60% for the Niger River (Fig. 4). During the extremely difficult

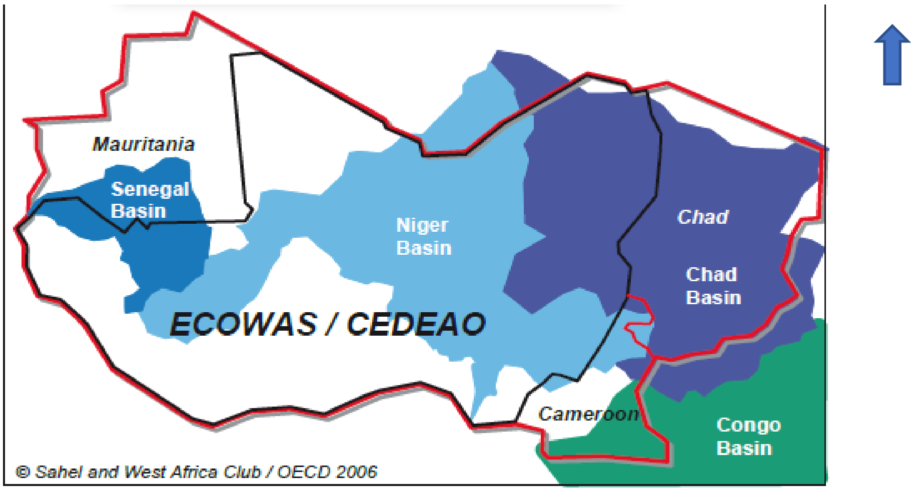

Fig. 1. West -African Countries

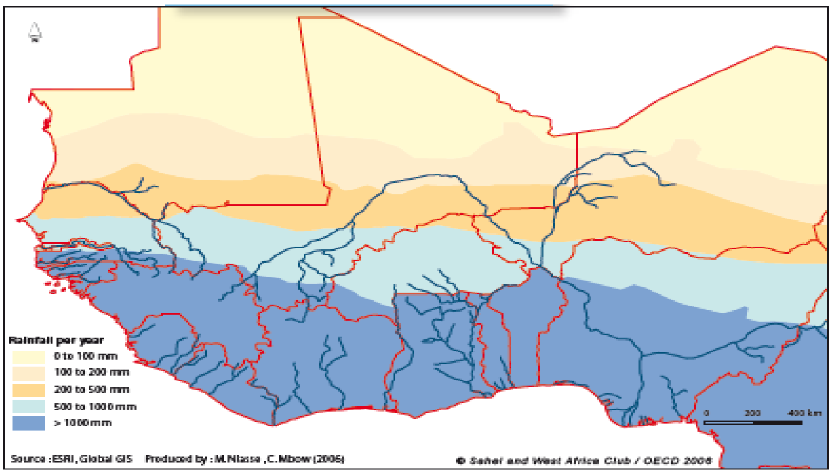

Fig. 2. Western African Bio-climatic zones

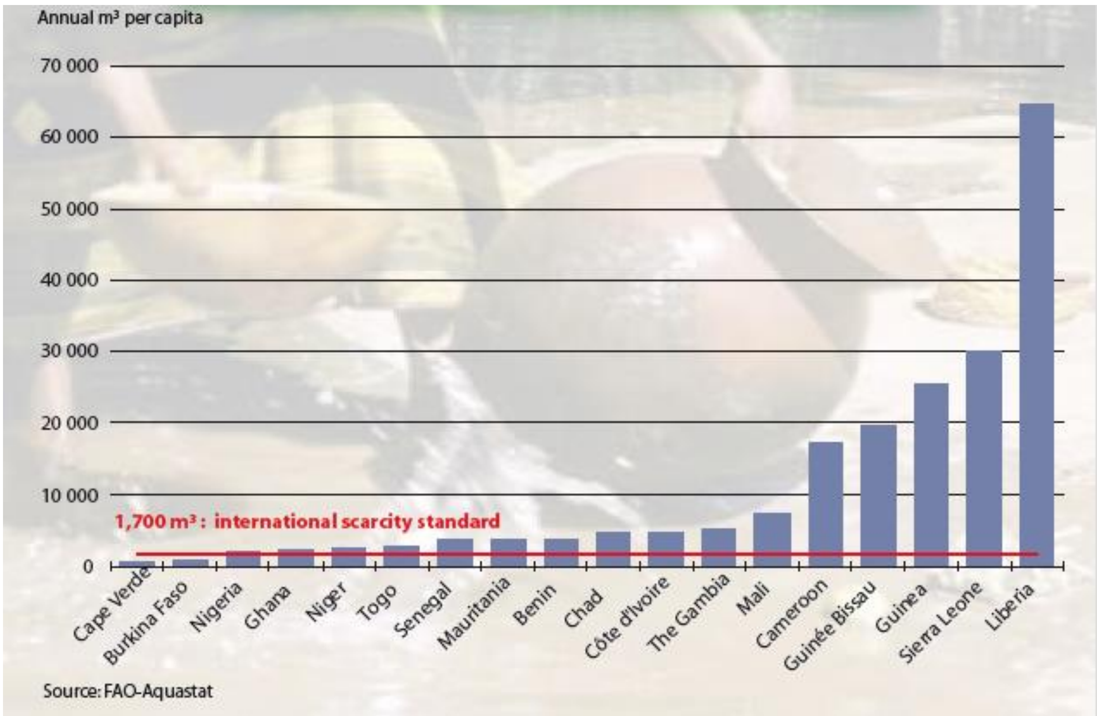

Fig. 3. Availability of Renewable Freshwater in West African Countries in 2003

years, there were exceptionally low water levels, to points where flows actually stopped, as was the case in 1983, 1984 and 1987 on the Bani tributary in Douna (Mali) or as in 1985 in Niamey on the Niger (Wolf, *et al*., 2003). The problem lies in the technical and financial difficulties of access to groundwater reserves of which very little is exploited today. It also lies in climate change and variability which have led to significant decline in the volumes of rivers over the past few decades. In other words, very little groundwater is exploited, and surface water is diminishing. This broadens the spectrum of water shortage which, even though is far from certain, has encouraged States in the region to prepare for the construction of an ever-increasing number of dams, irrigation canals or inter-basin transfer systems. The risks of disagreement and tension are real, but so far dialogue and cooperation have triumphed (Fig. 5).

