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Land use and water resources in Africa

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Abstract

This paper examines land use policy and agricultural water management in Africa from 1962 to 2011. For this purpose, data were gathered from Food and Agriculture Organization of the United Nations (FAO) and the World Bank Group. Using the FAO database, ten indices were selected: permanent crops to cultivated area (%), rural population to total population (%), total eco nomically active population in agriculture to total eco nomically active population (%), human development index, national rainfall index (mm/year), value added to gross domestic product by agriculture (%), irrigation water requirement (mm/year), percentage of total cultivated area drained (%), difference between national rainfall index and irrigation water requirement (mm/year), area equipped for irrigation to cultivated area or land use policy index (%). These indices were analyzed for all 53 countries in the study area and the land use policy index was estimated by two different formulas. The results show that value of relative error is\20 %. In addition, an average index was calculated using various methods to assess countries' conditions for agricultural water management. Ability of irrigation and drainage systems was studied using other eight indices with more limited information. These indices are surface irrigation (%), sprinkler irrigation (%), limited irrigation (%), spate irrigation (%), agricultural water withdrawal (10 km3/year), conservation agriculture area as percentage of cultivated area (%), percentage of area equipped for irrigation salinized (%), and area waterlogged by irrigation (%). Finally, tendency of farmers to use irrigation systems for cultivated crops has been presented. The results show that Africa needs governments' policy to encourage farmers to use irrigation systems and raise cropping intensity for irrigated area.

Key Words: *Africa; Agricultural water management; Land use policy index; Macroeconomic policies; Climate change; Hydrological Modeling.*

Introduction

Freshwater on land is a vital resource for terrestrial life, ecosystems, biodiversity and human societies (Vörösmarty et al. 2000, 2010; Steffen et al. 2015; Seddon et al. 2016; Albert et al. 2021). Continental water is stored in various reservoirs, unevenly distributed across geophysical environments and climates (Chahine 1992; Shiklomanov and Rodda 2003). It includes seasonal ice and snow, glaciers and ice caps, aquifers, soil water and soil moisture, and surface waters (Stephens et al. 2020). The latter, comprising of rivers, lakes, man-made reservoirs, wetlands, floodplains and inundated areas (Alsdorf et al. 2007), is of particular significance as it supports diverse and dynamic environments globally and pro vides important benefits and services to human society and economic activities (Oki and Kanae 2006). Surface waters are also an integral part of the global water cycle (Good et al. 2015; Trenberth et al. 2007), continuously exchanging mass with the atmosphere and the oceans, making them a key component of the climate system and its variability (Stephens et al. 2020). However, freshwater storage and flux, their spatial distribution and variability, remain highly unknown in many regions of the world (Rodell et al. 2018), preventing the development of adequate and sustainable strategies to manage water resources (Oki and Kanae 2006; Hall et al. 2014).

Due to the limited water resources, the role of macro-economic policies in agricultural water management is vital and undeniable. Africa has the most population growth in the world while, actual crop yield as percentage of potential yield is 40 % for North Africa and it is\30 % for Sub-Saharan Africa (FAO 2012); therefore, Africa needs specific attention. Namara et al. (2010) mentioned the role of agricultural water management to reduce poverty in the world via three pathways. Those are improvement of production, enhancement of employment opportunities and stabilization of income and consumption using access to reliable water (first pathway), increasing high-value products (second pathway), and finally by its role in nutritional status, health, societal equity, and environment (third pathway). They preferred improving the management of existing systems as selected strategy in North Africa. Valipour (2012, 2013a, b, c) mentioned the status of irrigated and rainfed agriculture in the world, summarized the advantages and disadvantages of irrigation systems, and attend to update irrigation information to select optimum decision. The present paper shows that 46 % of cultivated areas in the world are not suitable for rainfed agriculture because of climate changes and other meteorological conditions.

The value of irrigation-equip ped areas as share of cultivated areas was 5.8 % and the value of water-managed areas as share of cultivated areas was 6.7 % for Africa. In addition, Mati (2011) discussed the effects of optimizing agricultural water management for the green revolution in Africa. Hanjra et al. (2009b) and Burney et al. (2013) argued about the favorable impact of investments in agricultural water management for Sub-Saharan Africa. They claimed that poverty was significantly reduced in equipped area than in rainfed area, and concluded that investments in agricultural water management and complementary rural infrastructure and related policies were the pathways to break the poverty trap in Sub-Saharan African agriculture. Franks et al. (2008) examined developing capacity for agricultural water management in current practice and future directions. They suggested increased attention to monitoring and evaluation of capacity development, and closer links to emerging work on water governance. Khan et al. (2009) reviewed water management and crop production for food security. According to the authors, relations between water and other development-related sectors such as population, energy, food, and environment, and the interactions among them require reckoning, as they together will determine future food security and poverty reduction. Funnell (1994) discussed the intervention of government or other agencies into long-established irrigation schemes and also the possible implications of intrusion into the activities of farmers who have recently moved into irrigation in Morocco and Swaziland. He suggested that any attempt to encourage greater involvement with irrigation must be accompanied by economic measures which favor small-scale production.

