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The African Networks of Centres of Excellence on Water Sciences Phase II (ACE WATER 2)

Scientific activities outcomes

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Cover image: Waiting for the wet season at Victoria Falls on the border Zambia-Zimbabwe (Photo by Ezio Crestaz, Dec 2018)

Contributors

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FOREWORD

Although water resource problems are present in all regions of the world, no region is more affected than sub-Saharan Africa. Inadequate infrastructure and development deficits are among the main reasons why these regions are more affected and vulnerable than other parts of the world. Accessibility to water on the African continent is a crucial issue because resources (human, financial and infrastructural) are generally insufficient to ensure adequate and equitable water distribution and management, which would contribute to the continent's sustainable economic, environmental, and social development.

To effectively address this issue, it is essential to understand that improving access to water resources must be an integral part of economic and social development, as this contributes to increasing the economic development, the well-being of Africa's populations and, therefore, their political stability. The implementation of development programmes is often complex and lengthy; a paradox is particularly apparent in Africa. The instability of the poorest economies often hinders the implementation of medium- and long-term development programmes and thus, prevents the creation of infrastructural stability necessary for economic development. An additional aspect to be considered is that regions in which the population has limited access to water are also environments that can catalyse the spread of infectious diseases. This is becoming increasingly evident as a major handicap for their economic development; having a direct impact on the health of populations with consequences on political stability[1]. One example is estimated that malaria costs Africa more than US$12 billion a year, slowing its economic growth by 1.3% annually[2].

In this context, another water-related issue in Africa is sustainable agriculture, which is by far the most important economic activity in most African countries. Agriculture employs about two-thirds of the continent's labour force. It is important to note that 96% of agriculture in Africa is still rain-fed and that sub-Saharan Africa is subject to more extreme climate variability than other regions of the world. This impacts crops, creating an unstable production which undermines both: the food security of populations, and the stability of agriculture as an economic activity. Better appropriate and adapted water resource management policies would improve the efficiency of water resource uses, which would help to reduce the variability of its impact on African economies.

Both management and policies must include water storage, both surface and underground and their interactions, which is an essential element for the stability of African agriculture and the continent's energy development. However, it must also include an assessment of the risk of environmental impact. Hydropower is also seen as a trigger for industrial and regional economic development. As a clean energy resource, hydropower is relatively insensitive to global fluctuations in the price of hydrocarbons, but it is a sector that will suffer greatly from climate change-related variability[3]. Some African countries have significant renewable resources potential (photo-voltaic, bioenergy, wind and – along the Eastern Africa Rift Valley – geothermal energy), that could be exploited more actively, leading to benefits related to their low greenhouse gases emission and low sensitivity to climate change.

[1] World Health Organization Regional Office for Africa, 2019. Of the estimated 10 million deaths per year resulting from infectious diseases, the majority occur in Africa.

[2] The Lancet, 2005. Focusing on improved water and sanitation for health. J Bartram, K Lewis, R Lenton, A Wright.

[3] ECOFIN Agency. Juin 2020. Africa's hydropower segment needs to increase its resilience to climate change. Dams currently provide 17% of the continent's electricity and 23% by 2040. Climate variability represents a loss of 3% per year.

All these aspects describe, in a brief synthesis, how access to water, energy, agriculture, food security and ecosystems (WEFE NEXUS) appear to be closely linked sectors that are essential for the social and economic development of African countries. This can only be achieved through a better understanding of WEFE's multi-sectoral issues, the identification of priorities, their interlinkages and trade-offs, and the development of the knowledge and capacities that underpin responsible and sustainable decision-making in all sectors.

On 22 November 2006, African Ministers and the respective Councils for Science and Technology and Water (AMCOST and AMCOW, respectively) met in Cairo, Egypt, to recognise the need to create a coordinated network of African Centres of Excellence. These centres would focus on understanding the above-mentioned issues, among others, and creating and managing the knowledge, information and data needed to address them. Finally, the centres would be responsible for developing and training appropriate expertise and proposing concrete solutions to policymakers under the leadership of AUDA-NEPAD and with the support of the AMCOW Executive Secretariat. By resolution, Council delegates committed to establishing the AU-NEPAD Network of Centres of Excellence on Water Science and Technology as a first step. Since 2009, in the framework of the ACEWATER project, the European Union has started to support the establishment of this African network. Its main objectives are research, sharing of technology transfer and human capacity development for junior and senior professionals and technicians in the water sectors in Africa. The project is funded by the Directorate General for International Cooperation and Development (DG DEVCO) and coordinated by the Joint Research Centre (JRC) of the European Commission with the collaboration of UNESCO-IHP. The project addresses the main continental and regional priorities in the water sector as defined by the African Union (AU), African Ministers' Council on Water (AMCOW), Regional Economic Communities (RECs), River Basin Organisations (RBOs) and other key stakeholders.

Over the past four years, research has been carried out in close collaboration between the JRC, the UNESCO-IHP and more than 30 research institutions involved in the AU-NEPAD Centres of Excellence in Africa to jointly address the main challenges related to the Water-Energy-Food-Energy-Ecosystem (WEFE) nexus. This analysis has been undertaken in the main African river basins, namely: The Gambia, Senegal, Niger, Blue Nile, Lake Victoria and Zambezi. It has been demonstrated that an integrated analysis is needed to address the full range of environmental and socio-economic issues accompanying the development of these sectors. Furthermore, the associated human capacity development (HCD) in these sectors is a key element of sustainability.

This report presents the findings, conclusions and recommendations arising from the various activities on the WEFE Nexus in Africa. More than 80 deliverables, including technical reports, good practice manuals, databases, templates, HCD products and policy briefs have been produced over the years. This document and the associated policy briefs represent a summary of this important work. They demonstrate how long-term collaboration between research and policy institutions (through the sharing of information, data and knowledge) contributes to and is a source of sustainable development. The continuity of this collaboration will ensure that policy-makers in the future will have more informed options for making knowledge-based decisions to address current challenges at the regional, national and local levels. The results of this study will be integrated into the **AMCOW African Knowledge Hub** to make knowledge and products easily accessible to AU Member States and other key stakeholders. Primarily, to encourage and support all partners to engage in learning, knowledge and information creation and exchange in the search for solutions.

Such a collaborative network, including support and collaboration with the EU and UNESCO, should use the demonstration of its effectiveness presented in this report as **a solid basis on which to build for the future**. Future objectives for the coming years should allow for the creation of a think tank under the aegis of AMCOW to bring together policymakers, research and training institutions, and to include the private sector. This will help address the increasingly complex challenges that will arise over the coming decades. Together with the JRC and UNESCO-IHP, it will also be an opportunity to make even more ambitious progress under the **Joint Africa-EU Strategy**, which provides the policy context. This collaboration will contribute to the development of a **green economy** while improving **access to energy**, to further work to develop **digital transformation** (transforming satellite data and analysis into networks for sharing knowledge, capacity building and information), to create more **sustainable growth and jobs** by working together for **more constructive cooperation and governance**, and to contribute to more **sustainable migration and mobility** that ensures the stability of the region with its capacities.

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The editors would like to acknowledge the contribution of the former JRC colleague Paolo Ronco, who was actively involved in the management, design and implementation of the ACEWATER2 project over three years, between 2016 and 2019. Their gratitude also to Ms. Veronica Girardi, European Commission, DG/INTPA, who assisted the project implementation throughout the years: her support was always helpful, and motivating.

Many different stakeholders actively contributed to identify objectives and key priorities at continental and regional scale, shaping the project scientific program over the selected river basins and its implementation, and to address cross-cutting issues. Their names appear in many parts of this long collection: in the foreword, in the introduction to the regional networks' programs, and in the summary of the outcomes of the scientific research implemented by the CoEs and independent experts, in collaboration with JRC and UNESCO.

The editors would like to acknowledge also the other stakeholders and policy makers who, contributed to the project success by actively taking part in the discussions held at the project meetings, and in the side events. Their proactive and inspiring aptitude led to investigating new and constructive ideas, and greatly facilitated the access to key information.

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The editors recognize that many other stakeholders may have indirectly contributed to the design and implementation of such a challenge scientific effort and may have not been explicitly mentioned in the report despite the efforts made in trying to include everyone. In this case, the editors would like to apologize for any missing reference.

Furthermore, the project team would like to thank all the experts and colleagues, who contributed to this broad document. Their work is key to contributing to the scientific advancements in the WEFE nexus assessment over Africa, filling the gaps between science and policy making, contributing to a more sustainable development and to help creating a better world.

INTRODUCTION

The report summarizes the key ACEWATER2 project scientific achievements of the activities implemented by the African CoEs (Centers of Excellence), supporting Institutions, leading experts and the JRC. The outcomes of few ongoing research projects at JRC complements the overall framework.

The first three chapters focus on the analysis of the WEFE (Water-Energy-Food-Ecosystem) nexus assessment at regional scale over the two formerly existing networks of CoE, in Western and Southern Africa, and the 2018 newly established network of CoE in Central-Eastern Africa.

The study areas were identified jointly by the different project stakeholders and CoEs, at the early stage of the project and, for Central-Eastern Africa, immediately after the network setup in 2018, in good agreement with the priorities identified at AU, AMCOW, RECs and RBOs level. The selection process took into account the socio-economic and environmental relevance of the basins, their transboundary nature, the specific scientific expertise available and interest in promoting cross-country institutional collaboration and scientific exchange best practices.

The analysis was conducted over few of the largest and highly relevant river basins in sub-Sahara Africa, by the Institutions and with the specific objectives stated here below:

- Gambia, Senegal and Niger river basins, in Western Africa; the UCAD (Senegal), acting also as the network Secretariat, focused on the former two basins, addressing the interlinks between climate variability, climate change, water availability, agriculture development and the impacts of existing (e.g. Manantali and Diama) and planned dams. Given the synergies with another ongoing project in the basin (WEFE Senegal), main current outcomes of this later, as related to the topic of the Water-Energy-Food-Ecosystem vulnerability, are summarized as well. On the other hand, AGRHYMET (Niger) developed, in collaboration with JRC, a SWAT hydrological model at Niger river basin scale, the second wider hydrological basin in Africa. The activity led to the analysis of simulation scenarios in two selected sub-basins. A comprehensive review of WEFE nexus relevant issues over Nigeria was complemented by the NWRI (North Nigeria) and the Un. of Benin (South Nigeria), paving the road for future modelling refinement over the region, down to the Niger river delta.
- Blue Nile and Lake Victoria basins in Central-Eastern Africa, both part of the Nile river basin, the largest basin in Africa. The University of Khartoum (Sudan), acting also as the network Secretariat, and the EIWR (Ethiopian Institute of Water Resources) of the Addis Ababa University (Ethiopia) focused on the analysis of climate, hydrology, hydropower production and agriculture in the Blue Nile river basin up to the confluence with the White Nile, aiming at estimating the potential impacts of the GERD (Great Ethiopian Renaissance Dam), currently under construction. On the other hand, the Makere University (Uganda) and ICPAC (the IGAD Climate Prediction and Application Centre, Kenia) investigated the WEFE nexus challenges over the Lake Victoria, including, among others, the surface water, groundwater and lake water quality, mainly impacted by the use of fertilizers in agriculture and the release of untreated waste water, further to the lake level oscillations and future expected trends, based on a water allocation model calibrated over the region. In parallel, ICPAC supported the research of all the CoEs in the network, providing access to processed climate data and conducting specific climate variability analysis to support risk analysis and future scenarios assessment.
- Zambezi river basin, in Southern Africa, the fourth largest one in Africa, extending over 8 countries. In accordance with priorities identified by ZAMCOM, the Zambezi Water Course Commission, the activities were structured around few major research topics, as reported here below jointly with information on the responsible Institutions:
    - Climate - setup of a regional database and analysis of climate variability, by the Un. of Botswana (Botswana);

- Hydrology - data collection, database setup and preliminary data assessment by the Un. of Stellenbosh (South Africa), also hosting the network secretariat, and river basin hydrological model implementation and simulation scenarios assessment face to climate change projections, implemented by the Rhodes Un. (South Africa) in collaboration with the JRC;
- Hydropower - modelling joint hydrological and energy production scenarios, to assess the impact of climate change, in collaboration between a leading expert from the Un. of South Florida (USA) and the hydrology modelers (see point above). A hydropower economic assessment was addressed by the IWEGA (Mozambique).
- Agriculture – characterization of the current status, traditional practices and future perspectives at basin scale, by the Un. of Malawi (Malawi) and the Un. of KwaZulu-Natal (South Africa). The overall framework is complemented by an assessment of groundwater use at basin scale, based on identification of exploitation area and crops water demand.
- Groundwater hydrology – hydrogeological and hydrochemical mapping at basin scale, based on refinement of the SADC-GMI cartography, by the Un. of Western Cape (South Africa), and country scale analysis by the Un. of Zambia (Zambia) and the NUST (Zimbabwe). A basin scale finite element groundwater flow model was setup and future scenarios simulated, based on a joint effort of the Un. of Zambia and the JRC.
- Water governance and information systems, relevant to ZAMCOM in setting up effective policy-science dialogue and improve data management and sharing practices. Activity implemented by the CSIR (South Africa).

A fourth chapter covers the scientific research and technological developments that have been addressing cross-cutting topics, mostly of continental relevance, and specific project requirements. The latter include efficient data/documentation management and software developments aimed at supporting scientific analysis and efficient communication of research results. Activities have been implemented in a collaborative way, involving CoEs, JRC and few leading sector experts. The overall framework is complemented with the outcomes of few ongoing institutional JRC projects of relevance to the WEFE nexus debate.

The contributions are structured around the topics below:

- human capacity development priorities in the water sector, and priorities of the water sector face to the agri-energy sector;
- water power nexus in the African power pools, addressing the specificities of the major sub-regions (Western, Central/Eastern and Southern Africa), further to the North Africa;
- geothermal industry in East African countries, along the EARS (Eastern Africa Rift System), from Eritrea down to Zambia, contributing to the debate on role and future potentials of (competing) renewable energy sources vs. fossil fuels;
- urban development and regional connectivity in Africa;
- status of groundwater resources management and modelling in Africa, being groundwater a strategic fresh water resource for building a more resilient society;
- water loss through evaporation vs hydropower production assessment at major dams in Africa vs. hydropower production, the topic relating to the debate on renewables face to large investments planning in hydropower development;
- climate variability and heat waves analysis in the project river basins;
- analysis that led to the setup of a water cooperation atlas in Africa, complemented by the development of a dedicated geospatial web platform;
- project documents and data management in the framework of Aquaknow, a JRC Knowledge Management System addressing the specific needs of the water community.

The other annexes of the ACEWATER2 administrative report collect full scientific project deliverables, including reports, manuals, databases and models' setup. Reference to these annexes can be made for an in-depth analysis.

Photo credits: Cesar Carmona Moreno

Niger river at Niamey

SCIENTIFIC RESEARCH IN WESTERN AFRICA

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The European Commission DGs DEVCO and JRC collaborated with and the NEPAD Western African Water Centres of Excellence (WANWATCE) within the EU-AU project "Support to the New Partnership for Africa's Development (NEPAD) Centres of Excellence in Water Sciences and Technologies".

The collaboration established aimed to conduct scientific research over the Western African region, addressing key topics relevant to the WEFE (Water-Food-Energy-Ecosystem) nexus assessment over the selected transboundary river basins (Gambia, Senegal, and Niger). The main objective was to investigate competing water demand, sectors interdependencies and tradeoffs face to the challenges of increasing pressure (population growth, irrigation expansion, water quality deterioration) and considering the potential socio-economic impacts.

Partners institutions were:

- Université Cheikh Anta Diop de Dakar (UCAD), Senegal, acting also the Secretariat for the regional network of CoE;
- AGRHYMET (Centre Regional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle), Niger
- NWRI (National Water Resources Institute), Nigeria
- Un. of Benin, Nigeria

The existing regional climate database, setup in the first phase of the ACEWATER project, was developed and completed with up to date information and data.

The Senegal and Gambia river basins were investigated mainly to assess the impacts of climate variability on hydrology, irrigation in agriculture and environmental challenges (eg. at Senegal d).

The Niger river basin, the second largest one in Africa (after Nile) with its more than 2 million km^2, was investigated at both basin and country scale, with case studies in its Nigerian portion. The basin poses many challenges from a WEFE nexus perspective, including, among others, hydropower production, reservoir multipurpose optimization and release management, rainfed and irrigated agriculture development, impact of land use and agricultural practices, including livestock and fisheries, role of ecosystem services (natural parks, wetlands; inner and main delta regions), pressures on resources due to population increase, water quality issues (eg. oil spills in the delta), climate variability/change and related extreme events risks (drought, flood).

A hydrological model, calibrated at basin scale, was used to investigate simulation scenarios over selected sub-basins, addressing potential reduction of water availability and expansion of irrigated agriculture. A comprehensive and detailed bibliographic review was complemented for both North and South Nigeria, with specific focus on sample case studies highlighting the challenges arising from competing water use

The outcomes of the scientific research activities are expected to actively contribute to the enhancement of scientific and technical cooperation, including effective data management among relevant stakeholders, at both national and regional scale. At the same time, the research outcomes are aimed to support decision makers with science-and knowledge-based tools and methods towards an effective and cooperative water management.

All the research activities were identified in line with the regional priorities identified by the REC, ECOWAS/CEDEAO, and the river basin organizations, OMVS (Organisation pour la mise en valeur du fleuve Sénégal) and NBA (Niger Basin Authority), which could be summarized as follows:

- improving access to potable water, particularly for Sahel population impacted by conflicts and droughts, and contributing to poverty alleviation, sustainable development and environment preservation;
- improving data collection and knowledge sharing on groundwater resources, to promote state-of-the-art management practices and to implement drilling campaigns to address water supply challenges;
- to setup and operationalize the CEDEAO distributed regional water observatory (Observatoire Régional de l'eau) information system, aimed at supporting projects development, follow-up and evaluation through monitoring, data collection, harmonization and dissemination, as well as cooperation with existing information systems;
- to reinforce capacity building actions of regional Institutions and to promote their active role in the integrated water management process;
- to reinforce and operationalize the regional institutional and juridical framework, to promote participation of member States and all other public and private stakeholders (eg. directives on water infrastructures and transboundary water; legislation; harmonization);
- to improve coordination and synergies at regional and river basin scale;
- promoting specific programs on the assessment and protection of the regional water tower of the Fouta-Djalon massif.
- investigating frequency and magnitude of extreme events and related risks (floods and droughts in particular) in the context of climate variability and change;
- to investigate impacts and optimization of operational rules of existing and future human made infrastructures (eg. dams, water transfer schemas, irrigation in agriculture) and implications for hydropower energy production and navigation;
- to improve research and actions against soil and water quality degradation (eg. soil erosion, water salinization, salt water intrusion in the aquifers)
- to address environment degradation and human health risks related to artisanal mining, and particularly gold mining in the Senegal river basin (eg. release of untreated water, contaminated by highly toxic products);
- addressing specific environmental challenges in the Senegal river delta, as related to the complex interlinks among salt water intrusion, alien species development, flooding risks.

Climate Vulnerability and water resources variability in West Africa: Senegal and Gambia River Basin Cases Studies

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West Africa, particularly the Sudano-Sahelian zone, has experienced unprecedented climate variability over the last two decades. This study aims at contributing to a better understanding of climate variability and risks and their impacts on water resource availability in West African transboundary watersheds. The objective is also to establish updated knowledge bases for the analysis of climate variability and risk assessment as well as the search for sustainable solutions to overcome environmental and societal vulnerability. In this perspective, the updating of the West African climate database and its extension to the shared basins (Senegal and The Gambia) enables relevant analyses of climate variability and its impact on the environment and more particularly on the availability of water resources to be carried out. The two transboundary basins of Senegal and The Gambia straddle very contrasting climatic zones: the Guinean and Sudanese well-watered zones and the semi-arid and arid Sahelian zones. The average rainfall of the Senegal River basin is 550 mm.yr-1, varying from more than 1500 mm.yr-1 at the source in the Fouta Djalon mountain, to less than 200 mm.yr-1 in the northernmost part of Senegal. The Gambia River basin experienced significant rainfall variation in each riparian country ranging from 1200 to 1500 mm in Guinea; from 1200 mm in the north to 1500 mm in the south in Guinea Bissau and about 500 to 1000 mm in Senegal and The Gambia.

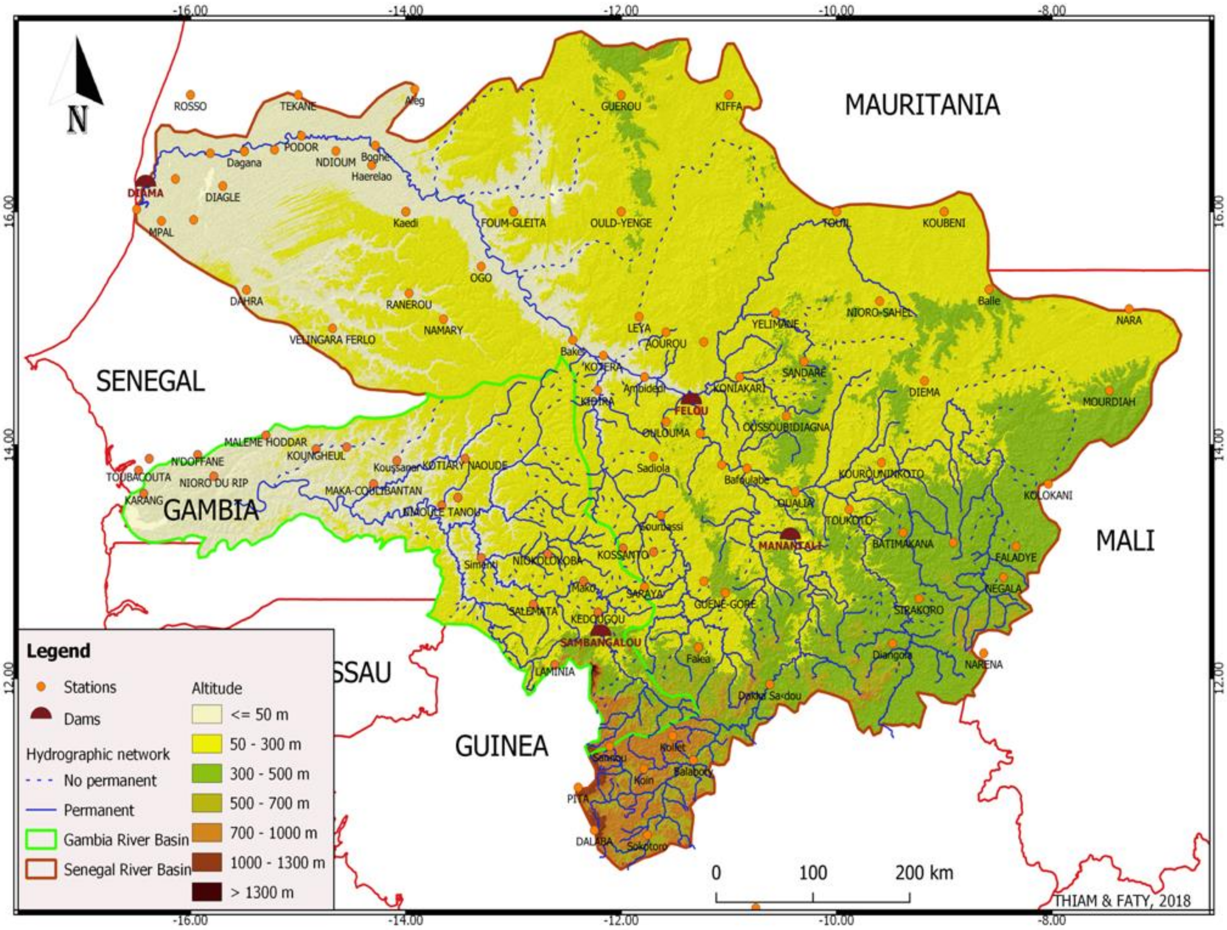
Keywords: climate variability; transboundary basins; hydro-rainfall data; drought; hydrological modelling

1. Introduction

The West African region has been subject to very high climate vulnerability for several decades (Irie et al., 2015). Recent studies on rainfall variability do not really argue in favour of improving surface water capital, especially considering the strong dependence between rainfall and water regime in these latitudes (Gaye et al., 2015). The deterioration of the climate is pushing more and more towards the use of surface water, the renewal of which could be compromised more or less in the long term.

The Senegal River (BFS) and Gambia River (BFG) basins are transboundary basins located in West Africa and distributed respectively between Senegal, Guinea Conakry, Mali and Mauritania - between The Gambia, Guinea, Guinea Bissau, Senegal (Figure 1). The hydrosystem of the two basins is influenced by the recent droughts that have affected the entire West African window since 1970. In order to overcome this climatic crisis, the States have set up basin organizations (OMVS on the Senegal River and OMVG on the Gambia River) for the control and management of water resources in the two basins. The two organizations are in charge of the implementation of the exploitation of hydraulic infrastructures, water management, sharing and cooperation between the riparian States. Understanding recent climate change and, above all, medium and long-term trends is an important development issue. It is in this perspective that this report entitled "Climate Vulnerability and Variability of Water Resources in West Africa": Case Studies of the Senegal and Gambia River Basins" is set out. The objective is to analyze climate variability and trends and their major impacts throughout West Africa, with a focus on the Senegal and Gambia river basins.

Figure 1: Presentation map of the study area



2. Methods and data

2.1. Presentation of data and analytical material

Within the framework of this study, nine reference rainfall stations were selected to carry out hydro-climatic analysis and determination of the impact of climate variability on water resources in the Senegal River Basin and The Gambia. The stations are presented in Table 1.

Table 1: Presentation of hydro-climatic data

Station	Mean T°c	Rel. Hum. (%)	Insol.(H)	Wind Speed (m)	Evaporation (mm)	P(mm)
Bakel	1979-2016	1982-2016	1984-2016	2012-2016	1981-2016	1918-2016
Labe	1971-2016	1971-2016	1971-2016	1971-2016	1971-2016	1923-2016
Siguiri	1971-2016	1971-2016	1971-2016	1971-2016	1971-2016	1923-2016
Kedougou	1970-2016	1970-2016	1982-2016	1980-2016	1970-2016	1918-2016
Saint-Louis	1980-2015	1980-2015	1981-2015	1981-2015	1981-2015	1848-2016
Matam	1960-2016	1960-2016	1960-2016	1969-2016	1960-2016	1918-2016
Mamou	1971-2016	1971-2016	1971-2016	1971-2016	1971-2016	1923-2016
Bansang	--	--	--	--	--	1980-2016
Oundou bac	--	--	--	--	--	1980-2016

Several tools have been selected for the processing of hydro-climatic data from the Senegal and Gambia river basins:

- The Khronostat software combines different statistical tests specific to a change in the behaviour of a variable in a time series. The most widely used tests, the best argued in the literature and the most robust were chosen;
- Xlstat is an intuitive statistical software allowing the calculation of time series. Xlstat is very easy to use; it runs in an Excel environment and offers more than 200 functionalities. In this project, Xlstat is mainly used for the calculation of statistical parameters;
- Hydraccess is a hydrology software developed by researchers from the French Institute for Research for Development (IRD). It allows to manage hydrological databases and to perform easily a set of common treatments on hydrological and rainfall data.

Climate change influences water reserves in Sudano-Sahelian Africa. It is therefore essential to develop geospatial tools to determine the impacts of climate on the environment of the Senegal and Gambia river basins. Thus, the combination of hydro-climatic analysis and remote sensing results is used to assess the level of climate change. For this purpose, Modis-Terra images were used to determine land cover types for better classification. Remote sensing tools have thus been mobilized to strengthen the analysis of hydro-climatic data. The imagery is also used to monitor environmental conditions on a regional scale and specifically for the Senegal and Gambia basins.

2.2. Methods

Several methods were used for processing and analyzing the data and producing the results.

2.2.1. Regionalization of rainfall data

The Thiessen polygon method was used for the regionalization of rainfall data. This method makes it possible to estimate weighted values taking into consideration each rainfall station and to highlight an overall average of the series. It assigns to each rain gauge a zone of influence whose area, expressed as a percentage (%), represents the weighting factor of the local value. The average rainfall over the basin is obtained by the formula:

$$P\ moy = \Sigma\ Ai.\ Pi/A$$

With Pmoy: average precipitation over the basin; A: total area of the basin; Pi: precipitation recorded at station i; Ai: area of the polygon associated with station i.

2.2.2. Calculation of rainfall and hydrometric indices

The calculation of the rainfall and hydrometric indices makes it possible to identify the major trends in the time series. On an interannual scale, they make it possible to highlight the deficit and surplus phases. They are calculated using the following formula:

$$x'_i = \frac{x_i - \overline{x}}{\sigma(x)}$$

x'_i	:	Reduced centered variable for year i (rainfall or hydrometric index depending on the variable studied)
$\overline{x}$	:	Time series average over the given period of time
$\sigma(x)$	:	Standard deviation of the time series over the given time period

The rainfall index is well suited to monitoring changes in vegetation dynamics in relation to changes in rainfall (Diallo et al., 2013).

2.2.3. Searching for trends and breaks in stationarity in time series

To highlight the stationary or non-stationary nature of the rainfall and hydrometric time series, statistical tests involving trend and break analysis were used. The term trend refers to a change in the properties of a random process that occurs gradually over the sampling period, whereas a break corresponds to a change that occurs suddenly, with the understanding that the properties remain stable on either side of the break year (Perreault, 2000). The breakage test was performed using KhronoStat 1.01 software developed by IRD.

2.2.4. Computation of mean break variations

For hydro-pluviometric variables with a break in the time series, it is interesting to calculate the average variations on either side of the break by applying the following formula (Ardoin-Bardin, 2004):

$$D = \frac{\overline{x}_j - \overline{x}_i}{\overline{x}_i} * 100$$

D	:	Deficit/surplus on either side of the breakup
$\overline{x}$	:	Average before rupture
x'_i	:	Average after rupture

2.2.5. Analysis of land use dynamics

Land use mapping was done through a series of operations. The elaboration of colored compositions allowed to distinguish the different objects on the images. This was followed by the choice of training areas (sites representative of the digital characteristics of the classes) which made it possible to define the spectral signatures of each landscape unit. These training areas serve as the basic elements of a supervised classification. Then the "maximum likelihood" classification algorithm was chosen to perform the classification. Finally, field surveys were used to validate the classifications carried out. In sum, the supervised classification by maximum likelihood consists in classifying pixels according to their resemblance to digital counts of geographic reference objects previously determined on the image and validated by field surveys (Kouassi et al., 2012). Given the reality of the terrain (a large watershed), we focused on the hotspots of Fouta Djalon, the Senegal River delta and the Gambia estuary. Based on the thematic classifications obtained, land use maps were produced. The Envi 5.1. software was used for the digital processing of satellite images and the ArcGIS 10.1 software for the determination of land cover type statistics.

3. Results and discussions

3.1. Statistical repartition of annual rainfalls

The homogenized annual precipitation chronicles were subjected to statistical processing. A dozen statistical laws (Brunet-Moret, 1969) were fitted to these annual precipitation samples. The results are recorded in the table below. Goodrich's law provides the best fit for all the stations studied.

The study area is divided into four climatic domains, namely Guinean, Southern Sudan, Northern Sudan and Sahelian. In dry recurrences, such as the dry centennial, if for the upper basin rainfall is still significant (above 1000 mm), it becomes very low, even random in the Sahelian domain, particularly in Bakel and Matam.

Table 2: Climatic domains in the hydro systems of the Sénégal and Gambia rivers

Frequencies	**Dry recurrences**					**Average**		**Wet recurrences**				
	0,01	0,02	0,05	0,1	0,2	0,5	0,8	0,9	0,95	0,98	0,99	**Climatic zones**
Recurrences (years)	100	50	20	10	5	2	5	10	20	50	100	
Mamou	1319,5	1360,6	1435,7	1514,9	1624,0	1860,8	2116,0	2251,8	2364,0	2489,8	2573,3	**Climat guinéen**
Labe	1316,7	1323,6	1341,2	1366,7	1413,8	1564,2	1801,3	1959,6	2107,4	2291,5	2424,3	
Mali	1257,1	1275,1	1312,3	1356,6	1424,7	1595,5	1808,0	1931,3	2037,9	2162,3	2247,5	
Tougue	1082,5	1118,0	1184,2	1255,9	1356,9	1582,6	1833,3	1969,0	2082,3	2210,4	2295,9	
Dinguiraye	1010,0	1033,2	1077,5	1126,4	1196,7	1357,9	1541,3	1642,1	1726,9	1823,5	1888,3	**south-soudanian climate**
Siguiri	872,5	892,6	933,8	982,6	1057,4	1243,8	1474,5	1607,9	1723,1	1857,3	1949,0	
Kédougou	808,4	836,6	890,2	949,2	1033,7	1226,2	1444,2	1563,7	1664,0	1778,1	1854,6	
Narena	758,4	810,2	893,8	971,8	1068,3	1249,7	1418,9	1501,4	1566,6	1636,8	1681,9	
Kenieba	732,4	774,3	847,6	921,7	1020,1	1223,4	1432,1	1539,9	1627,6	1724,7	1788,3	
Kita	664,0	686,5	729,7	778,0	847,9	1009,9	1196,3	1299,5	1386,6	1486,0	1552,9	**north-soudanian climate**
Bansang												
Kayes	402,0	420,5	455,9	495,2	551,9	682,6	832,3	914,8	984,4	1063,7	1117,0	**Sahelian climate**
Yelimane	316,3	325,6	345,7	370,8	411,1	517,7	658,0	742,1	816,2	904,0	964,8	
Nioro du Sahel	261,4	276,3	306,3	341,0	393,0	519,1	671,0	757,3	831,2	916,7	974,8	
Bakel	256,1	275,7	310,8	347,3	396,8	502,2	613,6	672,1	720,2	773,9	809,4	
Matam	165,2	179,2	207,5	240,4	289,9	410,3	556,0	639,1	710,4	792,8	848,9	

3.2. Flows analysis in the Senegal Basin

The analysis of the flows allows to determine the natural regime of floods and low flows in the Senegal River watershed. The flood regime in Senegal is that of an annual flood, linked to the rainy season in the upper basin. Peak floods, highly variable depending on the rainfall of the year, between 3,000 and 12,000 m^3/s^{-1}, can occur at Bakel from July to October. The peak flow at Bakel is most often in the first fortnight of September.

Downstream of Bakel, the inflows from Mauritanian tributaries to the Senegal River are negligible. On the other hand, the damping of the flood by flooding of the main bed and by evaporation is very important. Thus, the centennial flood peak of 8,300 m^3/s^{-1} at Bakel, is only 6,500 m^3/s^{-1} at Matam and 3,200 m^3/s^{-1} at Dagana.

During low water periods, the natural flow of Senegal is about 10 m^3/s^{-1} at Bakel. It can practically cancel out in certain dry years. The modulus of the river (average flow) is about 750 m^3/s^{-1}.

Due to the very low slope of the river, the flows remain moderate, even in case of floods. They vary from 0.1 to 0.6 m.s-1 during periods of low water levels (flows below 500 m^3/s^{-1}). They vary from 1 to 1.4 m.s-1 during the rise in water level and from 0.4 to 0.8 m.s-1 only during the flood.

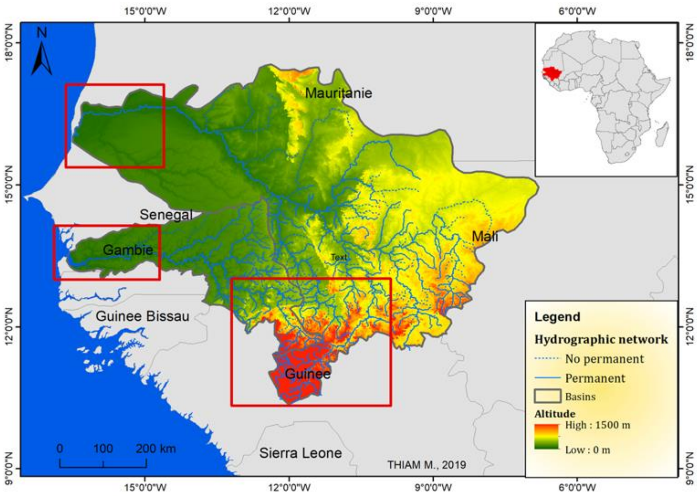
This great asymmetry between the rise and fall of the flood, due to the low slopes and the storage of water in the large bed, explains the absence of a clear height/flow (flood) law in the river downstream of Bakel.

3.3. Highlighting environmental vulnerability in the Senegal and Gambia River Basins through hotspots

In the study area covering the topographic basins of the Senegal and Gambia Rivers, three sites were targeted (Figure 2). These are the following sites: The Fouta Djalon massif, the lower estuary of the Senegal River and, the estuary of the Gambia River. Each of these sites illustrates a type of vulnerability or a combination of several types:

- The Fouta Djalon site is essentially marked by environmental vulnerability, mainly related to the effects of hydro-climatic variability and change and the related effects of community practices in response to these hydro-climatic shocks.
- In the Senegal River estuary, there is a combination of several types of vulnerability: environmental (instability of the estuary and change in the position of the mouth), social and economic, resulting from attempts to adapt to environmental changes.
- The Gambia estuary is an inverse estuary (Diop, 1990) and is therefore very vulnerable to the effects of marine dynamics and salt intrusion. It is a poorly studied site because it is poorly developed and its uses are very limited.

Figure 2: Location of studied hotspots in the Senegal and Gambia River Basins



Recent changes in the Senegal estuary have been widely studied (Kane, 2010; Niang, 2014; Kane and Niang, 2014; Niang et al., 2019). Therefore, this hotspot will not be included in this technical report.

3.3.1. Reforestation of the Fouta Djalon, myth or reality?

The analysis of the 2003 land use map (Figure 2) shows the following trends: predominance of vegetation or mangroves 52.40%, bare soils with 38.04%, bodies of water, which represent 0.15% and finally buildings occupying 0.08% of the total area of the study area.

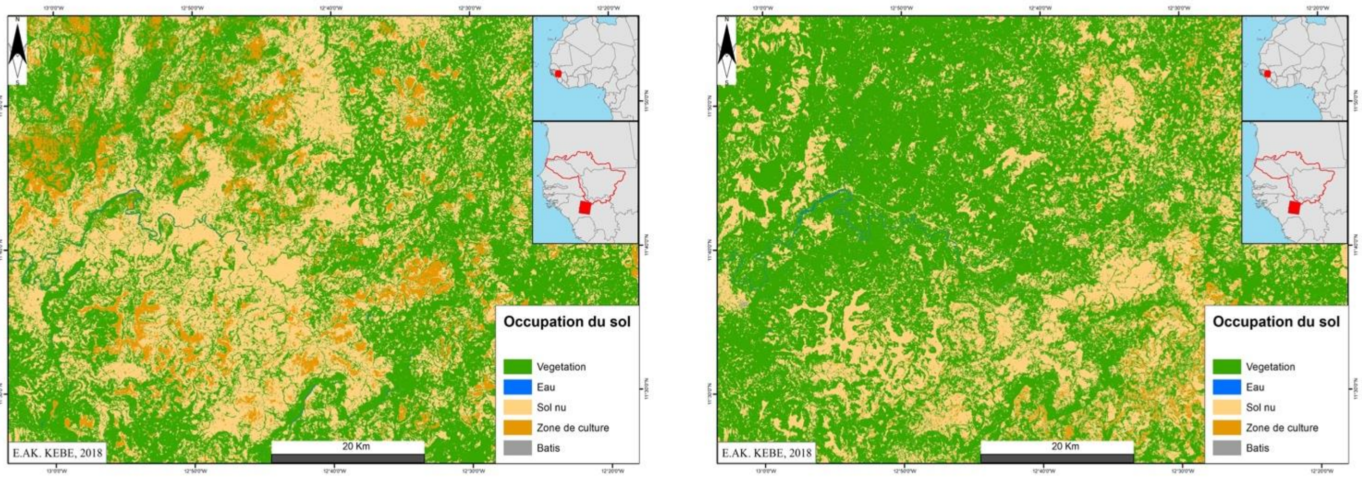
While in 2016, the entities areas are about 0.26% for water, the cultivated areas are about 4.18%, bare soils are estimated at 33.03%, and vegetation (62.38%), with a slight increase in built areas with 0.15% (table 3). The table below summarizes the statistical difference in land use in the Fouta Djalon massif.