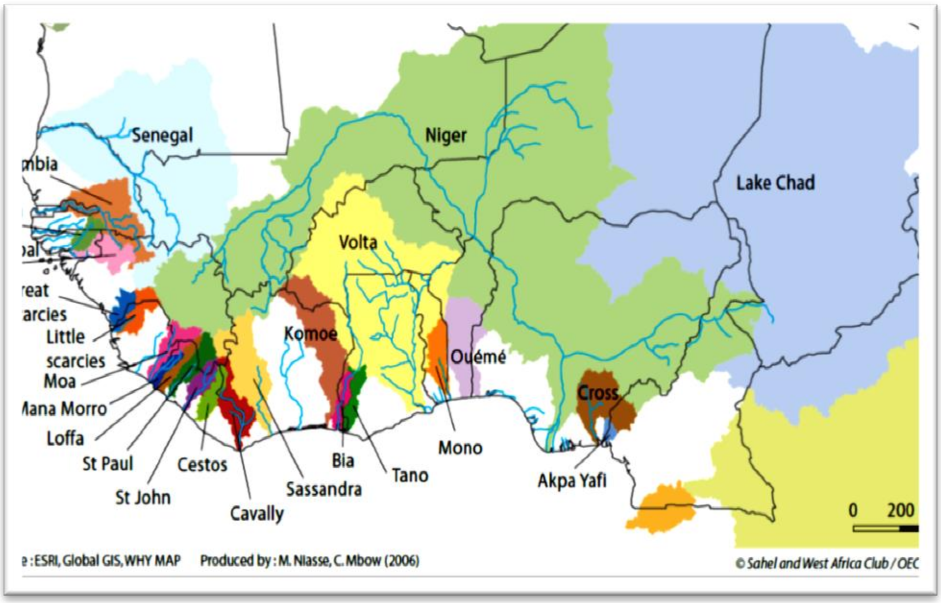

Fig. 4. Transboundary water resources in West Africa

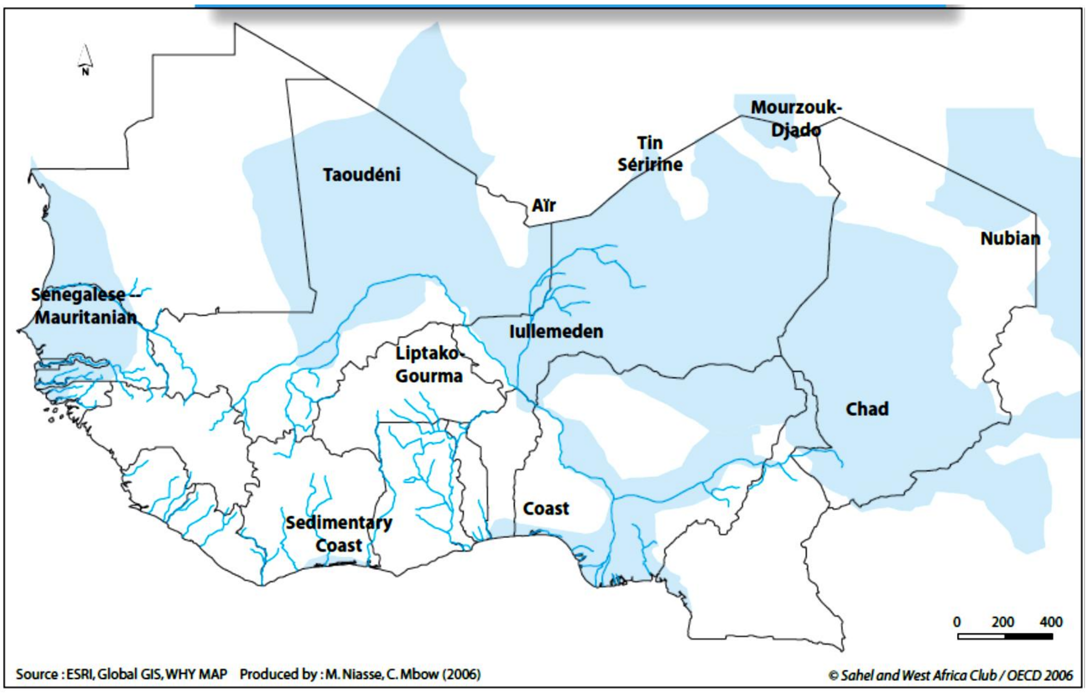

Fig. 5 Main Transboundary Aquifer Systems in West Africa

MATERIALS AND METHODS

Burkina Faso

Hydrology

Burkina Faso is located in the Soudano-Sahelian zone of West Africa (Fig. 1). It lies between latitudes 9°20' S and 15°5' N and longitude 5°20' W and 2°3' E and covers an area of 274,000 km^2. Burkina Faso has two main types of aquifers (Fig. 6). These are the continuous or generalized aquifer and the discontinuous aquifer. The continuous aquifers are the continental terminal and the weathered zone aquifers. The thickness, hydraulic conductivity and specific yield of these aquifers vary significantly over space but water can be abstracted from them irrespective of the location. The depth of the water table in the continuous aquifer varies between 10 m and 80 m. Area covered by this aquifer is about 11,000 km2 with an annual recharge of 430 million m^3 (about 38 mm). The saturated depth of the aquifer decreases from south west to north east, from about 50 m to 5 m. Assuming a drawdown of one-third of the saturated depth, it is estimated that about 1-3 billion m3 of water can be extracted from this aquifer. The weathered zone aquifer is found mainly in the Bobo Dioulasso and Tenkodogou regions but also in other areas of Burkina Faso. In general, this aquifer has a depth of 10-50 m. In Bobo Dioulasso, this aquifer has 10-30 m of weathered layer which gives an average yield of 0.5-5 m^3 hr-1 with transmissivity between 1.9-5.5x10-4 m^2 s-1. The piezometric head is between 10 m and above the bedrock (Fig. 7) (Duffau and Ouedraogo, 2009; BGS, 2002; Mahrh, 2003).