Effects of climate change on water resources in Africa

Observable and potential effects of climate change on water resources in Africa include: flooding, drought, change in the frequency and distribution of rainfall, drying-up of rivers, melting of glaciers, receding of water bodies, landslides, and cyclones among others.

Flooding

For millennia, humans have settled in floodplains in order to till fertile soils, use the flat terrain for settlements, gain easy and safe access to water and use rivers for transport (Pavel, 2003). Riverine floods are a natural phenomenon; they have always occurred, and populations have benefitted from them to whatever extent possible (for example, in ancient Egypt the natural annual flooding of the Nile brought much needed nutrients to irrigated soils). In recent times, humans have become more exposed to flood risk as encroachment into flood plains and lack of flood response plans increase the damage potential.

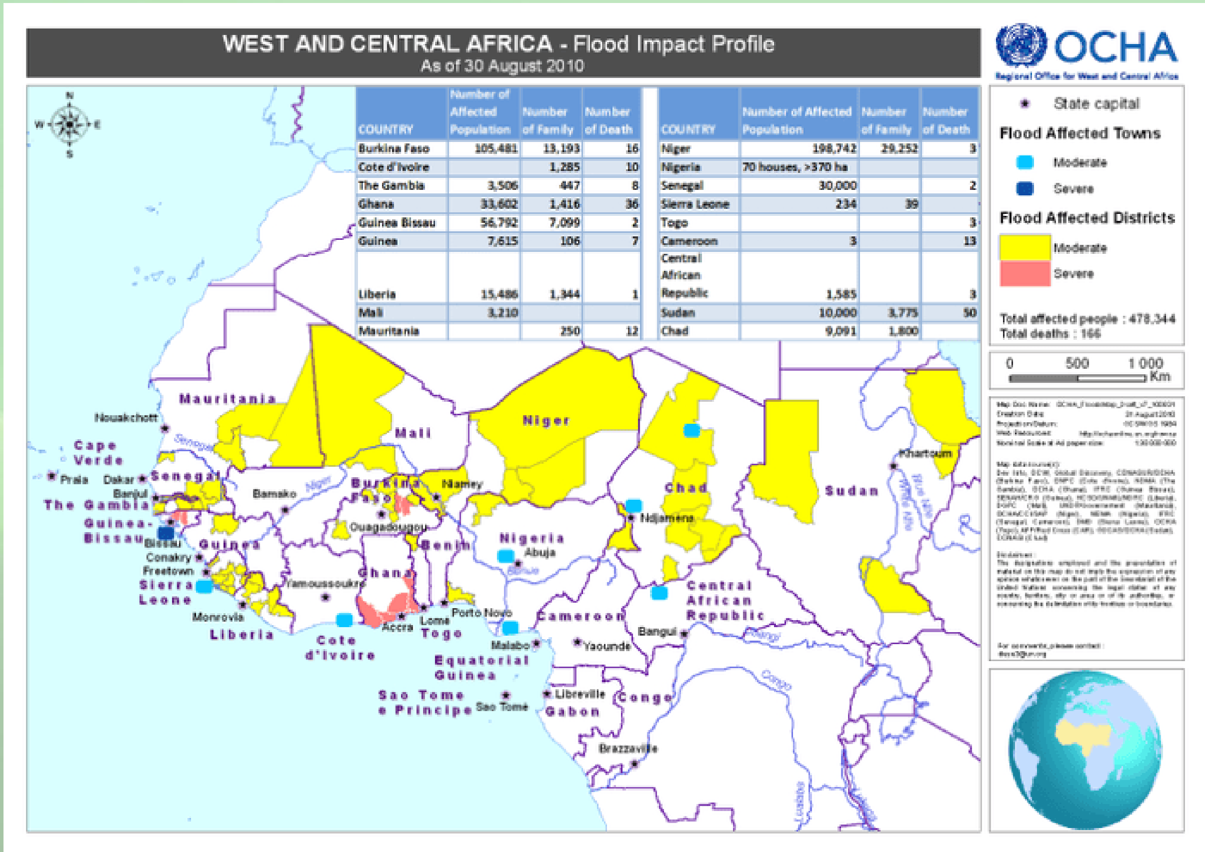

Figure 1: Flood map of Central and West African regions Source: United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (2010).