The re-greening of the area is due to a return of rainfall in 2005. The increase in built-up areas is also reflected in an increase in the number of active areas, resulting in an increase in cultivation areas.

Table 3: Land use in the estuary of the Fouta Djalon Massif

Spatial units	2003		2016	
	Surface ha	*Surface %*	*Surface ha*	*Surface %*
Water	3326	0.15	5812	0.26
Vegetation	1192880	52.40	1420210	62.38
Bare soil	884213	38.84	751925	33.03
Housing areas	1893	0.08	3458	0.15
Cultivation area	194267	8.53	95176	4.18
Total	**2276579**	**100**	**2276582**	**100**

Figure 2: Land use map of the Fouta Djalon massif in 2003 (a) and 2016 (b)



(a) **(b)**

3.3.2. The estuarian of the Gambia River Basin

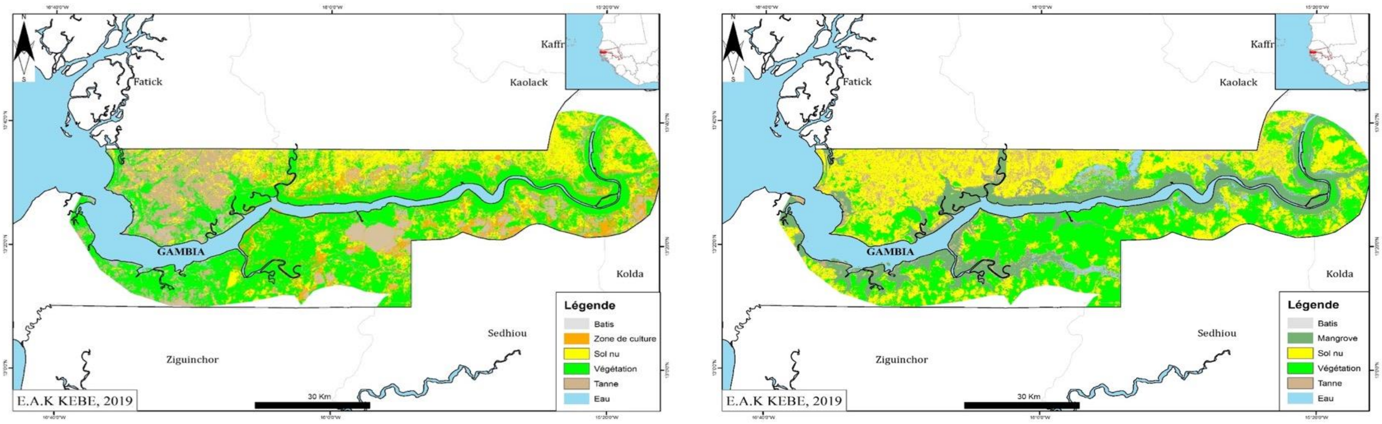
The Gambia River ends in the Atlantic Ocean with an estuary extended from Banjul to Gouloumbo, 492 km upstream (Lamagat et al, 1987). The estuary covers an area of 36,000 km^2. Its salinity decreases as you move away from the mouth and Mangroves follow the river for about 220 km. The degradation of mangroves is one of the most important issues in this environment. Indeed, this mangrove is considered as one of the last reserves in West Africa. Analysis of the 2003 land use map (Figure 3) and table shows the following trends: predominance of water bodies, which represent 22.19% of the total area of the study area, vegetation or mangroves 16.39% and bare soils, which occupy 18.06% of the area and buildings 17.01%. While in 2016 (Figure 3), the plan areas are in the order of 16.67%; mangroves (16.67%); bare soils are estimated at 19.85%; cultivation areas are in the order of 28.12% (Table 4). The table below summarizes the statistical difference in land use in the estuary of the Gambia Basin.

Land use mapping between 2003 and 20016 in the Gambia estuary revealed some changes with a decline in vegetation - mangroves. Bare soils are increasing north of the study area. Water surface classes also increase. The consequences of irregular rainfall, which has also resulted in unprecedented periods of drought, have strongly contributed to the gradual abandonment of agricultural practices but also to the movement of people to cities for the conversion of activities (rural exodus).

Table 4: Land use characteristics in the Gambia River estuary

Spatial units	2003		2016		Differences (%)
	Surface ha	Surface en %	Surface en ha	Surface en %	
Water	7987000	22,19	6000000	16,67	**5,52**
Vegetation	5900000	16,39	6000000	16,67	**-0,28**
Bare soil	6500000	18,06	7144400	19,85	**-1,79**
Built	6123530	17,01	6734156	18,71	**-1,70**
Cultivation area	9404267	26,12	10121444	28,12	**-1,99**
Total	**36000000**	**99,76**	**36000000**	**100**	

Figure 3 : Land use map of the Gambia River estuary in 2003 (a) and 2016 (b)



(a) **(b)**

4. Conclusion and recommendations

Given the geopolitical position of the hydrosystems of the Senegal River Basin and The Gambia, the acquisition of hydro-climatic data was very delicate. It took a great synergy of efforts to obtain the data despite the presence of basin organizations such as OMVS and OMVG.

Rainfall and hydrological data provide an essential knowledge base for water resource assessment and decision-making in the context of climate change and variability. Thus, we will have to cooperate with basin organizations (OMVS and OMVG) for a synergy of action consistent with well identified research axes and in a logic of partnership in research and development.

This report has highlighted the main fluctuations in rainfall and water regime in the Senegal River Basin and the Gambia Basin while highlighting land use in the Fouta Djalon hotspot, the Senegal River Delta estuary and the Gambia estuary.

The use of hydrological indices made it possible to visualize and subdivide the studied chronicles into several intervals according to dry or wet conditions and to characterize the extent of dry periods and their intensity. The hydrological drought indices indicate that the most intense droughts have occurred since 1970.

Land use in the Fouta Djalon-Delta hotspots of the Senegal River Delta and Gambia Estuary shows land use trends such that water bodies and biodiversity are decreasing at the expense of bare surface expansion.

The following actions have been carried out:

- Creation of a rainfall database for the Senegal River Basin;
- Creation of a hydrometric database (water flow) of the Senegal River basin;

- Acquisition of Landsat Oli 8 satellite images for the Fouta Djalon hotspots - the estuary of the Senegal River and The Gambia for land cover and land use mapping ;

- Development of an environmental database (GIS) to highlight environmental problems in selected hotspots (Senegal River estuary, Gambia River estuary and Fouta Djalon mountain)

- Update of the former ACEWATER1 database of Senegal with the 24 rainfall stations for climate vulnerability.

5. Limitations of the study and perspectives

In the phase of collecting hydro-climatic data from the stations of the Senegal River and the Gambia, we are confronted with some problems that constitute the limits of the study:

- Some rainfall and hydrometric stations as well as data from Mauritania and Guinea were inaccessible;
- Most of the stations are not updated because of the Covid-19 pandemic;
- Lack of climatic data (temperature-humidity-evaporation) at basin scale (Senegal and Gambia river basins);
- Problems related to the acquisition of rainfall, hydrometric and socio-economic data constitute a major constraint of the Senegal and Gambia river basins.

Within the framework of this project, future prospects will essentially be to develop scientific cooperation between the UCAD team and the WEFE Senegal project to pool efforts in order to move to the stage of hydrological modeling of the Senegal River basin with SWAT software.

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Water Energy and Food Ecosystem vulnerability in the Senegal River

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Africa developing countries are confronted with the challenge of effectively managing natural resources to achieve higher outcomes in several sectors, such as pointed out in the Sustainable Development Goals while ensuring sustainability and environmental protective solutions. This challenge requires even more effort in transboundary river basins, such as the Senegal River Basin, due to complex and cross-sectoral technical and political realities. To this scope in this report a preliminary identification of WEFE Nexus related issues in the Senegal river basin are identified and summarized. These issues also include interactions between key sectors (i.e. water, energy, agriculture, and environment), concretely: hydropower development using multi-purpose infrastructure and the social and environmental impacts associated; high climate variability and its impacts on the production system, the nature and people, particularly on the poorest and rain dependent socio-economic communities; improvement of production systems (irrigation, rain-fed, flood recession agriculture) to increase crop production and food security; navigation improvement to enhance commerce and support development; environmental protection and safeguarding of specific ecosystems (such as the Delta); water quality and impacts on water-related diseases and socio-economic dynamics.

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1. Introduction

Africa developing countries are confronted with the challenge of effectively managing natural resources to achieve higher outcomes in several sectors, such as pointed out in the Sustainable Development Goals (United Nations (UN), 2015), while ensuring sustainability and environmental protective solutions.

This challenge requires even more effort in transboundary river basins, where solutions should be balanced not only across competing sectors and scales but also taking into account the specific and eventually different and competing development objectives of the riparian countries. In this regard, a sound, integrated and inclusive transboundary management approach is clearly needed to effectively address coming and future challenges at river basin scale, while ensuring at the same time sustainability.

In recent years, the Water, Energy, Food and Ecosystems (WEFE) Nexus approach has taken a center stage as an integrative approach meant to integrate both management and governance across the multiple sectors that its four components involve (e.g. agriculture, food, fishing, livestock, energy, forest protection, water quality etc.) and its concept has rapidly expanded (Albrecht et al., 2018; Keairns et al., 2016). The use of such approach should overcome the traditional view of single sectors as separate entities, featuring them instead as complex and inextricably systems (EC, 2019) where interlinkages and feedbacks across sectors should be carefully addressed. Currently, the European Union (EU) is actively cooperating with the African Union (AU) in several policy initiatives framing the demand for the WEFE nexus approach to water development in Africa. In this context, the WEFE Senegal project (APPUI A LA GESTION DES RESSOURCES EN EAU ET DU NEXUS EAU-ENERGIE-AGRICULTURE DANS LE BASSIN DU FLEUVE SENEGAL) which is funded by the European Union is being implemented by the the Joint Research Centre (JRC) of the European Commission and the AICS[4] in collaboration with the OMVS[5], the Directorate-General of International Cooperation and Development (DG DEVCO) and the European Union Delegation in Dakar (Senegal).

The main goal of this project is to contribute to and strengthen the WEFE framework in the Senegal river basin, in order to improve the understanding of the interactions between water resources management, climate change and the evolution of agricultural activities in a rural economy. Concretely, the scientific component of the project aims to:

(a) Strengthen technical/scientific knowledge on relevant components and issues identified in the Senegal River Basin, in collaboration with local/regional technical actors;

(b) Promote sustainable management measures in coherence with the policies and governance of the basin, taking into account regional (Water Management Master Plan, Common Energy Policy, Energy Transport Master Plan, Regional Action Plan for the Improvement of Irrigated Crops, Strategic Environmental Action Plan etc.) and national policies;

(c) Provide support for the assessment and evaluation of alternative measures and solutions as proposed by the OMVS.

2. The Senegal River Basin

The Senegal river is the second longest river (1800 km) in West Africa and its transboundary drainage basin covers about 410,000 km2, over Guinea, Mali, Mauritania, and Senegal (10, 54, 26 and 15 % respectively). Born in the Fouta Djallon massif in Guinea, the Senegal river travels across Guinea and Mali and, after the confluence of the Bafing, Bakoye and Falémé rivers, traces the border between Mauritania and Senegal until it meets the Atlantic ocean, near Saint-Louis in Senegal (**Errore. L'origine riferimento non è stata trovata.**). The journey of the river constitutes a lifeline for the 7.5 million of people of the basin (16% of the riparian countries' population) but also for the economy of the riparian countries and the region. Due to the high dependency of the main livelihoods in Senegal River Basin (SRB) on water (agriculture, livestock, fisheries), around 85% of its population lives close to the river (UN, 2003).

Table 1. Main Senegal river basin characteristics

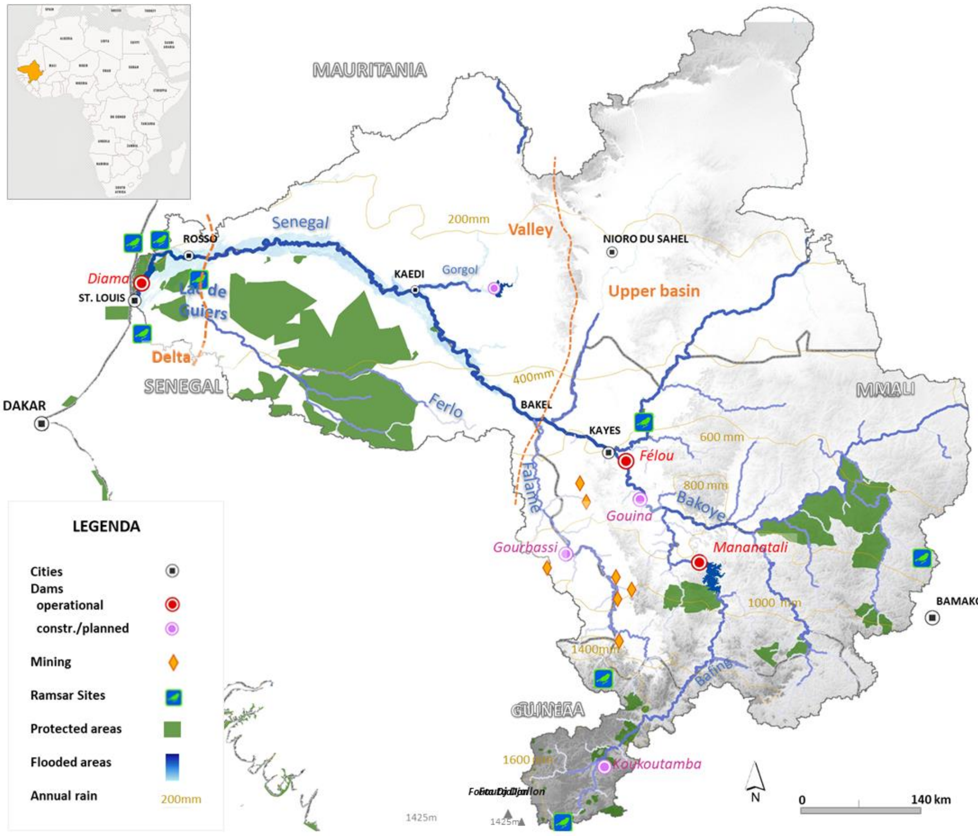
Senegal River Basin Factsheet			
Surface area		340 000	km^2
Precipitation	Mean	550	mm/yr
	Range	200 - 1500	mm/yr
Discharge			
Bafing Makana	< 80s	330	m^3/sec
	> 2010	267	m^3/sec
Bakel	< 80s	778	m^3/sec
	> 2010	611	m^3/sec
Population (2015)	hab.	7 980 000	
	density	23-25	hab/km^2
	rural	29.6	%
	growth	2.8	%
	hab. (2025)	9 000 000	
Agriculture			
Harvested Area		21 500	km^2
Cropland	ESA 2014	79 000	km^2
Dominant crops	SDAGE	Millet, Maize, Sorghum (51%) Rize (7%), pulses (12%), oils	
Irrigated area	SDAGE	75 600	ha
Livestock			
	Cattle	16	milions
	Goats-sheeps	46.5	milions
	Poultry	96.6	milions

In 1972, Senegal, Mauritania and Mali decided to join their efforts in developing the basin through the establishment of the Organisation pour la Mise en Valeur du fleuve Sénégal (OMVS), which is considered as an example of transboundary cooperation due to the effective implementation of the principle of equitable sharing among member states (regarding both the ownership of hydraulic infrastructure and the benefits associated to water resources at the national level). In

[4] AICS: Italian Agency for development cooperation. Web: https://dakar.aics.gov.it/
[5] OMVS :Organisation pour la mise en valeur du fleuve Sénégal. Web: http://www.omvs.org/.

2006, Guinea joined the OMVS. Despite the efforts made by the four riparian countries during the last three decades with regard to the basic dimensions of human development, they still show values of the Human Development Index (HDI) among the lowest of the world (ranking in the interval position 159-182 for a total of 189 countries) and are catalogued as Least Developed Countries (UNDP, 2018). Therefore, the development of the basin is of vital importance for the four countries, which face up significant challenges due to biophysical and socioeconomic determinants, such as the climate variability increase in the region, a high population growth rate (around 3% per year) or the lack of job opportunities.

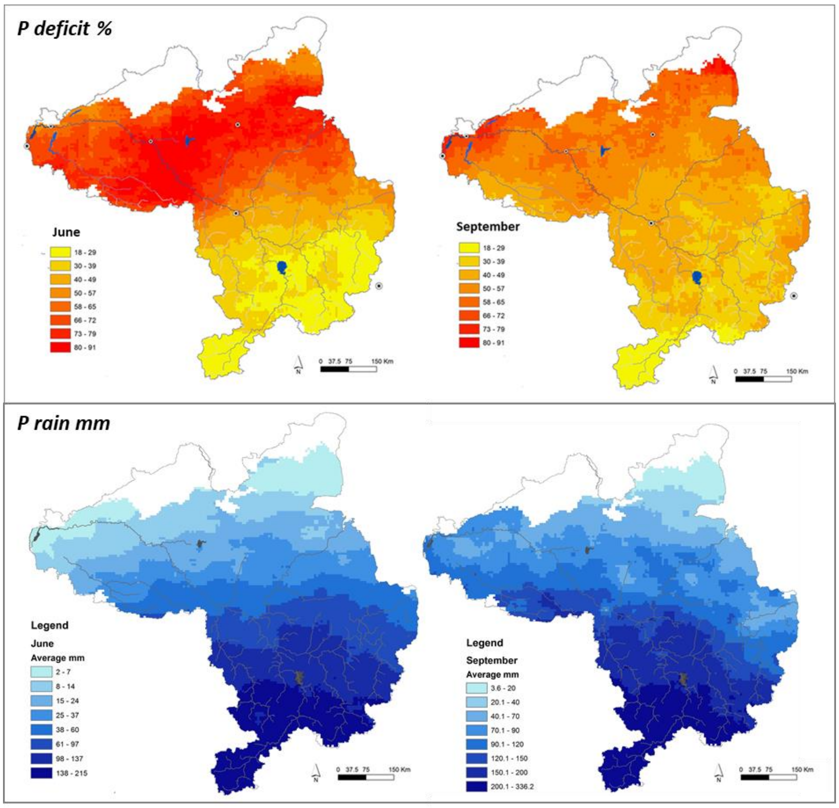
Figure 1. The Senegal River Basin.



The SRB is highly vulnerable to climate variability and changes, due to the great interdependence between climate and socioeconomic activities, and it could be further challenged by the increasing pressures posed by its population dynamics on natural resources, the subsequent changes in land use and the competition among sectors and users. West Africa has suffered a severe drought which started in the late 1960's and continued for more than 40 years (e.g. Nicholson et al., 2000; Bodian et al., 2014), impacting severely the discharge of the largest rivers in the region (Senegal and Niger rivers). However, in the case of the Senegal river, several authors have identified a turning point in both rainfall and river discharge between 1993 and 1994, when these variables started to show some signs of recovery (Hubert et al., 2007; Bodian et al., 2020). Concretely, there is evidence that the recovery of annual rainfall in the Senegal River basin is leading to the improvement of surface water availability (Bodian et al., 2020), even if the persistence of this change should still be verified. Concerning trends in annual discharge river flow data, several studies (Pastori et al. 2020) evidenced the presence of statistically significant positive trends between 80’s and 2020.

In any case, future water resource availability is not easy to predict, as Regional Climate Models (RCMs) outputs often do not converge in Western Africa and the complexity of hydrosystems' responses in this semiarid region cannot be disregarded (Karambiri et al., 2011). Concretely, the so-called Sahelian Paradox portraits the increase of runoff which took place in Sahelian basins for three decades in spite of the persistent drought, and it has been largely attributed to dramatic changes in land use. (e.g. Descroix et al., 2009). Climate variability is also specifically important due to its influence on agricultural production (above all when it comes to rainfed systems, which are the most widespread accounting for more than 90% of cropland and an important source of food security self-sufficiency for a great part of the rural population) and is a supporting analysis helping stakeholders in taking appropriate measures to reduce risks and impacts. Climate variability analysis developed in the framework of the WEFE Senegal project (Cattaneo et al, 2010) focused on the assessment of several indicators, such as precipitation deficit, heat waves magnitude index, the Standardized Precipitation Index (SPI) and the characterization of dry spells. Results showed higher precipitation deficits and variability specifically in areas with lower precipitation, that are strongly dependent on rainfall for both human and livestock water supply, as well as for sustaining rainfed agriculture and pastureland. (see for example Figure 2: monthly deficit and average precipitation for only 2 months during rainy season are here).

Figure 2. Precipitation deficit (% divergence with respect to mean climatology) with a return period of 20 years (top) and Average monthly precipitation (bottom) over the Senegal river basin for June and September.



There is a high hydropower potential in the basin and even if currently only two plants are being exploited (one under development), the four riparian countries and the OMVS have planned to increase the number of reservoirs, in order to meet the expected growing demands as well as to regulate the high inter and intra-annual water availability of the basin (Tractebel, OMVS, 2013). The existing dams play the main role in river flow regulation, hydroelectricity production and development and control of irrigation (including flood recession control). In the middle valley and delta, agriculture, pastoralism and fishing are the main activities and employ a large part of the working population, therefore providing most of the household income (even if clear and detailed disaggregated data are not available so far). All this region is poor and extremely dependent on the flood-related cropping activities in the depressions along the river for food security (Diouf, Y., 2015).

If properly designed, the development of hydraulic infrastructures could act as a buffer against climate variability. Raso et al. (2019) performed an ex-ante economic evaluation of the Manantali and Diama dams and highlighted their ability to partially hedge natural variability and, hence, their economic potential under changing conditions (for both operational and structural changes)). Initially, the OMVS ambitions in relation to the implementation of these schemes were high: improving food security through the development of irrigated agriculture (240,000 ha in Senegal, 126,000 ha in Mauritania and 9,000 in Mali), supplying the three fast growing capitals with electricity (considering an economic viability level of power production of 800 GwH/yr) and enhancing the river's navigability. However, years later the results are mixed: irrigated agriculture has developed at a slower pace than expected with mixed and controversial socio-economic and environmental results (Manikowski and Strapasson, 2016) and navigability has not undergone a real increase as far as Mali, although the goals for starting the hydroelectric power production were fulfilled by the end of 2002 (Mietton et al., 2007). Currently, the OMVS still hopes to create a continuous and lasting navigable waterway of more than 900 km between Saint-Louis (Senegal) and Ambidedi (Mali) (IFGR, 2018). In any case, future developments in the basin should consider the existence of different perspectives among the riparian countries and the specific challenges of the different regions of the basin. Tilmant et al. (2020) performed a probabilistic trade-off analysis between competing uses and evidenced the existence of two main coalitions, contending and competing for specific advantages and developments strategies. While upstream countries (mainly Mali and Guinea) are highly interested in hydropower services, downstream countries (mainly Senegal and Mauritania) prioritize food production and ecosystem services in the valley and Delta areas Tilmant et al. (2020). Also the strategic action plan 2017-2037 of OMVS and its roadmap present key actions to be implemented for the management of priority environmental issues in the 3 zones (Fouta Djallon, Upper basin in Mali, Delta – targeted by OMVS and corresponding to the water planning and management plans elaborated in 2013) and for operationalising the Water Charter 2002, the legal framework of reference for the Nexus, along with specific actions on gender.

Besides, a limited understanding of the interdependences among the components of the Water-Energy-Food-Ecosystems (WEFE) nexus in the SRB has led to limited informed decision-making processes and multiple undesirable impacts following the implementation of Manantali and Diama dams. For example, the development of irrigated agriculture thanks to reservoirs might not be able to replace the total losses induced in flood-recession farming, which plays a significant role in food security in the area ((Manikowski and Strapasson, 2016; Barbier and Thompson, 1998). According to Sall et al. (2020), current reservoir operation rules in the SRB assign the lowest priority to flood-recession agriculture, reducing the flooded area and the duration of the flood and, thereby, threatening the future of this farming practice and other types of livelihoods or ecosystem services (e.g. freshwater fish production, estuarine/marine fishery nursery grounds and dry season forage). Other negative outcomes of water regulation and changes of the hydraulic regime in the SRB included deforestation, massive population displacements, groundwater and fishing depletion, increase of the number of invader aquatic species and the rise of waterborne diseases (DeGeorges and Reilly, 2006; Mietton et al., 2007; Diessner, 2012). With regard to this last issue, dam-induced changes in salinity and the provision of new suitable areas for the development of freshwater snails (irrigation channels, rice fields) have resulted in the spread of schistosomiasis throughout the Middle and Lower Valleys of the SRB, subsequently increasing its prevalence and intensity among the human population (Picquet et al., 1996; Southgate, 1997). Besides, Dia et al. (2008)

demonstrated the changes on the composition of malaria transmission, vectorial system and epidemiology due to the implementation of dams in the Senegal river.

Specifically, combating water-borne diseases is one of the key challenges in the SRB, due to the rapid increase in the prevalence of multiple diseases that were already present in the area (e.g. malaria, urinary schistosomiasis, diarrhea, intestinal parasitic diseases), and the appearance and subsequent expansion of the previously cited intestinal schistosomiasis, a much more dangerous form of the disease (which particularly affects agricultural and fishing populations and impairs productivity, due to its debilitating nature) (Monde, 2016). Regarding Schistosomiasis, since a while hybrid forms of the disease that jump in between man, livestock, rodents, etc. are observed, adding another level of complexity to the attempt of interrupting the transmission chains. In addition, the hybridisation man/livestock imposes an economic dimension of Schistosomiasis on the farming sector (besides the economic consequences arising from the impacts on human productivity, education, etc.) (Léger et al., 2020).

Besides, children in the SRB show the highest prevalence of another waterborne gastrointestinal parasite (*Blastocystis*) worldwide (El Safadi et al., 2014) due to poor hygiene, sanitation and water supply from unsafe sources, along with close contact with domestic animals and livestock. According to the individual country profiles, the environmental risk factors account for about one third of the total mortality in all cases, and specifically poor water quality issues clearly dominate the health impacts in all riparian countries, closely followed by risk factors linked to poor indoor air quality (WHO, 2009) (**Errore. L'origine riferimento non è stata trovata.**).

Table 2. Environmental burden of disease for selected risk factors

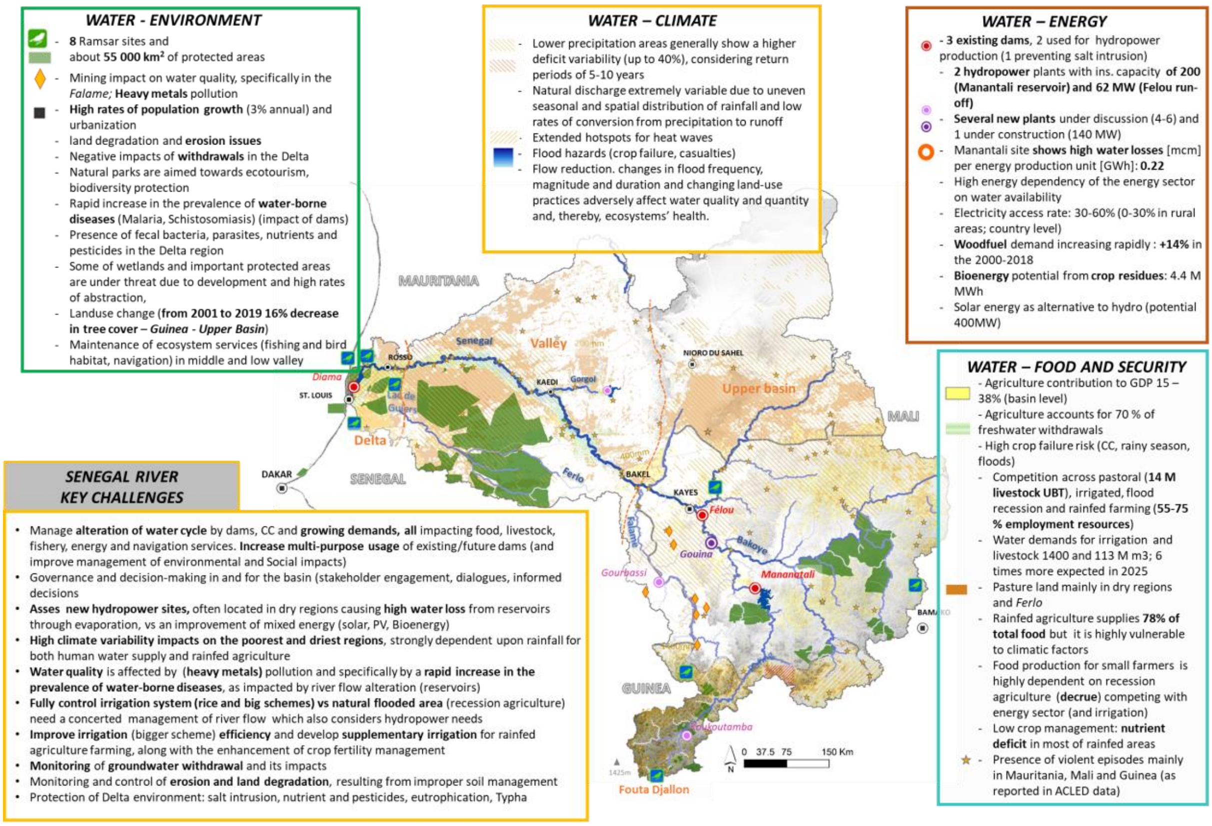
WHO statistics (2004)	Deaths/year							
	Guinea		Mali		Mauritania		Senegal	
Risk factor	n.	%	n.	%	n.	%	n.	%
Water, sanitation and hygiene	9600	60.4%	22600	58.1%	2300	62.2%	12900	81.1%
Indoor air	5700	35.8%	15300	39.3%	1200	32.4%	6300	39.6%
Outdoor air	600	3.8%	1000	2.6%	200	5.4%	1800	11.3%

Even if less important and requiring a low priority in the basin if compared with vector and water-borne diseases and drinking water quality issues, also water pollution with chemicals could be a potential problem in certain zones. The growing agricultural development is increasing nitrate concentrations, although nutrient concentrations in the SRB reveal a relatively low human impact (in comparison to rivers in developed countries, where nutrient water pollution is still a major environmental issue for several rivers. (Mbaye et al., 2016, Malago et al., 2019). Besides, Troussellier et al. (2004) found eutrophication issues in the Senegal river estuary, due to the combination of numerous pollution sources in the area of Saint Louis city and the limited renewal of estuarine water. Regarding pollution due to heavy metals, El Mahmoud-Hamed et al. (2019) assessed the presence of cadmium, lead and mercury in freshwater fish in the Senegal river in Mauritania and warned that they could pose a health risk in certain locations, such as in Kaédi and Boghé, due to high exposure (eating) frequency. Land-based plastic waste inputs into the ocean is another rising issue, as mismanaged plastic waste generally ends up in drains, landfills and inland water bodies and finally into the marine area, although most Western African countries are implementing policies to curb it (Adam et al., 2020). In this regard, it is estimated that only in Senegal (where the river mouth is located) more than 250,000 tonnes of plastic waste were mismanaged in 2010 (and thereby susceptible of becoming marine debris), and this amount was expected to triplicate in 2025 (Jambeck et al., 2015).

1.1 Key WEFE Nexus challenges

Supplying sufficient water, food, and energy while maintaining environmental sustainability is a growing challenge due to rapid population growth, changing lifestyles, ecosystem degradation, increasing water scarcity, political rather than analysis-based, cross-sectoral inclusive decision-making, and an uncertain future climate. By analyzing OMVS documents, and scientific contributions most urgent challenges to be addressed in the basin are summarized here. These issues also include interactions between key sectors (i.e. water, energy, agriculture, and environment), concretely: hydropower development using multi-purpose infrastructure; high climate variability impact on the poorest and rain dependent socio-economic communities; improvement of irrigation systems to increase crop production and food security; flood recession agriculture; navigation improvement to enhance commerce and development; environmental protection and safeguarding of specific ecosystems (such as the Delta); water quality and impacts on water-related diseases; and finally monitoring of groundwater withdrawals. Some key factors and challenges across the SRB have been summarized and highlighted in following map (**Errore. L'origine riferimento non è stata trovata.**).

Figure 3– Senegal river basin challanges



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Hydrological modelling and water management in the Niger river basin. SWAT model setup and identification of scenarios in a WEFE context

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The complex nature of the challenges that Africa has to face up to meet its development goals requires integrate approaches, able to tackle the interdependences between water, energy, food security and ecosystems. The end of single sector policy perspectives is especially critical in transboundary river basins, where neglecting these linkages might eventually have a great potential for conflict. This is the case of the Niger river (the third longest one in Africa) and its associated aquifers, shared by nine Western African countries and a key water resource for the continent. Here, an integrative modelling framework is developed to assess the combined impacts of multiple drivers at the basin scale, including climate change and variability, land use changes and soil and water management. Concretely, SWAT model was selected due to its physically based characteristics and capability to represent the effects of management practices on the different components of water, soil and nutrient balances. This study presents the main features of the model setup, calibration results and outputs from preliminary application and testing experiences.

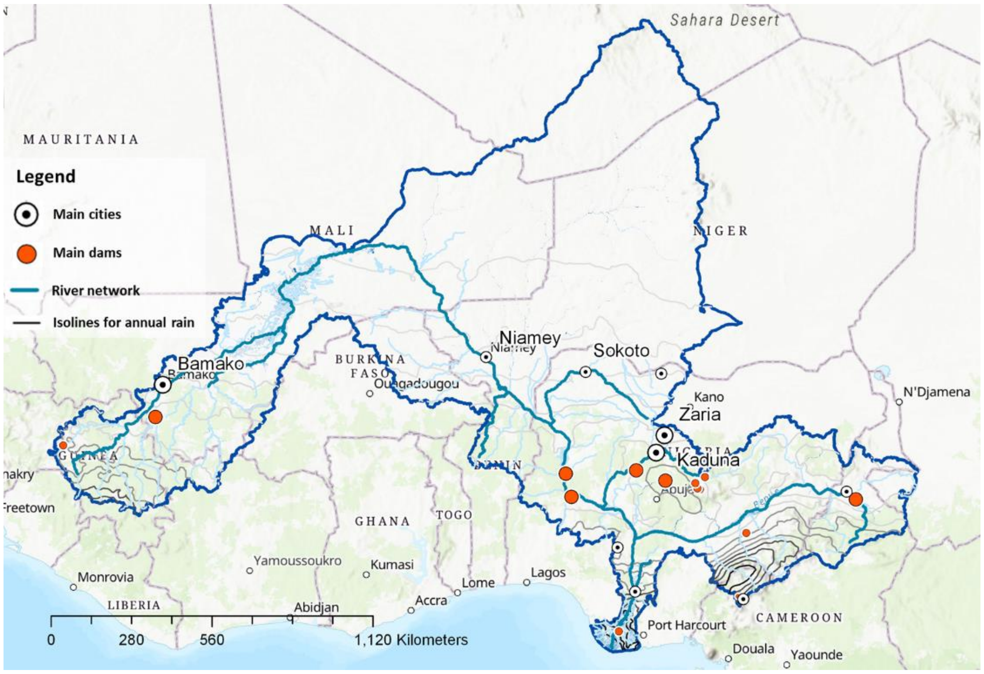
Keywords: Niger river basin, hydrological modelling, SWAT

1 Introduction

The Niger river basin, located in Western Africa, covers 2.1 million of km^2 (7.5% of the continent) and spreads unevenly over nine countries: Benin (2.5%), Burkina Faso (3.9%), Cameroon (4.4%), Chad (1.0%), Côte d'Ivoire (1.2%), Guinea (4.6%), Mali (30.3%), Niger (23.8%) and Nigeria (28.3%) (Figure 1). Across the 4,200 km journey from its headwaters in the Fouta Djallon Massif in Guinea to the terminal delta in Nigeria, the Niger river (the third longest one in Africa) constitutes an artery for trade and migration, a source of potential conflict and an opportunity for cooperation (Andersen et al., 2005). Together with its associated aquifers, it is one of the most important water resources of the continent, supporting large-scale irrigation, fisheries and livestock herding, providing drinking water, generating hydropower and allowing navigation. In addition, the Inland Niger Delta is one of the largest Ramsar sites in the world, a hotspot of biodiversity and a vital part of eco-regional network (Zwarts et al., 2006). However, the basin is also extremely vulnerable due to its complex hydroclimatic and socioeconomic context. Regarding future projections, Akumaga and Tarhule (2018) considered that changes in intra-seasonal rainfall could pose serious risks for food security in the region and may require changes in the cropping patterns and management.

Regarding the climate, the basin is characterized by a pronounced variability, both spatially and temporally. The Niger river cuts across all the main climatic zones in Western Africa (Guinean or Equatorial forest zone, the Transitional tropical belt, the Soudan Savanna zone, semi-arid or Sahel savanna belt, and the desert region), and steep gradients of rainfall, temperature, humidity and evaporation can be found within the basin. Runoff generation varies from 2000 mm in the terminal delta in Nigeria and the extreme southern tip of the headwaters to nearly zero within the desert zone and large parts of the Middle Niger and Inner Delta (MNID) (Tarhule et al., 2015).

Figure 1. Niger river basin, hydrological physical limit.



Besides, the semi-arid Sahel savanna zone is characterized by a strong interannual rainfall variability. Beginning in the late 1960s, this zone suffered one of the most dramatic episodes of interdecadal climatic variability ever measured, with annual rainfall deficits between 25 and 75% in relation to the 1950-1969 time period persisting over the next two decades (Lebel and Ali, 2009). Short-term changes in the precipitation trends could be even more dangerous: Landis et al. (2017) concluded that negative precipitation variability (i.e. a short-term dry spell) is more likely to trigger political violence in the basin than precipitation changes in the long run.

The geology and soils of the basins also influence water availability: the river "loses" nearly two-thirds of its potential flow in the Inland Delta area (between Ségou and Timbuktu, where the terrain is swampy and sandy) due to seepage and evaporation (Frenken and Faures, 1997). Regarding groundwater, aquifer depths are shallow in the Upper Basin, but significant aquifers (also shallow) exist along most of the Niger river in the Inland Delta as well as the Middle Niger and the Benue. Key groundwater resources include the Iullemeden Aquifer System, one of the main perennial sources of drinking water (IAEA, 2017; OSS, 2011) and the unconfined Continental Terminal aquifer, which extends from the northern Inland Delta towards the Middle Niger and also into the Sahara desert in Mali and Niger (Andersen et al., 2005). Werth et al. (2017) found a rise in groundwater stocks for the whole Niger due to land use changes between 2003 and 2013, which could help to mitigate possible future droughts and to deliver water to remote areas. However, increasing groundwater recharges may be accompanied by reduction in water quality (Favreau et al., 2009). These authors even concluded that the indirect impacts of land use change on water quantity and quality could be much greater than the direct influence of climate variability.