Climate change and groundwater availability

Evaluation of the groundwater capability of Burkina Faso by MEE (2001) uncovers that the country has an all-out groundwater stockpiling capability of 402 billion m^3 (Fig. 7). The examination of the piezometric head versus precipitation (Fig. 4) indicated that that groundwater has a positive relationship to the precipitation with a delay of 1–4 months because of the transmissivity of the unsaturated zone as shown in Fig. 4. The upward and downward movement patterns observed in groundwater level are reflecting the impact of interannual precipitation varieties. Changes in effective precipitation, only as expanded evapotranspiration, are fundamental to understanding the effect of climate inconstancy on groundwater recharge mechanism. Ultimately, Over the period from 1995 to 2019, the seasonal fluctuations of groundwater ranged from a few centimeters to about 2m (Fig. 4) (Sauret, 2008).

Figure 8 shows strong variation of piezometric heads in short distances in many locations. This is mainly attributed to the geology of the country. Most of the rocks that constitute the geology are heavily fractured and trap water during the rainy season. Shallow water tables (< 10 m) are found primarily in dried river beds, flood plains and inland valleys. Considering that Burkina Faso is a landlocked country whose people support a traditional agricultural economy, if well developed, groundwater could play a crucial role in boosting small scale agricultural production to liberate many from poverty. A comprehensive groundwater inventory in Burkina Faso is needed. Groundwater resources in Burkina Faso are less developed compared to many West African countries. Due to the fragile hydrological environment of the country, groundwater plays an important role in meeting the water needs, particularly the domestic water needs of the rural people.

Ghana

Groundwater Hydrology

Ghana is located on the west shoreline of Africa between latitudes 4°44' N and 11°15' N and longitude 1°12' E and 3°15' W, (Fig. 9) and involves a surface area of around 239,460 km^2. Two main aquifer systems can be identified: the weathered zone aquifer system (regolith aquifers) and the fractured zone aquifer system (Fig. 9). The thickness and productivity of each aquifer system in the different formations vary, but generally, the regolith aquifers occur at the base of the thick weathered mantle, have low permeability and high porosity due to high clay content. The fractured zone aquifers are normally discontinuous and limited in area. The regolith layer in the Voltaian formation (Fig. 9) is thin and unsaturated in many areas and therefore provides only limited amounts of groundwater. Hydrogeologically, the Voltaian terrain is the most complex and least understood of all the formations in Ghana. Recharge to all the aquifer systems in Ghana is mainly by direct infiltration of precipitation through fractured and fault zones along the highland fronts and also through the sandy portions of the weathered zone (Kortatsi, 1994). Some recharge also occurs through seepage from ephemeral stream channels and pools of accumulated runoff during the rainy seasons. Though there is some contribution from regional aquifers, the source of recharge to the aquifers in Ghana, particularly aquifers in the north of the country is mainly through precipitation (Obuobie *et al*., 2012).

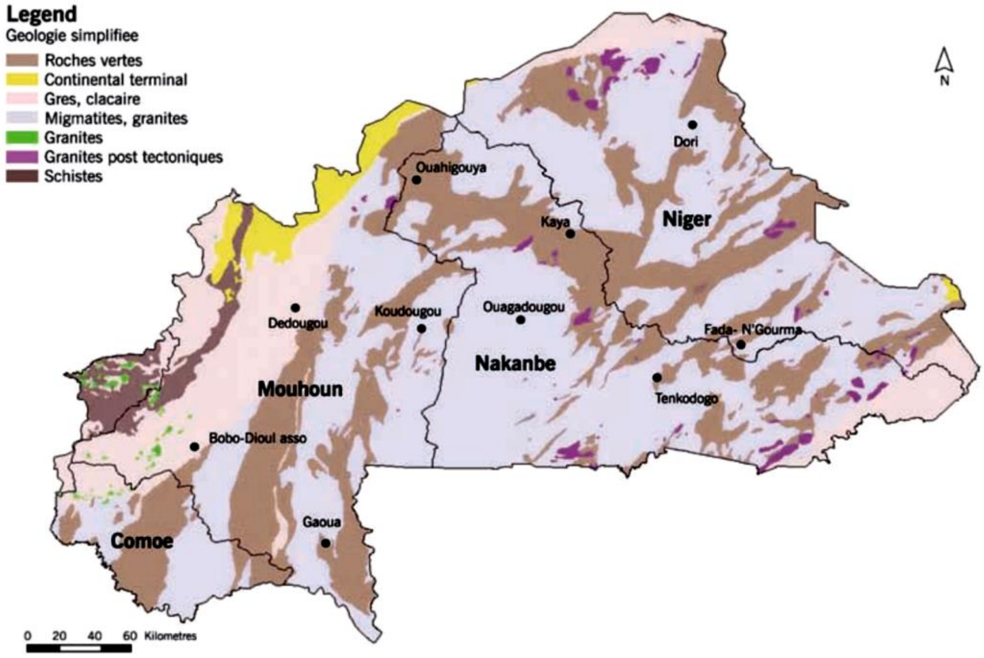

Fig. 6. Geological map of Burkina Faso (Mahrh, 2003)