Floods can occur in arid areas as well as humid areas. In tropical near-coastal regions, they generally result from cyclones that can drop a year's worth of rainfall in a day. According to the BBC News (2007), about 14 countries, namely Burkina Faso, Chad, Ethiopia, Ghana, Kenya, Liberia, Mali, Niger, Nigeria, Senegal, Sudan, Togo, Uganda, and Rwanda, are the worst hit by flood in the African continent. Scores of people have died and hundreds of thousands have been displaced by the floods that have submerged much of the continent's most productive farmland, hence necessitating urgent food, shelter and medicare. In the same vein, episodes of flood accounted for 26 per cent of total disaster occurrences in Africa during 1971-2001 (Vordzorgbe, 2003) with devastating effects. In North Africa, the 2001 disastrous flood in northern Algeria resulted in about 800 deaths and economic loss of about $400 million. In East Africa, the El Niño-related flood in 1997/1998 destroyed infrastructure and property worth about $1.8 billion in Kenya. In Mozambique, the 2000 flood (worsened by two cyclones), reduced the annual economic growth rate from 10 per cent to 4 per cent, caused 800 deaths, affected almost 2 million people of which about 1 million needed foods, displaced 329,000 people and destroyed agricultural production land, among other negative effects. The worst single episodes of flood in Africa occurred in East Africa: one event in 1997 killed 2,311 people in Somalia; another in 1999 affected 1.8 million people in the Sudan (AWDR, 2006).

Floods across Africa are reported to be the worst in decades in some places and extend in an arc from Mauritania in the west to Kenya in the east. At least an estimated 1.5 million people are so far affected (World Food Programme, WFP, 2007). According to the Cable Network News, CNN (2009), torrential rains and flooding since June have affected 600,000 people in 16 West African nations. The worst hit have been Burkina Faso, Senegal, Ghana and Niger, where many lives and property have been lost to severe flooding events.

Drought

The term drought may refer to a meteorological drought (precipitation well below average), hydrological drought (low river flows and low water levels in rivers, lakes and groundwater), agricultural drought (low soil moisture), and environmental drought (a combination of the above) (Bates et al., 2008). The socioeconomic impacts of droughts arise from the interaction between natural conditions and human-induced climate change factors such as changes in land use, land cover, and the demand for and use of water. In some cases, the frequency of occurrence of droughts is exacerbated by human induced changes in land cover. Excessive water withdrawals can increase the likelihood and impact of drought. Droughts have both direct and indirect consequences for human livelihoods (Pavel, 2003). A direct consequence is cropping loss, which can cause starvation if alternative food sources are not available. Indirectly, water shortages contribute to the spread of disease, because people lack water for basic hygiene. An example of a consequence of drought is shown in Figure 2, where nomads lost hundreds of their cattle due to drought.

Figure 2. Carcasses of drought-stricken cows in Kenya. REUTERS/Thomas Mukoya

Climate change is projected to increase the risk of drought over much of Africa in the 21st century. The regions where droughts have occurred seem to be determined largely by changes in sea surface temperatures, especially in the tropics, through associated changes in the atmospheric circulation and precipitation as seen in Table 1. Since the late 1960s, droughts have caused much suffering in Africa. Severe droughts were experienced in 1973 and 1984 when almost all African countries suffered reduced rainfall, which particularly affected several million people in the Horn of Africa, the Sahel and Southern Africa (AWDR, 2006). Droughts are endemic in both Southern Africa and the Sahel region of western and northern Africa.

Economic impacts

Climate change can affect many important sectors of the economy by influencing the supply of and demand for goods and services (WBGU, 2008). Empirical evidence shows that there will be changes in the supply and demand of food commodities as a result of low yields resulting mainly from drought and flooding events. The changes will also affect the profitability of farming and the affordability of food. According to Miller and Yates (2005), future climate change could influence municipal and industrial water demands, as well as competing agricultural irrigation demands. Municipal demand depends on climate to a certain extent, especially for garden, lawn and recreational field watering, but rates of use are highly dependent on utility regulations. Industrial use for processing purposes is relatively insensitive to climate change as industry most often prefers to meet target outputs rather than consider the environmental implications of its activities.