In relation to the socioeconomic context, the basin is characterized by its growing population (more than 112 million of people, with an increase rate of more than 3% per year), high poverty levels and food insecurity issues (Vaucelle, 2015). Besides, the United Nations Human

Development Index, a composite ranking based on national income, life expectancy and adult literacy rate, ranks all of the Niger Basin countries within the lowest quintile of its values, and 7 out of the nine riparian countries are identified as Least Developed Countries (LDCs) (Ogilvie et al., 2010, Vaucelle, 2015). The basin's population is mainly rural (64%) and a significant part of the northern zone is unpopulated. Livelihood strategies include dry and wet season cropping systems, pastoral systems, crop-livestock systems and fishing. Therefore, agriculture (mainly rainfed) represents about 80% of the employment and a large part of the gross domestic product (GDP), with crop production alone contributing up to 25-35% (Namara et al., 2011). Hence, the Niger River is a corridor of productivity which, for thousands of years, has provided the population with a mean of subsistence diversified and dynamic, enabling it to survive even during the worst drought periods. Regarding energy production, the electrification rate of the basin is one of the lowest in the world (only 35% in the Sahel zone) (Vaucelle, 2015).

As a result, water resources and demands are unevenly distributed within the basin, and riparian countries can be categorized into water producers, consumers, both producers and consumers, and minimum contributors and consumers. According to Medinilla (2017), Guinea is the main water producer, while Benin to some extent contributes to the flow of the main artery, and the headwaters of the Benue are located in Cameroon. Main water consumers include Mali and Niger, and Nigeria is both producer and consumer, controlling the Niger Delta and a significant part of the Benue. The least affected countries by the use and management of the river are Cameroon, Chad, Burkina Faso and Côte d'Ivoire (because they have no access to the main riverbed), while Guinea, Mali, Niger and Nigeria are the main stakeholders within the basin, due to their economic and ecological dependence on the Niger river's main artery.

In this context, the Niger Basin Authority (NBA), established in 1980 by the 9 riparian countries, aims to coordinate national water resource management efforts through an integrated development plan for the basin, in order to improve the life conditions and prosperity of the population. Currently, the basin has a great potential for development: it is estimated that only 9% of the agricultural lands are irrigated, whereas only 25% of the potential hydropower capacity is installed (NBA, 2015). In the Upper Niger and Bani river basins, Liersch et al. (2019) estimated that irrigation demand could raise from 7% of the average annual Niger discharge to one third in 2045. However, Sylla et al. (2018a) concluded that, under a 2ºC global warming scenario, irrigation potential, which is directly controlled by the climate, would decrease even in regions where water availability increases. According to Van Der Wijngaart et al. (2019), irrigation potential estimates vary greatly depending on the scale of irrigation schemes, whether the resource is surface or groundwater, expected and actual irrigation costs but also on determinants of irrigation development.

The supply of enough water, energy and food, along with ecosystem maintenance, could be regarded as a growing challenge (Yang et al., 2018). River basin management requires the capability of assessing hydrological changes resulting from climatic variations and from soil and land resources management. In this context, the use of comprehensive models is recognized as extremely valuable, as it supports the quantification of water dynamics as impacted by climate and landuse changes and by human natural resources management. Indeed there is a wide range of models with variable complexity and capabilities of simulating these impacts, ranging from empirical methods, conceptual models, to physical-based models. However, it is also clear that the complexity of data requirements would increase along with the number and complexity of the process simulated, and thus the availability of these necessary inputs could constitute a challenging issue in some regions. In this context, the open source, well document SWAT Soil and Water Assessment Tool has been successfully implemented across multiple basins worldwide, due to its capability to simulate soil, water and nutrient balances (References)In this regard, several modelling studies and approaches have been already developed in the Niger River Basin. Model application generally focused on specific regions of the basin like the Upper Basin (Angelina et al., 2015, Eisner et al., 2017) while others were focused on the whole basin (e.g. Aich et al, 2014, Sheffield et al, 2014). However, although these previous studies provide specific insight into the impacts of different drivers on water resources, they generally targeted a single sector at a time.

This study proposes a comprehensive methodology to tackle the muldimensional nature of impacts on the Niger basin water resources through the development of a specific SWAT model and a set of scenarios, which combine climate, land use and management projections. The study is structured as follows: Section 2 presents the selected methodology and the collection and analysis of the necessary data for model and scenario development; Section 3 summarizes the preliminary results of model calibration and scenario evaluation and; Section 4 is devoted to the discussion of further research lines.

2 Methods and data

The Soil and Water Assessment Tool (SWAT, Arnold et al., 1998), a process-based, semi-distributed model, is one of the most used models for long-term simulation at river basin level, due to its ability to integrate the hydrological processing with the simulation of the soil, water and nutrient balances, together with their impact on crop growth, soil erosion and sediment transport and water quality. In addition, the model is very well documented and open source, with a large community of researchers and developers involved and continuously active. The model operates at daily time steps and the watershed is divided into subbasins, which are further divided into hydrological units (HRUs) consisting of unique combinations for each subbasin of soil, land use and slope. Therefore, SWAT needs input data for topography, land use, soil, climate and land management.

In first place, SWAT was forced to use a predefined delineation of streams and watersheds using the HydroSHEDS data (WWF, 2018. https://hydrosheds.org/). HydroSHEDS is derived by the SRTM (Shuttle Radar Topography Mission) with a spatial resolution of 3 arc sec. This dataset was also selected as it ensures the reproducibility of model setup in the case of the appearance of new versions and further data availability. In addition, several data quality checks and improvement techniques have been used to assure the closeness of the river network correspondence to reality. The basin topography is so characterized by a range of altitude between zero and 2972m. The sub-basins and rivers considered for the final setup of the Niger basin consisted in 5534 regular polygons (with an average area of about 380 km^2) and segments (one river for each subbasin).

The land use map was derived from the global landcover data produced by ESA (Bartholomé and Belward, 2005). The data has a resolution of 300m and, for this setup, 7 land occupation classes have been used: agricultural land, forests, pastoral land, water bodies, water surfaces and residential areas. In addition, agricultural land was allocated to the dominant crop type, according to the crop distribution obtained through the Spatial Production Allocation Model (SPAM, 2005)

Soil type and characteristics were defined using the Harmonized World Soil Database (HWSD), version 1.2 (FAO and IIASA, 2012). For each subbasin, we assigned the dominant soil type. The available water capacity and the soil saturated hydraulic conductivity were calculated using pedotransfer functions as proposed by Rawls et al (2016).

Daily precipitation was obtained from the global gridded MSWEP dataset at 0.25 degrees resolution (Beck et al, 2017). Daily data for the other atmospheric forcing variables (minimum and maximum temperature, solar radiation, wind speed and relative humidity) were obtained from ERA-Interim (Dee et al., 2011). The whole dataset of climate data covers the period 1989–2012 and comprehends 1976 virtual stations over the Niger basin.

The modelled crop management consists of planting, fertilization, irrigation, tillage and harvesting operations. The timing of management operations was implemented according to the heat units accumulated by crops. Reservoirs were identified and characterized based on FAO data, integrated and refined by means of own AGRHYMET data. A total of 46 reservoirs were included within the SWAT setup.

3 Results

3.1 Model calibration

Due to the wide extension of the Niger basin, strategies to test model performance should be able to reduce the time and resources needed for the model run, as specifically calibration and validation procedures require a huge number of recursive running cycles. To overcome these issues, we selected an approach based on the identification of homogeneous and independent subbasins on which the analysis could be focused. Concretely, 8 main subbasins have been identified and used for calibration purposes up to now: the upper basin with outlet in Koulikoro, the upper basin of Bani, the Inner Delta, the Sirba basin, the Mekrou river basin, the Niger valley and the basin flowing to Kende and finally the Benoue basin (Figure 2).

To assess the model performance for both calibration and validation, we used several indicators as proposed by Moriasi et al. (2007). We considered the Pearson correlation coefficient (r), the coefficient of determination (R2), the Nash-Sutcliffe coefficient (NSE) and the Kling Gupta coefficient (KGE). The focus was on the KGE and NSE parameters: the KGE may be decomposed into correlation, bias and relative variability between the simulated variables and the observed ones; the NSE has widely used for testing the performance of hydrological models. In this study, we consider that KGE values higher than 0.5 are good and higher than 0.7 are very good. The same applies to the Nash-Sutcliffe coefficient.

Table 1. Goodness of fit indicators selected to test model performance

Indicator	Formula	range	best score
Pearson's correlation coefficient	$r = \frac{\sum_{i=1}^{n}(M_i - \bar{M})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})^2}\sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}}$	-1 à 1	1
R^2 coefficient of determination	$R^2 = \left(\frac{\sum_{i=1}^{n}(M_i - \bar{M})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})^2} * \sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2}}\right)^2$	0 à 1	1
KGE	$KGE = 1 - \sqrt{(r-1)^2 + \left[\left(\frac{\sigma_s}{\sigma_m} - 1\right)\right]^2 + \left[\left(\frac{\bar{S}}{\bar{M}} - 1\right)\right]^2}$	0 à ∞	0
Nash Sutcliffe efficiency	$NSE = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2}$	-∞ à 1	1

Where:

M_i et S_i are respectively the observed and simulated flows on day i;

$\bar{M}$ et $\bar{S}$ are respectively the observed and simulated mean flows over the period

σ_m et σ_m are respectively the standard deviation of the observed and simulated flows.

A sensitivity analysis was conducted to identify the most relevant parameters in light of their influence on the model output. These parameters were specifically targeted in the calibration process by means of the SWAT-CUP tool (Abbaspour et al., 2012) and include: 1) parameters linked to groundwater dynamics (such as ALPHA Baseflow, GWQMN, RCHRG_DP, GW_revap, GW_delay) and; 2) parameters controlling soil water balance (e.g CN2 Curve number, SOL_AWC or soil water holding capacity, Ksat, FC; for parameters description refer to SWAT model technical documentation).

The performance of SWAT in streamflow simulation has been assessed over a total of 28 selected gauging stations located throughout the basin. Main summary statistics are reported in Table 2 .

Figure 2. Subbasins and discharge stations used for testing the model performance

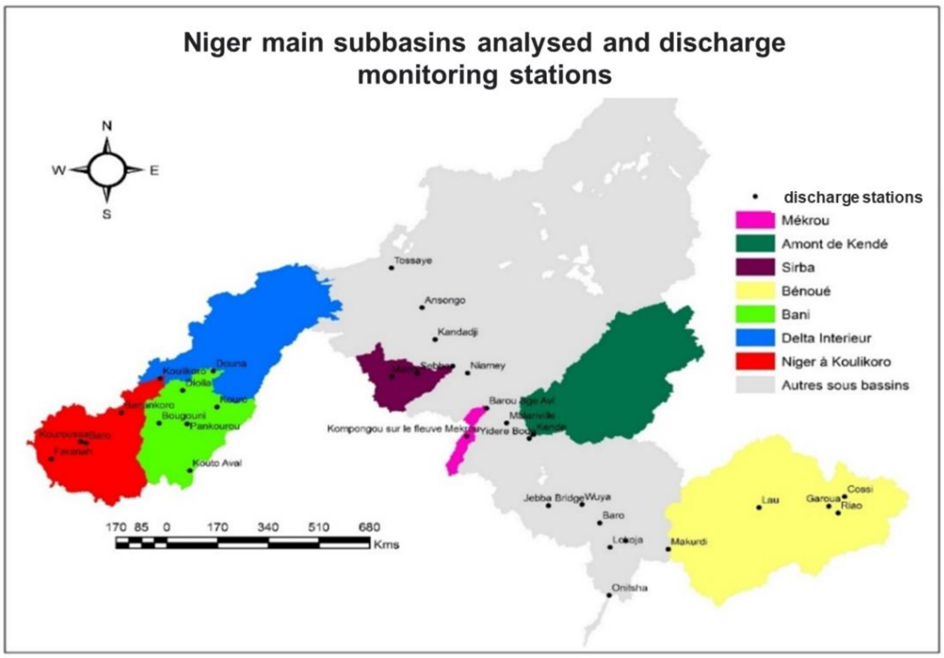


Table 2. Summary statistics for several indicators of model performance after calibration.

Stations	NSE	r	R2	KGE
Ansongo	*0.7*	*0.86*	*0.74*	*0.82*
Banakoro	*0.27*	*0.89*	*0.79*	*0.08*
Baro_Guinee	*-0.29*	*0.74*	*0.54*	*-0.26*
Baro_Nig	*-5.1*	*0.5*	*0.25*	*-0.85*
Barou_Mekrou	*0.87*	*0.94*	*0.89*	*0.89*
Bougouni	*0.67*	*0.85*	*0.73*	*0.64*
Dioila	*0.36*	*0.84*	*0.7*	*0.4*
Douna	*0.36*	*0.78*	*0.61*	*0.56*

Faranah	*0.31*	*0.74*	*0.54*	*0.61*
Garbey	*-0.01*	*0.57*	*0.32*	*0.46*
Garbey_Kourou	*0.34*	*0.75*	*0.56*	*0.67*
Garoua	*-0.15*	*0.64*	*0.41*	*0.45*
JebbaBridge	*-13.7*	*0.43*	*0.18*	*-2.24*
JidereBode	*-0.56*	*0.78*	*0.61*	*0.13*
Kandadji	*0.55*	*0.83*	*0.69*	*0.74*
Kende	*0.68*	*0.86*	*0.74*	*0.73*
Kompongou	*0.7*	*0.84*	*0.71*	*0.82*
Koulikoro	*0.24*	*0.85*	*0.72*	*0.11*
Kouro	*-0.47*	*0.58*	*0.34*	*0.2*
Kouroussa	*0.36*	*0.83*	*0.69*	*0.19*
Lokoja	*0.12*	*0.83*	*0.69*	*0.37*
Makurdi	*-0.05*	*0.65*	*0.42*	*0.06*
Malanville	*-0.53*	*0.77*	*0.59*	*0.19*
Niamey	*0.58*	*0.86*	*0.73*	*0.72*
Onitcha	*0.1*	*0.92*	*0.84*	*0.24*
Pankourou	*0.5*	*0.84*	*0.71*	*0.31*
Tossaye	*0.76*	*0.91*	*0.83*	*0.81*
Wuya	*-1.51*	*0.59*	*0.35*	*0.04*

On average, 40% of the considered gauging stations have a KGE greater than 0.5 and 25% of them have a KGE greater than 0.7. Besides, 32% of the stations show NSE values greater than 0.5 and 14% of them present NSE values greater than 0.7 (meaning that about half of the stations resulted with good quality fit). The average coefficient of determination of the 28 discharge stations is 0.6, while the mean value of the Pearson correlation coefficient is 0.77 (Figure 3).

Visual appraisal of monthly streamflow confirmed that monthly variations were well captured and that peak flows are properly reproduced. However, the model either underestimated or overvalued some of the flows in relation to the observed ones (Figure 4).

Figure 3. Spatial distribution of different model performance indicators along the Niger river network.

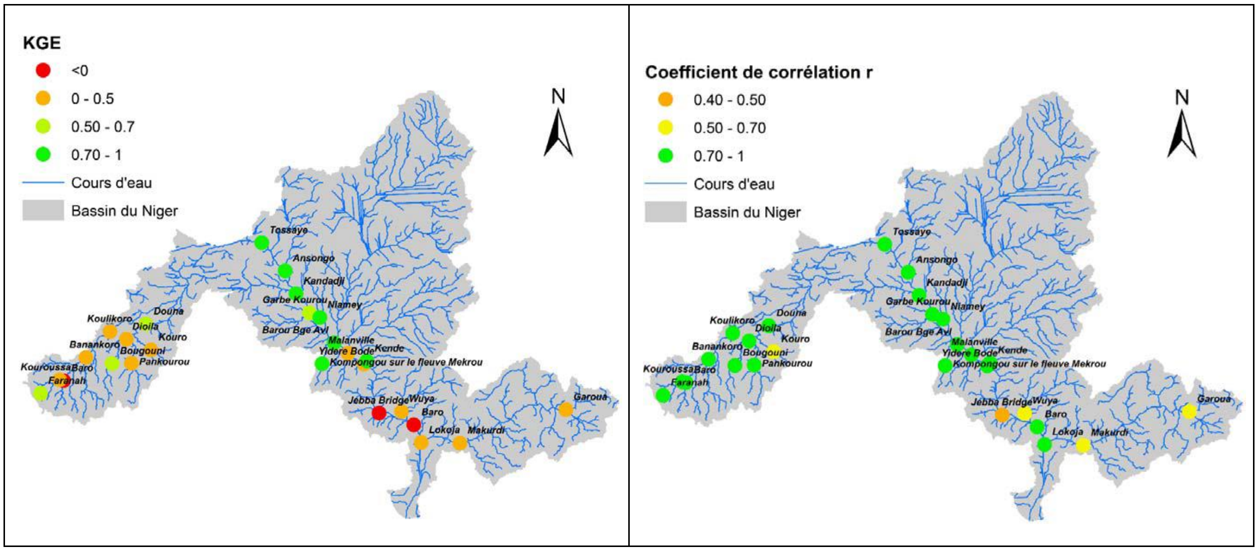
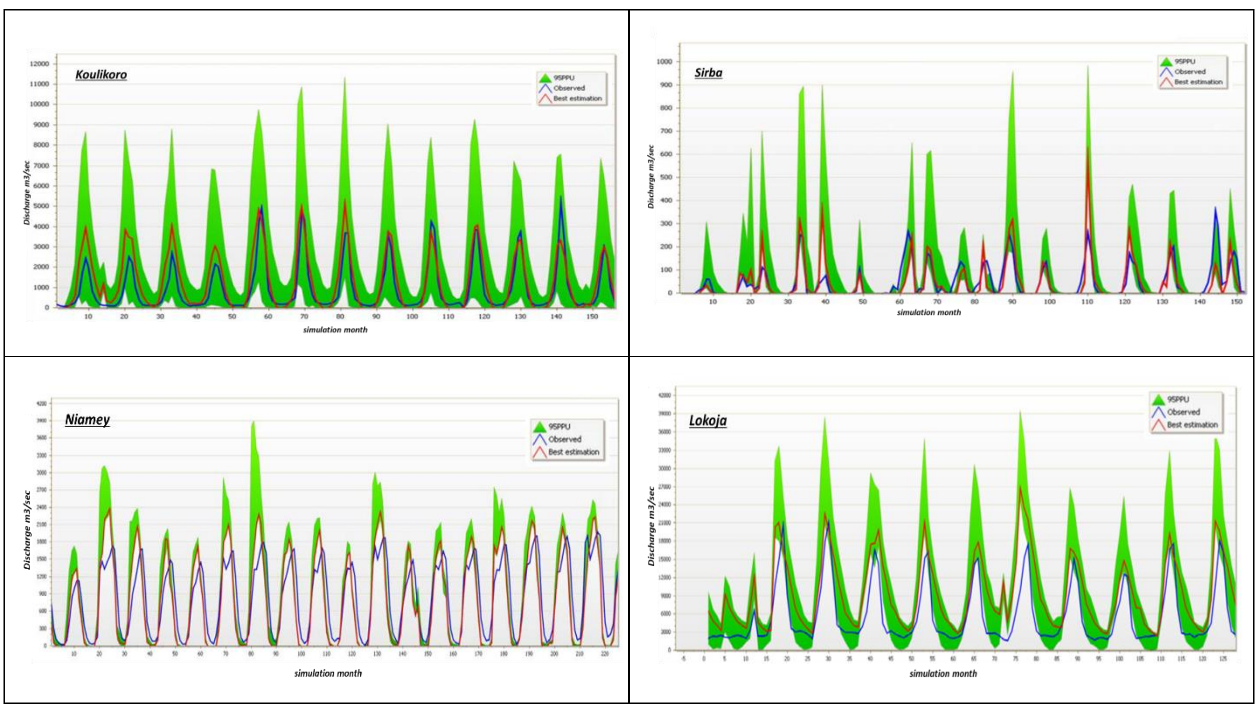


Figure 4. Monthly time series of streamflow observed (blue lines) and simulated by SWAT (redline) at 4 selected gauging stations across the Niger River (in green the deviation band corresponding to 95 ppu).



3.2 Climate scenarios analysis

Scenario development constitutes the next stage within the scope of this study. The main goal is to assess the impacts of multiple drivers (e.g. climate change, land use trends and management strategies) on the future availability of water resources in the Niger basin.

CORDEX data

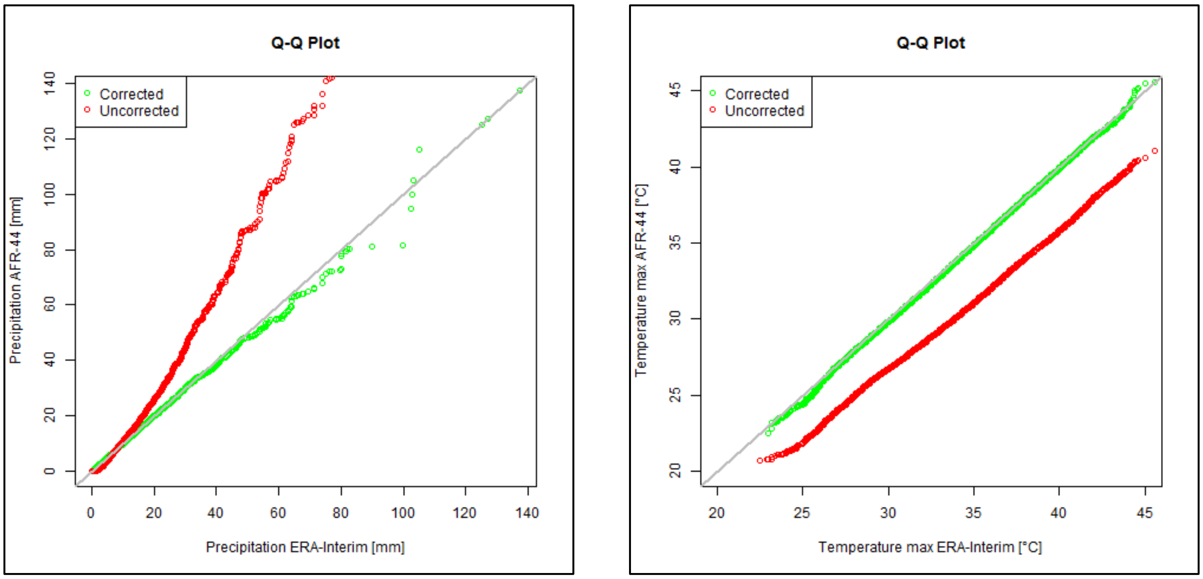
Regarding climate scenarios, we resorted to the data provided by the CORDEX project (available through the Earth System Grid Federation platform), which aims to improve the regional downscaling of climate models' output (Christensen et al., 2020). Initially, these scenarios were developed for the Mekrou basin, a tributary of the Niger river. The selected product was AFR-44, which covers the African continent (from 26.64°W to 60.28°E, and from 45.76°S to 42.24°N) and provides a spatial resolution of 0.44°. The grid contains 194 grid points in the East-West direction and 201 points grids in the North-South direction and, to consider the edge effects, at least 10 additional points were included in each direction for simulation purposes. Concretely, rainfall, maximum and minimum temperature data were obtained from the combination of the Global Climate Model (GCM) EC-EARTH with the Regional Climate Model (RCM) HIRHAM5, for the historical simulation run (from 1951to 2005) and two climate change scenarios (Representative Concentration Pathways (RCPs) 4.5 and 8.5), which cover the period 2006-2100.

Bias correction

As climate models' output suffer to a certain extent from bias (difference between the observed and the simulated values), it should be corrected to obtain accurate estimations of climate variables at smaller scales. Among the available bias correction procedures, here we applied the quantile to quantile (or quantile-mapping) technique (Li et al., 2010), which applies a statistical transformation to the future data based on the differences between the cumulative distribution function (CDF) of the observed values and the CDF of the simulated ones for the control period. Concretely, the control period in this study extends from 1990 to 2005, which is the common time span covered by ERA-Interim dataset (observed data) and the output from EC-EARTH/HIRHAM5 historical run (modelled data).

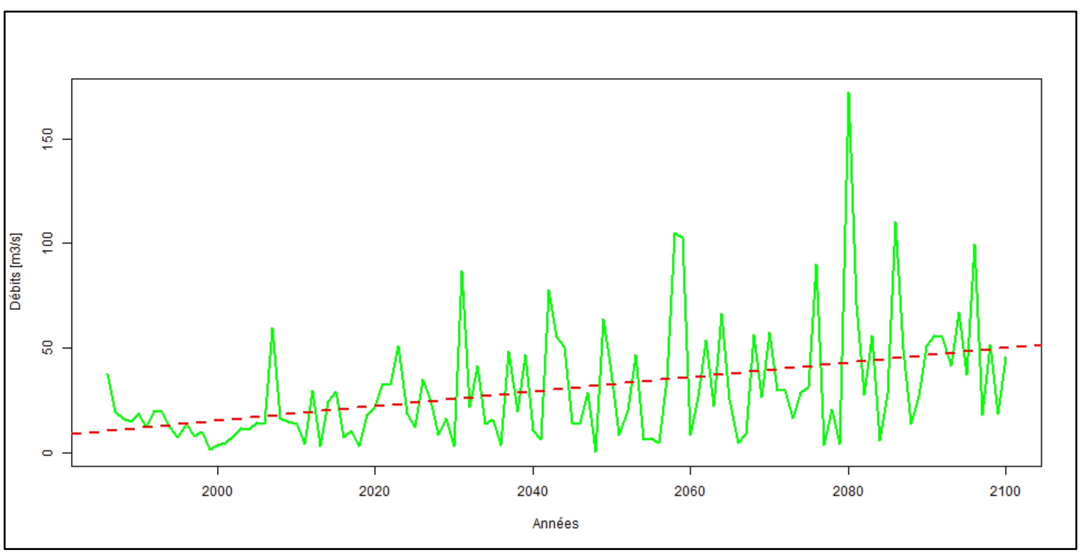
The figure 5 below represents the quantiles of the data from the simulations (before and after bias correction) as a function of those from the ERA-Interim data. It can be seen from these graphs that the curves of the corrected data (in green) are closer to the first bisector (line with the equation y=x, x>=0) than those of the uncorrected data (in red).

Figure 5. Q-Q plot between ERA-Interim rainfall data and HIRHAM AFR-44 model (1990-2005) (left) and between maximum temperature (right).



Once the bias was corrected, the future climate variables were used as inputs for the previously calibrated SWAT model. According to preliminary results, water volumes at the basin outlet show a smooth increase during the next decades in both scenarios (although it is even more pronounced when it comes to RCP 8.5) (Figure 6).

Figure 6. Temporal evolution of discharge flow at the Barou station according to the RCP85 scenario.



4 Discussion

This study presents the initial steps for the implementation of a comprehensive methodology to address the multidimensional nature of future impacts on water resources in the Niger basin, by means of the SWAT model and scenario development. Concretely, we expose the main features of the model setup, calibration results and outputs from preliminary application and testing experiences. One key aspect to be considered is the capability to easily retrieve good quality and updated data for the setup of management scenarios: such as reservoirs management, crop management, and water demands. Indeed the main objective of choosing SWAT model and to develop a setup and methodology in the Niger river, was because of its capability to integrate multiple aspects linked to soil, water and land management. The next stages of this research will be focused on further scenario development, aiming to assess the future availability of water resources as impacted by different management strategies, climate change and other trends.

Here, two initial climate scenarios were derived from the output of a GCM/RCM combination and used as inputs for the previously configured SWAT setup, to assess the potential effects of climate change on water resources. This is just one aspect to be considered, as climate change would impact water resources but it is just a driver in combination with many others. Indeed, in addition to climate change and variability, the basin faces up multiple challenges: degradation of land, water resources and associated ecosystems, vulnerability to disasters, inefficiency and poor performance of agriculture (both rainfed and irrigated), competing demands between sectors and water users and inadequate investment in water infrastructure. At a wider scale, inadequate public services, institutional and governance failure, high population growth and urbanization, poor macro-economic performance, and unemployment have also undermined the development of the basin (Namara et al., 2011). Most of these problems could only be tackled by addressing the most relevant interlinkages between water, energy, food and ecosystems (WEFE) through a comprehensive modelling framework. In this regard, the WEFE Nexus approach integrates management and governance across the multiple sectors involved, recognizing their interdependencies and the value of natural capital, ensuring coordination among stakeholders and identifying suitable policy solutions in order to optimize trade-offs and maximize synergies across sectors (Carmona-Moreno et al., 2019; Seidou et al., 2020)

The implementation of this approach in the Mékrou river basin (shared by Benin, Burkina Faso and Niger) showed that food unavailability due to insufficient local production could be reduced up to one third by enhancing the application and optimal distributions of fertilizers and irrigation (Udias et al., 2018). Yang et al. (2018) also explored the WEFE Nexus in the Niger basin and concluded that dam development can partially mitigate negative impacts from climate change on hydropower generation and also on ecosystems. However, Zwarts et al. (2006) integrated several aspects (hydrology, arable farming, livestock, fisheries, ecology and socioeconomics) in a decision support system for the Upper Niger and concluded that building new dams in this area is not an efficient way to increase economic growth and reduce poverty in the region. Instead, they proposed that development efforts should be aimed at improving the efficiency of the existing infrastructure, as well as of current economic activities in the Inland Delta itself. Ward and Kaczan (2014) pointed out the relationship between water poverty in the Niger basin and the existence of affecting access and supply, and institutional arrangements which impact the potential use of water resources.

Future work and research still need to be developed and has to focus in assessing how the implementation of alternative management measures across the river basin will perform in a global change context.

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Climate variability and extreme event, hydrology and reservoir management, agriculture and water in Northern Nigeria

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The study area covered the Niger River Basin (NRB) in the northern part of Nigeria. The basin has an area of approximately 2.3 million sq km spreading over 10 countries. The Basin has its largest part in Mali, Niger and Nigeria, each covering about 25% of the total basin area with approximately 100 million people earning livelihood mainly on the traditional, low input, rainfed farming, nomadic animal rearing and small scale irrigated agriculture. The Basin is drained by River Niger which covers a distance of approximately 4,200 km, joining its main tributary, the Benue River in south-central Nigeria and flows into the Atlantic Ocean. Nigeria alone contains 28.3 percent (424,500 square kilometers) of the Basin area and more than half of her major rivers are in the Niger River Basin. Almost 60 percent of Nigeria's population, or about 67.6 million inhabitants, live in the Basin.

Purpose and Objective

i. The main purpose of the studies is to provide a WEFE assessment in Northern Nigeria within the Niger River Basin. The specific objectives are to carry out research on:
ii. Climate database update, climate variability/change and extreme climate events and environmental (i.e. flooding, drought) and social impact analysis, food and water insecurity;
iii. Hydrology and water demand versus availability bi-sector (human supply, agriculture and energy);
iv. Inventory of large reservoir and management rules faced to water demand in agriculture and irrigation expansion, flood control, hydropower production, impact on groundwater recharge, environmental flow, water quality, including specific issues as reservoir sedimentation;
v. Agriculture (crops, spatial patterns, irrigation expansion) and best practices assessment (i.e. irrigation techniques, adaptive cropping patterns, rainwater harvesting techniques)
vi. WEFE interlinks and implications, leading to lesson learned contributing to both NRB hydrological model calibration/validation and assessment of simulation scenarios.

The variability in climate and as it impacts on the environment, food and water in the northern Nigeria, within the Niger River Basin (NRB) is very distinct. Two seasons are significant in Nigeria, wet and dry seasons. The annual rainfall has reduced significantly over 20% of the landscape and the amount of annual rainfall reduced by 50–350 mm in 64% portion of Nigeria. It has been observed that the climate of the region has undergone serious alterations in its underlying characteristics to the extent that a new mean and a new standard deviation were established. The increasing temperature and decreasing rainfall have led to frequent drought and desertification affecting large areas of arable land, thus reducing viable agricultural lands and crops' production. This has prompted massive migration and resettlement of people to areas less threatened by desertification.

The NRB is entirely drained by the Niger River originating from the mountains of Guinea near the border with Sierra Leone. In Nigeria, the Niger River is joined by numerous tributaries, including its most important tributary, the Benue River in Lokoja. The Benue itself rises in Chad and in Cameroon receives water from several tributaries. The Niger River thereafter heads southwards and empties into the Gulf of Guinea through a network of outlets that constitute the maritime Niger delta.

Water is a major contributing factor for increasing both agriculture outputs and sustainability in production systems like power supply. Allocation of available limited water resources for sustainable water use have been issues of increasing concern, leading to higher water demand and consumption. The estimated cumulative water demand of the Local Government Areas (LGAs) of each of the major states (Sokoto, Kebbi, Zamfara and Katsina) of the Basin in Nigeria ranges between 16,846,845 and 97,288,485 litres per day. However, the total water demand for each local government within these considered states is reported to be about 4,010, 897, 289 litres/day.

There are over 450 dams/reservoirs available in Nigeria within the Basin. The dams' properties and attributes are highly variable with maximum height of 115m at Shiroro dam and minimum of 9m at Swashi dam. Tiga dam has the longest crest length of 5,790m while the Kubli dam has shortest length of 110m. The highest reservoir capacity was 15,000MCM at Kainji dam, while Gusau dam has the lowest of 3MCM. The highest reservoir area of 392,000m2was found at Dadinkowa dam, while the smallest of 179m2 was at Gubi dam. The spillway capacity of 7900MCM was identified as being the highest in Kainji dam and the least of 63MCM at Doma dam. Only few of the dams were originally designed for hydropower generation. These include Bakolori dam designed to supply 10.4MW of electricity, the Dadinkowa dam to supply 40MW of electricity and the Kainji dam. Almost all the dams were used for water supply, irrigation, flood control, fishing, and livestock farming. Only few are used for navigation and tourism.

On the agricultural production activities within the Basin, the Niger River basin scale and diversity provide a remarkable cross section of the efforts placed by African smallholder farmers to produce the food security requirements for the population. Rainfed agriculture cannot be relied upon in order to meet the food security potential and employment generation target. Consequently, irrigation projects have opened up more hectares of land for cultivation in the Niger basin, especially in the northern part of Nigeria. The most common methods of irrigation employed include surface method - furrow, border/bay, flooding; sprinkler - centre-pivot, travelling gun; and subsurface irrigation methods.

The hydrological simulation of the Hadejia-Jama'are basin, located in semi-arid north eastern Nigeria using Soil Water Assessment Tool (SWAT) model indicated that the full implementation of all the planned water resource developments would have severe consequences for the basin's flood plain wetlands and areas further downstream. Reduced river flow would lead to a decline in the area of wet season inundation and will dramatically reduce the productivity of an area which is currently one of the most productive in northern Nigeria. The reduced productivity from the flood plain would not be replaced by yields from the formal irrigation since the water resources of the basin might not be able to support the envisaged extent of these schemes.

In the same vein, Hadejia-Jama'are-Komadugu-Yobe river basin (HJKYRB), one of the major river basins of which the water resources are vital to the sustenance of the livelihood of the growing population in Northern Nigeria. The basin is among those which proper management of the scarce resources due to competing demands is of growing concern. In predicting the Stream flow of Hadejia-Jama'are-Komadugu-Yobe river basin using SWAT model, based on the calibration and validation results, the coefficient of determination (R2) and Nosch-Sutcliff Efficiency (NSE) obtained suggested that SWAT could be useful as a decision support tool for water resources management policies in the basin. The most sensitive of the 17important model parameters determined during calibration was CN2 which relates to land cover and land use.

Conclusions

This research work under the NEPAD ACE 2 was carried out over the Niger River Basin in the northern part of Nigeria in order to carry out WEFE assessment in the north of Nigeria addressing climate, hydrology, dams and agriculture issues and analysis of interlinks and implications. The major part of the north of Nigeria falls under influence of this Basin and hence lives and means of livelihood are affected by the hydrological, hydrogeological, socio-political occurrences in the basin, which have their impacts from the influence of climate change.

Since climate change has its effects, water demand becomes high for domestic, agriculture, hydropower, and industries. The effects have caused untold hardship on the people both economically, socially and health wise. Climate change has been a serious challenge and its predictions are associated with high uncertainties in West Africa. With the current global drive for cleaner energy sources, hydropower remains one of the sustainable renewable energy substitutes for fossil fuel.

At the downstream end of the Niger River is Nigeria, which contains 28.3 percent (424,500 square kilometers) of the Basin area. The Niger Basin covers five (5) River Basin Development Authorities in Nigeria, which are Sokoto-Rima, Upper Benue, Lower Benue, Upper Niger and Lower Niger River Basin Development Authorities. Both rainfed and irrigated agriculture are practiced within the confine of the Basin in Nigeria and is substantial. Rainwater harvesting should be intensified in for domestic purposes. The agricultural crops cultivated under irrigation are mostly corn (maize), legumes and vegetables.

Recommendations

To check the diminishing rainfall regime of the area, the study suggests the following, which if implemented, will impact positively on the regional weather and climate, improve the hydrological regime and stabilize the ecosystem. Hopefully, the desiccation of the last 40 years would be reversed, with droughts becoming less frequent:

I. local and regional development policies that recognize the fragile nature of semi-arid environments should be adopted in pursuing livelihoods especially in the area of agriculture;
II. more effort should be made to discourage deforestation while encouraging soil and water conservation strategies;
III. governments at both the local, state and national levels should embark upon massive tree planting projects throughout the northern parts of Nigeria;

IV. Water could be transferred from rivers with surplus yield in southern Nigeria to regions of water deficit in northern Nigeria.