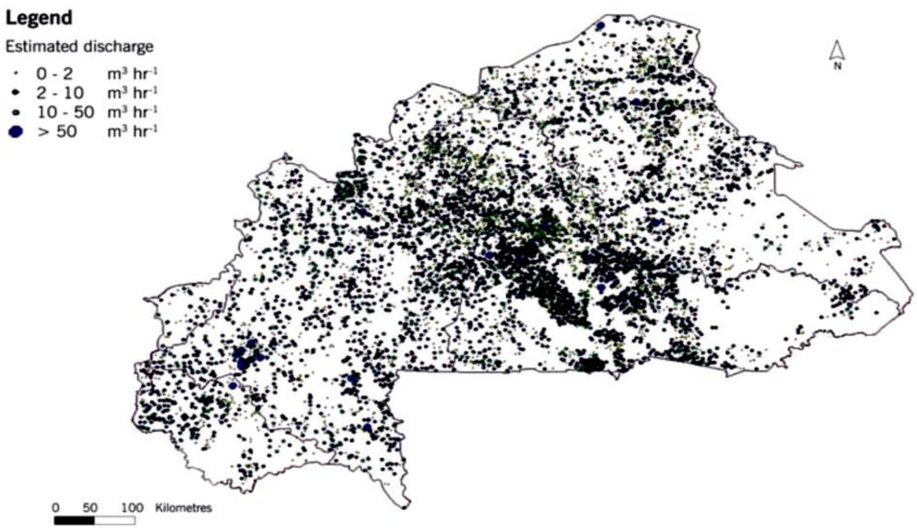

Fig. 7. Map showing discharge of wells across Burkina Faso (Mahrh, 2003)

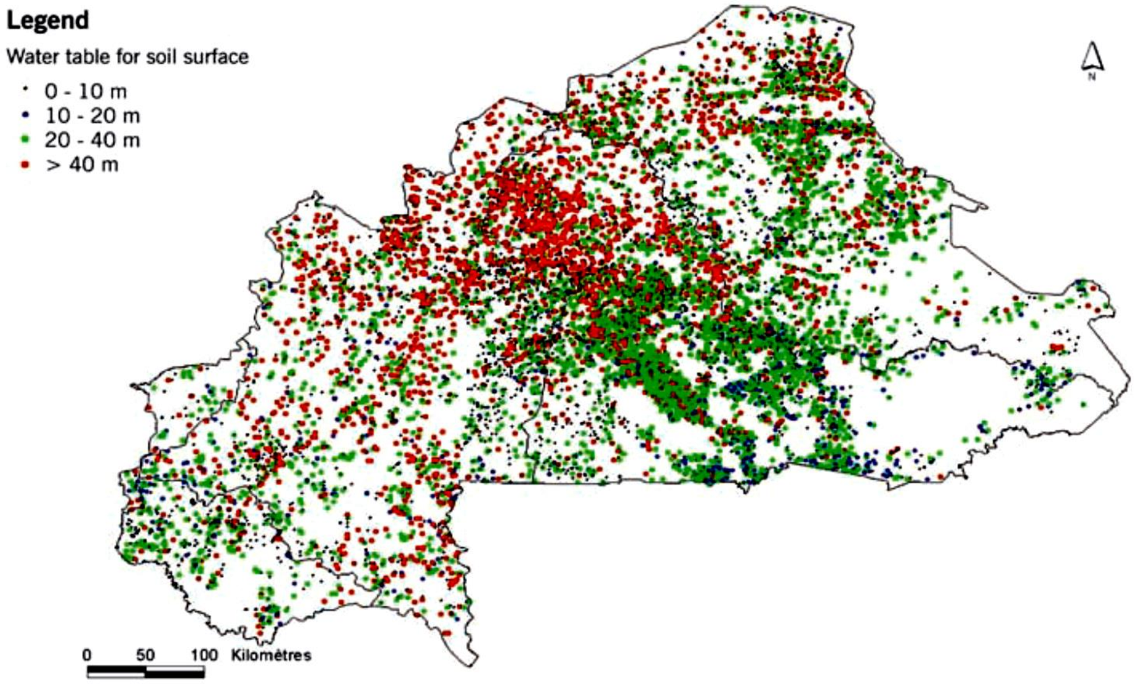

Fig. 8. Distribution of piezometric heads of different wells in Burkina Faso (Mahrh, 2003)

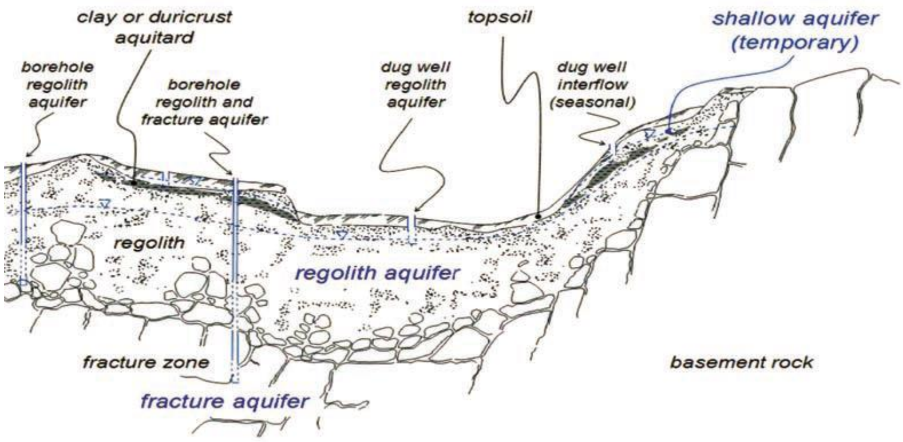

Fig. 9. Groundwater occurrence in basement rock in Ghana (HAPS, 2006)