The World Bank's Water Resources Sector Strategy quotes examples of impacts of climate variability on economic performance. In its 2003 report, the Bank noted that the drought in Zimbabwe in the early 1990s was associated with an 11 per cent decline in GDP; the floods of 1999 in Mozambique led to a 23 per cent reduction in GDP (Pavel, 2003). The scale of these losses highlights the need for water planners and managers to have a better understanding of the mechanisms of climate variability and their relationships with hydrological extremes such as floods and droughts. Economic losses from natural disasters, including floods and droughts, increased three-fold between the 1960s and the 1980s; and ten-fold between the 1950s and the 1990s (Pavel, 2003).

The poor are among those who suffer particularly from the effects of water stress due to their vulnerability and inability to adapt. An increase in surface temperature will affect the livelihoods of the 70 per cent of Africans who depend on rain-fed agriculture. This will lead to low productivity, low income, and a low standard of living, thus completing the vicious cycle of poverty. Economic impacts from curtailment of hydropower generation from Lake Kariba as a result of the 1991-1992 drought were estimated to be the loss of US$101 million in GDP, US$36 million in export earnings, and 3,000 jobs (Benson and Clay, 1998, cited in Manase, 2009). In Mozambique, floods in 2000 cost the economy US$550 million, or 12 per cent of GDP (Grey and Saddoff, 2005, cited in Manase, 2009). Where climate change brings with it an increase in the frequency of extreme weather events such as flooding and drought, the risk of damage to property and infrastructure also rises. Insurance companies will need to significantly increase the amount of capital they hold to be able to provide insurance cover at a level comparable to that of today (WBGU, 2008).

Observing Surface Waters from Space in Africa

Surface Water Elevation from Earth Observation

Surface water elevation of inland water bodies is a key parameter in hydrology and water resources and has been long measured through historical gauge networks (Fekete et al. 2012). Over Africa, where traditional in situ measurements are sparse, a comprehensive monitoring of surface water elevation still remains a challenge. Moreover, the lack of fiducial in situ measurements can possibly be a limitation regarding the ground validation of remote sensing products.

Although, up to now, no satellite mission has been specifically designed to survey inland water elevations, satellite altimetry has been extensively used in the last three decades to remotely sense surface water elevation variations in lakes, rivers, reservoirs, and flood plains (Calmant et al. 2008) and improve the long-term monitoring of Africa's hydrology. Radar altimeters onboard satellites are initially designed to measure the ocean surface topography by providing along-track nadir measurements of water surface elevation (Stam mer and Cazenave 2017). Over the continents, pioneering studies in the Amazon basin (Fassoni-Andrade et al. 2021) quickly demonstrated the capacity of retrieving accurate sur face water elevation from radar echoes and adapted retracking procedures at the intersection of the satellite ground track with a water body (Birkett 1998; Frappart et al. 2006; Da Silva et al. 2010). These intersections, named virtual stations (VSs), are defined by the sat elite orbit configuration, the repeat cycle of which define also the temporal interval sampling of altimetric observations (generally 10, 27 or 35 days) (Normandin et al. 2018; Papa et al. 2012a). At a given VS, surface water elevation is estimated through the inversion of the signal round-trip propagation time between the satellite and the Earth's surface, which provides the range. Several corrections (in hydrology, essentially due to delayed propagation through the atmosphere or the interaction with the ionosphere and geophysical corrections due to the dynamics of Earth's surface) need to be applied to this range to retrieve the surface water elevation. The height of the reflecting surface, given in respect to the height of the satellite above the reference ellipsoid, is then corrected from the local undulation of the geoid in order to be converted into an orthometric height or geoidal altitude of the water body, the variable that is useful for hydrologists. For a detailed and complete description of the characteristics of the different satellite altimetry missions and the estimation of surface water elevation for hydrology, including the various re-trackers used, altimetric waveform description, the specific corrections (geoid gradient for lakes, hooking effect for rivers and small water bodies), the associated errors and biases, the different acquisition modes [Low Resolution Mode (LRM), SAR, SAR Interferometric (SARIn)], we refer to Cretaux et al. (2017).

Several groups or institutions around the world provided time series of surface water elevation, covering a wide range of water bodies and applications. Table 1 provides the main sources and databases (non-exhaustive) that provide surface water elevation time series over Africa.