In order to assuage the impacts of climate change in Nigeria, the following adaptation strategies should also be undertaken:

I. Provision of foot-bridges across road tracks/roads and road passages for use in times of floods especially in the farming communities;
II. Rain-water collection systems should be provided for all stakeholders. Boreholes should also be provided outside the flood reaches of the possible flood belts and waterfronts;
III. Improved presence of local government personnel to promote:
   a. Enlightenment/campaigns on public health needs of the communities.
   b. Provision of Insecticide Treated Nets (ITNs) and screened windows for households in the farming communities.
   c. Provision of revolving drugs fund for meeting the public health needs of stakeholders in the communities.
IV. Provision of government subsidized of all agricultural inputs (Seeds, Fertilizers, Agro-chemicals, improved local breeds of livestock, Outboard Engines, fishing nets, etc.) for all stakeholders in the farming communities. Community cooperative groups' formation, credit assistance and varied support for Women-in-Agriculture involved in post-harvest operations should be greatly improved;
V. Provision of appropriate community-led management for seaside/ coastal areas (particularly in the oil producing communities) to assure improved agricultural production through shrimp culture, cage fish culture, beel fisheries, and equipment and inputs provision;
VI. Support for stakeholders through empowerment, training, equipment provision, credit assistance and training workshop support/provision;
VII. Strengthening of support for service providers at the community level through:
   a. Credit assistance for seaside vehicle transportation systems especially for coastal oil producing communities.
   b. Boat haulage systems
   c. Establishment of technology development centers (for all agricultural sub-sectors: crops, livestock and fisheries alongside the gender specific processing and preservation operations).
VIII. Provisions and strengthening of skill acquisition/development initiatives for all stakeholders through:
   a. Agricultural extension training/workshops.
   b. Health extension training/ services.
   c. Equipment and inputs demonstration.
   d. Seed-money provision for poverty reduction.
   e. Community based organizations' support initiatives.
   f. Skill development centers' provision.
   g. Community markets provision/expansion.
IX. The federal, state and local governments should engage in participatory community projects' implementation through the management of policies and regulations relevant for the moderation of agricultural production laws that can assure sustainable livelihoods and as well help mitigate change impacts;
X. The federal, state and local governments should establish participatory community consultation systems for farming communities in Nigeria especially in the coastal oil producing states for assuring cost-effective, renewable and sustainable projects, planning and implementation that can help mitigate the impacts of incessant climate change;

XI. Governments should intensify efforts on tree planting. Trees have the capacity to trap carbon dioxide which would have otherwise escaped into the atmosphere. Trees can also reduce storm effects, loss of houses, processing sheds, etc.;

XII. Governments' new irrigation schemes to dry lands to improve water use efficiency and minimize moisture stress for crops particularly in the northern parts of the country should be greatly improved in scope, numbers and frequencies of provision for farming communities.

The water demand review should be done periodically since realistic assessment of regional water consumption is essential in understanding how water suppliers can accommodate variations in time and type of use. And much more in order to realize significant development and economic improvement, Integrated Water Resources Management (IWRM) should be practiced in all areas of water need.

WEFE Nexus assessment in the Nigeria delta basin, Southern Nigeria

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This study Examines the Water, Energy, Food and Ecosystem (WEFE) nexus assessment in the Niger Delta basin of Nigeria. One major component of the Niger Delta basin is that it has been a constant receptor of the unrelenting pressure and assault in the ecosystem and this has adversely affected the living condition of the people. Hence there is the need to create scenarios and tools for decision making in respect of water, energy and agricultural management. In the study, flood frequency analysis was carried out using Rainfall data collected from NIMET and river discharge data from Nigeria hydrological service agency (NHSA). Three probability distribution models, namely Generalized Extreme Value GEV, Generalized Logistic (GLO) and Generalized Pareto (GPA) distributions were employed for flood analysis using return period of 2, 5, 10, 25, 50, 100 and 200 years respectively. The parameters of the distribution were estimated using the L-moment method. Also, effects of topography and landuse on flooding within the study area were evaluated using DEM obtained from Shuttle Radar Topographical Mission database (SRTM). Arc Hydro extension in ARCGIS environment was then used to delineate the sub-watersheds of the Lower Niger Delta river basin and streams within the study area. In order to ascertain the ability to meet water demand for water supply, food production, energy generation and environmental sustainability, the WEAP model was used in modeling. The study revealed that the climate of Niger Delta River basin is characterized as seasonal with a short dry season and that the location of the Intertropical Discontinuity (ITD) is at the coast. Flooding of the area is common due to sea level rise and other factors. Results from the hydrological modeling using WEAP revealed that there is poor infrastructure and water resources management within the region. Contribution of water supply due to tributaries is relatively low and does not affect streamflow of the Lower Niger River appreciably. Water withdrawal is also relatively low as it does not exceed 0.1% of streamflow.

Keywords: *WEFE Nexus, Probability Distribution Models, L-moment, Hydrological Modelling*

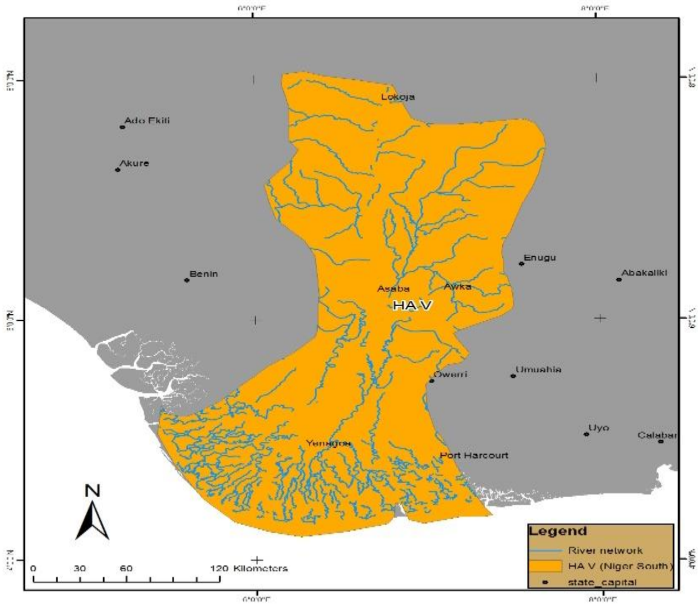
1. INTRODUCTION

1.1 BAKGROUND

Although the study area is Southern Nigeria, emphasis was placed on the Niger river Basin from the tributary of the Niger-Benue river down to the Gulf of Guinea where the rivers empties into the Atlantic Ocean. (Fig 1)

The Lower Niger Basin consists of a network of meandering rivers and creeks with Mangrove Swamp and Rain Forest vegetation. The extent of the basin covers 42,874 square kilometres and is situated on both sides of the Niger River.

Figure 1: *Lower Niger River Basin*



The climatic condition around the study area is typically humid tropical climate with high rainfall for most parts of the year and dry harmattan from November to January which accounts for the dense mangrove and rainforest vegetation characterizing the area. The average annual rainfall is from 1500-2000 mm, temperature range is 22o to 27o during the raining season and between 28o to 35o during dry season. River Niger and Benue have built-up the huge Niger Delta due to the combined action of sea waves and depositional action of the river emptying into the sea. Rivers systems within the study area present rich runoff due to the high annual rainfall from 1500-2000 mm. The large flood caused by high rainfall intensity often takes place and brings flooding problem in urban areas located in the lower basin. This is particularly the case with coastal towns such as Warri, Port Harcourt, Patani, Forcados, Benin City, Yenegoa etc. The river's mouth is clogged by transported sediment load from the upstream and a number of lagoons are formed along the coastline. It is to be noted that this is the area in Nigeria where most of the hydrocarbon exploration and exploitation activities take place and there has been a high level of pollution of both surface and ground water within the study area.

1.2 AIM AND OBJECTIVES

The aim of the study is to provide baseline data for climate variability analysis, climate risk assessment and WEFE Nexus interdependence evaluation for the creation of scenarios and tools for decision making in respect of water, energy and agricultural management in the lower Niger River basin to improve the living condition of the people.

The objectives include:

a) Collect meteorological and hydrological data for climate variability analysis and risk assessment.
b) Carry out modelling and simulation of climate variability/change induced events particularly flooding and their impacts on food and water security.

c) Carry out inventory of dams and reservoirs within the study area and the potentials for their use in meeting water demand, for household and industrial use, agriculture and irrigation, hydropower generation and flood control.
d) Carry out hydrological analysis and modelling of selected sub catchments for scenarios modelling to determine the impact of land cover / modifications on food and water security.

2.0 METHODOLOGY

The meteorological data that were obtained included Rainfall, Temperature and Relative Humidity. Only rainfall data were analysed because data were available for more stations, unlike temperature and relative humidity. Rainfall data were analysed in order to evaluate the rainfall seasonality in Niger Delta Basin. The method used to examine rainfall seasonality in the study area involved computing of average monthly and annual rainfall in each of the stations. Percentage of mean was the statistical tool employed for seasonal variation. In this case the mean rainfall figures during the wet season and the dry season months were added to get the wet and dry season totals. The percentages of both the wet and dry season totals in relation to the mean annual totals were calculated. The extent of seasonality period was determined based on Nigeria climatic seasons.

River discharge data were obtained from Nigeria Hydrological Service Agency (NIHSA), Benin-Owenna River Basin Authority (BORBA) and Niger Delta River Basin Authority (NDRBA) and they included daily stream flow measurement obtained from the different gauge stations. Daily stream flow measurement obtained from the different gauge stations (Lokoja, Onitsha and Ugbonoba) were analysed. The data were used for flood frequency analysis. Owing to the stochastic nature of the hydrologic phenomena that governs extreme flood discharge, it is fundamental that we investigate most hydrologic processes such as rainfall and droughts by simply analysing their records of observations (Ehiorobo et al, 2013). Effective analysis and determination of extreme flood discharge requires the use of statistical frequency analysis or fitting of probability distribution models to the series of recorded annual maximum discharge (AMD) (Sharma and Singh, 2010). The flood frequency analysis was carried out by employing three probability distribution models namely; Generalized Extreme Value (GEV), Generalized Logistic (GLO) and Generalized Pareto (GPA) distribution all of which have three parameters each. The parameters of the distributions were estimated using the L-moment method. The annual maximum discharge data at each location were ranked in ascending order of magnitude and the corresponding probability weighted moments i.e. b0, b1, b2 and b3 for the sample data were computed. The corresponding L-moment ratios (L-CV,L-Skewness and L-kurtosis) were described as follows:

- L-CV (Coefficient of variability) = τ_2
- L-Skewness = τ_3
- L-kurtosis = τ_4

The adequacies of the fitted probability distribution models were evaluated by the use of four (4) goodness of fit (GOF) criteria namely: Root Mean Square Error (RMSE), Relative Root Mean Square (RRMSE), Mean Absolute Deviation Index (MADI), Maximum Absolute Error (MAE).

Flood frequency analysis focused on the following stations; River Niger at Lokoja, River Niger at Onitsha and Okhuwan at Ugonoba, the results obtained in the previous study by Izinyon and Ehiorobo (2014) was adopted for Okhuwan at Ugonoba. For each of data availability, the maximum discharge was determined. The two-time series of annual maxima of River Niger at Lokoja and River Niger at Onitsha were 44 years and 24 years respectively after removal of all missing values. The probability weighted moments (PWMs) and L-moments and L-moment ratios for each sample data were computed using MS- EXCEL programming. The parameters of the best fit probability distributions at the stations were estimated using the governing equations.

The best fitting from amongst the probability distribution models fitted to the observed data at the stations were selected by subjecting the respective predicted discharge values (based on GEV, GLO and GPA distributions) to statistical goodness of fit tests. The overall goodness of fit of each distribution was judged based on a scoring and ranking scheme by comparing the relative magnitudes of the statistical test results obtained for the three distributions. The distribution with the lowest values of RMSE, RRMSE, MAE and MADI is considered the best with respect to the test criteria and is assigned a score of 3, the next is assigned a score of 2 and highest values is assigned a score of 1. The overall score of each distribution was obtained by summing the individual point scores and the distribution with the highest total point score selected as the best distribution model. The best fit probability distribution model at a station was utilized to estimate quantiles for different return periods. The return periods of interest that were utilized are T= 2 years, 5 years, 10 years, 25 years, 50 years, 100 years and 200 years respectively.

In order to ascertain the viability of the lower Niger river to meet the Water Demand for water supply, food production, energy generation and environmental sustainability taking cognizance of climate change and variability, the Water Evaluation and Planning System (WEAP) model was used to carry out water demand and supply modelling of the Lower Niger River Basin. WEAP is a river basin simulation software which includes opportunities for scenario evaluation as well as water balance calculations (Amato et al., 2006). The modeling of the water demand was carried out based on survey data of the domestic water demand, earth observation data for the agricultural water demand, and estimation of the industrial water demand and on calculations of the minimum environmental flow of the Niger River. The modeling of the water supply was carried out based on gauge data (from Lokoja Gauge Station and Onitsha Gauge Station), climate data and earth observation data of the Lower Niger Basin. To calibrate the streamflow of the Lower Niger River two streamflow curves were entered in the WEAP model. As the model observes the surface runoff in the Lower Niger River Basin below Lokoja only, the average monthly streamflow curve of Lokoja Gauge Station was entered as the head flow for the Lower Niger River. Additionally, monthly streamflow data from Onitsha Gauge Station were used.

For estimating the Environmental Flow, the original average monthly streamflow curve of Onitsha Gauge Station was shifted by a number of percentiles using the Global Environmental Flow Calculator (GEFC). Therefore, the compliance of the modeled streamflow with the calculated environmental flow can be checked at Onitsha Gauge Station. The annual activity was divided into the different states which are part of the Lower Niger Delta Basin. It was generally assumed that the entire states cover their water demand through the Niger River. A Human Population Growth Rate of 2.6 % (data.worldbank.org) was defined. An Annual Water Use Rate per unit of activity was used to calculate the total volume of water needed for the demand site. This study adopted the WHO standard for Nigeria which is 120L/c/d (43.92 m3/c/year). Monthly Variation requires a monthly water demand rate in percentage. It considers the seasonal variation of the water demand as more water is demanded during the dry season than for the wet season. The simulation of the Industrial Water Demand was undertaken like the simulation of the Domestic Water Demand using the Annual Activity Level, the Annual Water Use Rate, the Monthly Variation of Water Use and the Consumption Rate. An Annual Water Use Rate per unit of activity was used to calculate the total volume of water needed for the demand site. Due to lack of data, the industrial water use rate for each state was estimated. Splitting the annual industrial water usage in Nigeria of 1.97 billion m^3 in 2010 (AQUASTAT 2019) into water usage rates relative to the GDP of the Nigerian states (C-GIDD

2010), it was assumed that the industrial water withdrawal of the states is relative to the GDP of these states.

The Agricultural Water Demand was calculated on a catchment scale taking the land use and climate into account. A classification of the Land Cover in the project area was done according to the European Space Agency's Climate Change Initiative Land Cover database (Defourney et al., 2015). The Land Cover Classifications were assigned to the respective areas in the Lower Niger River Basin. The climate data for the project area was directly accessed through WEAP. A monthly precipitation time-series was used. Kc-Value: The crop coefficient (Kc), presents the evapotranspiration of a certain crop relative to the reference crop. Usually Kc-Values are used for crops, other Kc-values for non- agricultural land cover types have been calculated. Kc-Values have been adopted in accordance with a study by Amato, et al. (2006). The amount of water required to sustain aquatic life and other water use downstream of the Lower Niger River was adopted for the Environmental Flow. This flow parameter is assumed to sustain the flow regime in both the wet and excessive dry season.

To estimate the recommended streamflow, the Global Environmental Flow Calculator (GEFC) developed by the International Water Management Institute (IWMI) was used. It shifts the flow duration curve of the natural flow by a certain number of percentiles places, each representing an Environmental Management Class. The Catchment Delineation Mode from WEAP was used to define the boundaries of the Lower Niger River Basin and the catchments within the basin. It uses HydroSHEDS digital elevation data to automatically delineate catchments and rivers (Lehner et al., 2008). Six (6) river tributaries with their corresponding drainage areas were identified for the project area of the Niger River Basin below Lokoja. Their catchments were called: Obajana Shed, Ero Shed, Ubo Shed, Orle Shed, Ohordua Shed and Anambra Shed. Further smaller catchment areas were added up to three (3) further catchments along the Niger River: Niger Section 1, Niger Section 2 and Niger Section 3. The catchment characteristics were abstracted and they are the basin area, elevation bands, land use patterns and precipitation data. Each states' water demand was divided into three parts: Domestic Water Demand, Industrial Water Demand and Agricultural Water Demand. Each was inputted as an owned demand site on the model. While the Agricultural Water Demand was modeled directly in the catchment areas, Domestic Water Demand and Industrial Water Demand were added with demand nodes. The analysis of the linkages in the Water, Energy, Food and Ecosystems nexus (WEFE) was undertaken for the status quo (Current Accounts) and for different scenarios covering developmental, economic and climatic changes for the next 10 years.

3.0 RESULTS AND DISCUSSIONS

Results of rainfall data analysis indicated a northward increase and then a northward decrease in the mean annual rainfall (mm/year) (from 1981-2016) and the mean wet season rainfall (mm/year) (from 1981-2016). Initially, the increase in the mean annual rainfall was from Ogoja (1955.13 mm and 1613.40mm) to Calabar (3122.81 mm and 2408.56mm) and then the decrease in rainfall was from Uyo (2498.16 mm and 2009.13mm) to Port-Harcourt (2283.61 mm and 1849.43 mm). Thereafter, there was a northward increase in rainfall in Warri (2813.45 mm and 2260.37mm) followed by a sudden decrease from Benin (2171.28 mm and 1738.43 mm) to Akure (1430.04mm and 1194.83 mm). According to Adejuwon (2012), the South- North rate of change in rainfall experienced in the Niger Delta Basin may be attributed to Inter-tropical discontinuity (ITD), which migrates gradually northwards and more rapidly southward through the whole wet season period. Besides ITD, Cameroon mountain may also influence the northward increase in rainfall from Ogoja to Calabar area

(Adefolalu, 1983). Relief is another factor that brings about an increase in rainfall when meteorological conditions are favourable (Adejuwon, 2012). The percentage contribution of mean wet season rainfall (mm/year) (from 1981-2016) to the mean annual rainfall (mm/year) (from 1981-2016) was highest in Akure with 83.55% and lowest in Calabar with 77.13%. Climate change has altered not only the overall magnitude of rainfall but also its seasonal distribution and inter-annual variability worldwide (Feng et al.2013, Easterling 2000, Zeng et al. 1999).

The Niger Delta area of Nigeria, which contains one of the highest concentrations of biodiversity on the planet, in addition to supporting abundant flora and fauna, arable terrain that can sustain a wide variety of crops, agricultural trees, and more species of freshwater fish than any ecosystem in West Africa, could experience a loss of about 40% of its inhabitable terrain in the next thirty years (Finance and Development (F&D), 2008). This perceived situation can be attributed to unfavourable farm practices found in the area among other factors (including the carelessness of oil industries in oil spillage, natural gas flaring, over exploitation of natural resources and natural disaster like flooding). As majority of the people living in the Niger Delta are farmers and fishermen, the environmental and social consequences of climate change is putting livelihoods at serious risks. The impacts of climate change are not limited to cropping and agro-pastoralism, it is being felt on fisheries and aquaculture. There is need to focus on the impact on fisheries ecosystems and the food and nutritional security and livelihoods of fish dependent communities. Hence, evaluating rainfall seasonality will be useful for agricultural planning.

Flooding poses serious problem for the economic activities in the Niger Delta especially natural sectors such as farming and fisheries (about 50% of the fishes consumed in Nigeria is from the Niger Delta). Coastal vegetation especially the mangroves have been lost to flooding. Generally, rise in sea level will exacerbate flooding of the coastal areas thereby dislodging coastal fishing settlements and infrastructure, as well as changing the general inshore and ocean dynamics. Coastal mangroves which serve as nursery grounds for a large variety of fishery organisms will also be decimated. Hence, flood frequency analysis will help to effectively manage flood. The results from the studies indicated that the Generalized Logistic (GLO) and Generalized Extreme Value (GEV) distribution can be used to describe the discharge data for some areas within the Niger Delta Basin (Lokoja-GLO and Onitsha-GEV). Also, both the Generalized Pareto (GPA) and the Generalized Logistic (GLO) distribution can be used for analysis of annual maximum series data at River Okhuwan at Ugonoba in Benin Owena River Basin. Thus, these distributions can be used for future flood prediction within these areas. The contribution of water, mainly due to tributaries, is relatively low and does not affect the streamflow of the Lower Niger River strongly. This is explainable with the high evapotranspiration in the watersheds. The water withdrawal is relatively low, too. It never exceeds 0.1 % of the streamflow. This can be explained by the fact that most of the domestic water use is met by groundwater and the agriculture is not irrigated and the industry is only using the water to cool their machines.

4.0 STUDY LIMITATION AND THE WAY FORWARD

The problems associated with data collection in the Niger Delta Basin include:

- Data Availability: Data in many of the stations are not up to date as there are gaps in some of the stations within the study area (data were not available for all stations within the study area).

- Shell Petroleum Development Company (one of the agencies from which data were to be collected) policy is non-sharing of their data with a third party. This has been a major problem for us in respect of data sharing.
- Over the years, the River Basins in Nigeria have been poorly gauged and poorly mapped. Discharge measurements were neglected and poorly carried out and as a result, data were poorly managed and stored.
- The Nigerian Meteorological Agency (NIMET) that harvest data on Rainfall, Temperature and Relative Humidity etc. have decided to commercialize their data for research as a result of poor funding by government.

Arising from the above, we are recommending that:

- River Basin Authority and Nigeria Hydrological Agencies should be more funded to carry out continuous data collection for research and development.
- Government should make it mandatory that the oil and gas companies operating in the Niger Delta region and other parts of the country make their data available for research.
- NIMET should see researchers as partners in progress and not as competitors, as commercializing their data is affecting the Nation environmental development and protection.

5.0 CONCLUSION AND RECOMMENDATIONS

Based on the study the following conclusions were drawn:

- The Niger River and Benue have built up the huge Niger delta due to the combined action of sea waves and depositional actions of the rivers emptying into the Atlantic Ocean.
- Rivers system within the study area present large runoff due to high annual rainfall from 1500 – 2000mm. The large flood caused by high rainfall intensity brings flooding problems to most urban centers in the lower Niger delta river basin.
- This is the major area in Nigeria where most of the hydrocarbon exploration and exploitation activities take place and there have been a large level of pollution of both surface and ground water within the study area.
- The study revealed that the climate of the Niger Delta Basin is characterized as seasonal with a short dry season. The location of the ITD is at the coast.
- Beside these factors, other dominant factors controlling rainfall in the Niger Delta Basin include sea surface temperature anomaly (SSTA) and the local factors.
- The wet season starts in March and ends in November and the dry season starts in December and ends in February.
- A short dry season (August Break) was observed towards the ending of the mid wet season.
- Generalized Logistic (GLO) and Generalized Extreme Value (GEV) distribution are the best probability distribution to describe discharge data within the Niger Delta Basin (Lokoja-GLO and Onitsha-GEV).
- Generalized Pareto (GPA) and the Generalized Logistic (GLO) distribution is best suited for analysis of annual maximum series data at River Okhuwan at Ugonoba in Benin Owena River Basin.
- The study further revealed that majority of the people living in the Niger Delta basin are farmers and fishermen, however, environmental and social factors associated with climate change and oil producing multinational and local companies are putting the livelihood of the people at serious risks.

- From the hydrological modelling of the water demand and supply of the lower Niger River Basin (using the WEAP model), it was revealed that there is still poor infrastructural management for water supply in the region.
- Based on analysis of water supply within the basin, the studies show that contribution of water supply due to tributaries is relatively low and does not affect the stream flow of the lower Niger River appreciably.
- The water withdrawal is relatively low, it does not exceed 0.1% of the stream flow. This is as a result of the fact that most of the domestic water use is met by groundwater and agriculture is not irrigated and industries only use the water to cool their machines.

The following are recommended from the study:

- The findings from assessment of rainfall seasonality in the Niger Delta Basin should be used to predict the date for the onset and cessation of rainfall in the region as this will be helpful for sustainable water resources management and agricultural production in the region.
- Government agencies should use information from the flood frequency analysis for future flood prediction so as to develop flood protection infrastructures in the region to improve the economic condition of the people. Also, the information should be used for flood hazard management.
- The WEAP model which was used for the hydrological modelling of the water demand and supply of the lower Niger River Basin should be utilized for planning and management of water supply in the Niger Delta Basin.
- More attention should be paid to data collection and management by agencies such as Nigeria Metreological Agency NIMET, Nigerian Hydrological Science Agency NHSA, River Basin Development Authority and other related agencies, as the gaps in available data is creating problems for meaningful research and development in climate modelling, WEFE Nexus Assessment etc.

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The Blue Nile River in Khartoum, Sudan, upstream of its confluence with the White Nile.
Photo credits: Waddah Hago

SCIENTIFIC RESEARCH IN CENTRAL-EASTERN AFRICA

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One of the aims of the Central-Eastern Africa collaboration is to conduct scientific research over the Eastern African region, aiming to address key questions related to Water-Energy-Food-Ecosystem (WEFE) nexus. The scientific research activities were conducted for the Nile River Basin, focusing on the Blue Nile and the Lake Victoria subbasins. The main objective of the research conducted on the Blue Nile Basin was to investigate the expected impacts of increasing water demands (due to, for example, population growth and agriculture expansion) and dam development (e.g., the Grand Ethiopian Renaissance Dam) on water availability, electricity, generation, and environmental flows. The main objective of the Lake Victoria research component was focused on modeling water usage, sector interdependencies, and WEFE tradeoffs and synergies under increasing pressures due to population growth, irrigation expansion, water quality deterioration, groundwater quality, and environmental concerns related to lake levels and eutrophication.

The research activities were conducted and led by:

- Water Research Center, University of Khartoum, Sudan, also acting as the Secretariat for the regional network of CoE;
- Ethiopian Institute of Water Resource, Addis Ababa University, Ethiopia
- Makerere University, Uganda
- IGAD Climate Prediction and Application Centre (ICPAC), Kenya

The ICPAC regional hydro-climate database over the entire IGAD region was made accessible to the partner Institutions. The ICPAC also analyzed climate-related risks in the Nile Basin, including historical and projected frequencies of droughts and floods.

In the Blue Nile case study, a suite of water allocation models was used to assess water availability and the impacts of the Grand Ethiopian Renaissance Dam on hydropower production, water use for irrigation, and environmental flow. In the Lake Victoria case study, a water allocation model was set up to assess future water demand trends considering population growth and development of irrigated agriculture, hydropower development, and the impacts of climate change and anthropogenic pressure on river flows the Lake Victoria water levels.

The outcomes of the scientific research activities are expected to enhance scientific and technical cooperation, including data management, at both national and regional scales. Simultaneously, the research outcomes aim to support decision-makers with science- and knowledge-based tools and methods for effective and cooperative water management.

The above-mentioned research activities were framed in line with key regional priorities and future programs identified by the Intergovernmental Authority on Development (IGAD) in Eastern Africa and the Nile Basin Initiative (NBI) and summarized as follows:

- Analyze water scarcity in the region, considering climate change and the current and growing competing demand for water resources;
- Boost transboundary water governance and cooperation between riparian countries by facilitating the application of hydro-diplomacy at multiple levels, strengthening

capacities of governance of shared water resources (Transboundary water governance and cooperation and BRIDGE - River Dialogue and Governance - projects);

- Enhance capacity building on international water law and hydro-diplomacy, aimed at promoting national, regional, and international cooperation and facilitating the adoption of best practices in water governance;
- Develop water infrastructures development to mitigate climate change impacts and water scarcity;
- Enhance the management of groundwater and transboundary aquifers to improve community resilience and food production, to boost economic activity, and to foster regional cooperation by filling knowledge gaps, strengthening knowledge systems, and assessing the feasibility of specific investments (e.g., Horn of Africa groundwater initiative project);
- Address the 2017-2027 NBI priorities, including water security (meeting rising water demand); energy security (unlocking and optimizing hydropower potential); food security (increasing agricultural productivity); environmental sustainability (protecting and restoring degraded ecosystems); climate change adaptation (preparing for climate change impacts); transboundary water governance (bringing people together to build a common ground for win-win benefits).

Climate Variability and Extreme Events over the Greater Horn of Africa: Case study of Lake Victoria and Blue Nile Basins.

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Extreme climate events such as drought and floods with severe impacts over the Greater Horn of Africa (GHA) have been on the rise over the past decades. These events negatively impact the regional ecosystem, livelihood, and economy which heavily depends on rain-fed agriculture, while in the energy sector largely depends on hydropower, thus shifts and variability in rainfall and temperature could hinder the development and economic growth of the region. Therefore, assessing the risk/monitoring of these events in the past, present and future are critical for community resilience and understanding of the Water-Energy-Food-Ecosystem nexus. We used the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) methods with the Climate Research Unit and CORDEX datasets to assess the level of drought and flood risk. This was done for the GHA region and further focusing on two basins over the region: Lake Victoria and the Blue Nile basins. Hydrological drought time intervals were utilized. Preliminary results show that, at the regional scale, there were more extreme wet conditions before the 1970s with 1961 observed as the wettest on record. After the '70s, more dry conditions were observed with 1984 and 2011 noted as the driest years. The periodicity of these dry/wet conditions was observed to be three years which can be attributed to the El-Nino Southern Oscillation. An increasing trend of abnormal wet conditions from 1961 to current was observed over Lake Victoria basin. However, the Blue Nile basin has recorded more dry conditions in the recent past, thus reducing inflows into the Nile River. A projection into the future indicates that the region is likely to experience high frequency of dry/wet conditions for both RCP45 and RCP85 covering a wide geographical area. Thus, these results here can support decision-making processes through scenarios-based-analysis at the basin and regional levels.

Keywords: *Drought, Extremes, Lake Victoria, Blue Nile, Horn of Africa*

Introduction

The analysis of this investigation was done over the Greater Horn of Africa (GHA) with major focus on the Blue Nile Basin and the Lake Victoria Basin. The GHA region is prone to extreme climate events such as droughts and floods (Ghebrezgabher et al., 2016) which has severe negative impacts on key socio-economic sectors since the region greatly depends on rain-fed agriculture as the back born of the region economy. The region has also hot and dry climate, particularly in the northern and eastern parts and the lowlands, with sparse vegetation, while precipitations are concentrated mostly in the highland areas. The climate of the region has three seasons i.e. March-April-May (MAM), June-July-August-September (JJAS), and October-November-December (OND) (Mwesigwa et al., 2017). The MAM and OND are majorly over the equatorial and southern sector of the region while JJAS occurs in the northern sector. The major controller of the seasonality in the region is the Inter-Tropical Convergence Zone (ITCZ) together with the monsoon winds (Mwangi et al., 2014).

Lake Victoria is the world's largest tropical lake and the largest lake in the African Great Lakes region. The lake supports the largest freshwater fishery in the world, producing 1 million tons of fish per year and employing 200,000 people in supporting the livelihoods of 4 million people (Awange et al., 2007). The Lake Victoria Basin has a population of about 40 million people and the average population density is about 250 people per square kilometer. The LVB covers about 180,950km2 and Kenya occupying 22%, Tanzania about 44%, Uganda 16%, Burundi 7% and Rwanda 11% (Awange et al., 2007). The LVB has socioeconomic activities that accounts for about 34% of the Gross Domestic Product (GDP) in Burundi, 32% in Rwanda, 29% in Kenya, 23% in Uganda and 25% in Tanzania (USAID, 2018). Besides, the LVB act as a significant climate modulator for the region. The LVB on the Kenyan side has a high potential for hydropower development, however, this potential is still underutilized and only two sites have been developed to harness hydroelectric power, one each on river Sondu/Miriu and Kuja/Migori (Okungu et al., 2005). Waterfalls occur along most of these rivers such as Kuja, Nzoia, Sondu-Miriu and Yala have huge falls, thus have great potential for development of hydro power.

The Nile Basin is considered among the most complex and unique river basins in this region. The Blue Nile sub basin (BNB) comprises only 8% of the total Nile Basin catchment area; however, it contributes to almost 60% of the main Nile River flow at Aswan Dam in Egypt (El Shamy and Sharaky, 2014). The BNB support the livelihoods of many people residing along the basin and this through providing water for agricultural activities. Agriculture is the main source of income for people residing in the BNB since many are practicing irrigation agriculture. According to El Shamy and Sharaky (2014), basin is under consideration for various hydropower and irrigation projects. The Economic benefits of the BNB are closely related to additional hydropower generation, improved navigation and increased food production (Block and Strzepek, 2010). Lives and livelihoods of the people in the BNB are strongly linked with livestock management and crop production. According to Haileslassie et al. (2012), over 95% of the food-producing sector in upstream areas (i.e. Ethiopia) is based on rain-fed agriculture. In Sudan, downstream, the Blue Nile supplies water for major irrigation development and also for livestock production. The two basins are critical in the region, thus assessing the impact of extreme climatic condition is important and that's the basis of this assessment.

Methods

Atmospheric observed/satellite data (rainfall, temperature (maximum, mean, and minimum), and potential evapotranspiration (PET)) was obtained from ICPAC, Climate Hazard Group (CHG), and the Climate Research Unite (CRU) data library of the University of East Anglia. The CHG Infrared Precipitation with Station is mainly satellite plus gauge station data at a resolution of 0.05^0 and a temporal resolution of one month from 1981 to 2017 (Funk et al., 2014; Katsanos et al., 2016). Monthly CRU data (rainfall, temperature, and PET) at a spatial resolution of 0.5^0 was used from 1901 to 2017 (Harris et al., 2014) to determine how climate has changed in the past. Future projection data from the Coordinated Regional Downscaling Experiment (CORDEX) was used to assess the scenarios of the future (Osima et al., 2018) over the region.

Hydrological drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after many months of meteorological drought (Melo and Wendland, 2016). In this analysis meteorological drought indices (SPI and SPEI) were used to assess this hydrological drought at 12, 24, 36, and 48 time steps. The SPI method developed by McKee et al. (1993), was used to assess abnormal wet and dry conditions using precipitation only (Tsakiris & Vangelis, 2004; Türkeş & Tatlı, 2009). It's a normalized index representing the probability of occurrence of an observed rainfall amount when compared with the rainfall climatology at a certain geographical location over a long-term reference period. Negative SPI values signify deficit in rainfall, whereas positive SPI values signify surplus of rainfall. Drought intensity event can be classified based on the magnitude of negative SPI values such that the greater the negative values of SPI are, the more severe the event would be (Table 1). This method was adopted by the World

Meteorological Organization (WMO) as a standard measure of meteorological drought. This method only uses precipitation in computation of drought ignoring the contribution of temperature.

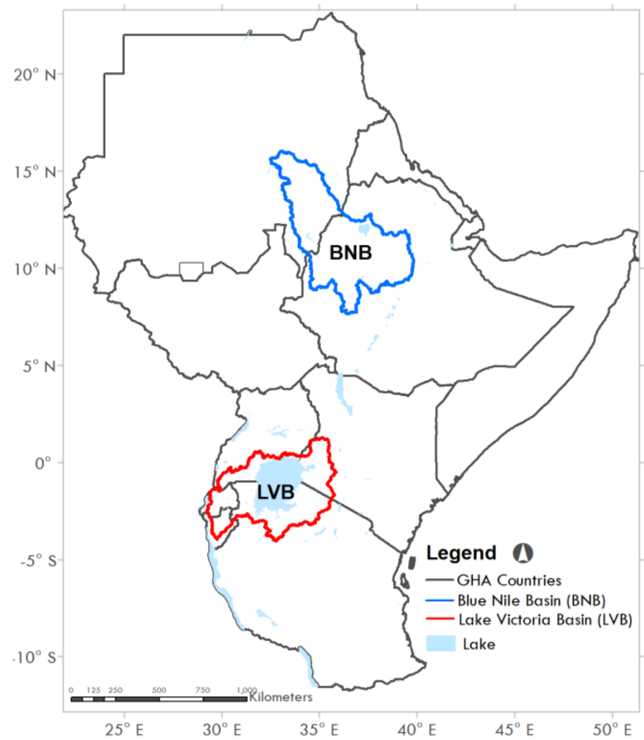
Table 1: Category of drought based on the SPEI value (Source: Ghebrezgabher et al., 2016)

SPI	**Drought Type**
0 to -0.99	Mild drought
-1 to -1.49	Moderate drought
-1.5 to -1.99	Severe drought
≤-2	Extreme drought

A more complex method of monitoring drought is the SPEI. This method is said to be an extension of SPI which is widely used in drought monitoring, hydrology and climatology studies (Vicente-Serrano et. al., 2010; Beguería et al., 2014; Stagge et al., 2015). It takes into consideration the aspect of potential evapotranspiration and precipitation to determine drought using the timescale as that of SPI. According to Vicente-Serrano et al. (2010) SPEI can be used to quantify the dry and wet conditions at different time scales. I order to determine periodicity of these extremes, the concept of periodograms adopted (Glynn et al., 2005). The x-axis on the periodograms are articulated in multiples of 1/12; noting the folding frequency to be 0.5 cycles per month there are 6 cycles per year. At the folding frequency, the features on this periodogram will be mirrored on the other side hence conventionally the higher frequencies are not plotted. The power spectra have a high peak at approximately 0.32 cycle per year (frequency of 0.3/12); corresponding to periods of about 37.5 months.

Analysis of both SPI and SPEI were done using R-Programming language and NCAR Command Language (NCL). This analysis was conducted of the GHA area shown in Figure 1 below with BNB highlighted in blue and LVB in red.

Figure 1: Study are of the Greater Horn of Africa with focus on Blue Nile Basin (Blue Color) and Lake Victoria Basin (Red Color).



Discussion

Rainfall and temperature data for the basins (Observed and Projections) in Grid format

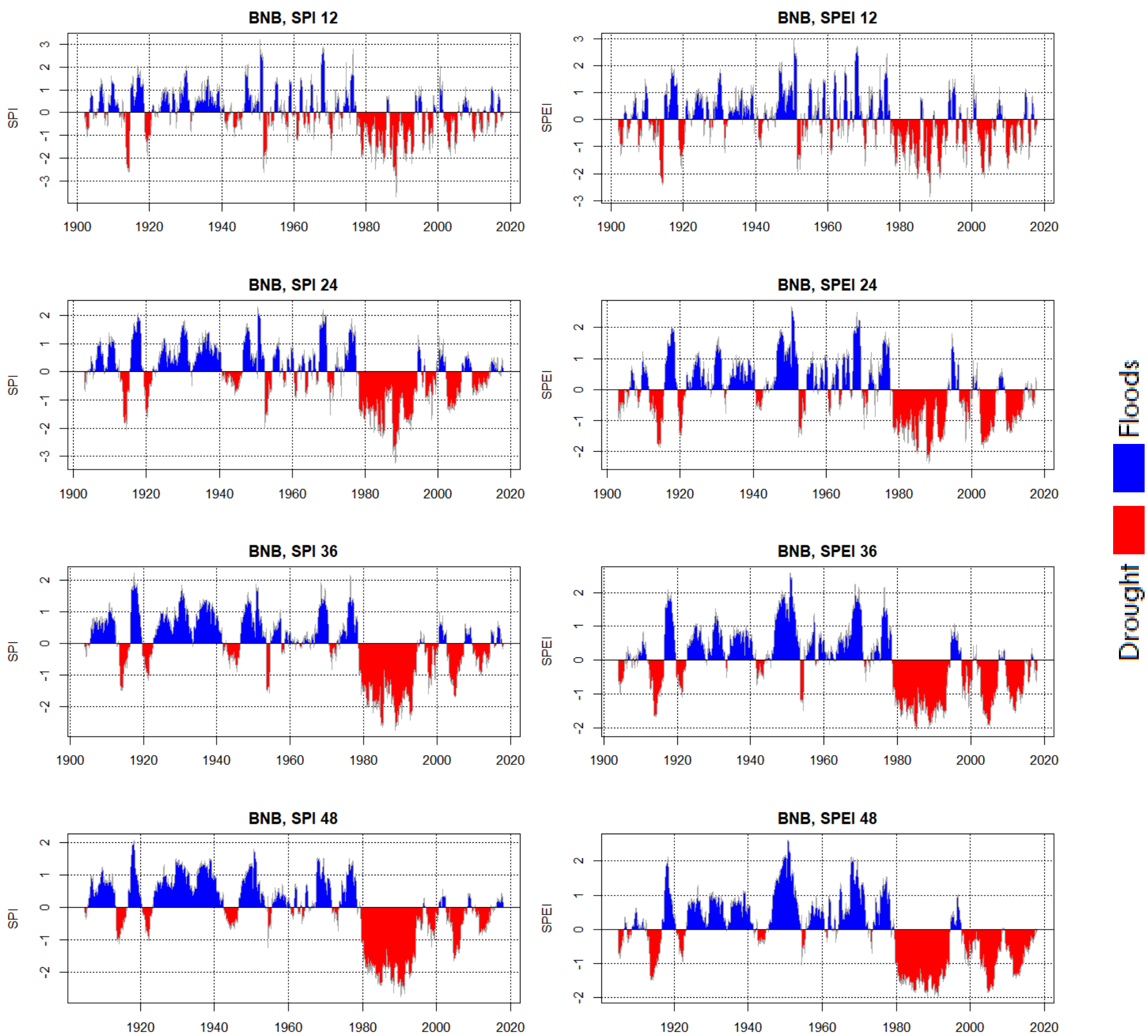
Observed grid data over the basins for Rainfall, Temperature, and Potential Evapotranspiration were made available over ICPAC open access geoportal (http://geoportal.icpac.net). All historical data sets are at a resolution of 0.05 degrees and in NetCDF format which can be read by a number of software such as Xconv, CDAT, R, NCL, FERRET, GrADS, among others. Future CORDEX projection data sets were also provided for the basins and GHA. The GIS shapefiles for the basins (BNB and LVB) were also shared though the platform.