Climate Change and Groundwater Availability

It is necessary to understand the effects of the dynamics of climate change and other stresses on groundwater resources sustainability in Ghana. In Ghana and the West African sub-region, optimal groundwater resources management is integral to economic development under climate change conditions. Further, climate change may worsen the situation as recharge is dependent on rainfall in northern Ghana. Therefore, it is important to understand exactly how climate change will impact on recharge to the groundwater for sustainable development and management of the resource. Previous groundwater studies in Northern Ghana barely analyzed the combined impacts of climate change on the recharge to the groundwater (Fig. 10). The recharge values have been estimated using the various methods including water balance, chloride mass balance, water table fluctuation and hydrological modelling. Based on this data, the recharge for the country generally varies from 1.5-19 percent of the annual rainfall (Obuobie *et al*., 2012). The review of Fig. 10 reveals an immediate connection between normal month to month precipitation (mm) and groundwater level. All groundwater levels show responses to precipitation as augmentations, spatio-transient quantities of precipitation lead to an assessment of connection between rainfall intensities mm/month and depth of groundwater in meter below land surface (mbls) as well as timing of response (Fig. 10). A factual issue which can be observed in different localities. Savelugu locality, shows modestly little responses of 0.1 to 0.4 m, (Fig. 10). Kadia locality show greater responses some place in the scope of 1.0 and 1.6 m, separately. The greatest responses are seen at Kpataribogu locality of 5.1 m in 2012. The delayed response between maximum precipitation and the corresponding groundwater levels recommends that some constraint of precipitation must be reached before the inundation of soil moisture content and the surplus water goes to the aquifer. Under climate change conditions whereby groundwater recharge reduces by 12.5 and 25% by 2030 and 2050, respectively (Yidana, 2019).

Mali

Groundwater Hydrology

Mali is a Sahelian nation in West Africa. It is situated between latitudes 10^{o} and 25^{o} N, and longitudes 13^{o} W and 5^{o} E. The groundwater aquifers in Mali can be categorized into 3 major groups, namely, continuous/generalized, fractured semi-continuous, and fractured discontinuous (MMEE, 2006) (Fig. 11). The continuous/generalised aquifer is associated with geological formations which are slightly or not consolidated. These aquifers are made up of secondary Quaternary sediment deposits and they form the Continental Terminal/Continental Quaternary. They are generally 20 to 50 m thick and could reach 100 m in some locations. The fractured semi-continuous aquifer is made of limestone, dolomite and grey rocks overlaying the Continental Terminal.The fractured discontinuous aquifer is essentially made of schist. Monitoring of the groundwater systems in Mali was started in 1981. As of 1990, a total of 210 piezometers in 103 sites around the country were regularly monitored for water quality and piezometric levels. Piezometric heads recorded in Mali fluctuate between levels < 200 m AMSL to > 350 m AMSL. On an average, most of the country is located between levels 200 and 300 m AMSL (MMEE, 2006). Groundwater is abstracted

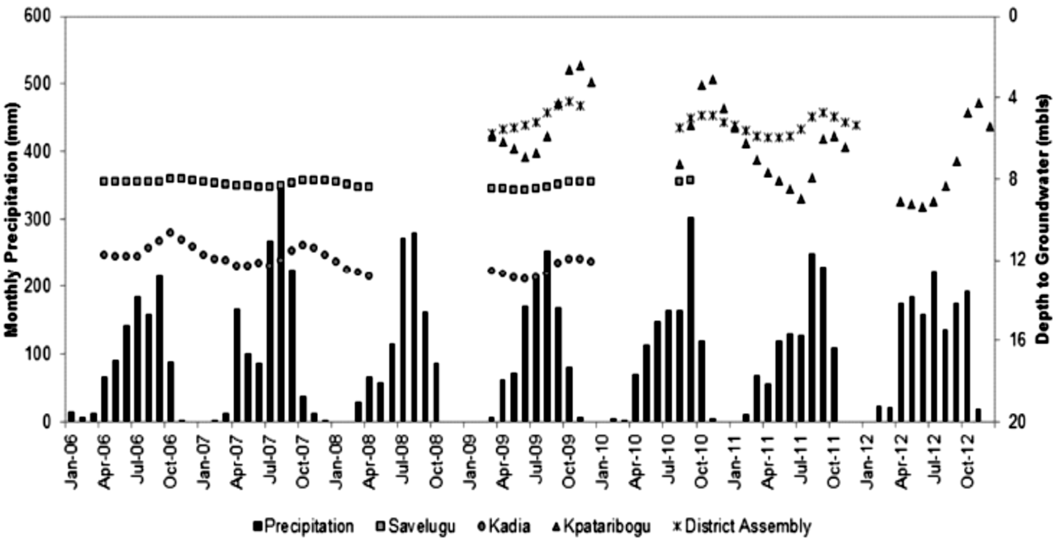

Fig. 10. Average monthly precipitation (mm) and groundwater level response measured in meters below land surface (mbls) at the study sites (Lutz *et al*., 2015)

from nearly all the administrative regions in Mali. Pumping tests done so far show transmissivity in the continuous/ generalized aquifers to be on average about 1.3 x 10-3 m^2 s-1 and varies between 1.4 x 10-7 m^2 s-1 and 5 x 10-2 m^2 s-1. In the fractured aquifers, average transmissivity is estimated at 2 x10-4 m^2 s-1, ranging between 1.4 x 10-7 and 2 x 10-2 m^2 s-1 (MMEE, 2006).

Climate Variability and Groundwater Response

Groundwater resources in Mali are commonly under-misused and there are no critical inescapable issues with groundwater accessibility. The complete groundwater resources in Mali is assessed at 2.7 trillion m^3. The degree of groundwater misuse, essentially for drinking water flexibly, is low: it is assessed to be 66 billion m^3. Groundwater is to a great extent misused by boreholes and enormous large-diameter wells, of which there are an expected 15,100 boreholes and 9,400 huge width wells (Pavelic *et al.*, 2012). Average recharge rate is assessed at around 5 mm/year, which constitutes roughly 16% of mean annual precipitation (Fig. 12). Fluctuation of groundwater levels indicate somehow connection among groundwater and surface water (Traore *et al.*, 2018).

Highest groundwater availability is found to exceeds 150,000 m^3 km^{-2} in areas where mean annual precipitation exceeds 700 mm (UN, 2009). The inspection of Fig. 12 reveals that recharge diminishes from 1970 to 2050 with regular events of extreme dry seasons. For sustainable use of groundwater resources in the country, it is important to establish a relationship between discharge and recharge of the groundwater.