The in-depth assessment and validation of the water levels derived from the satellite altimeter over lakes, rivers and other inland water bodies were performed worldwide against in situ gauges (Frappart et al. 2006; Da Silva et al. 2010; Papa et al. 2010a; Ričko et al. 2012; Cretaux et al. 2018; Kao et al. 2019; Paris et al. 2022; Kittel et al. 2021a; Kitambo et al. 2021), with satisfactory results and uncertainties ranging between few centimeters to tens of centimeters, depending on the environments (Cretaux et al. 2017). Radar altimetry over African lakes the large lakes (Fig. 1) of Central Africa (Chad, Fitri) and East Africa (in the Rift and adjacent regions, such as Lakes Victoria, Tanganyika and Malawi) are icons of Africa's tremendous water resources and valuable sentinels of the effects of climate variability and change. They remain highly dependent on the long-term rainfall characteristics (Becker et al. 2010; Hernegger et al. 2021), and they also influence the climate locally (Nicholson and Yin 2002). For instance, rainfall over Lake Victoria was found to be 30% higher than in the surrounding land areas, since part of the evaporation returns directly to the lake through precipitation (Asnani 1993; Anyah et al. 2006). Syn chromous variations in water level records on the three largest lakes in the Rift region are explained by large-scale climate mechanisms associated with oscillations of warm and cold phases of El Niño (Ogallo 1988; Nicholson 1996; Ropelewski and Halpert 1996; Stager et al. 2007) or the Indian Ocean Dipole (IOD) (Hastenrath et al. 1993; Marchant et al. 2006), or the Atlantic SST (Sea Surface Temperature) anomaly patterns (Janicot 1992). The IOD is also partly driving the lake water level over East Africa, modulated by El Niño Southern Oscillation (ENSO) events (Mistry and Conway 2003; Birkett et al. 1999). Tier ney and Russell (2007) further highlighted the significant influence of the Indian Monsoon variability and the migration of the Inter Tropical Convergence Zone (ITCZ) on African lake levels. The use of an 80 year-record of in situ level data at Lake Malawi (1916–1995) helped with identifying the links with the rainfall variability over the catchment and the f lows of the Zambezi River (Jury and Gwazantini 2002), consistent with large-scale climate variability that helps the prediction of lake levels a year in advance. Finally, other studies have shown that global warming has an impact on precipitation and temperature variations with consequent changes in African lake levels (Xu et al. 2005; De Wit and Stankiewicz 2006).

Surface Water Extent from Earth Observation

The extent of surface water bodies and their variation is of primary importance to the water, energy and biogeochemical cycles and the maintenance of biodiversity of the Afri can continent. In many regions of Africa, water bodies cover a large portion land's surface area, with strong seasonal and interannual variability that play a key role in the carbon cycle (Hastie et al. 2021; Hubau et al. 2020), biogeochemistry processes (Borges et al. 2015) and the occurrence of water-related disasters such as flood risk in populated areas. Measuring the distribution and variability in the extent of surface waters across different spatial and temporal scales has always faced great difficulties, especially using the in-situ networks. It is indeed very difficult to estimate on the ground the variations in sur face water extent in large floodplains and wetlands, especially under vegetation or during extreme events such as inundation. Even in the era of remote sensing observations, it still remains a challenge.

A variety of remote sensing techniques employing a wide range of observations in the electromagnetic spectrum, including visible, infrared, or microwave observations (Alsdorf et al. 2007; Prigent et al. 2016; Huang et al. 2018), have been developed in the last decades to estimate the distribution of surface water from very fine spatial resolution (few meters) to coarser ones (~ 50 km) covering various temporal scales and periods. These remote sensing techniques are now widely used in hydrology and water resource research.

Depending on the sensors or the applications they are developed for, these observations include a large range of space/time resolutions, most of the time resulting from a trade-off between temporal and spatial coverages and sampling (Chawla et al. 2020). For instance, SARs show very large capabilities to measure surface water extent at high resolution (10–100 m) but often suffer from a low temporal revisit time, making them not suitable to monitor rapid hydrological processes. In one hand, optical and infrared sensors have good spatial/temporal resolution, sometimes with ~ 10 m resolution and a few days revisit, but their capabilities are limited in tropical and subtropical Africa regions because of dense clouds and vegetation. On the other hand, passive microwave sensors offer frequent tempo ral sampling, sometime twice daily, but the observations are generally at low spatial resolution (~ 10–50 km) thus limiting their use to the monitoring of large surface water areas. As already mentioned in the previous section regarding surface water elevation, many methodologies regarding the monitoring of surface water extent from space in tropical environments have been originally conducted in the Amazon Basin (Fassoni-Andrade et al. 2021); with the African river basins only recently benefiting from these advances.