Climate extreme (Flood/Drought-SPI and SPEI)

The analysis were done using SPI time steps (run) of 12, 24, 36, and 48 to represent hydrological drought. On a regional scale, there were more events on extreme wet condition (floods) observed between the periods 1901 to 1970. This started declining after the 70's with more dry conditions being observed. The wettest year in recorded from the analysis is 1961 while the driest year is 1984 over the GHA region. Run 24 to 36 of gave a decreasing trend meaning that the region is likely to have more drought in the future. With a significant relationship between SPI and total storage deficit index (Awange et al., 2016), increase in dry condition will have a negative impact on surface water availability as well as ground water. This extreme events over the region can be attributed to the El Nino Southern Oscillation (ENSO) which plays a key role.

Analysis over the LVB shows more occurrences of dry condition between 1901 to 1960 in all the runs and more wet conditions from 1961 to 2017. There recent two major extremes observed over the basins are 2005 for extreme dry condition and 1961 as the wettest year on record. The observed increasing trends over the basin may result to more extreme wet conditions that will lead to floods within the basin. These observed conditions are primarily attributed to the Indian Ocean Dipole (IOD) with a secondary contribution by the ENSO (Awange et. al., 2016). The drought index for BNB shows a decreasing trend overtime (Figure 2) observed in all the SPI/SPEI run time steps, meaning that, there were more drought in the recent past over the basin. The basin was also observed to have experienced one of the longest drought on record which occurred from 1980 to 1995, clearly shown in run 36 and 48 of Figure 2. A study by Elkollaly et al. (2018) over the eastern Nile shows that 1984 and 1987 were years of maximum drought severity which is in line with the finding of this study.

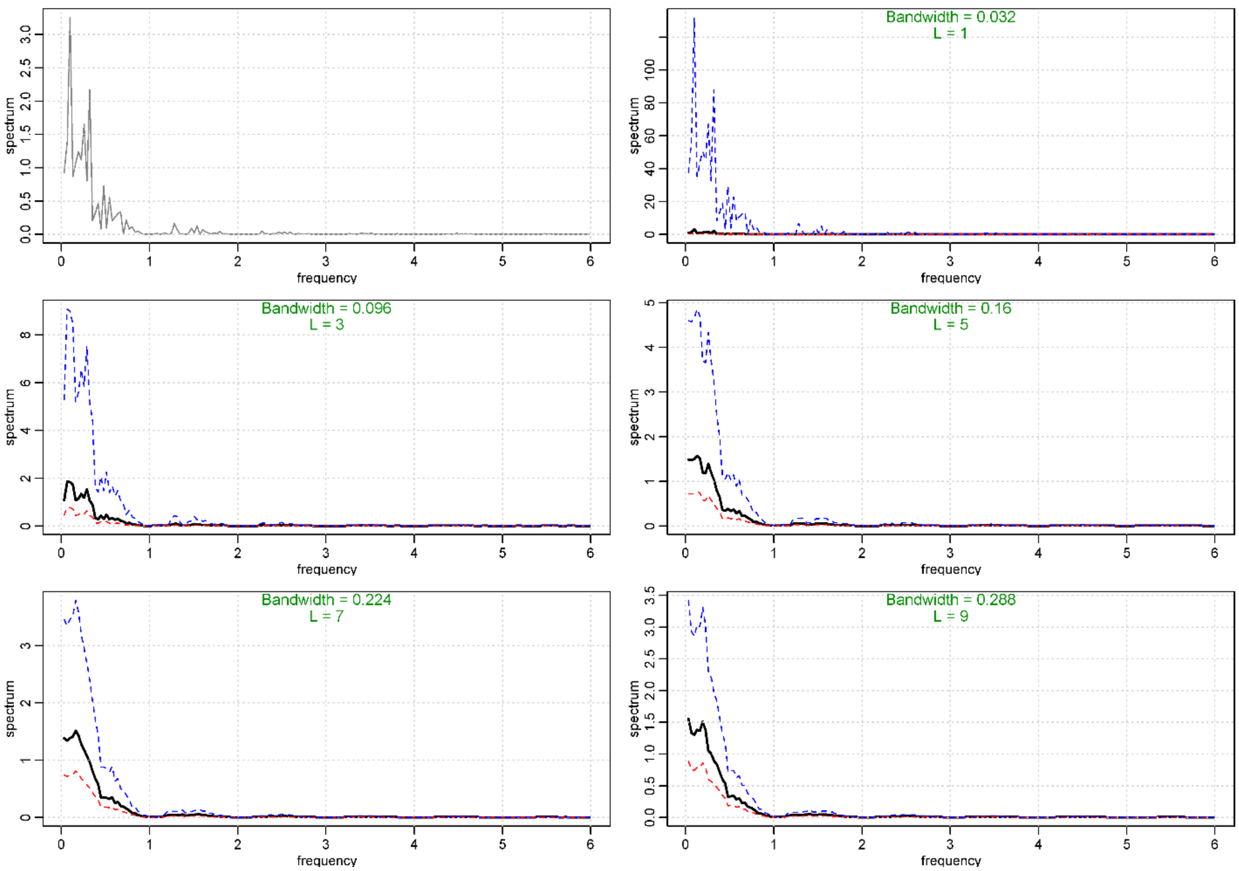
Figure 2 Standardized Precipitation Index (SPI) for Blue Nile Basin using CRU data for the period 1901-2017. The SPI time scales used are 12, 24, 36, and 48 months, where the red and blue colors represents drought and floods respectively.



Periodicity

From the analysis, the periodograms for SPI and SPEI values computed at merely all scales under consideration (12, 24, 36 and 48 months) were found to yield same results. Variations in the drought episodes are here seen to have a period of about 3 years which can be attributed to ENSO events and IOD. The smoothing filters out noise of the sequence averaged periodograms on the 12 -month scaled SPIs from the Blue Nile basin, across bandwidths 1 to 9 (Figure 3), show and example on a peak around frequency of 0.3. The blue dotted lines at top and red dotted lines at bottom are 95% confidence intervals.

Figure 3 Sequence of averaged periodograms on the 12 -month scaled SPIs generated using precipitation data from the Blue Nile basin, across bandwidths 1 to 9.



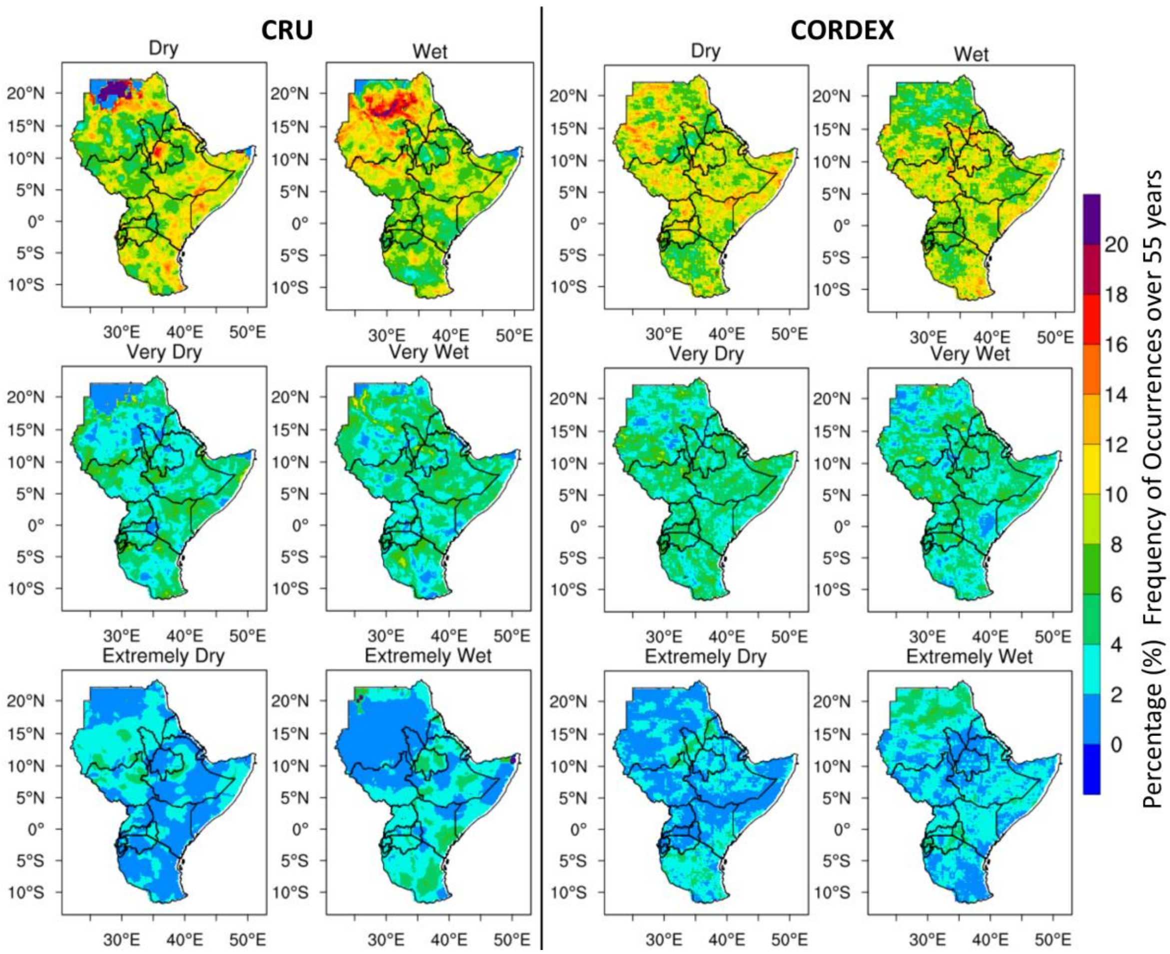
Frequency

Spatial frequency analysis was used to filter spatial properties (Swearer, 2011) of drought over the region for SPI time steps of 12, 24, 36, and 48. Figure 4 presents the historical frequency of wet and dry conditions for time step 12 for both CRU and CORDEX. The frequency of dry/wet categories are higher than those of very dry/wet and extremely dry/wet categories in the region, for both CRU and CORDEX. The pattern of frequency observed in CRU is well replicated in CORDEX, but, the extreme dry/wet categories are not well represented over region by the model historical data. However, BNB and LVB signals are well captured in the extreme category of dry and wet. The SPI/SPEI classes for the categories used are presented in Table below.

Table 2: Categories used to analyze the dry and wet condition over the region presented in the maps.

SPI/SPEI	***Category***	***SPI/SPEI***	***Category***
-1 to -1.49	Dry	+1 to +1.49	Wet
-1.5 to -2	Very Dry	+1.5 to +2	Very Wet
< -2	Extremely Dry	> +2	Extremely Wet

Figure 4: Historical flood and drought frequency maps for SPI-12 for CRU (left) and CORDEX (right) over a period of 55 years (1951 to 2005).



The percentage frequency of drought (dry) and floods (wet) are high under the Dry/Wet category over the GHA region including the BNB and LVB basins, but very low under the extremely Dry/Wet category. This pattern is observed in all the time steps i.e. 12, 24, 36, and 48 used in this analysis for the different Representative Concentration Pathways (RCP) scenarios (RCP45 and RCP85) for the periods 2021-2050 (mid-century) Figures 12, 13, 14, &15 and 2061-2090 (end of century). High frequency of Dry/Wet are not wide spread over the two basins but are seen as isolated patches. However, this gives an idea of how the future is like be. The categorization of Dry/Wet classes are given in Table 2 above.

Conclusions and recommendations

We set out to assess climate variability and extreme events over the GHA region in perspective of WEFE nexus, inline of hydropower, and reservoir multipurpose optimization. The result showed that, at the regional scale using SPI and SPEI, there were more extreme wet conditions before the 1970s with 1961 observed as the wettest on record. After the '70s, more dry conditions were observed in the region with 1984 and 2011 observed noted as the extreme years. The periodicity of these dry/wet conditions was observed to be three years which can be attributed to the El Nino Southern Oscillation. The result confirmed that the recent food insecurity issues in the GHA region are caused by extremely dry conditions. Results from the historical frequency analysis showed that the most affected areas in terms of drought were; much of Sudan, eastern Ethiopia, much of Somalia, much of Kenya, central and eastern Tanzania, and much of the central part of BNB. Floods, on the other hand, affected mostly Sudan, the northern part of South Sudan, central Ethiopia, and northeastern Kenya.

A projection into the future (2021-2050) indicates that the region will experience a high frequency of dry/wet conditions for both RCP45 and RCP85 covering wide areas. Countries that are likely to be affected during this period are; Sudan, South Sudan, eastern Ethiopia, eastern Kenya, and Somalia. This is also a clear indication of high rainfall variability in these countries since the frequency of both dry and wet conditions is high. Towards the end of the century (2061-2090), Somalia is likely to experience the highest impact of drought and floods in the region. It's recommended that countries should consider this finding as they develop their countries national and strategic plans in to the future. This is critical and will contribute to smart climate development such as the need for hydro-power dams over the LVB to control floods and generate electricity.

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Water-energy-food-ecosystem nexus assessment in the Blue Nile Basin in Sudan

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This study analyzes past and future scenarios for the water-energy-food-ecosystem (WEFE) nexus in the Blue Nile Basin in Sudan. Water availability, hydropower generation, irrigation water supply, and environmental flows are the components considered in the current assessment. A calibrated daily rainfall-runoff and water allocation model was used to quantify the four nexus components and their interlinkages. The model includes three storage reservoirs (Grand Ethiopian Renaissance Dam, Rosaries Dam, and Sennar Dam), seven inflow nodes, five irrigation demand nodes, evaporation losses from reservoirs, return flows from irrigation schemes, and transmission losses from river reaches. Due to a scarcity of ground rainfall data in the study area, a pixel-to-point evaluation was conducted for four satellite-based rainfall products, and the best-performing one was used as a boundary condition for the rainfall-runoff component of the model. The model was used to assess the historical and future association of seven WEFE nexus indicators. Results show a historical association between environmental flow supply, irrigation water supply, and water availability. The heightening of the Roseires Dam in 2013 affected most of the nexus indicators. Results reveal that the steady-state operation of the Grand Ethiopian Renaissance Dam will positively affect irrigation water supply, hydropower generation, and environmental flows in the Blue Nile Basin in Sudan.

Keywords: Irrigation; hydropower; environmental flow; water allocation; WEFE Nexus

1. Introduction

It is widely acknowledged that overcoming the challenge of resource scarcity requires adopting integrated management approaches, as opposed to fragmented approaches, to achieve long-term water-energy-food-ecosystem (WEFE) sustainability (Hoff, 2011). The challenge of resource scarcity can be associated with two issues the world is going through. On the one hand, the rapidly swelling urbanization, the growth of the middle-income class, and the changes in lifestyles are placing stress on resources. In 1950, around one-third of the world's population lived in cities, while in 2000 every one in two people was a city dweller. The proportion of the urban population is projected to increase to two-thirds by 2030, which indicates a high growth rate of the middle-income group (UNDP, 2015). On the other hand, it is projected that the global population will grow to 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100 (UN, 2015a). In 2015, about 800 million people were living in extreme poverty and suffered from hunger, approximately 1.2 billion people had income lower than 1.25 USD per day (Bhattacharyya et al., 2015), and above 160 million children under age five had a low height for their age attributable to insufficient food (UN, 2015b). Water scarcity is affecting more than 40 percent of the world population. These effects will be amplified by climate change, which could expose around 250 million people to water stress in Africa alone (UNDP, 2015).

The WEFE nexus theoretical framework illustrates a need to advance our understanding of the interactions between water use and management, energy production, food production, and environmental requirements. This knowledge is pivotal to circumvent future supply deficiencies that would hinder development and to ensure sustainable access to water, energy, and food while maintaining the environment in acceptable status. In recent years, a considerable amount of literature investigated the WEF nexus in transboundary river basins. Bazilian et al. (2011) studied the interlinkages of WEF from a developing country perspective and argued that holistic treatment of the three resources in the context of transboundary river basins improves allocation, enhances economic efficiency, and minimizes negative externalities. Nevertheless, they found that tools and expertise are not yet available to bring the WEF nexus approach into practice. Keskinen et al. (2015) applied the WEF nexus approach to the Mekong River Basin and found that water and food security are likely to be altered by hydropower development. Keskinen et al. (2015) and Strasser et al. (2016) compared the Integrated Water Resources Management and the WEF nexus approaches and concluded that the latter treats the water, energy, and food sectors in an equal manner. However, they found that some aspects, such as livelihoods, climate change, and the environment, are not explicitly considered in the WEF nexus approach (Keskinen et al., 2015). Kibaroglu and Gürsoy (2015) studied the evolution of transboundary WEF management policies in the Euphrates–Tigris River Basin and their impacts on cooperation between riparian countries. They found that the compound nature of pressures and drivers in the Euphrates–Tigris River Basin necessitates adopting a nexus approach to reach a win-win situation between riparian countries. Pittock et al. (2016) developed a comprehensive WEF nexus framework for the Mekong River Basin that shows the interplay of WEF nexus variables. Strasser et al. (2016) proposed a methodology to assess water-energy-food-ecosystem nexus in transboundary river basins and presented results for the Alazani/Ganykh, the Sava, and the Syr Darya transboundary river basins.

Assessing the WEFE nexus is often carried out by separate disconnected institutional entities. For instance, water management institutions often treat food and energy production as end-users; food and agricultural institutions see water and energy as production inputs; energy institutions treat water as an input resource (Howells et al., 2013). The need for the WEFE nexus approach originated from the growing scarcity, recent supply crises, and failures of individualism in sectorial management (Al-Saidi and Elagib, 2017). While the integrated management approach of water, food, energy, and the environment is relatively new (started in the 2000s), calls for water-food, water-energy, and food-energy nexus approaches date back to programs in the 1980s by the United Nations University (Bhattacharyya et al., 2015).

The WEFE nexus approach did not have much attention in Africa compared to other regions in the world. Endo et al. (2017) review several water, energy, food, and climate-related studies on Africa to assess their nexus orientation. They found that most of the studies on Africa did not include all nexus sides. Some nexus research has been recently conducted for the Nile Basin. Basheer and Elagib (2018a) examined the water-energy nexus for the White Nile and the Jebel Aulia Dam. They introduced the water-energy productivity, which is defined as the amount of water lost to evaporation from a reservoir for each unit of hydro-electricity generation. Basheer et al. (2018) explored the impact of transboundary cooperation in the Blue Nile Basin on the water-energy-food nexus. They found that a higher level of cooperation increases basin-wide benefits. Elagib et al. (2019) investigated the urban water-energy-food nexus in Khartoum State at the confluence of the Blue Nile and the White Nile. They found a strong relationship between hydrological phenomena (such as flood and drought) and the resource nexus. Stamou and Rutschmann (2018) analyzed the trade-offs and synergies between hydropower generation and irrigation water supply in the Upper Blue Nile Basin using the parameterization-simulation-optimization method.

This study assesses the water-energy-food-ecosystem (WEFE) nexus in the Blue Nile Basin in Sudan. The Blue Nile is the largest tributary of the Nile River in terms of annual flow contribution. We develop a descriptive framework is developed for the interplay of water, energy, food, and ecosystem resources in the Blue Nile Basin in Sudan in the context of river water availability, hydropower generation, irrigation water supply, and environmental flows. We develop, calibrate, and validate water allocation and hydrological model for the Blue Nile in Sudan using RiverWare and HEC-HMS. The model includes three storage reservoirs (Grand

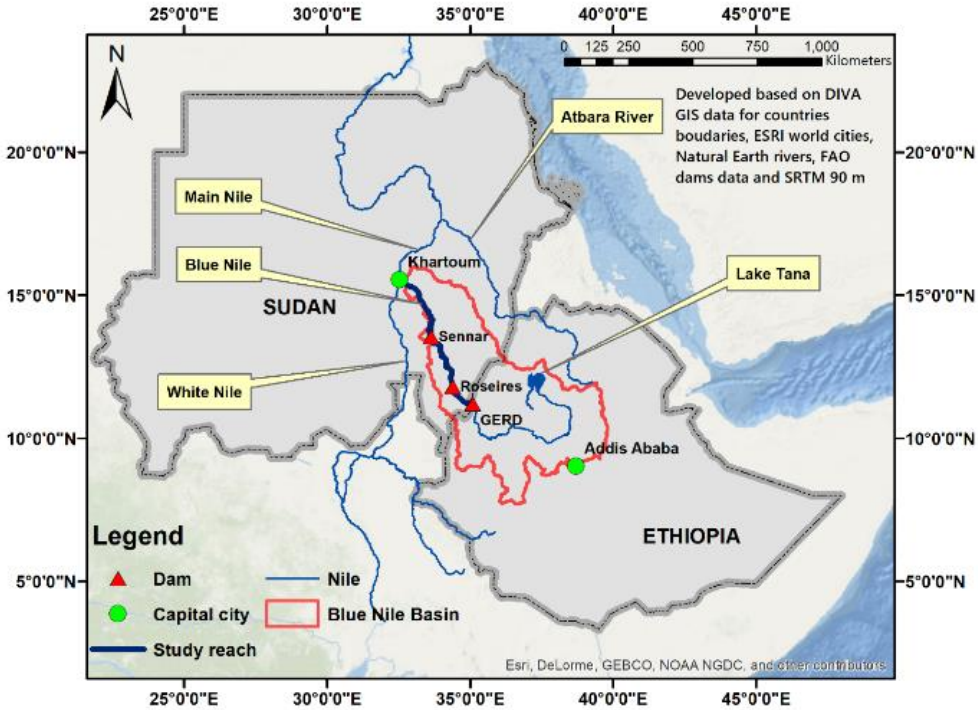
Ethiopian Renaissance Dam, Rosaries Dam, and Sennar Dam), seven inflow nodes, five irrigation demand nodes, evaporation losses from reservoirs, return flows from irrigation schemes, and transmission losses from river reaches. The model was used to assess the historical and future association of seven WEFE nexus indicators, which are annual river flow, annual energy generation, evaporation losses, water-energy productivity, irrigation water supply shortage, risk of irrigation water supply shortage, and risk of environmental flow violation. Due to a scarcity of ground rainfall data in the Blue Nile Basin in Sudan, a pixel-to-point evaluation was conducted for four satellite-based rainfall products, and the best-performing one was used as a boundary condition for the rainfall-runoff component of the model. The evaluated satellite rainfall products include the African Rainfall Climatology Version 2 (ARC2.0), the Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations version 2 (TAMSAT2), the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR), and the Climate Hazards group Infrared Precipitation with Stations version 2.0 (CHIRPS 2.0).

2. Study area

The study area extends over the Blue Nile reach from Grand Ethiopian Renaissance Dam (GERD) to the confluence point of the Blue Nile and the White Nile (see Figure 1), including all major water inflows, abstractions, and infrastructures.

The Sennar Dam became operational in 1925 to supply 126,000 ha of cotton in the Gezira scheme with irrigation water by gravity from headworks located within the dam on the left bank of the Blue Nile. In 1962 two 7.5 MW turbines were installed in a power station on the west side of the dam to utilize the downstream flow for hydropower generation (MoIHES, 1977). Implementing the Managil extension of the Gezira Scheme led the Sudanese government in the year 1925 to investigate a proposal for the construction of a dam with a capacity of at least 1.0 BCM near the Roseires Town. Two years later, the location of the dam was confirmed. The provision of storage larger than 1.0 BCM became increasingly important, especially after the completion of the Managil extension. Therefore, in 1955 the Sudanese government appointed the firms of Sir Alexander Gibb & Partners and Coyne et Bellier of Paris to conduct a joint study on the consequences of constructing a larger dam at Roseires than the one proposed earlier in 1925. The two firms suggested a design for a dam that would be constructed in two stages (MoIHPS, 1966). The first stage of the dam was completed in 1966, followed by an attempt to construct the second stage in the 1990s, which stopped because of the economic situation of Sudan at that time (Roseires Dam Heightening Unit, 2005). The heightening of the dam started again in May 2009 and was finished in January 2013 (DIU, 2016). The water stored in the reservoirs of the Roseires and Sennar dams is essential for irrigated agriculture schemes because the flow of the Blue Nile is seasonally variable. In addition to providing agricultural water, Roseires and Sennar dams serve in hydropower production.

Figure 1. *General features of the Blue Nile Basin downstream the GERD.*



Large-scale agricultural development in the study area began in 1925 with the commissioning of the Gezira Scheme. During the late 1950s and 1960s, the Managil extension was constructed, which more than doubled the total area of the Gezira. The total area of Gezira and Managil schemes amounts to around 840,000 Ha. The Gezira and Managil remain the only gravity-fed scheme based on the Blue Nile in Sudan and represent more than 50 percent of irrigated agriculture in Sudan. Weighty development in pumping irrigation from the Blue Nile took place in the 19th century in reaction to the 1950s increase in cotton prices. The Blue Nile pumping developments include the construction of the Gunied, Rahad Phase1, and Suki Schemes, which took place during the late 1960s in addition to North West Sennar Sugar scheme in the 1970s (IWMI, 2012; MoIHES, 1977).

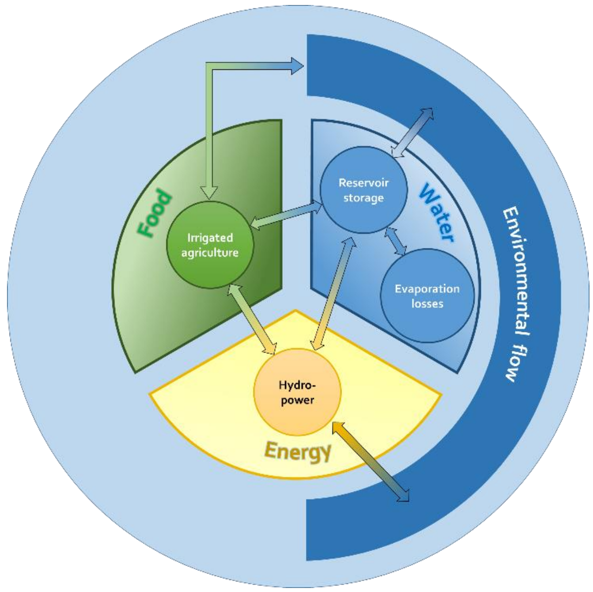
On April 2, 2011, the Ethiopian government announced the start of the currently under construction Grand Ethiopian Renaissance Dam (GERD) with a power capacity of 5150 MW, ranked as the largest in Africa and the tenth-largest globally. The GERD is located on the Blue Nile River 20 kilometers upstream of the Sudanese Ethiopian border.

3. Methods

3.1 WEFE nexus framework

Dams represent a clear example of the WEFE nexus because they are often multipurpose and serve more than one sector. Figure 2 shows a theoretical framework for the WEFE nexus in the study area. The primary purpose of storage dams in the Blue Nile Basin in Sudan is to provide water for irrigation. This purpose sometimes contradicts with hydropower production depending on the location of the irrigation intakes with respect to turbines. Although dams can potentially provide benefits through storage, the larger the storage, the more water is lost to the atmosphere through evaporation. Evaporated water leaves the river system with no chance to be recaptured. The ecosystem is also often affected by dams. Usually, minimum environmental flows are reserved to ensure that the ecosystem is conserved. In principle, environmental flows conflict with irrigation water supply and hydropower generation since it reduces reservoir storage. However, in some cases, it positively affects hydropower production since the minimum environmental flow can be passed through hydro turbines to generate electricity (Sennar dam, for example).

***Figure 2**. Interconnections of water, energy, food, and ecosystem considered in this study.*

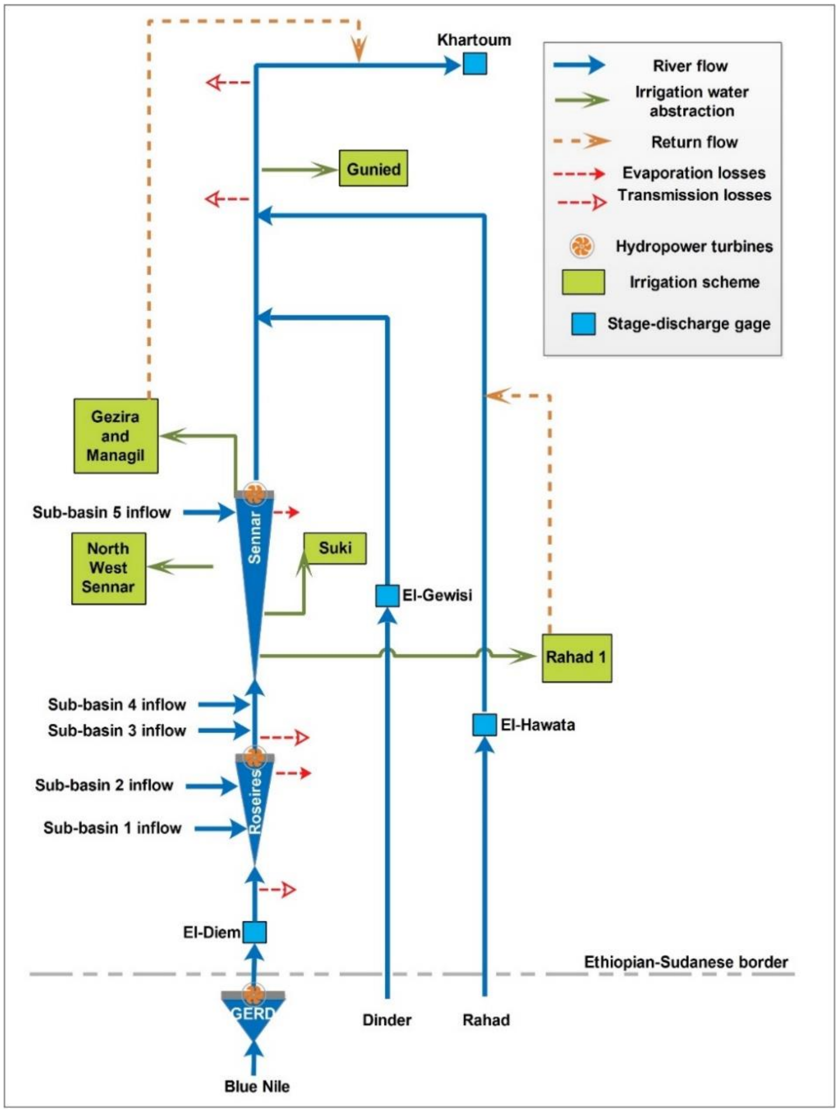


3.2 WEFE nexus modeling

In this study, a daily water allocation and rainfall-runoff model was developed for the study area. The model was calibrated and validated over the 1984-2016 period. Figure 3 shows a schematic of the model developed herein. The model includes three storage dams (GERD, Roseires Dam, and Sennar Dam), seven inflow nodes, five irrigation demand nodes, evaporation losses from the storage reservoirs, return flows from irrigation schemes, and transmission losses (i.e., channel evaporation and percolation) from river reaches. The model is driven by the inflows from the Blue Nile, Dinder, Rahad, and Sub-basins 1-5 and dam operating rules. These rules were obtained from Basheer et al. (2018). River flow data for El-Gewisi, EL-Hawata, and El-Diem gages were used as inflows for the Dinder, the Rahad, and the Blue Nile, respectively. The rainfall-runoff component of the model has been used to simulate the inflow from sub-basins 1 to 5 because they are ungaged. Due to the scarcity of ground rainfall stations in the study area, the performance of satellite-based rainfall products was evaluated, and the best performing one was used as a boundary condition to the rainfall-runoff component of the model (see Section 3.3).

Water allocation was simulated using RiverWare, a river and reservoir simulation software developed by the University of Colorado Boulder (Zagona et al., 2001). RiverWare is capable of simulating hydraulic and hydrologic processes of reservoirs, river reaches, diversions, canals, abstractions, groundwater interaction, hydropower production, water ownership, and water accounting transactions. The object-oriented approach of RiverWare allows the user to create a network of objects, link them, populate each one with data, and select the appropriate physical process. RiverWare's rule-based simulation enables simulating operating policies using logical statements rather than explicitly specified input values for operations. HEC-HMS was used to simulate rainfall-runoff in the study area. HEC-HMS, developed by the Hydrologic Engineering Centre, is a freely accessible numerical model (computer program) that includes a variety of methods to simulate rainfall-runoff of dendritic watershed systems. HEC-HMS simulates watershed precipitation and evaporation, runoff volume, direct runoff, baseflow, and channel flow (HEC, 2008). R, an open-source programming language, was used in evaluating the performance of satellite-based rainfall products. R provides several packages and functions for downloading remote sensing data, extracting pixel values, and calculating the average of pixels within sub-basins (R Core Team, 2015).

***Figure 3**. Schematic of the water balance model.*

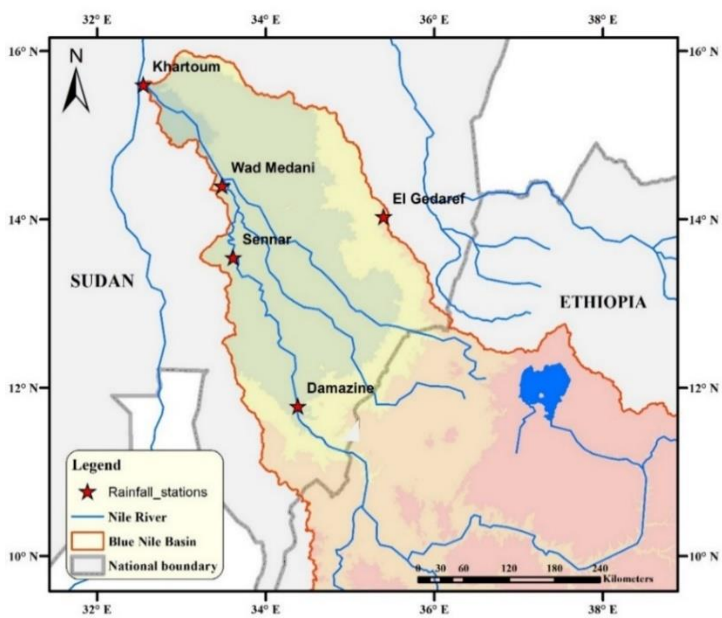


3.3 Evaluation of satellite-based rainfall products

Due to the limited number of rainfall gauges in the study area, four satellite-based rainfall products have been evaluated, and the best performing one was used as a boundary condition to model rainfall-runoff in the study area. The evaluated satellite-based rainfall products include the African Rainfall Climatology Version 2 (ARC2.0; Novella and Thiaw, (2013)), Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations version 2 (TAMSAT2; Maidment et al. (2014)), Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR; Ashouri et al. (2015)), and Climate Hazards group Infrared Precipitation with Stations version 2.0 (CHIRPS 2.0; Funk et al. (2014)).

To measure the difference between satellite estimates and ground observations, a pixel-to-point evaluation was conducted for the satellite products at the locations of five ground rainfall stations using the available measured data (1999 to 2009). Figure 4 shows the locations of the five ground stations. Six performance metrics were used to conduct the evaluation. Those metrics can be categorized into two groups: (1) error metrics that include the root mean square error (RMSE; Chai and Draxler (2014)), the mean bias error (MBE; Legates and McCabe Jr (1999)), and the coefficient of determination (R^2; Legates and McCabe Jr (1999)) (2) categorical metrics that include the probability of detection (POD; Toté et al. (2015)), the false alarm ratio (FAR; Diem et al. (2014)), and the equitable threat score (ETS; Ebert et al. (2007)).

***Figure 4**. Rainfall stations used in this study.*



In order to draw an overall conclusion on the best performing product based on all performance metrics, the overall unified metric (OUM) was calculated for each of the evaluated satellite-based rainfall products. OUM is a performance metric developed by Basheer and Elagib (2018b). Equations 1 and 2 below show the calculation procedure of OUM. High OUM values indicate poor performance and vice versa. We refer the reader to Basheer and Elagib (2018b) for further information.

$$\mathrm{UM}_{rj} = \sum_{i=1}^{p} R_{rji} \qquad (1)$$

$$\mathrm{OUM}_{r} = \sum_{j=1}^{e} \mathrm{UM}_{rj} \qquad (2)$$

Where UM_{rj} is the Unified Metric of the rainfall product r at the station j, p is the number of aggregated performance metrics, R_{rji} is the performance ranking of the rainfall product r at the station j based on the performance metric i, OUM_{r} is the Overall Unified Metric of the rainfall product r, e is the number of stations, and UM_{rj} is the Unified Metric of the rainfall product r at the station j.

3.4 Simulation scenarios

In this study, 34 simulation scenarios were examined. The examined scenarios comprise of a historic baseline scenario for the 1984-2016 period and a scenario with the GERD (in steady-state operation) on the river system. The latter scenario was examined across 33 hydrologic sequences (each 33 years long). The hydrologic sequences were developed using the index-sequential method (Kendall and Dracup, 1991; Ouarda et al., 1997). In the 33 scenarios that include the GERD in full operation, the operation of the Roseires and Sennar Dams was modified to keep them at their full supply level. This modification has been recommended by several studies (Basheer et al., 2018; Wheeler et al., 2018, 2016). In this study, the steady-state operation of the GERD was assumed to target a power rate of 1,400 MW. Wheeler et al. (2018) found that this power rate would maximize the firm annual energy generation of the dam.

4. Results and discussion

4.1 Performance of satellite-based rainfall products

Figure 5 shows the performance metrics of the four satellite-based rainfall products at five locations. It is evident in the figure that the ARC2 has the best performance in terms of ETS, R^2, RMSE, and FAR at all locations compared to the other rainfall products. ARC2 has the second-best performance in terms of POD and MBE.