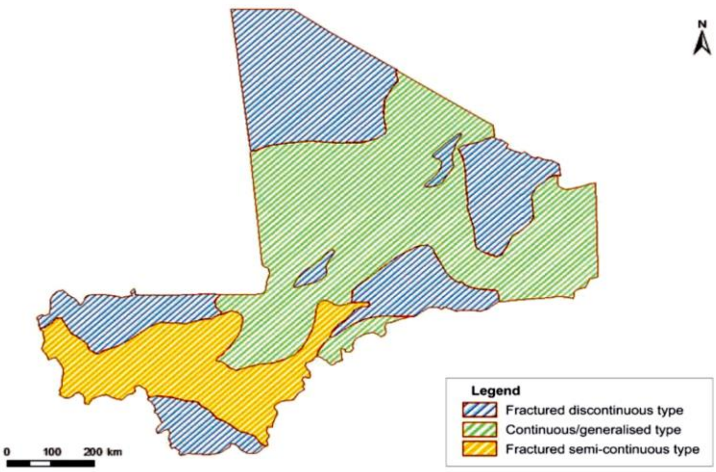

Fig. 11. Groundwater aquifers in Mali (MMEE, 2006)

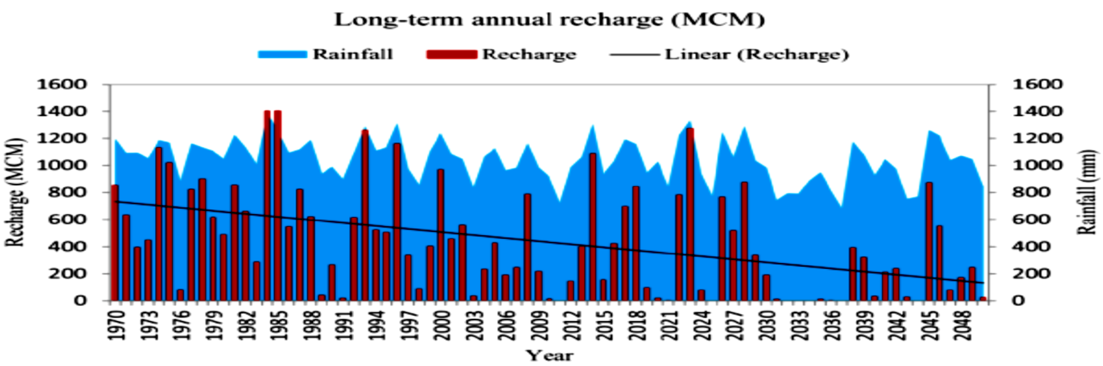

Fig. 12. Long-term groundwater recharge in million cubic meters (MCM) calculated using historical and future climate data from scenario based on the Thornthwaite (Toure *et al.*, 2016)

Mozambique

Geography

Mozambique is located on the eastern coast of Southern Africa confronting Madagascar, between latitudes 10°27' S and 26°52' S and longitudes 30°12' E and 40°51' E. It covers an area of about 800,000 km^2 and has around 2,800 km of sea shoreline. The sedimentary basins form by far, the most productive aquifers in Mozambique (Fig. 13). In the south, these form an extensive unconfined aquifer which is well replenished because of high rainfall and is easily exploited. Miocene carbonates also form good aquifers where they are karstic. These cover around 25,000 km2 south of the Save river. The water table in this aquifer occurs at around 50 m depth. Yields can reach up to 20 m^3 hr-1 (in the alluvial valleys of the Limpopo and Incomati) (Fig. 13), but are more often around 5 m^3 hr-1 (DNA, 1987).

Climate Variability and Groundwater Response

Assessing the impact of climate change on groundwater is complex and remains plagued by uncertainty. Rising temperatures will inevitably have a negative impact on both recharge of aquifers and on overall storage. Increased temperatures lead to high evaporation of water from the soil surface, so there is less water available to percolate into the soil. Up to a certain limit, increased temperatures lead to increased transpiration by plants until temperatures reach a level where stomata close to minimize moisture stress within the plant. Natural vegetation is generally less subject to transpiration stress than crops.Regional groundwater flow and saltwater transport models were constructed based on limited hydrogeological data and preliminary calibrations were performed in the Great Maputo aquifer, Mozambique. Regional groundwater flow and saltwater transport models were used to investigate potential impacts of sea level rise and increased groundwater abstractions (Fig. 10) according to Trasvina *et al*. (2019), current groundwater abstractions account for 6% (22 Mm^3 /year) of the total discharge; Impact of climate change can be observed under a sea level rise , 1.0 m, water budget components change slightly, mostly with regard to flow from and towards the sea. Rise in sea level will enhance salt water intrusion in the coastal areas. Chloride concentrations increase along the coastlines mostly within 1 km inland after 50 years (Fig. 10). However the coastal area along the Maputo City being higher in elevation compared to the sea level will be less sensitive to the seawater intrusion (Trasvina *et al*., 2019).

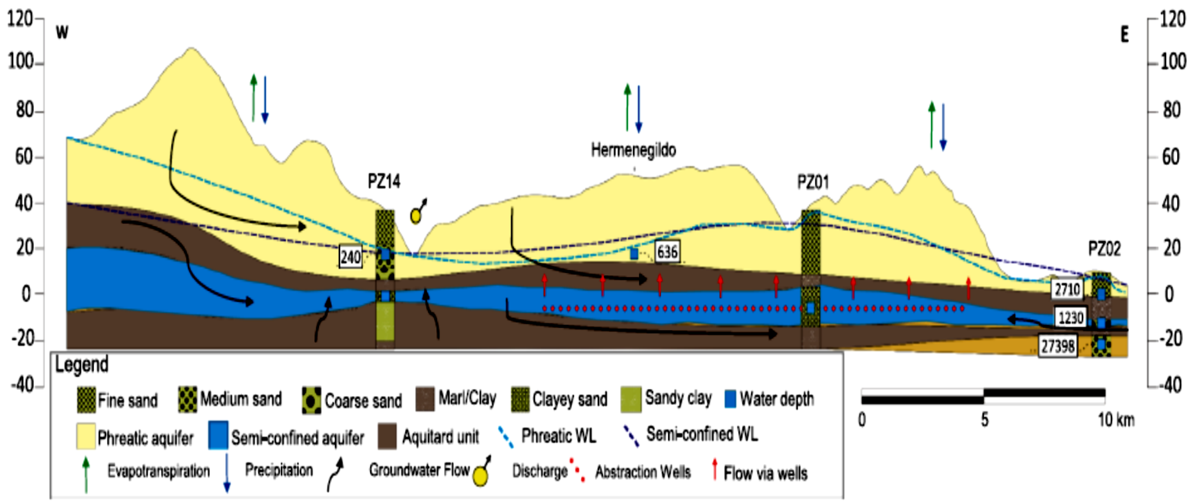

Fig. 13. profile of the groundwater system West to East Mozambique (Nogueira, 2017)