Following the use of SARs to delineate surface water extent in the Amazon floodplains and tropical forest environments (Hess et al. 1995, 2003), efforts have been carried out to undertake similar studies in the Congo River Basin that hosts several seasonally or Perma nently flooded areas, such as the Bangwelu and Upemba swamps or the Cuvette Centrale in the Middle Congo. Seasonal flooding dynamics and vegetation types were thus derived from the Japanese Earth Resources Satellite-1 (JERS-1) (Rosenqvist and Birkett 2002) or the use of multi-temporal SAR coverage, such as the Scan SAR mode of ALOS/PALSAR SAR data (Lee et al. 2011). They conclude that the JERS-1 SAR mosaics may serve well to appraise the maximum extents of flooding in the Congo River basin, but perform poorly to assess the dynamics and ranges of the variations. Bwangoy et al (2010) and Betbeder et al (2014) employed a combination of SAR L-band and optical imagery to characterize the Cuvette Centrale land cover. They estimated the wetland extent to reach more than 360,000 km2, representing about 32% of the total area.

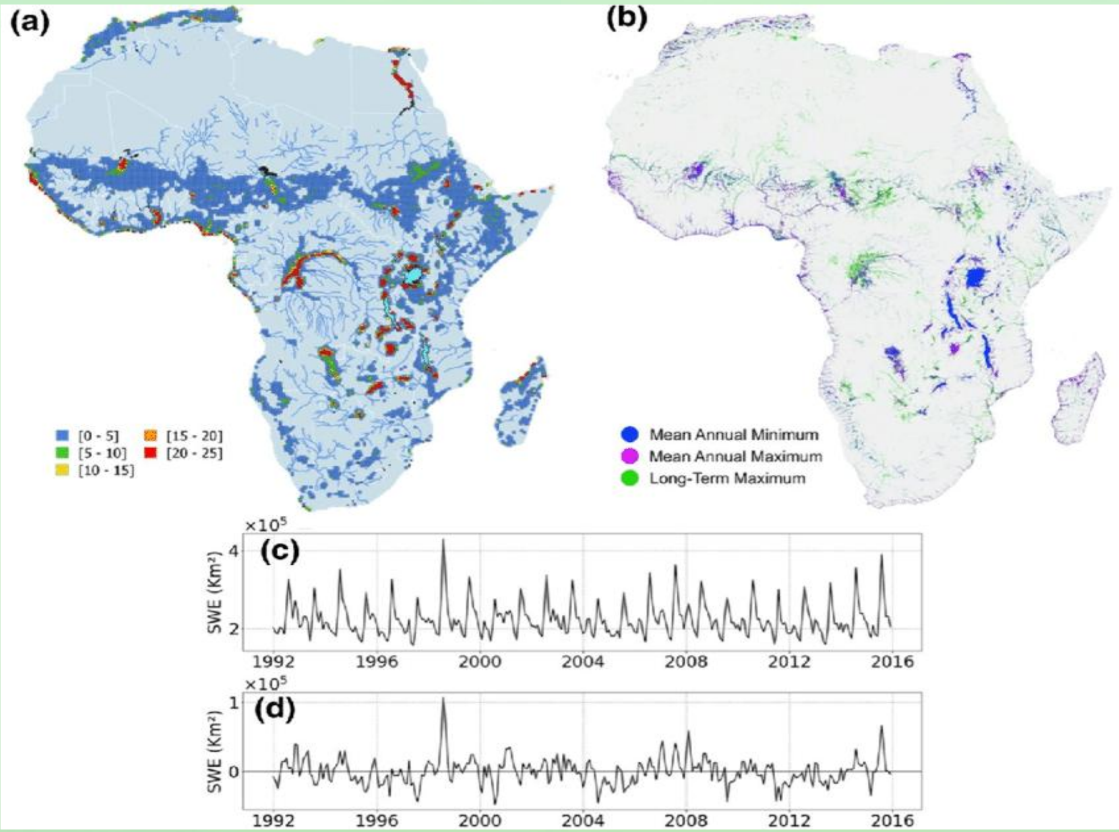

Figure 3 Characterization of surface water extent from multi-satellite techniques over Africa.
a Mean surface water extent (1992–2015) from GIEMS-2 expressed in percentage of the pixel coverage size of 773 km2 (for visual purpose, only pixels with a value > 0.1% are displayed). b Surface water extent at 500 m spatial resolution from GIEMS-D15. c Time series of surface water extent aggregated over Africa, and d Cor responding DE seasonalized anomalies obtained by subtracting the 24-year mean monthly value from individual months,

The Use of Earth Observations for Modeling Surface Waters and Hydrological Processes in Africa