***Figure 5**. Performance metrics of the evaluated satellite-based rainfall products*

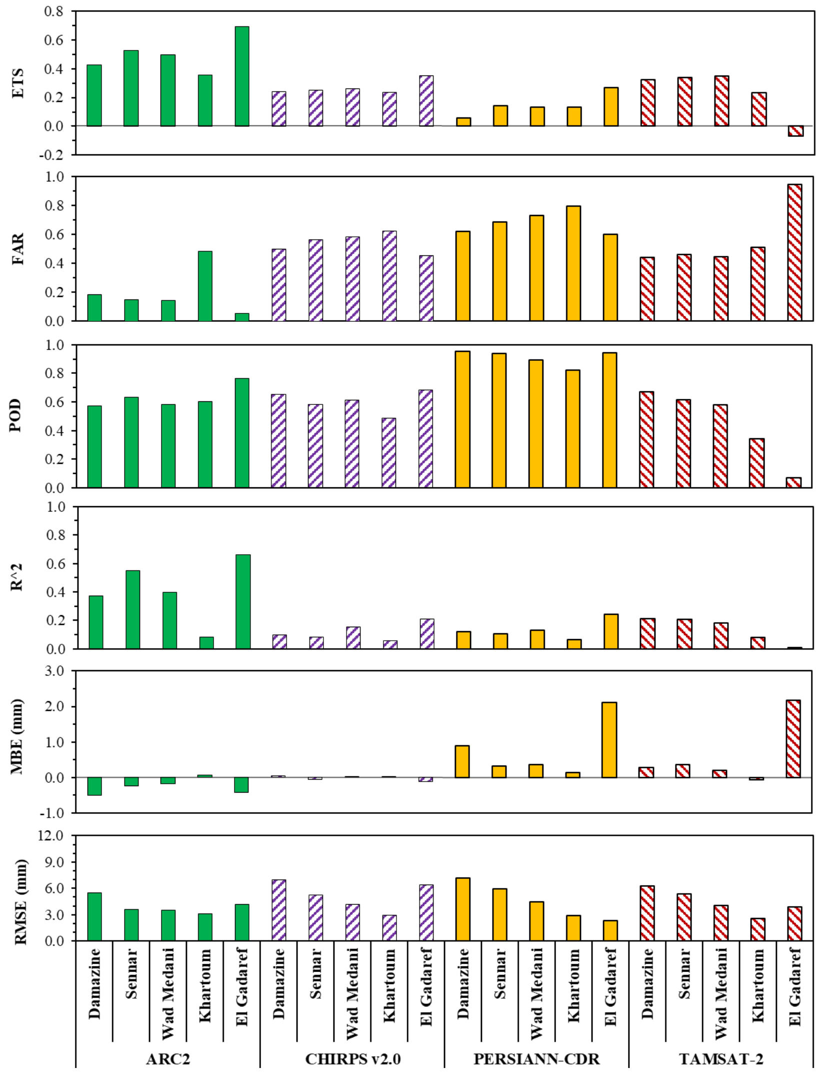
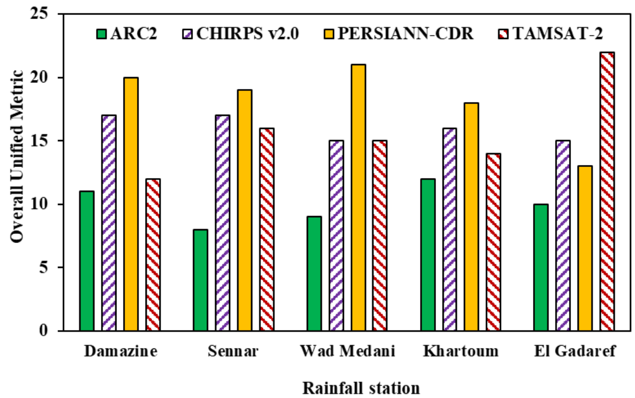


Figure 6 shows the overall unified metric of the four satellite-based rainfall products. The figure shows that ARC2 outperformed the other satellite-based rainfall products at all evaluation locations. Therefore, ARC2 has been used as a boundary condition to model rainfall-runoff in the study area.

Figure 6. *Overall performance of the satellite-based rainfall products in the study area*



4.2 Model performance

Table 1 shows the performance metrics and performance ranking of the model at the Roseires and Sennar dams and the Khartoum Gage based on the recommendations of Stern et al., (2016) on performance ranking of hydrological models. The model accurately captured the inter- and intra-annual behavior of the Blue Nile. The high R^2 values show that the variation in the simulated flow could explain a large portion of the variation in the observed flow. Generally, the model showed better performance in the calibration period than in the validation period. This is because there is uncertainty around the operation of the Roseires Dam since the heightening of the dam in 2013.

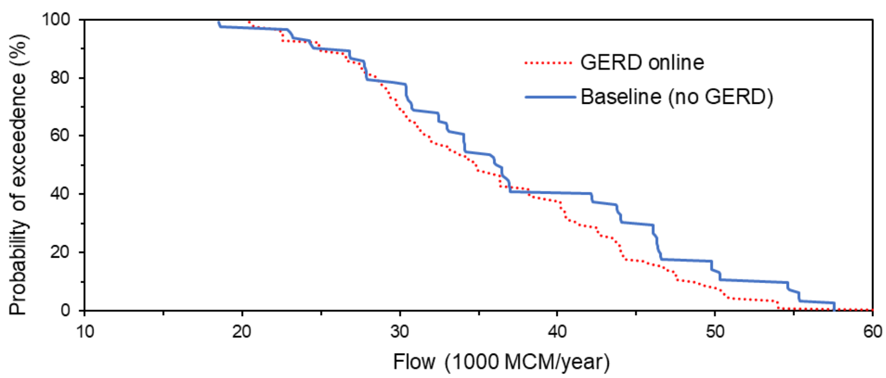
Table 1. Model performance at three locations in the study area

Location	Performance metric	Calibration		Validation	
		Metric value	Ranking	Metric value	Ranking
Roseires Dam	R^2	0.97	Excellent	0.94	Excellent
	NSE	0.96	Excellent	0.98	Excellent
	MPE	0.88	Excellent	0.84	Excellent
Sennar Dam	R^2	0.95	Excellent	0.93	Excellent
	NSE	0.95	Excellent	0.96	Excellent
	MPE	-1.30	Excellent	8.95	Excellent
Khartoum Gage	R^2	0.90	Excellent	0.91	Excellent
	NSE	0.90	Excellent	0.92	Excellent
	MPE	0.26	Excellent	-13.08	Very good

4.3 Water-energy-food-ecosystem nexus assessment

Figure 7 shows the probability of exceedance of the annual flow of the Blue Nile at El-diem with and without the GERD. The figure shows that the steady-state operation of the GERD would reduce the inter-annual variability of the flow, as explained by a reduction in the maximum annual flow and an increase in the minimum annual flow compared to the baseline. The decrease in variability would positively affect water availability in the Lower Blue Nile Basin. However, it implies a negative impact on recession agriculture along the Blue Nile.

Figure 7. Exceedance probability of the Blue Nile flow at El-diem with and without the GERD

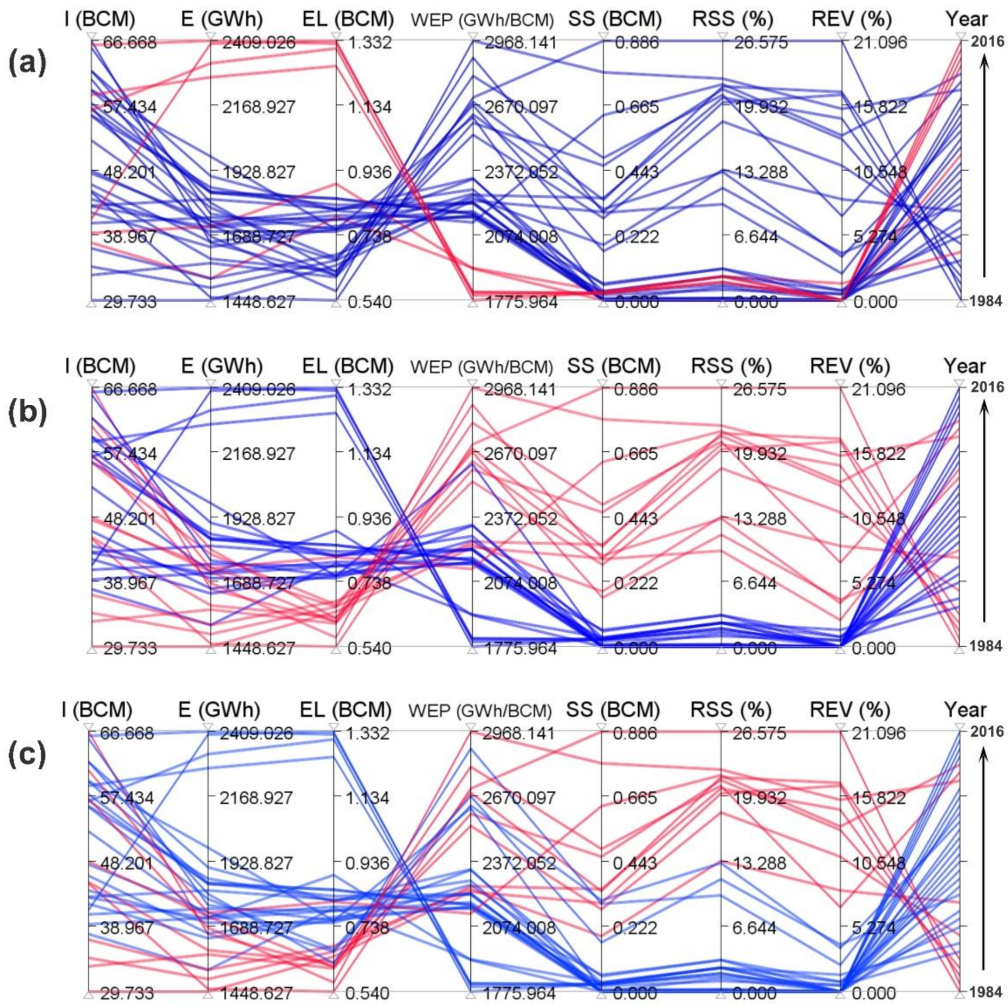


In this study, we used the annual energy generation and the annual water-energy productivity (WEP) as indicators for hydropower generation in the study area. The WEP is a water-energy nexus indicator developed by Basheer and Elagib (2018a) and is defined as the amount of energy produced per unit of water lost in the process. Figure 8 depicts the WEFE nexus indicators of the Blue Nile in Sudan. The colors in Figure 8a distinguish the years with high and low water-energy productivity. The figure shows a historical annual energy generation in the study area in the range of around 1450 to 2410 GWh. The WEP took a range of 1775 to 2968 GWh/BCM from 1984 to 2016. Figure 8a shows that most of the years with high annual energy generation and low WEP are after 2012. The heightening of the Roseires Dam in 2013 is the reason behind this behavior. This heightening increased both energy generation and reservoir evaporation, with a higher increase in the latter than in the former resulting in a decrease in the WEP. The WEP can be increased for the Roseires Dam by utilizing the increase in hydropower potential that resulted from the heightening. Hydropower turbines with a high capacity could be installed in the Roseires Dam to achieve that. Operating the reservoir at lower level could also be used to increase the WEP; however, this will result in water supply shortages bearing in mind that hydropower generation is not the primary purpose of the dam.

The analysis of hydro-energy generation and reservoir evaporation in Sudan during the steady-state operation of the GERD reveals the following with all hydrologic conditions: total annual energy generation from the Roseires and Sennar Dams of around 2560 GWh, total annual evaporation from the Roseires and Sennar Dams of around 1.735 BCM, and WEP of around 1575 GWh/BCM. These results indicate that the GERD would further decrease the WEP in Blue Nile Basin Sudan due to an increase in reservoir evaporation at a faster rate than energy generation. Increasing the WEP would require utilizing the untapped hydropower potential from the Roseires and Sennar dams that the GERD would provide as a result of less inter-annual variability in river flow.

The annual irrigation water supply shortage (SS) and the risk of irrigation water supply shortage (RSS) were used in this study as indicators of water-food nexus. The RSS is defined by Wheeler et al. (2016) as the percentage of days in the year with supply shortages. Figure 8b shows that from 1984 to 2016, the annual irrigation water supply shortage and the annual risk of irrigation water supply shortage ranged from 0 to 0.9 BCM and 0 to 27%, respectively. A high association is evident between the annual irrigation water supply shortages (SS), risk of supply shortages (RSS), and river flow (I). The highest shortages and risk occurred in the year 1985 during the drought of the 1980s and 1990s. The blue lines in Figure 8b indicate the instances with low irrigation shortages. It can be noticed that the years with above-normal flow conditions often have low irrigation shortages. Moreover, low shortages are evident from the year 2013 due to the heightening of the Roseires Dam. The results show that the steady operation of the GERD would eliminate the irrigation water supply shortages in the study area. This is mainly due to the more regular flow the GERD would provide, as shown in Figure 7.

Figure 8. Parallel plots of the historic annual (1984-2016) water-energy-food-ecosystem nexus indicators: (a) Blue- and red-colored lines represent years with high and low Water-Energy Productivity (WEP), respectively; (b) Blue- and red-colored lines represent years with low and high irrigation water shortages, respectively; (c) Blue- and red-colored lines represent years with low and high environmental flow violation, respectively. I = inflow; E = energy generation; EL = evaporation losses; WEP = water-energy productivity; SS = irrigation supply shortages; RSS = risk of irrigation supply shortage; REV = risk to environmental flow violation.



The annual risk of environmental flow violation (REV) was used to assess the linkages of the ecosystem status with the other nexus components. The REV is the percentage of days in the year where the minimum environmental flow requirements have been violated. Equation 3 was used to calculate the REV.

$$REV = \frac{Dv}{DY} \times 100\% \qquad (3)$$

Where REV is the risk of environmental flow violation in the i^{th} year, Dv is the number of days where environmental flow requirements have been violated in the i^{th} year, and DY is the number of days in the i^{th} year.

The minimum environmental outflow from the Sennar Dam is 8 MCM/day, according to the Sudanese authorities. The blue-colored lines in Figure 8c mark the instances with a low risk of environmental flow violation in the study area. Figure 8c reveals an association between environmental flow provisioning, irrigation water supply, and the hydrologic condition. The highest REV occurred in the year 1985. The heightening of the Roseires Dam reduced the REV significantly. The analysis of the steady-state operation of the GERD showed that the dam would eliminate any risk of environmental flow violation. This is due to the more regular flow that the GERD would provide.

5. Conclusions and way forward

The integrative approach of the water-energy-food-ecosystem nexus offers an opportunity to utilize resources more efficiently by taking into account their interconnections in management and planning. However, there remains an operationalization gap due to the lack of tools and assessment metrics (Liu et al., 2017). This study is an attempt to quantify the interlinkages of the water, energy, food, and ecosystem in a resource stressed and data-scarce region. The study region is the Blue Nile Basin downstream in Sudan. This region has experienced past persistent hydrological droughts, recent dam development, and will soon experience a major dam development in the upstream.

A daily rainfall-runoff and water allocation model was developed for the study region to quantify some WEFE nexus indicators. The model covers the 1984 to 2016 period and includes the major water-related infrastructures and their operating rules. Due to data scarcity in the study region, four satellite-based rainfall products have been evaluated using a pixel-to-point approach, and the best performing one was used as a boundary condition to model the rainfall-runoff component of the model. The results show that the African Rainfall Climatology Version 2 (ARC2) has the best performance compared to the other evaluated satellite rainfall products. The historical (1984 to 2016) nexus indicators show an association between environmental flow provisioning, irrigation water supply, and the hydrologic condition. The heightening of the Roseires Dam in 2013 reduced the irrigation supply shortages, reduced the risk of environmental flow violation, increase hydropower generation, increased evaporation losses, and increased the water-energy productivity. The results show that the Grand Ethiopian Renaissance Dam would eliminate the risk of environmental flow violation, eliminate the irrigation supply shortages, increase hydropower generation, increase evaporation losses, and reduce the inter-annual variability in river flow.

The results of this study show a promising role that satellite data can play in data-scarce regions. A more extensive evaluation of all the available satellite-based rainfall products would be needed to exploit the potential of this emerging data source fully. The analysis conducted herein uses the index-sequential method to analyze future scenarios. However, this method does not take into account non-stationarity in the climate system. Future studies could focus on examining the WEFE nexus under transient climate conditions.

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Water-Energy-Food-Ecosystem (WEFE) Assessment in the Upper Blue Nile upstream of GERD

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Blue Nile River is the main source of water for hundreds of millions of people in Ethiopia, Sudan and Egypt. Natural resources in the Nile Basin are under enormous pressure due to population growth, economic development, increased energy and food needs. Among the multiple challenges the Blue Nile Basin poses, figures boldly the impact of land use on the water quality and quantity. Consequently, the impact produced on human and ecosystem health as a result of water quality deterioration and water quantity depletion is a cause for high concern. The aims of the project are to acquire and document baseline database on hydrology and water use (EIWR.1), to assess Water-Energy-Food-Ecology (WEFE) nexus (EIWR.2), and to develop a methodological guideline to assess the impact of water access and quality on public and ecosystem health in the Blue Nile Basin upstream of Grand Ethiopian Renaissance Dam. The approaches implemented in the current study are collecting and screening observed rainfall, streamflow, and irrigation water demand data from existing feasibility and design reports (EWRI.1), applying MIKE Hydro water allocation model for WEFE nexus assessment (EIWR.2), and developing methodological guidelines for water quality assessment using the Driver-Pressure-State-Impact-Response framework (EIWR.3). The main findings of the project are observed rainfall, streamflow, irrigation water demand data documented in excel file format (EIWR.1), WEFE nexus over the BNB upstream of GERD shown no evidence of water-energy-food-ecology security problem given the condition the model was developed (EIWR.2), and methodological guidelines for water quality assessment was developed. The spatial distribution of the documented rainfall and streamflow data are very sparse. As a result, the reliability of the input data highly limits the consumption of the modelling output without due considerations. Remote sensing and reanalysis of data might improve, the model outputs.

Keywords: Upper Blue Nile, WEFE nexus, DPSIR, database, GERD

Headlines: MIKE Hydro model showed no shortage in irrigation water demand and power generation deficits

DPSIR is proposed as a guideline for water quality assessment.

Introduction

Blue Nile River is the main source of water for hundreds of millions of people in Ethiopia, Sudan and Egypt in the Nile River basin with a drainage area of 324,530 km^2 (Peggy and Curtis, 1994). The Upper Blue basin is 176,000 km^2 in area (Conway, 2000) and it is the largest of Ethiopian basins in terms of volume of discharge. The topography is dominated by an altitude ranging from 485 meters to more than 4257 meters. The livelihood of the people in the basin is heavily dependent on rain-fed agriculture and small-scale irrigation schemes (Fenta et al. 2014). The basin is also characterized by poverty, rapid population growth, environmental degradation, and frequent natural disasters (Abtew and Melesse, 2014). The Blue Nile basin is increasingly experiencing multi-dimensional pressures including population growth, climate change and variability, deforestation, land/soil degradation, as well as increasing upstream-downstream tension on water use rights. Ethiopia has so far little utilized

the water resources of the Basin although it contributes nearly 84% of the annual flows of the Nile (Block and Strzepek, 2010). Sustainability of the Nile River Basin water resources development is highly linked with a regular assessment and management of the level of interdependency and integration that exists among Water-Energy-Food and Ecosystem (WEFE) nexus.
Environmental changes not only influence water quantity but also water quality. In view of this, the following objectives were set: i) to acquire and document baseline database on hydrology and water use in the Blue Nile upstream of Grand Ethiopian Renaissance Dam (GERD), (ii) to assess WEFE nexus, including the implementation of a hydrological and water allocation framework, hydropower and agricultural water management over the Blue Nile Basin upstream of GERD, (iii) to develop a methodological guideline to assess the impact of water access and quality on public and ecosystem health in the Blue Nile Basin.

Objectives

Objective 1: To develop a baseline database on hydrology and water use and related report in the Blue Nile upstream of GERD.

Objective 2: To prepare a Comprehensive assessment report on WEFE nexus over the Blue Nile Basin upstream GERD

Objective 3: To develop Guidelines on methodological approach to impact assessment of water access and quality on health in the Blue Nile Basin

Method

The kind of approach used for deliverable EIWR.1 was collecting and screening observed rainfall and streamflow data from existing feasibility and design reports in the upper Blue Nile Basin. Spatial and temporal patterns of the collected data were developed. Irrigation water demand, irrigation scheme area, and dominant crop from their respective design and/or feasibility reports were acquired. Deliverable EIWR.2 (the WEFE nexus assessment) was implemented using MIKE Hydro water allocation model. MIKE HYDRO input data i.e. irrigation water demand, reservoirs' gain/loss, depth area-volume characteristics, operation rules and power demand were adopted from feasibility studies, design reports and informed assumptions for power generated. Seven sub-catchments were delineated from SRTM 30 m resolution DEM using the flow stations locations and tributary confluences. Four reservoirs such as Lake Tana, Deddessa reservoir, Fincha reservoir and GERD were considered. Monthly irrigation demand data from different irrigation scheme studies (feasibility studies) were considered for food security. Tana-Beles hydropower (estimated), Fincha hydropower (actual) and GERD (estimated) were considered for energy security. Once the river flow for each catchment was estimated/established, reservoirs, irrigation water use and hydropower nodes were added. The release from reservoirs were also evaluated for ecological flow availability. Relevant data such as depth-area-volume, rainfall on the reservoir, evaporation loss from the reservoir were adopted from feasibility study report of the four reservoirs (Lake Tana, Fincha, Deddessa and GERD). Finally, deliverable EIWR.3 was realized using multiple tools such as the Driver-Pressure-State-Impact-Response framework (DPSIR), the Systems Approach Framework (SAF), and the Social-Ecological Systems Framework (SESF). The Driver-Pressure-State-Impact-Response (DPSIR) framework has been proposed to serve as a research methodology for the assessment of changes on the water quality/quantity in the BNB due to land use and the consequent impact on the public and ecosystem health produced by water quality deterioration and water quantity depletion. Moreover, the relationship between water quantity/quality and the ecosystem services of the BNB was briefly discussed.

Discussion

Both observed rainfall and streamflow data were considered on the supply side of available water in the upper Blue Nile basin. Seasonal and annual total rainfalls for 100 meteorological stations were interpolated using ordinary kriging with spherical semi-variogram model. Long-term average monthly streamflow data were acquired at different gauging stations (9 gauging stations). Irrigation water is the only water use considered on the demand side. Existing and ongoing irrigation schemes, their areal extent and dominant crop were reported.

Prediction of streamflow in ungauged catchment principle were applied in order to obtain river flow for each catchment. Streamflow estimation for ungauged catchment is implemented by transferring the ratio of streamflow to rainfall at different gauging stations to the outlet of the ungauged catchments in order to calculate streamflow (Gianfagna et al. 2015). For Lake Tana and Kessie catchments, observed streamflows were adopted directly while for other catchments´ the estimated flows were used. With these streamflow data the MIKE HYDRO model was updated for further analysis. The results of simulated irrigation and power generation indicated that water demand deficit and power deficit were observed in Lake Tan sub-basin. For Fincha Irrigation scheme, actual irrigation water demand is obtained from master plan study. However, the streamflow at the confluence of Fincha River to Blue Nile River was estimated during master plan study, and hence adopted. Actual operational data were adopted form estimation of power deficit. MIKE Hydro output for Fincha sub-catchment displayed that there was no water demand deficit for the existing irrigation scheme as well as the hydropower generation. MIKE Hydro output for Deddessa sub-catchment showed that there was no water demand deficit for the existing irrigation scheme. MIKE Hydro output for GERD sub-catchment manifested that there was no power deficit at GERD hydropower scheme although actual power generation data is not yet existing as the Dam is not yet commissioned.

In order to assess and analyze the prevailing socio-economic activities, land use and the consequent changes on the state of the water bodies regarding water quality, and most importantly the impact produced on the public and ecosystem health, sound methodological approaches should be adopted. As a result, a robust and updated tool was suggested to identify, select, process and analyze information about the issue.

Conclusions and recommendations

- Spatial and temporal rainfall data are collected for annual, seasonal and monthly scales though the distribution of rainfall stations is less for downstream region of the upper Blue Nile Basin.
- Streamflow data are also documented for annual, seasonal and monthly scales.
- Assessment on WEFE nexus over the BNB upstream GERD was conducted using MIKE HYDRO Basin model.
- Input data for the model development were collected from various feasibility studies and design reports of water resources infrastructure in the basin.
- The model output indicated that all catchments in the basin had sufficient water to satisfy the demands for irrigation and hydropower except Lake Tana catchment.
- Lake Tana catchment has irrigation and power generation deficit with the implication of energy and food security issues. Kessie, Fincha, Deddessa and GERD catchments did not show sign of deficit for both irrigation and hydropower generation.
- In addition, the ecological flow at each catchment thereby the basin was more than satisfied.
- Therefore, WEFE nexus over the BNB upstream GERD shown no evidence of water-energy-food-ecology security problem given the condition the model was developed.

- Lack of actual power generation data for the existing hydropower stations (e.g. Tana Beles hydropower station) and design operation rules for the future power generation (GERD) influenced the actual representativeness of the model simulations.
- Moreover, lake of streamflow observation for some catchments may impact the model accuracy.
- In summary, the reliability of the input data highly limits the consumption of the modelling output without due considerations.

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Hydrology and Water Balance of Lake Victoria sub basin

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In the framework of the project scientific component, the CEANWATCE, this project addressed the WEFE nexus interdependences and evaluated sustainable bridging-gap solutions. The specific objectives were to perform hydrological and water balance assessments, including water uses within a scenario based analysis under different climate pressures and management practices focusing on the Lake Victoria basin (LVB). LVB is transboundary river basin which is Africa's largest freshwater lake in which the riparian countries are Burundi, Kenya, Rwanda, Tanzania and Uganda which is the most downstream country. In this study, water balance components were calculated from calibrated and validated hydrological/rainfall runoff model for the Lake Victoria basins. The impact of current and future water resources availability due to climate variability, uses and infrastructure was evaluated through water resources modelling. The model was simulated over a 30 year (1981-2010). Good calibration results were achieved in most of catchments, the Lake Victoria Water Level simulation results shows that the model was able to capture the water level variation well. There was however the period 1998-1999, the model underestimated the lake water level, this may be due to underestimation of the convectional rainfall over the Lake. There will be a reduction the Long Term Lake mean water level of 0.47m and 0.55m for the SC1 and SC2 respectively. There is less impact on the lake water level because almost 80% of the inflow water to the Lake is from precipitation on the Lake itself. Future water use will increase water demand deficit for both domestic and irrigation uses but more deficit will be faced by the irrigation sector. As a recommendation, it will be useful to investigate various forms of precipitation products over the Lake to get a broader view of the actual precipitation variability since there are no ground based measurements data available.

Keywords: WEFE nexus, Modelling, Lake Victoria basin

1 Introduction

In the framework of the project scientific component, the CEANWATCE (Central-Eastern Africa Network of WATer Centers of Excellence) identified, by means of collective sharing, the Blue Nile Basin (BNB) and the Lake Victoria Basin (LVB), as sub-catchments of the Nile being very relevant for the development of common research undertakings. These basins pose many challenges from a perspective of Water-Energy-Food-Ecosystem (WEFE) nexus, including, among others, hydropower, reservoir multipurpose optimization and release management (in particular the BNB), rain-fed and irrigated agriculture development, impact of land use and agricultural practices (including livestock and fisheries), role of ecosystem services (natural parks, wetlands), pressures on resources due to population increase and climate variability/change and extreme events risks (drought and flooding).

This project addressed the WEFE nexus interdependences and evaluated sustainable bridging-gap solutions. The specific objectives that was addressed by the IGAD Climate Prediction and Applications Centre (ICPAC) on hydrology, water balance and Hydropower was; to perform hydrological and water balance assessments, including water uses within a scenario based analysis under different climate pressures and management practices focusing on the LVB of the Nile Basin.

1.1 Study Area

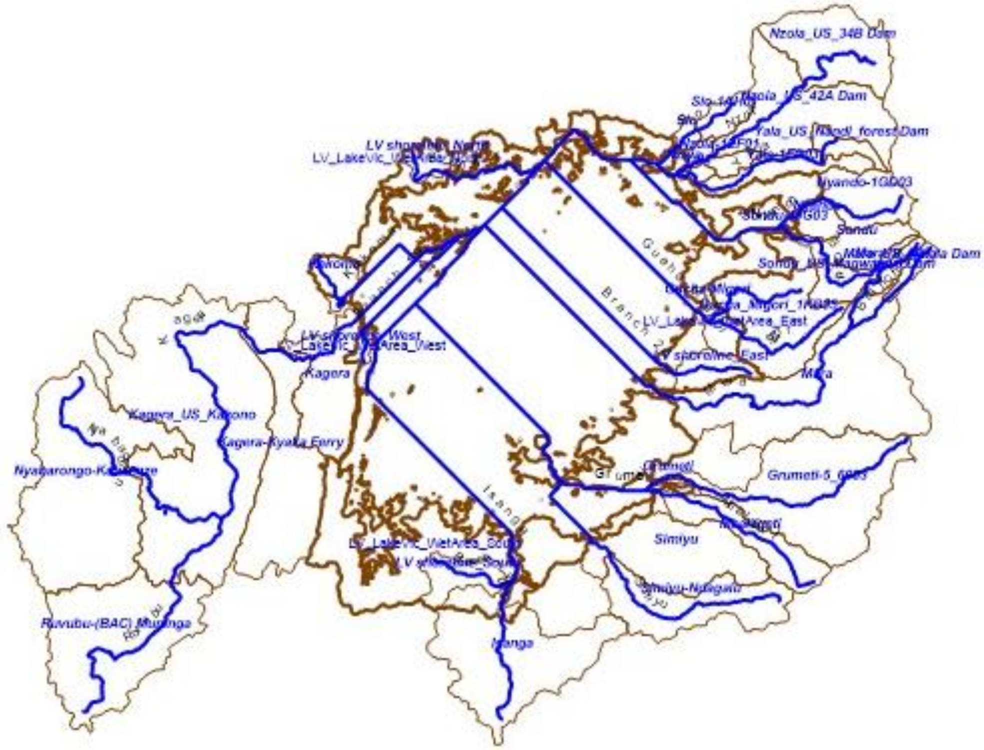
Lake Victoria basin (LVB) is transboundary river basin which is Africa's largest freshwater lake at its exit. The riparian countries are Burundi, Kenya, Rwanda, Tanzania and Uganda which is the most downstream country. The LVB covers 180,950 square kilometres, with Tanzania occupying 44 %, Kenya 22 %, Uganda 16 %, Rwanda 11 %, and Burundi 7 % of the land area (LVBC, 2018). The growing population, with an average annual growth rate of 3%, exerts increasingly greater pressures on its natural resources (UNEP, 2006). Thus the use of the water related resources supports the livelihood needs of the inhabitants of the basin.

2. Methodology

In this study, water balance components were calculated from calibrated and validated hydrological/rainfall runoff model for the Lake Victoria basins. The impact of current and future water resources availability due to climate variability, uses and infrastructure was evaluated through water resources modelling. The water resources model included current and planned future water use/infrastructure development and Lake Victoria and associated operation rules. The model was simulated over a 30 year (1981-2010) period datasets and calibrated and validated at river gauging and water level points where data existed. Mass balance error and Nash-Sutcliffe Coefficient was used to guide the calibration process.

MIKE HYDRO Basin software was used in this study for delineation, Rainfall Runoff and Water Resources Modelling. MIKE HYDRO Basin is a commercially-available, multipurpose, map-based decision support tool developed by the Danish Hydraulics Institute (DHI) for integrated river basin analysis, planning and management (DHI, 2019). SRTM DEM 90m DEM, was processed within MIKE HYDRO Basin and used for catchment delineation (Fig 1). Sub-catchments were delineated upstream of points of interest such as River gauging station that was used for calibration, location of current major infrastructure and location of future major infrastructure that were selected to be included in the model. Due to the difficulty of modelling numerous small catchments and islands that drain directly in to the Lake Victoria, these areas were lumped and grouped as Lake Victoria East, West, North and South sub catchments.

Figure 1. Delineated Sub Catchments-Lake Victoria Basin



2.1 Input Data

Precipitation

There was a lack of observed rainfall data for this study and thus public domain datasets was the best option. The CHIRPS datasets (Funk et al, 2014), was used for the simulation period 1981-2010.

Streamflow data

River discharge data were required for this study in order to calibrate rainfall-ruonff models. The Lake Victoria Basin is a transboundary river basin with five riparian countries thus each country has its own network hydromet stations. Efforts were made to try and get data from these countries and also from research collaborator, Makerere University and only 8 river gauging stations data were obtained. Two more stations data were obtained from anonymous sources on condition that it cannot be shared with the stakeholders. Most of the stations have less than 50% data availability over the simulation period, quality assessment was done for the river discharge data and all were found to be of good quality for use in calibration and validation.

Evaporation data

Potential ET (PET) together with precipitation are the two basic inputs required to run rainfall runoff models. Due to the limited number of evaporation station available in the region and lack of access to it, indirect simple methods for estimation of potential ET was considered. One such method is the temperature based Blaney-Criddle Method (Allen et all, 1986). Using gridded monthly temperature data from the Terrestrial Hydrology Research Group at Princeton University as inputs to this method, monthly PET was calculated for each 0.25 deg grid size over the LVB. This data was then rendered as time series and areal sub catchment monthly average PET (mm/d) calculated for each of the modelled sub catchments.

Water Level data

Lake water level data was obtained from the Theia-CNES center as well as from Makerere University. The former is based on satellite altimetry data using Jason, Envisat, Saral and Sentinel Satellites, while the latter is observed data at the Jinja town, Uganda. Since the two data are at different datum, it was necessary to convert the observed data from absolute to relative water level data. A value of 1123.5m datum adjustment was found to give the best fit. The satellite data is available from 1992 while the observed is available for the entire simulation period.

Domestic/Municipal water demand data

Domestic and municipal water demands depend largely on population and level sanitation. In the Lake Victoria sub basin estimated population data for sub catchment in the year 2000 was available and this data was projected for the years 2030 and 2050 using the World Bank population growth estimates. The demands were thus estimated using 50liters per capita per day which is the lower value of WHO recommendation of 50-100 litres per capita per day. The lower value was assumed due to the fact that most of the population are rural with no modern sanitation facilities.

Irrigation Water Demand

Irrigation water demand data was collated mainly from a study done by the Food for Thought (F4T) project (FAO, 2011), which had a baseline for 2005 and projections for year 2030 and 2050. The F4T report had irrigation demands for administrative units or districts rather than sub catchments so the proportion of each unit in a catchment was used which assumes uniform distribution of irrigated area within each administrative unit. The data was cross checked with available Irrigation as well as water resources master plans (GoR, 2010; JICA, 2013; FAO, 2014; JICA, 2018). The cross check was performed at the sub basin level (e.g Lake Victoria basin in Tanzania or Lake Victoria North Catchment Area in Kenya) since the Master plans have current and projected irrigation demand at that level.

Current and Planned Reservoir data

The only existing reservoir in the Lake Victoria Basin is the Sondu-Miriu which has day storage facility, however there are several planned reservoirs in the basin. The minimum data required for modelling are the Target power, water demand, bottom, top of dead storage, crest levels and level area volume relationship were sources from literature (JICA 1992, AfDB 2018) and where lacking estimated.

2.2 Rainfall-Runoff Modelling

Model calibration involves manual adjustment of model catchment parameters until a good fit between the model catchment runoff and observed river flow is achieved using the criteria mentioned above. The model was calibrated using observed daily streamflow for the baseline period of 1981-2010. A split approach was used to apportion observed data for calibration and validation based on the length and period of data availability. In ungauged catchments or ones where no observed data was available mainly in Tanzania and border Mara and Kagera catchments, average parameter values were used between Mara and Kagera catchments.

2.3 Water Resources Model Setup and Comparison Indicators

A baseline water resources model was set-up for the Lake Victoria sub basin using the Mike Hydro model, with the outputs from the rainfall-runoff model (stream/natural flow) together with current water use/infrastructure development and Lake Victoria and associated operation rules. Two Scenario models were also built from the baseline and included projected future water use/infrastructure development. Climate variability was implicitly taken in due consideration through the modelled rainfall-runoff output. The details of the scenarios are shown in Table 1. The scenarios take into consideration WEFE issues such water Demand for domestic municipal, irrigated agriculture and hydropower energy.

In the model the reservoirs were operated to meet the demands for the purpose of development (e.g hydropower) as well as downstream demand within the river and no minimum flow requirement was set in this scenario simulations.

Table 1: Details of Modelled Scenarios

Scenario	**Forcing data**	**Water Demand**	**Infrastructure**
SC0 - Baseline	1981-2010	2010	2010
SC1 - Near Future	1981-2010	2030 (projected)	Planned Infrastructure
SC2 - Far Future	1981-2010	2050 (projected)	Planned Infrastructure

In order to compare the performance of the scenarios the following simple indicators were selected.

Long Term Average river discharge at tail end of river reaches: The long term daily simulation results was analysed for each river at the last node feeding in to the Lake to calculate these indicators.

Water demand satisfaction rate: As the model calculates the daily water demand deficit in absolute (volume) as well as percentage form, average values for the entire simulation will be calculated for all river for each scenario.

Sub Basin wide Hydropower Produced: The average hydropower (MW) produced by each of the hydropower station will be summed up for each scenario.

Change in long term Lake Victoria water Level: The long term change of Lake Victoria compared to the baseline (SC0) will be evaluated as an impact of the upstream water use on the lake. This assumes the outflow from the lake will continue to follow the 'agreed curve'.

3. Results and discussion

3.1 Rainfall Runoff Modelling

Good calibration results were achieved in some catchments while in others it was difficult to improve the results beyond the tabulated values (Table 2). It was observed that the length and quality of observed data is particularly critical in achieving good calibration and validation results.

Table 2. Calibration and Validation Results

No	River Gauging Station	MBE (%)		NSE (-)	
		Calibration	Validation	Calibration	Validation
1	1AH01	36.2	8.5	0.248	0.456
2	1EF01	15.3	-35.8	0.723	0.078
3	1FG03	20.4	-31.8	0.450	0.277
4	1GD03	141.0	11.0	-0.351	0.348
5	1JG03	-19.0	22.0	0.143	0.614
6	1KB05	47.2	0.70	0.095	0.657
7	1LA03	8.9	-10.2	0.399	0.315
8	Simiyu	33.0	-13.0	-0.129	0.577
9	Kagera	3.3	2.1	-2.12	-0.909
10	Rusumo	18.8	14.9	-0.975	**0.477**

3.2 Lake Victoria Sub Basin Water Balance

In the Lake Victoria Water Level simulation (Figure 2), the model was able to capture the water level variation well with the exception of the high rainfall period (1998-1999) which was associated with the El Niño phenomena. This may be due to underestimation of the convectional rainfall over the Lake by CHIRPS rainfall product.

Based on the simulation model output over the entire simulation period of 1981-2014, mean outflow from the LVB catchments as well as an estimate of the Lake Victoria water balance were calculated(Table 3). Although the catchment outflows represent the natural flows from the catchment not all of it flows into Lake Victoria as there are consumptive water uses such as irrigation and municipal supply that reduce the flow in the Lake which is what the observed flows indicate. The Lake Victoria water balance however includes net flows to the lake as well as estimated over the Lake Precipitation and Actual Evaporation.

The LVB catchments simulated water balance values compare well with the observed Long term mean values in the literature. Differences do exist and can be attributed to different mean period and in particular the observed data includes the high precipitation and streamflows observed in the early 1960 which is outside the range of the modelling period. Model inaccuracies include accuracy of input precipitation data also account for the difference.