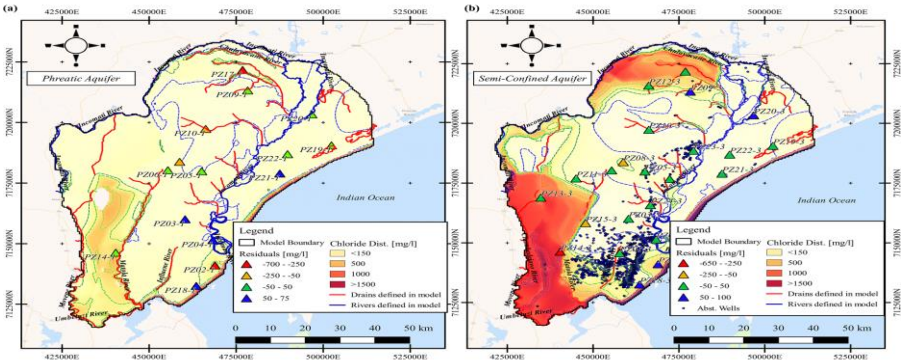

Fig. 14. Simulated Cl distributions in groundwater in case of water-table and semi-confined aquifer types under the scenario of rise in sea level (Trasvina *et al*., 2019)

Niger

Groundwater Hydrology

Niger is a landlocked country situated between latitudes 11°37' N - 23°33' N, and longitudes 0° E -15° E with a total area of 1,267,000 km^2. The aquifer system in Niger can be classified as continuous and discontinuous aquifers.The continuous aquifer consists of the Continental Terminal, Continental Intercalaire, Sandstone D'agades, Sandstone De Teloua, and Sandstone Primaires. The Continental Terminal aquifer consists of clay and clayey sandstone with sand. It is an unconfined aquifer which extends across the whole of the Niger basin (Fig. 15). The Continental Intercalaire aquifer is composed of sandstone, clayey sandstone, sand and clay and has a thickness of 500-700 m. (CIEH, 1986). Recharge to this aquifer from precipitation is negligible. The Sandstone De Teloua aquifers are in the northern part of the country and are mainly confined, having depth of between 30 and 90 m. There is little information available on the mechanism and rates of groundwater recharge in Niger. The shallow aquifers of the country are mainly recharged by seasonal rainfall and flooding. The recharge mechanism in most areas is most likely to be pistons-flow as this is typical of recharge behaviour in the Sahara/Sahel areas (Scanlon *et al*., 2006).

Climate Variability and Groundwater availability

Niger is the driest country in the Sahelian-Saharan area. Current levels of groundwater resources and their exploitation are threatened in three ways (Erler *et al*., 2019), Climate change predictions of increased temperatures as well as more erratic and variable rainfall during the present century are likely to lead to a decrease in recharge, as more water will be lost to transpiration and evaporation. Areas with basement complex geology and lower rainfall are the most vulnerable to declining aquifer discharge (Fig. 16).

1. Population growth rates in rural areas at about 3 percent per annum mean that twice as much drinking water will be required in 25 years. Urban areas relying on groundwater for drinking will be much more vulnerable due to rapid urbanization.
2. Technological changes probably pose the greatest threat to groundwater sustainability. Any increase in the use of motorized pumping places additional stress on any aquifer. Although currently beyond the purchasing power of smallholders, there is increasing promotion of both diesel and solar powered irrigation. While potentially manageable for very small garden plots, increased commercialization will require more water.

CONCLUSION

Groundwater in West Africa is one of the region's most precious resources. It is logical that future development, particularly in rural areas, will continue to maximize the value of groundwater for