Hydrological Modeling

Hydrological models are employed to numerically reproduce the hydrological functional behaviors and the water cycle processes through sets of mathematical equations. This representation of the processes related to the transition of rainfall to runoff through channels occurring at the land surface is termed hydrological modeling, which can also be under stood as a means of quantitative prediction for decision-making (Tshimanga 2022). Hydro logical modeling is commonly used to understand hydrological process, to predict hydro logical variables, particularly when and where they are not currently measured in situ, and/ or to predict the effects of future climate and explore "what-if" scenarios to understand the impacts of other changes, such as land use, dam building or urbanization. Quantifying all these processes is of paramount importance for hydrological prediction and water resources management under both stationary and non-stationary conditions, further com plicated by our limited ability to measure or assess the subsurface interactions where many complex water fluxes take place.

In the African continent, a number of hydrological model applications have been initiated to meet the purpose of processes understanding and predictions across different scales, as well as water resources management plans. Some of these initiatives include the development of new models that are fit for purpose in the context of the African hydrology. Particular reference is made to the Pitman model (Pitman 1973; Hughes et al. 2007), the Agricultural Catchment Research Unit (ACRU) model (Schulze and George 1987) and a Hybrid Atmospheric and Terrestrial Water Balance (HATWAB) model (Alemaw and Cha oka 2003) that have been developed and used for simulating hydrological processes under different African hydro-climatic conditions.

A large number of hydrological modeling structures are currently available, but they differ in the degree of detail of the description of processes, the manner in which processes are conceptualized, the requirements for input and output data, and the possible spatial and temporal resolution. The common practice now in hydrological modeling communities is to use or adapt model structures that have been relatively successfully performed elsewhere. In this regard, a large number of global or land surface models have been used under different conditions and for different purposes across the African continent (Tram bauer et al. 2013; Hughes et al. 2015; Boone et al. 2009; Grippa et al. 2017; Getirana et al. 2017b). Here, we do not intend to provide a classification of hydrological models, so more detailed information about the classification of these models can be referred to in the references cited.

Although hydrological modeling includes the transport of water through rivers, either implicitly or explicitly, there is still a need for more specialist models that simulate in detail the flow transport in channels and floodplains. These hydraulic models, also commonly referred to as hydrodynamic models, generally utilize some derivative of the Saint–Venant shallow water flow equations and are used to model river channel and floodplain processes more explicitly and in higher detail than would typically be undertaken with a hydrological model. Importantly, they provide spatiotemporal predictions of water levels and velocities, which allows the mapping of floodplain inundation dynamics and simulate sediment trans port characteristics. Satellite-derived observations of these parameters have also advanced our understanding of these processes and allowed calibration and validation where in situ data are sparce (Schumann et al. 2009).

Observational Challenges and Future Opportunities to Monitor African Surface Waters: Way Forward to Water Resources Management

African surface hydrology and terrestrial water cycle have undoubtedly benefited from more than 30 years of developments and studies using Earth Observation and models, as demonstrated and discussed in the previous sections. The use of remote sensing data has helped to improve our overall knowledge and under-standing of the variability and changes of surface water across the African continent, as well as the processes and mechanisms that drive them at various scales. Remote sensing data now represent a powerful complement to “classical” observations, and the synergy of both means is key to overcome difficulties in a region with sparse in situ networks and where many basins are still ungauged. This complementary exist in many aspects, since satellites often brings a mean to spatialize observations, over large-scale regions and sometimes at fine spatial resolution, while ground observations bring very accurate measurements with often high temporal frequency that no current satellite can compete with. Conversely, satellites give access to new quantities such as the inundated area, which are almost impossible to collect from the ground.

Therefore, remote sensing data dedicated to hydrology have strongly contributed to filling some gaps in the observational systems needed to accurately and comprehensively monitor the environment of Africa. Our review thus highlighted the main remote sensing products that are now available to study African surface water and how their use has con tributed to new findings and advances in hydrology across the region. Current limitations However, there are still many gaps that can be identified regarding our current knowledge of African surface water and the scientific community will need to tackle them in the near future to ensure a comprehensive monitoring and understanding of African hydrology. Some of these basic questions were listed in a community-based effort that synthetized 23 Unsolved Problems in Hydrology (Blöschl et al. 2019).