Figure 2. Comparison of Simulated and Observed Lake Victoria Water Level

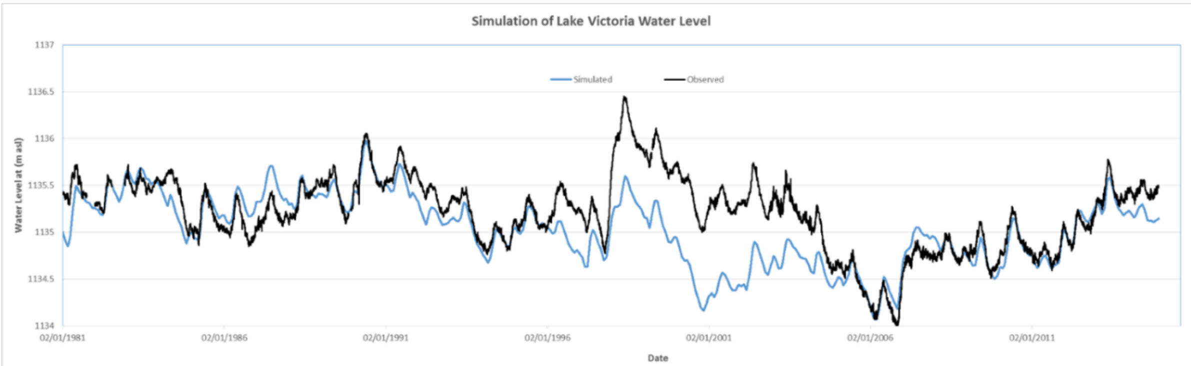


Table 3. Lake Victoria Water Balance

Component	**Simulated LTM Volume (km³/yr)**	**Comparison with Literature (km³/yr)**[1]
Rainfall	87	125
Inflows from Catchments	32	23
Evaporation	97	110
Outflow (to Victoria Nile)	23	38
Net Water Balance	-1	0

[1] : Regional Lake Victoria Environment Report, Chapter 3 Water Balance (LVEMP, 2005)

Table 4 gives the results of the scenario simulation, as can be seen from the Table there is a general reduction in mean flow in 2030 (SC1) and 2050 (SC2) compared to the baseline 2010 with the reduction in 2050 being higher than 2030. There is an increase in both domestic and irrigation water deficit as well as hydropower produced in 2030 and 2050 compared to the baseline. Municipal water demand deficit is lower than irrigation because it has a higher allocation priority but both will suffer in future due to increased demand even without considering climate change.

It is noteworthy that with new resevoirs and hydropower infrastructure hydropower generation is going to increase in future but the new reservoirs are not able to cope with increased municipal and irrigation water demand hence an increase in demand deficit. The increase in hydropower production in SC2 compared to SC3 is attributed to increase reservoir releases to meet increased downstream demand which benefits the hydropower production. Downstream flows will continue to decrease particularly in unregulated streams.

Regarding the Long Term Lake mean water level, there will be a reduction of 0.47m and 0.55m for the SC1 and SC2 respectively. There is less impact on the lake water level because as can be seen from the Lake water balance almost 80% of the inflow water to the Lake is from precipitation on the Lake itself.

Table 4. Scenario Results

Indicator\Scenario	**SC0 (baseline)**	**SC1**	**SC2**
Long Term Municipal /Domestic Average Deficit (%)	2.0	2.0	4.0
Long Term Irrigation Average Deficit (%)	5.0	12.0	18.0
Basin Wide Average Hydropower Produced (MW)	52.9	332.5	336.7
Change in Long term Lake Victoria water Level	-	0.47m	0.55m

4. Conclusion and recommendation

4.1 Conclusions

- In this study hydrological modelling and water balance assessments were performed for the Lake Victoria Basin. This included database preparation, rainfall-runoff modelling and scenario based water resource modelling.
- The simulated water balances for both the upstream catchments contributing flow to the Lake Victoria as well as the Lake Victoria were in good agreement with documented observed values in the literature.
- Water demands was projected into the future based on available literature on future population and irrigation water use. The water use together with planned infrastructure mainly reservoirs and hydropower's was used in scenario based water resources simulation for the period 1981-2010
- From the Scenario simulation results, future water use will increase water demand deficit for both domestic and irrigation uses but more deficit will be faced by the irrigation sector. The flows from the rivers in to the Lake Victoria will be reduced by up to 40% in SC2 for some rivers, however there will be about 0.5m drop in Lake water level compared to the baseline period climate due to large portion of the Lake water inflows being supplied by precipitation on the Lake itself. The simulations show that there will be a significant increase in hydropower production in future if the planned projects are actualized.

4.2 Recommendations

- It will be useful to investigate various forms of precipitation products over the Lake to get a broader view of the actual precipitation variability since there are no ground based measurements data available.

- Source for hydromet data for smaller tributaries to get a more accurate water balance is recommended.

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Hydrological trends, land use and climate change implications of maize yields in the Lake Victoria Basin

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Hydrological fluxes, land use and climate change are significant processes in the biogeochemical processes and agricultural productivity in the Lake Victoria Basin. The objective was to elicit hydrological trends with attendant quality and quantity components, assess land use change patterns as well as implications of climate change on maize yields in the LVB.

Keywords: Land Use Change; Climate Change, Hydrology, Lake Victoria Basin

Introduction

Hydrological fluxes are an important process in the insitu and exsitu biogeochemistry of the LVB. The LVB is also considered a sensitive ecosystem to global environmental change processes especially land use and climate change. Knowledge on the hydrological dynamics, land use change as well as implications of climate change on the yields of key income and food security crops in paramount in the ecosystem and livelihood sustainability in the LVB. Thus, this study evaluated hydrological dynamics on a short timescale, assessed land use and land cover and simulated potential future yield changes in selected maize varieties owing to projected changes in climate.

Methods

A suite of methods was used in the study including:

- GIS based SWAT model (Arnold et al. 2013) to assess the quantity and quality of water resources in the Lake Victoria Basin. All hydrological processes were simulated on a daily time step driven by climate data with digital elevation model (DEM), land use and soil considered as constants.
- Detection of trends and changes in Land use and Land Cover (LULC) in the LVB was undertaken from Landsat satellite imagery of 30-meter resolution. The pre-analysed satellite imagery data was provided by the Regional Centre for Mapping of Resources for Development (RCMRD) in TIFF format. The data and analysis covers a period of approximately 30 years spanning from 1985 to 2014, at an interval of 5 years.
- Regional climate model outputs for future time periods were generated from the Coordinated Regional Climate Downscaling Experiment (Giorgi et al., 2009). Climate projections under two RCPs namely; RCP4.5 and RCP8.5 were simulated. The Climate Hazards Group Infra-Red Precipitation with Stations (CHIRPS) gridded rainfall data (Funk et al., 2015), at 0.05 degree was used for the reference period, 1981-2018. Gridded temperature data (0.05-degree) on a monthly resolution from Climatic Research Unit (CRU), University of East Anglia was used. Projection of future climatic conditions was

confined to three future time slices i.e. Near future, 2016-2035; Mid-century, 2046-2065 and Far future, 2081-2100.

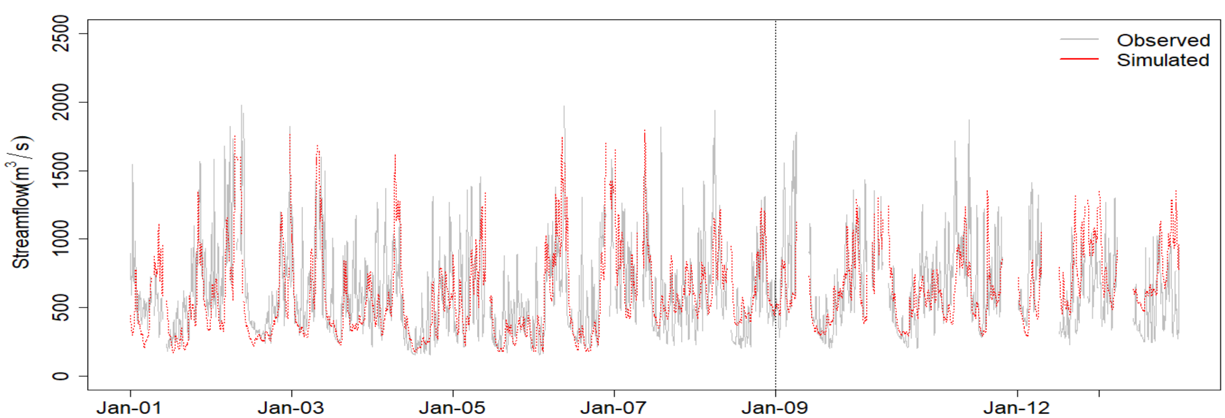
- The likely impact of climate change on maize yield was simulated using DSSAT model. Downscaled climatic data in combination with soil type (Petric Plinthic, Acric Ferralsol, dystric Regosols), maize varieties, management practices and other ecological conditions were embedded in the model and simulations run for selected areas in the Ugandan part of the LVB.

Results and Discussion

Hydrological dynamics of the basin

Figure 1 below exemplifies temporal dynamics of stream flow at the outlet of LVB on river Nile. A significant proportion of precipitation received is predominantly lost through evapotranspiration to the tune of about 84% over the LVB. Evapotranspiration pattern is not uniform over the lake, but exhibits the highest values in the lower altitude i.e. close to lake compared to the upper sub basins. Base flow/groundwater flow and surface runoff are the major processes contributing to discharge in the basin. About 9.5% of base flow and 5.2% of surface runoff is converted to stream discharge. The spatial distribution of water yield fluxes and sediment yield mirrors the general pattern of rainfall, by showing a higher contribution from Eastern sub basins in comparison with the Western sub basins of the LVB.

Figure 1. Hydrograph showing simulated and observed stream flow at the basin outlet (Victoria Nile) for the calibration (1986-2002) and validation (2003-2018) period.

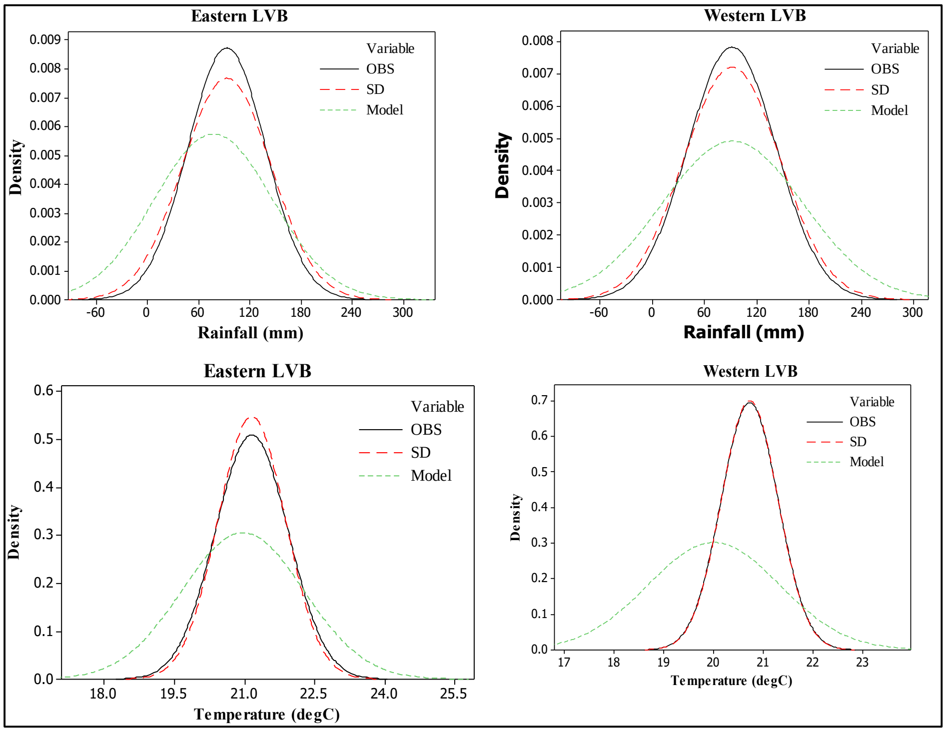


Land use change

Land use and land cover show a rapid increase in urbanization in the LVB with a change of over 800% observed between 1985 and 2014. However, agriculture still posits the largest proportion (ca. 46%) of the land uses and also increased between 1985 and 2014.

Climate change and implications on maize yields

In the near future, the short rains (OND) are projected to increase while the long rains (MAM) will decrease. An increase of 10-50% is projected for the OND in Eastern LVB, while for the Western, changes of between 0 to 10 % are indicated for the JJAS season. Overall, a decrease in the western and increase in the eastern LVB are projected. In the mid-century (2046-2065), the annual and seasonal changes in rainfall patterns are generally similar to the changes in the near future. Nearly all parts of the LVB are expected to receive less rainfall during the long rains. It is projected that there will be an increase in rainfall (up to 50%) during the short rains as well as annually for most of the areas. Later in the century (2081-2100), the annual and seasonal changes in rainfall patterns are projected to increase especially for the short rains (with a change of up to 60%).



Simulations show that maize yields for the local variety under current practices with low inorganic and organic input will decline. Improved varieties however show promise for improved yields under changing climatic conditions in specific geographic locations.

Conclusions

Urbanization is more rapid than agricultural expansion in the basin. A strong seasonal rather than annual alteration is likely to be experienced in terms of climate change. The OND season is likely to become more pronounced than MAM. Yields of the local maize variety is expected to be negatively affected but other varieties show promise of thriving under climate change in certain localities.

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View from the plane of Victoria Falls during the dry season
Photo credits: Nico Elema

SCIENTIFIC RESEARCH IN SOUTHERN AFRICA

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The collaboration established aimed to conduct scientific research over the transboundary Zambezi river basin, addressing key topics relevant to the WEFE (Water-Food-Energy-Ecosystem) nexus assessment. The main objective was to investigate the interlinks among climate variability, climate change scenarios, hydrology and groundwater hydrology, hydropower production, irrigation in agriculture, fishery and livestock, further to best-practices review in water governance and information systems.

The analysis addressed the competing water demand, sectors interdependencies and tradeoffs face to the challenges of increasing pressure (threats posed by climate change, population growth, energy demand increase, irrigation expansion, water quality deterioration and risks for ecosystems), considering the potential socio-economic impacts.

Centres of Excellence (CoEs) involved in the scientific research and their specific contributions, geographical scope being generally at basin scale except otherwise stated, were:

- Botswana University, Botswana - climate variability analysis;
- Un. of Stellenbosh, South Africa - hydro-climatological data collection and preliminary assessment;
- IWEGA (International Center for Water Economics and Governance in Africa; Centro Internacional de Economia e Governação de Água em África), Mozambique – hydropower economic assessment;
- University of Zambia – groundwater hydrology and hydrochemistry characterization at Zambia country scale, basin scale groundwater flow modelling;
- National University on Science and Technology (NUST), Zimbabwe - groundwater hydrology characterization at Zimbabwe country scale;
- University of Western Cape, South Africa – hydrogeological mapping;
- University of Malawi – agriculture status and future projections assessment;
- KwaZulu Natal University, South Africa – manual on best-practices in agriculture;
- (CSIR), South Africa – manual on best-practices in water governance and information systems

Additional contributors complemented the scientific research by addressing specific topics of relevance:

- hydrological modelling of the river basin and future scenarios assessment;
- hydropower modelling and future scenarios assessment face to the climate change challenges;
- geothermal industry status in East Africa, extending to the South over Namibia and Zambia.

The use of open access meteo-climate datasets, observed data and climate change scenarios allowed the analysis of climate variability and climate change and their implications on future water availability over the region. The application of a hydrological, a water management, and a hydro-energy model, allowed the analysis of hydropower potential and agriculture under current and future irrigation expansion. The assessments were developed taking into account the implications of climate change and competing water demand. Specific research on groundwater hydrology focused on hydrogeological mapping and hydrochemical characterization at regional scale, with particular focus on Zambia and Zimbabwe; the application of a groundwater flow model made possible the analysis of effective recharge uncertainties and interlinks between surface and groundwater hydrology. Among the other tasks, specific actions were taken to identify best-practices in agriculture and water governance and to contribute to the assessment of best-practices in water information systems.

The outcomes of the scientific research activities are expected to actively contribute to the enhancement of scientific and technical cooperation, including effective data management among relevant stakeholders, at both national and regional scale. At the same time, the research outcomes are aimed to support decision makers with science-and knowledge-based tools and methods towards an effective and cooperative water management.

All the research activities were identified in line with the regional priorities, as identified by the Southern African Development Community (SADC), the Zambezi river basin organization (ZAMCOM), and other key research Institutions as the SADC‵s Groundwater Management Institute (SADC-GMI). Institutions that made available their data to the project partners and actively contributed to shaping the debate and prioritising the actions.

The mentioned project set up allowed to efficiently investigate WEFE interdependences, issues and possible solutions, based on state-of-the-art review and scientific analysis, as for instance:

1. Assessing the impacts of changing water availability;
2. Supporting decision makers with science- and knowledge-based tools and methods;
3. Enhancing scientific and technical cooperation, including effective data management;
4. Providing scientific and technical assistance to informed policy making.

Climate variability and extreme events analysis in the Zambezi River Basin using Standardized Precipitation Evaporatranspiration index (SPEI)

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Key Words: Zambezi River Basin, Standardised Precipitation Evapotranspiration Index (SPEI), L-Moments.

Global climate change and variability leading to extreme manifestation of the climate has made the world to witness increase in frequency and intensity of climate events hence in both rapid and slow onset disasters such as floods and droughts respectively. This is particularly so for the countries in southern African region which experiences mostly a semi-arid type of climate together with an increasing population, land use and ongoing economic activities in the region. This in turn has resulted in hydrological uncertainties in the countries located in the lower latitudes with frequent water shortages in its rivers and dam storages thus affecting the livelihood such as agricultural food production, hydropower generation, fisheries and tourism.

To investigate specifically the slow-onset phenomenon, impacts due to changes in the atmospheric chemistry over the Zambezi river basin covering 1.39 million km^2 of area across 13 sub-basins in countries such as: Angola, Namibia, Zambia, Zimbabwe, Malawi and Mozambique have been undertaken. Since it is difficult to represent such a complex phenomenon with spatial variability in precipitation and the extent of water demand by way of evapotranspitaion at temporal scale, an attempt to represent them through the changes in dryness characteristics in the form of a common index such as: Standardised Precipitation Evapotranspiration Index (SPEI) for each sub-basin, has been used. The other reason for choosing this method was that it is multiscalar, uses temperature data for the computation of evapotranspiration along with Precipitation data and uses the method of L-Moments to model the moisture balance to obtain the monthly indices, hence considered as one of the potential indices for Integrated Water Resources Management (IWRM). Furthermore, in order to have a more meaningful result, long term climate data such as monthly precipitation and monthly temperature (maximum and minimum) data observed from 1970 to 2015 as provided by the Climate Research Unit (CRU) have been used.

Summary findings of this investigation showed that (i) Rainfall in general have decreased over the years across the chosen sub-basins. For example, about 75% of the 20 CRU-based stations showed a downward trend during the period 1970 to 2015. The decrease was as high as 25% while the increase was only up to 6%. (ii) Only 20% of the stations showed a statistically significant trend at 5% sigificance level (iii) The increase in minimum temperature was higher than that of maximum temperature, i.e. minimum tempretaure increased by between 5 to 12% while maximum temperature increased by between 2 and 7%. This showed that there were indication of climate change/variability and (iv) Even with those minor anomalies, the SPEI-12 values (which conforms to hydrological drought conditions) revealed that the river basin has been experiencing near normal conditions representing about 95% of the drought indices, followed by moderate conditions (wet and dry) at about 3.4%, and about 0.7 % of severe to extreme dry conditions.

Figure 1. Spatial distribution of MKZ for rainfall, maximum and minimum temperature in the Zambezi River basin

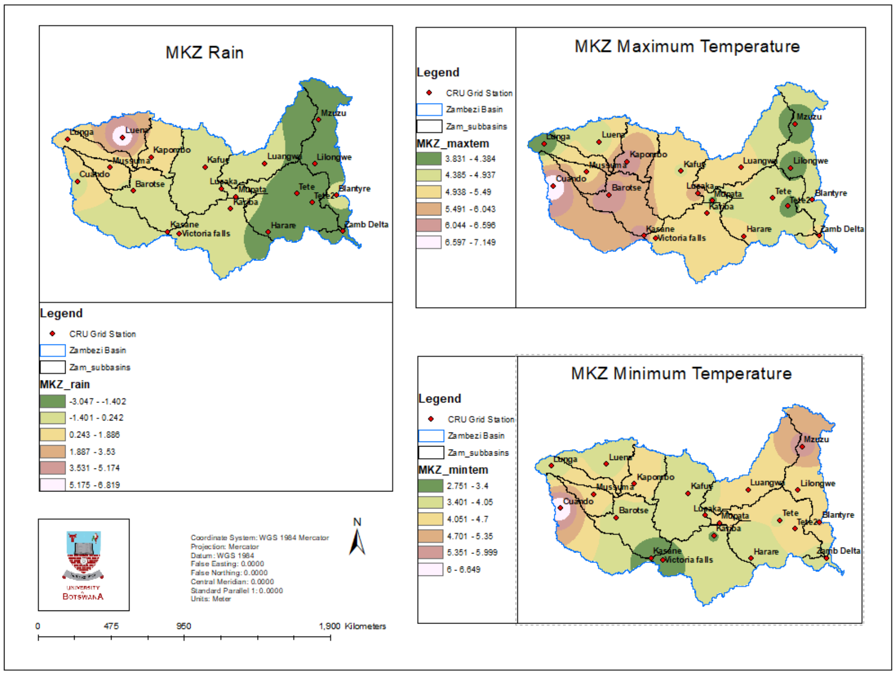
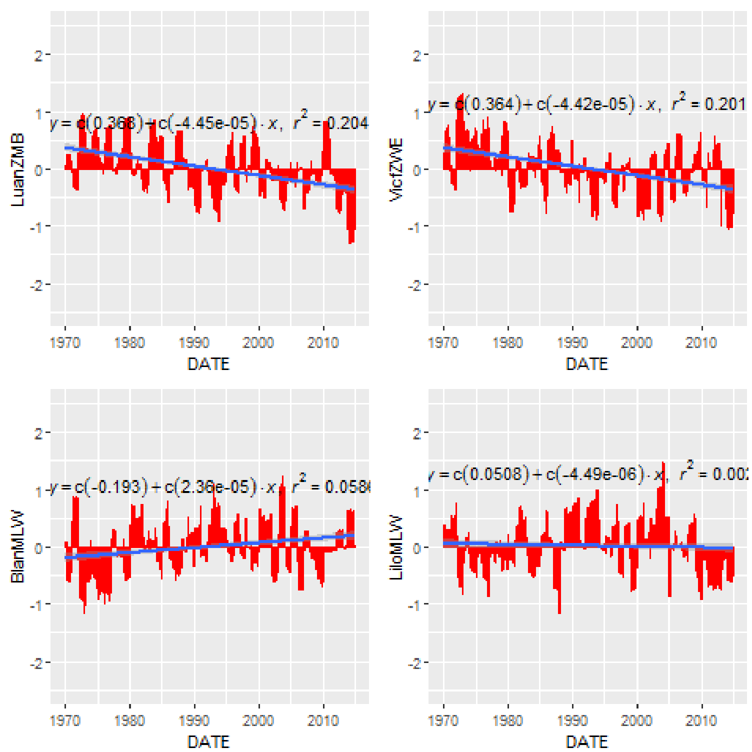


Figure 2. SPEI-12 results for Mzuzu, Tete1, Tete2 and Zambezi Delta showing decreasing and increasing SPEI



However, due to increasing temperatures, the basin may become more vulnerable as a result of increased evapotranspiration. This may affect water resources particularly within the context of climate change, land use change and population growth. The fact that about 90% of natural disasters are water related will need analysis from time to time for better management of the waters of this basin using IWRM concepts.

The development of guidelines and database for the hydrology of the Zambezi as a shared water resource in SADC

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The Zambezi as a shared water resource in SADC presented numerous sensitive issues related to data availability and data sharing. The data needed included climate, flow, agricultural water use, groundwater hydrology and use, water quality and all the flow information. The Zambezi is also used for power generation and this impact on flow.

The information base also included remotely sensed information, soils maps, landuse and the geomorphology of the total Zambezi catchment.

The project also looked at access to existing models and their applicability as management models, with the man aim to also be usable in terms of dam level responses related to power generation.

Three groups were found that developed models for the Zambezi Catchment. The first was a group at TU Delft, the second a group from Switzerland, and the last, a group from South Africa.. The first two used SWAT modelling and the last used the South African Pitman model, also known as SPATSIM. SPATSIM was made available to group and the group was trained to use SPATSIM

The SPATSIM (and Pitman) model is used by the South African water authorities as a water planning model. The model is based on flow measurements and response curves and mainly driven by distributed rainfall data.

SPATSIM was found to be a good model to use for the Zambezi Catchment and ultimate aim is to include SPATSIM in the ZAMCOM database system to be utilized for future water planning. This model was also easier to set up, making use of CRU climate data and all the flow data for the catchment.

1 Introduction

Hydrological modelling has become an important tool for hydropower project design and impact assessment, in an attempt to better understand the potential impacts of damming and alteration of the river flow could have on sedimentation, biodiversity and ecology. Basin-scale hydrological modelling has also been used, particularly in the developing world, to inform national development and prevent transboundary conflicts over a shared resource (Johnston & Smakhtin, 2014), although this is relatively new due to the complexity of the exercise (Ronco et al., 2010).

Modelling at a basin scale is complex and subject to high uncertainty, mainly due to the large volumes of data that are required – soils, topography, land-use types, weather etc. over vast areas. As put by Grayson and Blöschl (2000, p55):

> *"Models of catchment hydrology must represent complex systems made up of interactions between many components, most of which vary in space and time. There is little point in representing one component in great detail while greatly simplifying another on which it depends. "*

Data should be of good enough quality to ensure a good resolution, so a good understanding could be gained of the balance between water requirements of the hydropower station and of downstream user and ecological demand (Andersson et al., 2015; Grayson & Blöschl, 2000; Kusre et al., 2010; Pechlivanidis et al., 2011). However, at a basin-scale, information cannot be so complex and detailed that makes the model unusable (Grayson & Blöschl, 2000). Researchers have worked on the issue of scale in basin-wide hydrology for over two decades (e.g. Blöschl & Sivapalan, 1995). A lot of knowledge have been generated in the field of basin-wide hydrology, such as types of models and the pitfalls thereof. This article focussed on case studies to illustrate the options available for basin-wide hydrological modelling with respect to large hydropower projects.

2 Method

The aim was to find existing populated models and make them available as tools for development and management. Apart from modelling, the need existed to secure data for modelling and provide maps with baseline data for modelling. The quest was to find information related to the following:

- Topography
- Geology
- Surface flows
- Groundwater data
- Soils information
- Land use
- Climate
- Reservoir volume and level
- Reservoir discharge
- Water abstraction
- Trans catchment distribution/transfer of water

The range of models the group were interested in included mainly the semi-distributed type of models, focussing on runoff in sub catchments. All water reservoirs in the system and major flows I the system was important to the group. The models also had to be useful in terms of dam level responses related to power generation.

3 Results

The sources of information gathered included the instances indicated in Table 1.

Table 1. Known general resources of information related to Zambezi

Publisher	Resource	Access
ZAMWIS	Zambezi Hydrological data	http://zamwis.zambezicommission.org/
Delft University	SWAT model	https://www.tudelft.nl/en/ceg/research/stories-of-science/a-better-understanding-of-the-zambesi-river/
Stellenbosch University	NEPAD SANWATCHE	http://nepadwatercoe.org/centres-of-excellence/

Rhodes University	SPATSIM	https://www.ru.ac.za/iwr/research/software/
University of Zimbabwe	WEAP model and application	https://www.weap21.org/ , http://www.erc.uct.ac.za/sites/default/files/image_tool/images/119/Hydro-Zambezi/HZ-Water_Supply_and_Demand_Scenarios_Report.pdf
University of Zambia	Data	http://dspace.unza.zm:8080/xmlui/handle/123456789/1287
University of KwaZulu-Natal	ACRU Model	http://cwrr.ukzn.ac.za/resources/acru
CSIR	Climate data	https://www.csir.co.za/developing-african-based-earth-system-model
World Bank	Reports	http://siteresources.worldbank.org/INTAFRICA/Resources/Zambezi_MSIOA_-_Vol_1_-_Summary_Report.pdf https://openknowledge.worldbank.org/handle/10986/2958
ZAMCOM	Data and publications	http://www.zambezicommission.org/
Global Water Partnership	Reports case studies	https://www.gwp.org/en/learn/KNOWLEDGE_RESOURCES/Case_Studies/Africa/Zambia-Integrated-Water-Resources-Management-and-Water-Efficiency-planning-process-332/
Republic of Mozambique, National Institute of Disaster Management	Management modelling techniques, catchment information	https://hydro-at.poyry.com/zambezi/index.php
GRID-Arendal, UNEP	Catchment information	http://www.grida.no/publications/189
International Journal on Hydropower & Dams, Water storage and Hydropower development for Africa	African Dams Project online water resources database	https://infoscience.epfl.ch/record/209347 https://infoscience.epfl.ch/record/209347 https://lch.epfl.ch/page-7708-en.html

International Journal of River Basin Management	1-D hydro-morphodynamic model	https://www.scopus.com/record/display.uri?eid=2-s2.0-84882243902&origin=resultslist&sort=plf-f&src=s&sid=c3144c513b00cb8f20721d5d4546a0db&sot=autdocs&sdt=autdocs&sl=18&s=AU-ID%2826031638500%29&relpos=7&citeCnt=8&searchTerm=

A lot of time was spent trying to gather the models used in the different instances reported in Table 1. The conclusion was mostly, that the work was done for a project and that the models used for such a project is not accessible anymore. A further complication was that data sharing was a sensitive issue and the project had to resort to the Zambezi basin Comission (ZAMCOM) to gain the permission to use data belonging to all the Zambezi basin countries.

3.1 The sources for data

The only data that was freely available was the online accessible modelled climate data, satellite products in the form of maps of landuse, geology, topography and climate. The current accessible and preferred data sources for the Zambezi regarding this project, are indicated as follows:

- WACOZA datasets, including SASSCAL hourly and daily meteorological data, daily and monthly CHIRPS precipitation datasets and global surface summary (GSOD). https://aquaknow.jrc.ec.europa.eu/nepad-sanwatce
- WATCH WFDEI data, which is daily at 0.5 deg. It's a reanalysis dataset, i.e. it is based on climate model simulations, but it is the only one that would have internal consistency between all variables. ftp://rfdata:forceDATA@ftp.iiasa.ac.at/
- CRU data - it's an observational, gridded data product that includes monthly rainfall and temperature, but also calculated PET. http://www.cru.uea.ac.uk/data
- Other similar data sources: https://climexp.knmi.nl
- Particularly relevant to SWAT modelling: http://www.waterbase.org/download_data.html

The spectrum of climate measuring and recording devices used in SADC is actually very narrow. A full list of climate stations and data is provided on the CSAG website of the University of Cape Town (http://cip.csag.uct.ac.za/webclient2/datasets/africa-merged-cmip5/). Furthermore, SASSCAL has established Weathernet (www.sasscalweathernet.org/), which provides real-time data online.

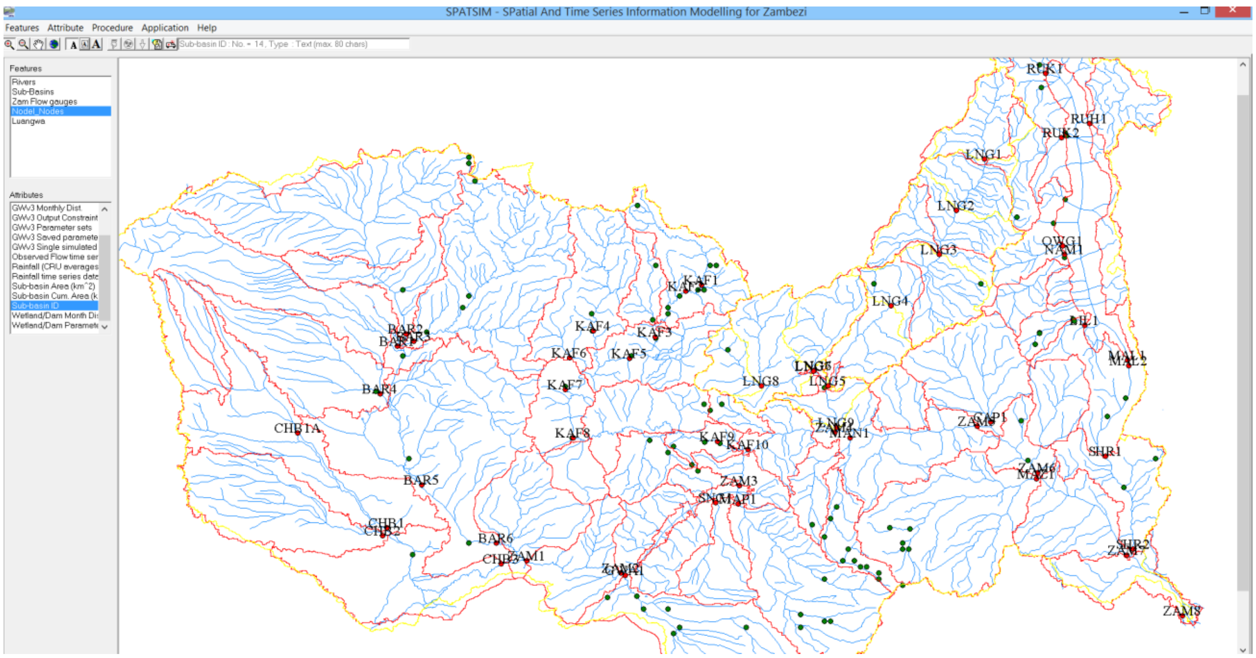
3.2 Hydrological models

The hydrological models that could be useful in the Zambezi catchment can generally be grouped as three types:

a. Watershed models, mainly physically based
b. Deterministic models
   i. Lumped (with parameters that do not vary spatially, not accounting for sub-basins)
   ii. Semi distributed (parameters that may vary in space, and with sub-basins like SWAT)
   iii. Distributed (with full variation in space based on user resolution selection)
c. Physically based models, based on overland flow making use of response equations (like SPATSIM and PITMAN) (Hughes, 2014)

The models that seemed the most useful and was accessible at the time was the SPATSIM/PITMAN model related to full catchment modelling and the WAFLEX model to model dam responses (Hughes, 2014; Winsimius, 2005; Savenije, 1995). The research group underwent training provided by Prof Denis Hughes from the Rhodes University regarding the SPATSIM model and using SPATSIM to generate data for the WAFLEX model. The current setup of the SPATSIM model was also accepted by ZAMCOM as a new addition to their quest to manage and model the flows of this large system. Figure 1 represents the Zambezi river model setup in the SPATSIM software.

Figure 1. The Zambezi hydrological model setup in SPATSIM



4 Conclusions and recommendations

A good insight into the current status of water resource management for the Zambezi was provided in this research. All the work done was included in a report and links were provided to the literature, the models and the modellers. The document also eluded on data availability both from SADC based resources as well as international resources. The resources indicated are repositories of raw data, modelled data and satellite derived products. The main source of raw data resides with ZAMCOM and is partly available on the ZAMWIS online information system.

The tools for water and power management is currently being developed by ZAMCOM as a priority and made available online through the ZAMWIS facility. This is however not yet a system that could reflect on different scenarios and early warning. The research therefore rather reflected on centres where expertise was developed in water resource management since 1995. The modelling done to data by these centres are not all accessible. The accessible models and modelling environments are, the SWAT model by the Delft group, the SPATSIM model by the Rhodes University group in South Africa and the WAFLEX model at NUST in Namibia.

The way forward in modelling is to set SWAT, WAFLEX and SPATSIM up using the same climate database. SWAT will be sensitive to changes in the landscape and generate flow responses that should feed into WAFLEX and SPATSIM. WAFLEX will reflect the maximum amount of hydropower possible related to water availability. SPATSIM will be set up as a tool to be used for general water planning and could replace SWAT.

It is also very important to develop the tools and sensitivity in modelling to such an extent that it can be imbedded in the ZAMWIS information system. The aim should be to increase the automation of modelling results from ZAMWIS, to also act as an early warning system. The data for ZAMWIS will also have to include defined in-field measurement and supported with remote sensed information.

The Zambezi is an international river system and the need for a regional information system like ZAMWIS may prevent future conflict and uncoordinated development in this region.

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Hydrological Modelling of the Zambezi River Basin

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Two hydrological models (Pitman and WEAP) have been established for the whole Zambezi River basin using 76 sub-basins. The initial model setups were based on manual calibration using the available observed streamflow data and include the impacts of known water abstractions, hydro-power dams and natural wetlands. The Pitman model was further applied to examine various scenarios of both climate change and future water use, and was used to examine some of the uncertainties in the links between observational data and the simulation of the main runoff generating processes.

1 Introduction

The Institute for Water Research at Rhodes University was invited by Stellenbosch University to participate in the African Union - NEPAD African Network of Centres of Excellence on Water Sciences and Technology - ACEWATER phase 2 project, specifically for the purposes of applying their experience of hydrological modelling in the sub-Saharan Africa region to establish a hydrological model for the whole Zambezi River basin. The initial Pitman model (Pitman, 1973; Hughes, 2013) setup was presented to members of the network at a workshop in March 2019, after which the model was further refined, and a version of the WEAP model was added for comparative purposes. Subsequently, through an expert contract with the European Commission, Joint Research Centre (and with their participation through the third author), the study was expanded to include running future scenarios of both climate change and water use. The details of the initial calibration are contained within a submitted paper (Hughes et al., 2020), while the scenario analyses are summarised in a further paper (Hughes and Farinosi, 2020a). Some of the uncertainties in the observational data used to establish the model and the linkages with model output uncertainties (particularly with respect to the simulation of specific runoff-generation processes) are discussed in another paper that is currently being prepared (Hughes and Farinosi, 2020b).

2. Initial model calibrations

The model calibrations were based on the observed streamflow or reservoir storage data for 46 out of a total of 76 sub-basins. However, the data for 8 of these gauged sub-basins were evaluated as being too inaccurate (or too short records) to be useful for the purposes of model calibration. Of the remaining 38, 17 represent headwater sub-basins. The quality of the data (e.g. number of missing months) and the length of records is highly variable. Both models were forced with gridded (0.5o) CRU rainfall data (1901 to 2017: https://crudata.uea.ac.uk/~timm/grid/CRU_TS_2_1.html), while the PET (potential evapotranspiration) data used for the Pitman model was based on LISVAP calculations (Alfieri et al., 2019) using ERA5 data for 1979 to 2018 (https://confluence.ecmwf.int/display/CKB/ERA5). For the WEAP model the PET estimates were based on climate data linked to the model.