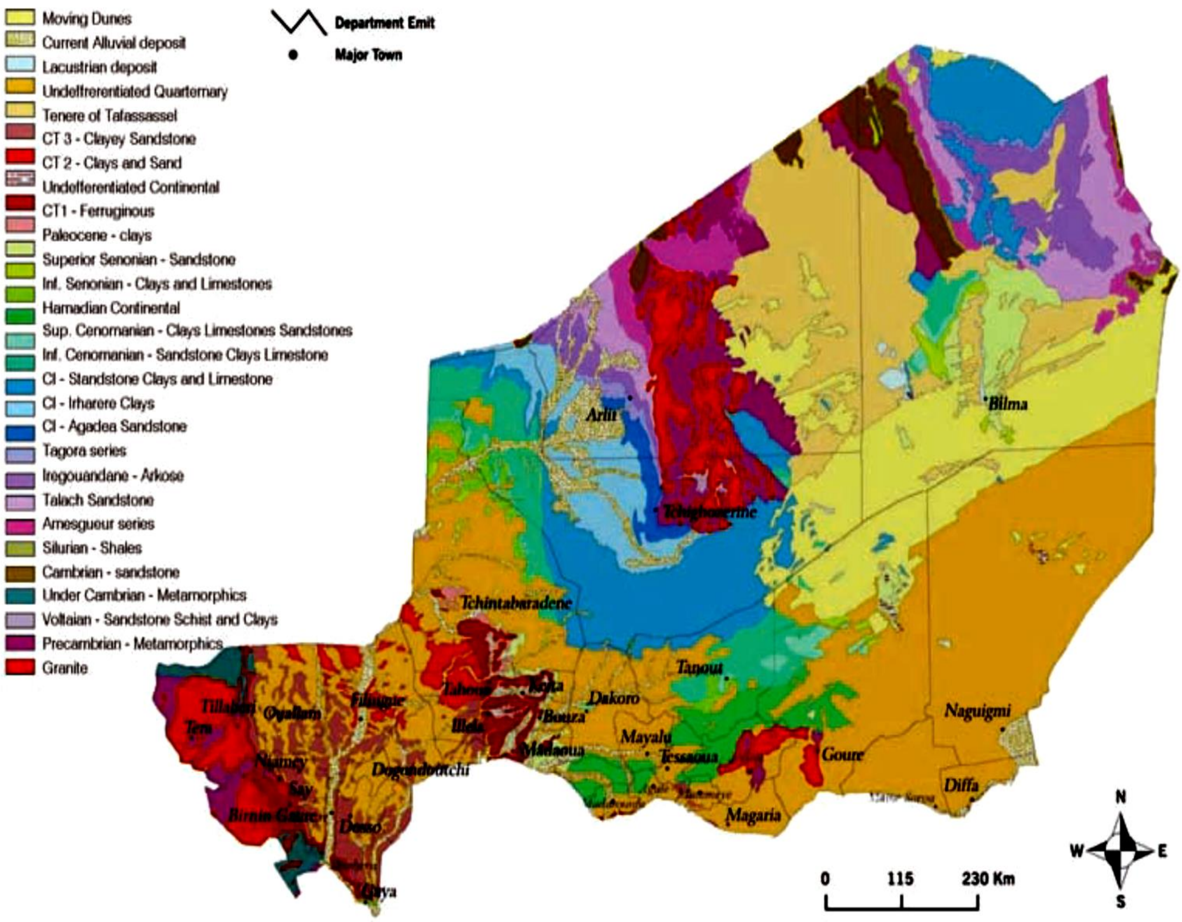

Fig. 15. Simplified geological map of Niger (Ministere de l'eau, de l'environnement et de la lutte contre la desertification, 2009)

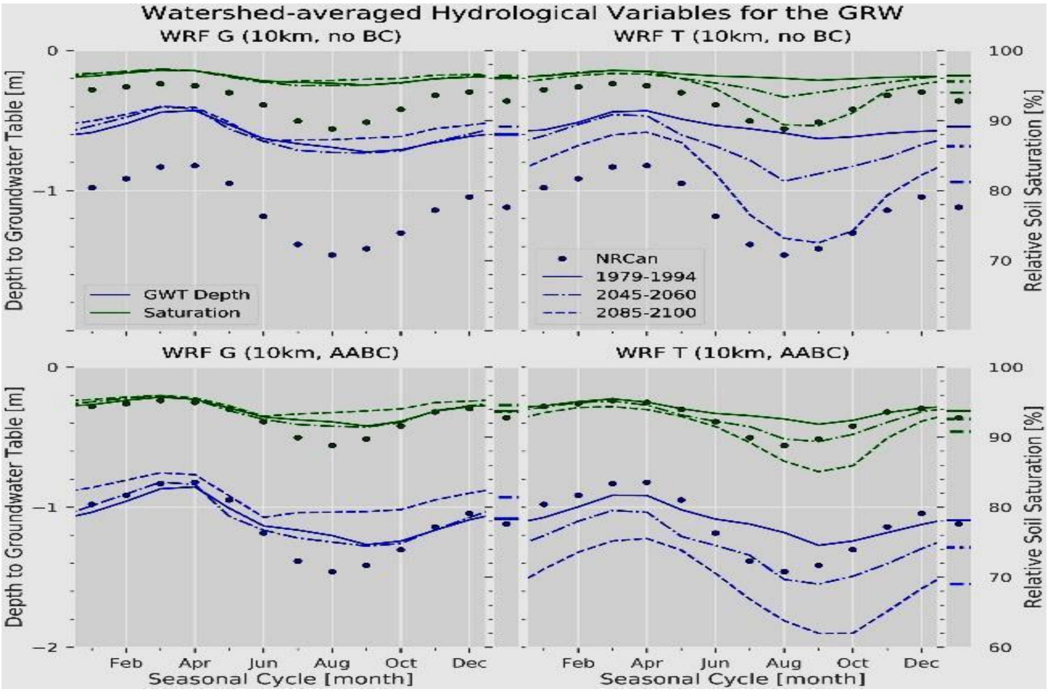

Fig. 16. The average seasonal depth to the groundwater table and relative soil saturation for the (left) WRFG ensemble and the (right) WRFT ensemble, (top) without and (bottom) with bias correction for the historical, midcentury, and end-century periods (Erle *et al*., 2019)

domestic consumption, livestock, and agriculture. With the likelihood of changing rainfall patterns associated with climate change, groundwater provides a critically important resource to sustain human health and livelihoods. In light of the theoretical availability of thousands of billions of m^3, the prospect of increasing consumption sixfold between 2000 and 2020 (from 11 billion to more than 60 billion m^3) is not frightening; even if we know that there are and will be problems at the local level. The problem lies in the technical and financial difficulties of access to groundwater reserves of which very little is exploited today. It also lies in climate change and variability which have led to significant decline in the volumes of rivers over the past few decades at a very broad level of generalization, predictions of the impact of climate change on groundwater can be expressed in terms of several factors, firstly, decreasing rainfall will mean less water for percolation into the root zone and eventually for interflow into the top of aquifers. Not only by total rainfall but also the nature of individual rainfall events greatly influences groundwater recharge. Secondly, rising temperatures will inevitably have a negative impact on both recharge of aquifers and on overall storage. Third rise in sea water level will threaten coastal aquifers that are so delicate, and because the management problems are much more complex than in inland locations, coastal aquifer management requires an entirely different set of skills. Furthermore, coastal aquifers are replenished by a combination of local rainfall and excess water draining toward the coast through normal streamflow; thus, unlike many groundwater-dependent systems, coastal aquifer management is both a local and a regional management issue. Last but not least in comparing population density with mean annual rainfall, most of the population of West Africa lives in areas with at least 500 mm of rainfall.

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