Without the pretention of making an exhaustive list of these incomplete knowledges, one can note from our review analysis some obvious and important gaps regarding surface water. For instance, many water bodies are still left with no observations or are monitored with temporal/spatial sampling which are not adequate to capture their characteristics or dynamics. Our review clearly demonstrated that radar altimetry is a very powerful for monitoring water bodies such as lakes and reservoirs located under the satellite tracks, but it is still blind to many smaller lakes and reservoirs that stand in between the ground-tracks. Some processes and mechanisms that drive the variability of water bodies also require observations with high temporal frequency which most current satellite missions don’t offer. These limitations therefore prevent a better understanding of the variability of water level and extent in small lakes, reservoirs, rivers and wetlands and how these water bod-ies interact in complex systems such as in the river floodplain and in river–lake continuums. Additionally, there is still a very limited knowledge of water level and slopes at fine spatiotemporal resolution over African surface water, as well as topography in floodplains and flooded forests, preventing to significant improvements in hydraulic modeling of the systems. Similarly, river discharge, which was historically one of the first variables measured in hydrology and the most used to develop and calibrate models, is still not properly measured from space, as discussed in Tarpanelli et al. (2021). This review stresses a need to accurately estimate river discharge across the continent with fine spatial and temporal resolutions.

Finally, we identified a strong need for monitoring water quality through remote sens ing, which remains challenging especially given the complexity of African inland waters. Using recent optical sensors, suspended sediment concentration could be retrieved with promising results over specific sites, but developing general algorithms to estimate this variable at the regional or continental scale remains a challenge. As part of river hydrology that involves flood dynamics, surface types and complex interactions, sedimentation processes need to be properly monitored to assess geomorphological changes in floodplain and river channels. Improving the observations of phytoplankton and the chlorophyll a dynamic using satellites is also identified as key since they contribute to healthy ecosystems, biodiversity and water security.

Way forward Monitoring and modeling the components of the hydrological cycle with Earth Observation have now become a reality and this will be reinforced further in the coming years. However, there is still an open path to bring all these scientific advances forward into effective applications in water resources management and related decision-making. Africa, like many regions worldwide, is currently facing an extensive human footprint on its freshwater which raises a new set of needs in this context. Complex water management problems thus call for integrated planning using Earth Observation monitoring tools. Remote sensing has the potential to emulate essential information for decision-makers (Fassoni-Andrade et al. 2021) and is bringing new ways to monitor "politically ungauged" regions where information is not publicly available as advocate by Gleason and Durand (2020). But these Earth Observation advances need to translate into real support to water and environmental governance. Thus, the remote sensing community is now facing real challenges as it needs to promote these new knowledges and datasets in a manner that is more useful for societies and to pave the way for innovation and decision support in Africa. Potential actions to take include to reducing the gap between scientific communities, by promoting interdisciplinary approaches toward more inclusive water systems, by training decision-makers to Earth Observation current progress and advances, by promoting open access datasets, tools and repositories. These actions should also include a better integration and support of African scientists in future programs related to water in order to reduce the disparity of opportunity and access to resources. Investment in science, from national and international communities, is also needed to fill these gaps, as demonstrated for the Congo Basin (White et al. 2021).

Conclusion

The potential wide-ranging impacts of climate change on water resources (availability, accessibility and demand) as reviewed above make a compelling case for the need to strengthen integrated water resources management institutions in respective southern Africa countries since decisions for water resources planning and management (including aspects of climate change impacts) are made within such structures. At catchment level it is then possible to make maximum use of current and future advances in the fields of geographical information systems, remote sensing, information management, and computer science in evaluating climate change impacts on water resources**.**

Incorporation of climate change information should be done even at regional level through such structures as the SADC protocol on shared water courses, as the region has 12 shared river basins (namely: Zambezi, Limpopo, Orange, Pungwe, Inkomati, Okavango, Ruvuma, Buzi, Kunene, Save and Usutu basins). Given such link ages, the projected reduction in the stream flow for the Zambezi basin, for example, will inevitably affect all the eight SADC riparian states (home to over 40 million people) in terms of water availability (e.g. for irrigation or hydroelectric power generation), wetlands, agriculture (Thornton et al., 2009), and tourism (Beck and Bernauer, 2011). It thus becomes imperative to enable collaborative regional training and research that critically evaluates the potential impacts of climate change on water resources in different southern Africa hydro-climatic regions so as to inform policy and improve adaptation measures.

Addressing the above research issues will ultimately help ad dress problem areas related to a number of climate and hydrological modelling issues discussed above, including parameter estimation, temporal and spatial scale of application, validation, climate-scenario generation, data, and modelling tools. Solutions to these problems would significantly improve the capability of models to assess the effects of climate change on water resources in southern Africa; hence water resources evaluation and management under a changing climate.

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