Figure 1 provides a map showing the 76 sub-basins, while ***Figure 2*** summarises the performance of the two models across the sub-basins with gauged streamflow data using the Nash coefficient of efficiency statistic applied to both untransformed and natural log transformed data. In general terms, the Pitman model achieved better performance (but this is partly a result of more experience of using this model in the region) than the WEAP model. The better calibrations were achieved in the Luangwa and Kafue sub-basins, while the semi-arid sub-basins of Zimbabwe were not very well simulated and the simulations in the lower parts of the Lake Malawi/Nyasa system were very poorly simulated. The main reason for this was the inability of both models to adequately simulate the observed water balance dynamics of the lake. ***Figure 3*** illustrates the models performance at Tete (downstream of Cahora Bassa dam at the outlet of sub-basin ZAM6) for periods before and after construction of the dam. The figure illustrates some of the problems associated with simulating the outflows of the main Zambezi River sub-basins that include quite substantial periods of missing data months, complex and often poorly documented operating rules for the main reservoirs, as well as all the cumulative effects of uncertainties in the simulations of the upstream sub-basins.

Figure 1. Sub-basins of the Zambezi River basin used in both model setups

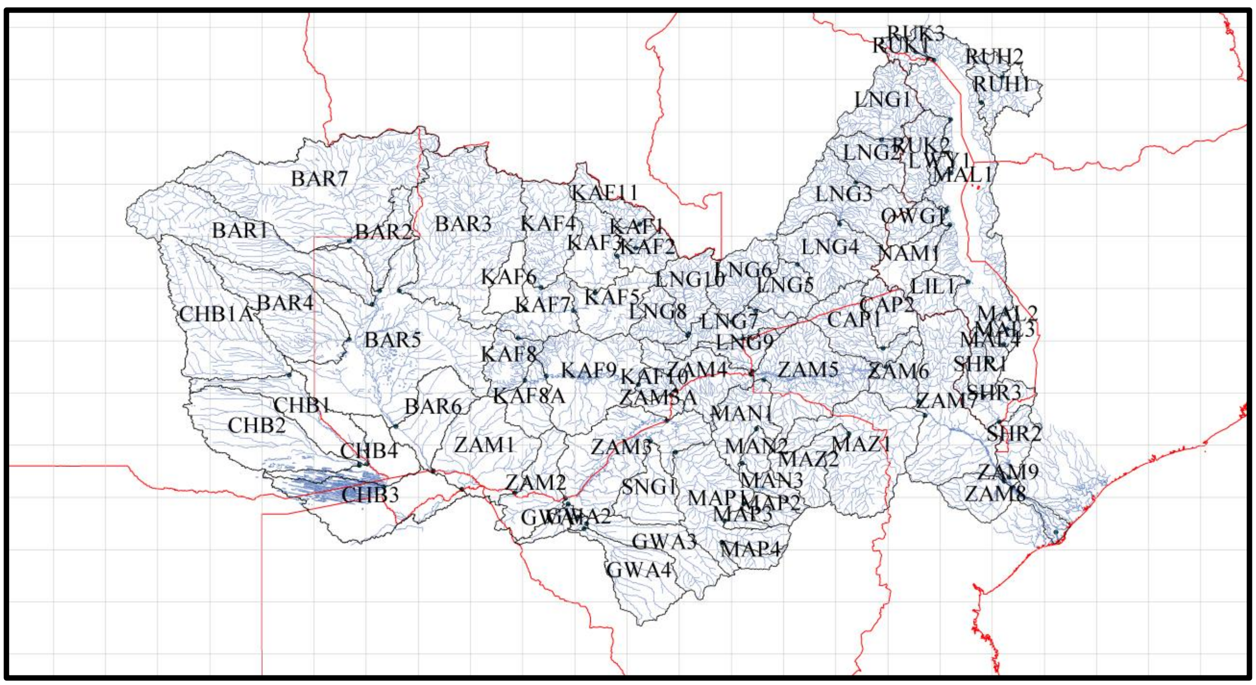


Figure 2. Performance statistics for the gauged sub-areas using the Pitman and WEAP models

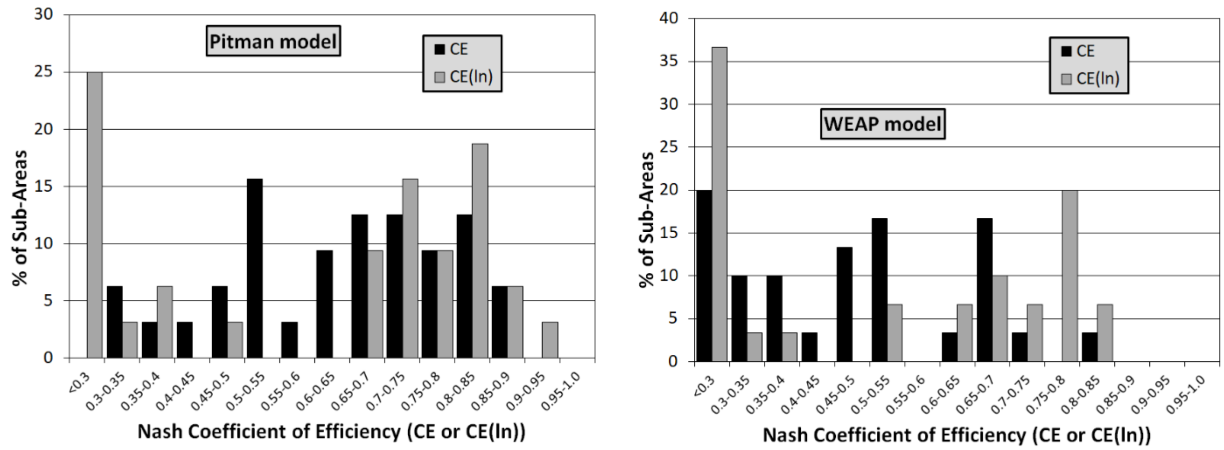
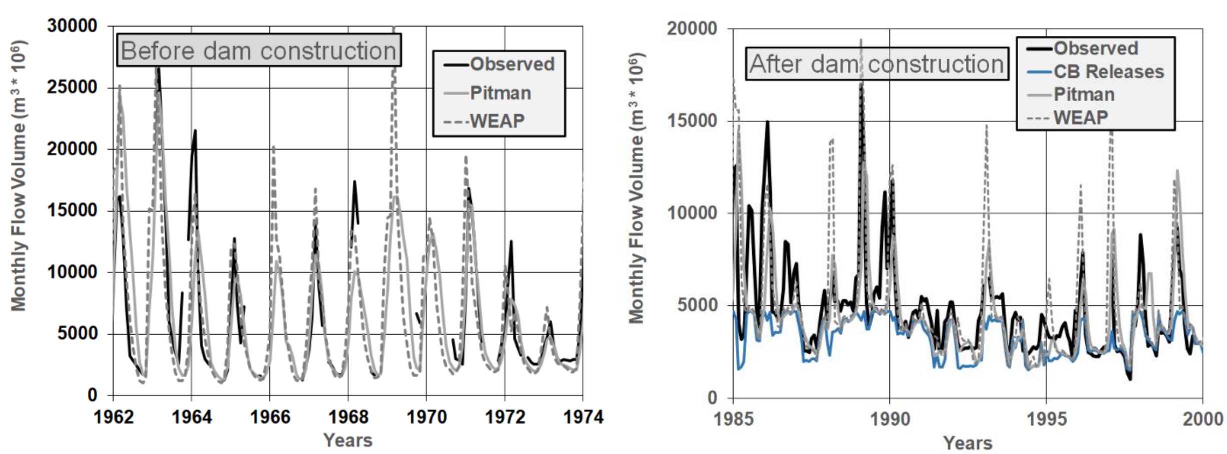


Figure 3. Performance of the models at Tete (sub-basin ZAM6) before and after construction of Cahora Bassa dam



3. Future scenarios

Table 1 defines the various scenarios that were run with the Pitman model during this phase of the project. The initial calibration did not include present day water uses, except where these were already well defined based on existing information, therefore S1A and S1B scenarios were based on historical climate data together with improved estimates of present day water use (A) and uncertainty estimates of future water use. The present day estimates were largely based on information about the extent of irrigated areas (IFPRI, 2019) and various sources of data on urban water uses, together with information about the location and maximum areal extent of water supply reservoirs (including distributed farm dams) from Pekel et al. (2016) and Gonzalez-Sanchez et al. (2020). There are clearly many uncertainties involved in converting these data into volumes of reservoir storage. Scenarios S2, S3 and S4 represent various combinations of climate and water use scenarios for 1.5°, 2° and 3° temperature changes. The rainfall and PET data inputs to these scenarios are based on climate models listed in ***Table 2***. The rainfall data were pre-processed to generate 250 stochastic rainfall ensembles that represent the range of rainfall changes (annual means and standard deviations, as well as seasonal distributions) suggested by the different climate models.

Similarly, the PET inputs to the model are ranges of expected future annual values for each temperature scenario (S2.2, S3.2 and S4.2). The 250 rainfall ensembles are combined with 200 randomly sampled PET values to generate a total of 50 000 output ensembles. The sampling process ensures that the inputs to all sub-basins are drawn from similar climate change impacts for each output ensemble.

Table 1. Definition of scenarios

Scenario	Definition
S1	Single run with CRU rainfall and historical reservoir releases (Kariba and Cahora Bassa) replaced with fixed operating rules.
S1A	Same as S1, but with improved estimates of present day water use.
S1B	Same as S1, but with uncertainty estimates of future water.
S2.1A	Ensemble rainfall inputs (1.5 º temperature scenario) & present day water use.
S2.2A	Same as S2.1A, but with changed evapotranspiration for 1.5 º temperature scenario.
S2.2B	Same as S2.2A, but with estimates of future water use.
S3.2B	All climate change effects for 2.0 º temperature scenario & future water use.
S4.2B	All climate change effects for 3.0 º temperature scenario & future water use.

Table 2. Climate models used in the assessment and the 30 year periods used to represent the three temperature change scenarios.

	Central year corresponding to the warming level of		
Model	**1.5 degree**	**2.0 degree**	**3.0 degree**
CCLM_CNRM_CM5	2029	2044	2067
30-years range	(2015-2044)	(2030-2059)	(2053-2082)
CCLM_HadGem2-ES	2018	2030	2051
30-years range	(2004-2033)	(2016-2045)	(2037-2066)
CCLM_MPI-ESM-LR	2028	2044	2067
30-years range	(2014-2043)	(2030-2059)	(2053-2082)
RCA4_MIROC5	2027	2043	2067
30-years range	(2013-2042)	(2029-2058)	(2053-2082)
REMO_IPSL-CM5A-LR	2022	2035	2054
30-years range	(2008-2037)	(2021-2050)	(2040-2069)
REMO_MIROC5	2027	2043	2067
30-years range	(2013-2042)	(2029-2058)	(2053-2082)

The scenario results were mainly evaluated at four critical sites in the system (KAF7, ZAM2, ZAM6 and MAL1). ***Figures 4 and 5*** summarise the results for the four sites for scenarios S2.2B and S4.2B compared with scenario S1 using uncertainty bands of the simulated flow duration curves. The graph for MAL1 and S2.2B uses the 50% exceeded line because the 95% exceeded result is zero outflows for the whole period, while only the 5% exceeded line for S4.2B includes non-zero flows.

Figure 4. Flow duration curve uncertainty bounds for scenario S2.2B above Itezhi-Tezhi dam (KAF7), above Kariba dam (ZAM2), below Cahora Bassa dam (ZAM6) and below Lake Malawi (MAL1).

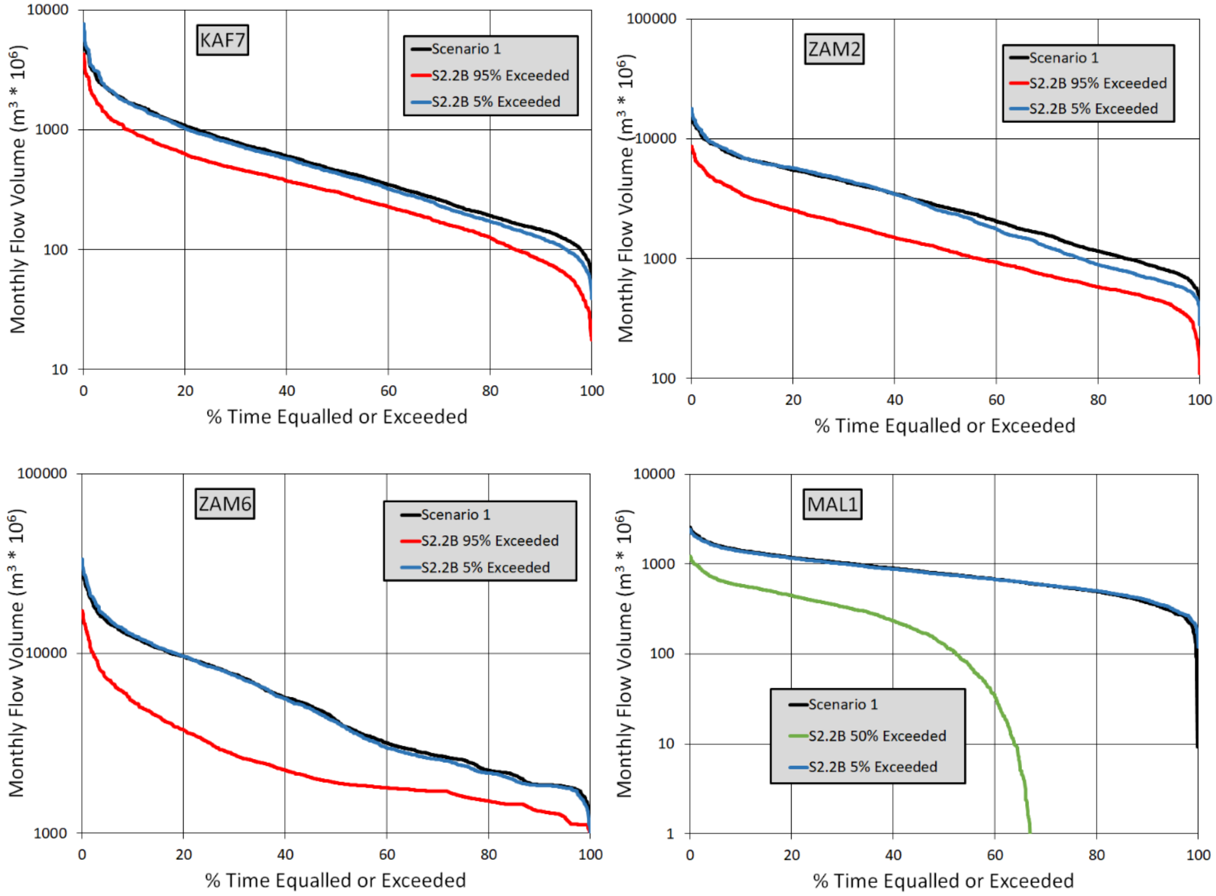
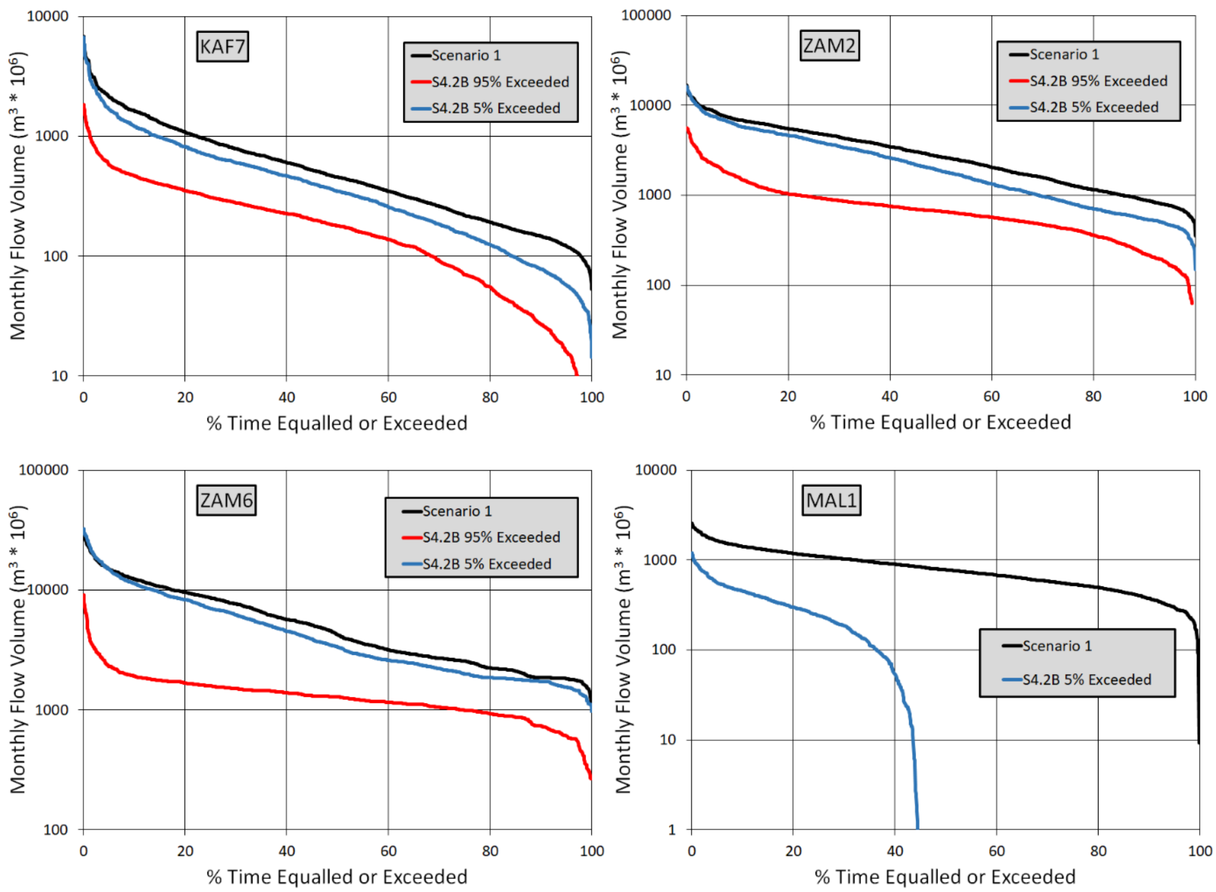


Figure 5. Flow duration curve uncertainty bounds for scenario S4.2B above Itezhi-Tezhi dam (KAF7), above Kariba dam (ZAM2), below Cahora Bassa dam (ZAM6) and below Lake Malawi (MAL1).



The following observations can be made about the scenario model runs:

- The different water use scenarios have relatively small impacts compared to the climate change effects, with the exception of some of the semi-arid sub-basins of Zimbabwe where there are quite high water uses relative to the available water.
- The differences between S2.1 and S2.2 (inclusion of evaporation effects) is relatively small at KAF7, but for sub-areas downstream of major reservoirs or wetlands, the additional impacts of assumed greater losses due to higher temperatures are much higher. These effects are particularly noticeable at MAL1 because of the sensitivity of the outflows to the large area of the lake and the direct effects of both rainfall and evaporative losses. Even scenario S2.2 shows that there is a moderately high probability of zero outflows for long periods of time.
- The differences between scenarios S2.2B and S3.2B are relatively small compared to the simulations of the effects of the next step in the temperature increase (i.e. from S3.2B to S4.2B). This is the case for all sub-basins and not just those below reservoirs and wetlands.
- While there are many uncertainties in the model setup, as well as the forcing climate data used for the scenarios, the results provide an indication of the possible future changes. They also indicate that the range (uncertainty) of possible future water

resources availability is still very high despite the recent improvements in climate models and more convergence in the predictions of different models.

- A very approximate estimate of the effects of climate change on power production at Kariba Dam suggests a change from 66% of full potential capacity (i.e. the dam always able to supply the turbines at maximum capacity) for S1, dropping to a range from 26% to 65% for S4.2B.

4. Further explorations of model uncertainties

The third paper in the series (Hughes and Farinosi, 2020b) explores some of the uncertainties in the simulations of specific runoff generation processes and the impacts of observational (both hard and soft) data uncertainties. The Pitman model generates total streamflow through four main processes; saturation excess surface runoff (dependent on moisture status and rainfall), adsorption excess surface runoff (only dependent on rainfall), interflow and groundwater outflows. The model was re-run in an uncertainty framework for 18 gauged headwater sub-basins using wide ranges of parameter values and the variation in the process simulations explored for those ensemble members that could be considered behavioural based on comparisons with the observed flows data. The use of additional data, such as MODIS actual evapotranspiration data, were able to help resolve some of the issues with poor rainfall data in some sub-basins (mostly in the Lake Malawi/Nyasa region). However, the possible range of process simulations that produce equally good results remains very high for almost all sub-basins (related to model equifinality; Beven, 2006).

One of the overall conclusions from this study is that additional information is needed to constrain some parts of the model if the uncertainties in the process simulations are to be resolved. An example is that the low flows can be simulated as interflow or as groundwater outflows and that the range of plausible groundwater recharge simulations is quite high for almost all sub-basins. If model independent data could be obtained to reduce the uncertainties in the simulation of recharge, some of the other model uncertainties could be better resolved.

While it is acknowledged that potential errors in the observed streamflow data can play a major role in modelling uncertainties, in most cases, we do not have access to the raw observational data (stage observations and rating curves) that would be needed to quantify these observational uncertainties. In the case of the Zambezi data, there are several gauges that have some periods of data that are inconsistent with other periods. These are quite easy to identify as 'gross' errors and those parts of the observed data ignored in the model assessments.

5. Conclusions and recommendations

It has been concluded that despite the uncertainties in the whole modelling exercise (related to data, model structure, spatial and temporal scales and parameter estimation), the model setups can be considered fit for purpose and should be useful for future water management purposes. The spatial scale that has been used is quite coarse (76 sub-basins), but the framework in which the models have been established is flexible enough for additional sub-basins to be added in the future. The key recommendations are mainly associated with further reducing the uncertainties within the data and model setup:

- A comprehensive assessment of the observed streamflow data accuracy that can include detailed recommendations to the national hydrometric agencies about which of the existing stations are critical for future water management decision making and for monitoring the real future impacts of climate change and increased water use.

- Further assessment of regional groundwater recharge patterns to reduce the equifinality within the model, and including more information about groundwater usage.
- Developing a better understanding of the dynamics of water exchange between river channels and some of the large wetland systems that exist in several parts of the Zambezi River basin.
- Updating and validating the information on present day water uses (source and purpose of use), as well as developing improved projections for future likely water uses and sustainability during periods of drought.
- Updating the climate change projections as new data become available, and particularly checking the quite uncertain relationships between projected temperature rises and patterns of evapotranspiration. This may also involve projections of future changes in land use and natural vegetation coverage consequent upon temperature changes.
- Risk assessments of different management decisions in the face of future uncertainty at different spatial scales and for different water resources sectors.

All of these recommendations should be pursued as part of a regional cooperation initiative that includes all of the riparian countries, as well as partners from outside the basin who can contribute additional technical expertise. Part of this cooperation should also include building capacity to make use of the developed models and to update them into the future.

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Future hydropower operations in the Zambezi river basin

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The objective of this study was to analyse how river flow dynamics and hydropower could be affected by future climate change. This study focused on four large hydropower dams located in the Kafue and Zambezi rivers: Itezhi-Tezhi, Kafue Gorge, Kariba, and Cahora Bassa. Future climate change could affect reservoir levels by decreasing water inflows and by increasing evaporation. Results showed a mild decrease in mean annual water levels for all reservoirs, with largest changes expected at Itezhi-Tezhi (-1.3m), with minor (0.1-0.2 m) average values for the other three dams. Comparison of flows downstream of dams shows an overall negative tendency, with largest changes expected during the wet months. Flow changes are expected to be the largest at Cahora Bassa (-30 to -49%), followed by Kariba (-12 to -51%), Kafue Gorge (-25 to -42%) and Itezhi-Tezhi (-15 to -35%). Changes in water levels and flows could result in mild negative effects on mean average hydropower generation and significant increases in interannual variability; largest changes are expected at Kariba, where annual generation could decrease from 5989 to 4152 Gwh/yr (-28.1 to -0.7%). At Itezhi-Tezhi, average annual hydropower is expected to change from 675 to 534-536 Gwh/yr (- 21%). At Cahora Bassa, average annual generation (18017 Gwh/yr) is expected to decrease by 2%. At Kafue Gorge, no significant changes were estimated for the mean annual energy production of 1445 kwh/yr. From a management perspective, it is quite possible modification of reservoir operation will be necessary to offset the projected changes in hydropower generation. To what magnitude re-operations could offset future changes was not directly quantified in this study, but given the large capacity of the main reservoirs in the Zambezi, it is likely that the effects of re-operations (guided by optimization) will be significant.

Keywords: Climate change, river hydrology, HEC-ResSim, hydrological alterations

Introduction

Water resources in the Zambezi river basin experience frequent extreme floods and droughts, and climate change is expected to bring even more unfavourable climatological and hydrological conditions (Fant et al. 2013; Schlosser and Strzepek 2015). Understanding what the implications of future hydrological changes to specific components of the Water-Energy-Food-Ecosystem nexus is critical to robustly project changes to natural resources and well-being of the region. Therefore, the general objective of this study was to analyse the impact of hydropower operation in the surface hydrological dynamics of the Zambezi river basin, and understand how such dynamics could be affected by future climate change. The overall goal is to provide feedback on how historical and future dam operations affect surface hydrology, so that this information can be used in refining hydrological projections, as well as in broader assessments of the Water-Energy-Food-Ecosystem nexus. This study entailed the synthesis of existing GIS and monitoring data provided by the JRC, Zambezi Water Resources Information Systems (ZAMWIS), and project partners; hydrological data analysis to detect past hydrological alteration; approximation of operation rules based on historical water levels and discharge; development of a reservoir operation simulation model; verification of the model for historical conditions, and evaluation of the effect of future climate change scenarios of reservoir water levels, river flows, and hydropower generation. This study focused on four large hydropower dams located in the Kafue and Zambezi rivers: Itezhi-Tezhi, Kafue Gorge, Kariba, and Cahora Bassa. These dams have been operating for several decades and there is some level of information about their design and operations. While there are a few other hydropower projects in the region, they were either too small or too remote to have significant effects on the Zambezi river proper, or there simply was no information available about them to be able to include them in this study.

Materials and Methods

Compilation of GIS and infrastructure design information

Information related to the location of dams along river networks, and their corresponding watershed was synthesized from information provided by ZAMWIS and from global datasets such as HydroSHEDS (Lehner and Grill 2013). In addition, data specific to the design and operations of dams (for example, total volume, design discharge, spillways, etc.) were compiled from different sources, including ZAMWIS, and World Bank (WB)'s State of the Basin report for the Zambezi (WB 2010). Specific design details were crossed checked between sources for consistency, and in the case when they were not available, they were estimated based on the available monitoring data.

Development of reservoir operations model

A model representing the routing of water through river channels, reservoirs and dam structures was prepared using the Reservoir System Simulator (ResSim) from the Hydrological Engineering Center (HEC) from the US Army Corps of Engineers. ResSim was developed in order to facilitate the planning, design, and operations of water infrastructure around a reservoir or a system of multiple of them (Klipsch and Hurst 2013). ResSim computes the water balance at hourly or daily resolution around the reservoir system, estimating flows and water levels at every structure and location of interest, as well as other system performance metrics, such as storage and hydropower generation. These calculations are carried out with ResSim using information on the location and physical features of dams, reservoirs, channels/rivers, in combination with time series of hydrological inputs (upstream river flows, catchment runoff, and evaporation) and operation rules (i.e., target water levels at which the reservoir should be managed every month). In addition to being widely used by the US Army Corps of Engineers, ResSim has also been used to investigate the effects of climate change on hydropower generation in other large river basins (Piman et al. 2015; Arias et al. 2020).

For the purposes of this study, the geographical domain of the model had upstream boundaries at the headwaters of the Itezhi-Tezhi and Kariba reservoirs, and downstream at the Tete river gauge on the Zambezi east of the Cahora Bassa. Other than the location of these boundaries, the model included 9 nodes were inflows from tributaries and watershed runoff were added. Flow through the Kafue and Zambezi rivers was characterized with 13 separate segments connecting the four reservoirs. Hydraulic routing through these segments was calculated using the Muskingum-Cunge method, assuming uniform (semi-circular) channels with total width estimated from aerial imagery. All rivers used a Manning's value typical of large rivers (0.04).

Stage-area-volume relationships, conveyance characteristics (e.g., outlet levels and capacity), and other plant characteristics were parametrize with information from ZAMWIS or from WB (2010). Even though information about guiding water levels was available in WB (2010), there were discrepancies between the prescribed levels and the physical limitations of dams' heights. Thus, a more realistic and reliable approach consisted in using historical average water levels at each reservoir, information that was estimated from the available historical records. A sensitivity analysis on the effects of varying these guiding water levels was carried out.

Simulation Scenarios

Based on the model configuration described in the section above, four different simulations were run with ResSim. The differences among these simulations consisted of (1) cumulative unregulated river flows for the Luangwa, Kafue (at Hook Bridge, upstream of Itezhi-Tezhi) and Zambezi (upstream of Kariba); (2) incremental runoff contributions at 9 locations; and (3) evaporation from each of the four reservoirs. These three different sets of information were characterized with simulation results from the Pitman/SPATSIM model (Hughes et al. 2020). Flow outputs from this hydrological model resulted in monthly time series for a total period of 116 years (1901-2017) in total volumetric units (million cubic meters). These time series were converted to daily flows (in m3/s) assuming constant flows through each month. Moreover, evaporation estimates from Pitman/SPATSIM consist of an annual total depth (in milimeters) and a monthly fraction of the total annual. These values were converted to time series by estimating monthly depths and assuming that the same monthly distribution was repeated every year.

The procedure mentioned above was implemented in four different simulation scenarios. The first scenario (BL) represented baseline historical climatological conditions as prescribed by the Climate Research Unit (CRU) time series. The other three scenarios (2.2B, 3.2B, and 4.2B) are based on future climate change results from six different Earth System models, in which each scenario represents an ensemble of six models for three different level of warming. Scenario 2.2B represents 1.5 degree of warming, 3.2B represents 2.0 degree warming, and 4.2B represents 3.0 degree warming (Hughes and Farinosi, 2020). All four simulations assumed the same physical infrastructure and operational curves. The simulations were run for 116 years, in which the first two were assumed to be the warm-up model period and were discarded from the analysis.

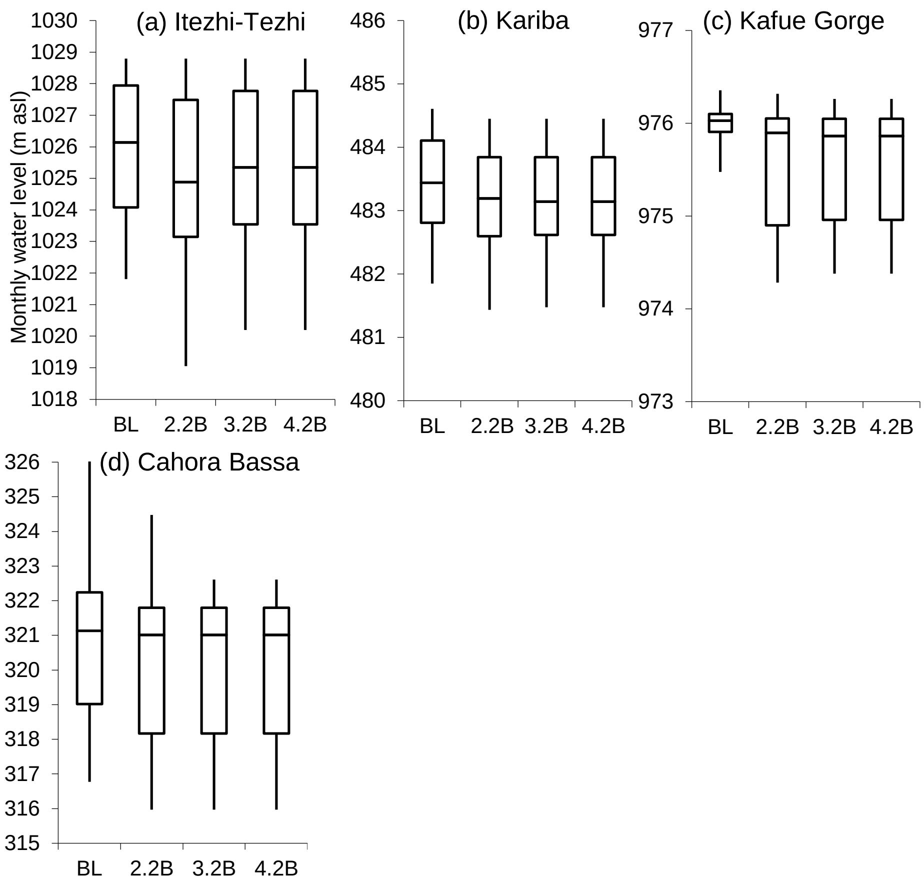
Comparison between the baseline and future scenarios were made in terms of annual average reservoir water level, total annual hydropower generation, monthly flows downstream of dams, and flow duration curves. Flow duration curves represent the probability that a given flow quantity is exceeded during the period of records. As such very high flows correspond to a low exceedance level, and low flows correspond to a high exceedance level. These curves are widely used in hydrology studies as they provide a cumulative and probabilistic approach at representing long-term time series (Vogel and Fennessey 1994).

Results and Discussion

Effects of future scenarios on reservoir water levels

Future climate change could affect reservoir levels by decreasing river inflows and by increasing evaporation. Overall, results from the simulations show a mild decrease in mean annual water levels for all reservoirs (Figure 1). Such mild changes were expected, because this set of future scenario simulations assumed the same guiding curve as the baseline scenario. That is, the model actually aimed at reaching to the same mean monthly water levels in the future climate change scenarios as it was prescribed for the baseline, so that water levels would only deviate from these guiding levels if the water balance around the reservoir was not satisfactory to meet the guiding curve. Overall, largest changes in mean water levels are expected for Itezhi-Tezhi, for which a median reduction of 1.3 m was estimated. Average values for the other three dams were in the 0.1-0.2 m range. Despite these mild average changes, probably the most concerning finding regarding water levels is the substantial fall in the lower bound of the water level distributions, represented by the 25th percentile and lower. This means that during dry periods, extremely low water levels could actually become even lower than they have been in the past. Focusing on the driest scenario (2.2B), for instance, the 25th percentile (analogous to the 90-day minimum level) could decrease by 0.2-1.0 m depending on the dam, with the greatest shortage expected for Kafue Gorge, followed by Itezhi-Tezhi, Cahora Bassa, and the lowest for Kariba. No major differences in water level projections were found among climate scenarios.

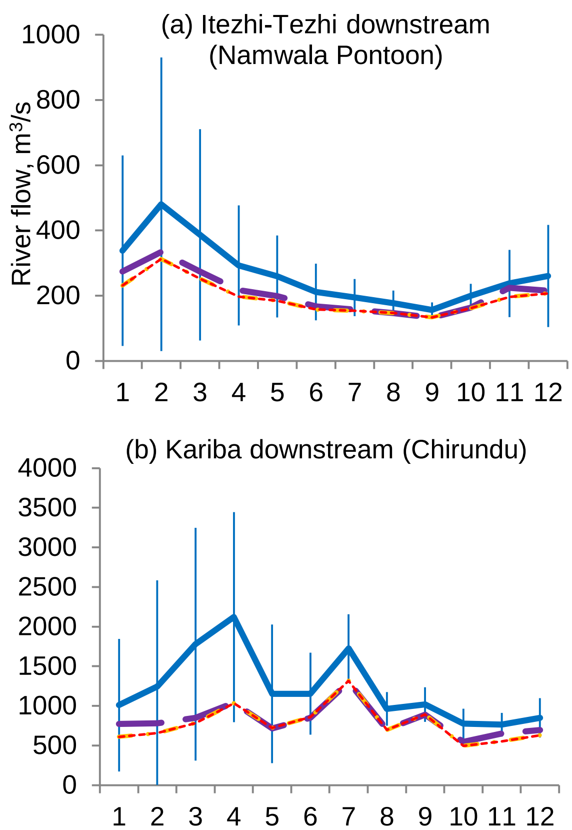
Figure 1. Effects of future climate change on mean monthly reservoir water levels. Upper, middle, and lower divisions on boxplots represent the 75th, 50th, and 25th percentiles, respectively. Upper error bar represents maximum water levels, whereas lower error bars represent one standard deviation.

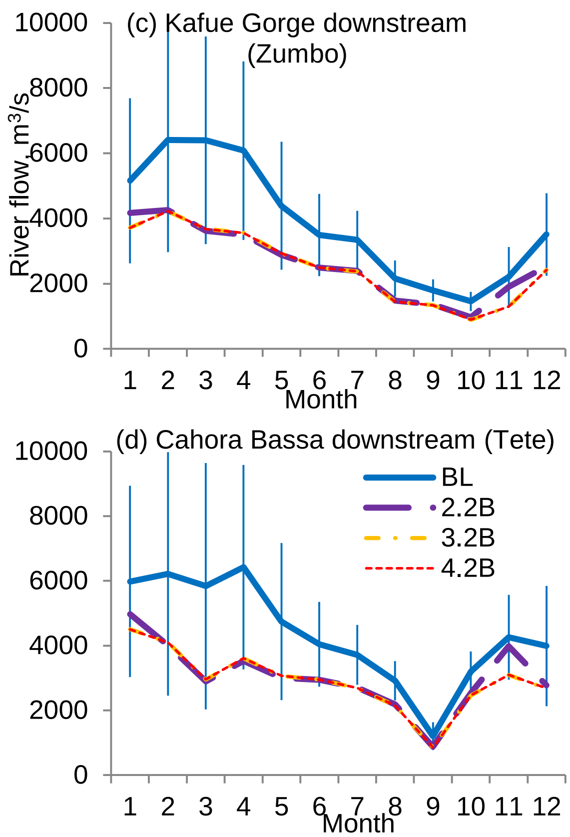


Effects of future scenarios on seasonal river flows downstream of dams

Comparison of flows at the closest station downstream of dams shows an overall tendency to decrease throughout the year, with largest changes (both in absolute and relative terms) expected during the wet months (Figure 2). In general, there was little difference in projections among the three future scenarios, with only noticeable changes during the months of November, December, and January. At Itezhi-Tezhi, largest changes occurred during the wettest month (February), when average flow is expected to decrease by 167 m^3/s, or by 35% from baseline (Figure 2a). Smallest changes are expected for the dry month of September, when flows are expected to decrease from 156 to 134 m^3/s (-15%). At Kariba, largest changes are expected during the month of April, when flows could decrease from 2121 to 1035 m^3/s (-51%), while smallest changes could occur during the month of September, when flows could decrease from 1017 to 893 m^3/s (-12%) (Figure 2b). At Kafue Gorge, largest flow change is expected during the month of March, with a reduction from 6397 to 3677 m^3/s (-42%), while the smallest is expected during the month of September, from 1792 to 1342 m^3/s (-25%) (Figure 2c). At Cahora Bassa, largest changes are expected during the wet month of March, from 5837 to 2959 m^3/s (-49%), and smallest changes are expected during the driest month (September), with a reduction from 1208 to 855 m^3/s (-30%) (Figure 2d). Overall, the net reduction in dam discharges and river flows as a result of climate change is consistent with previous studies of the effects of climate change on Zambezi's water resources using results from the Coupled Model Intercomparison Project used in the Intergovernmental Panel for Climate Change fourth Assessment Report (CMIP3; Fant et al. 2013).

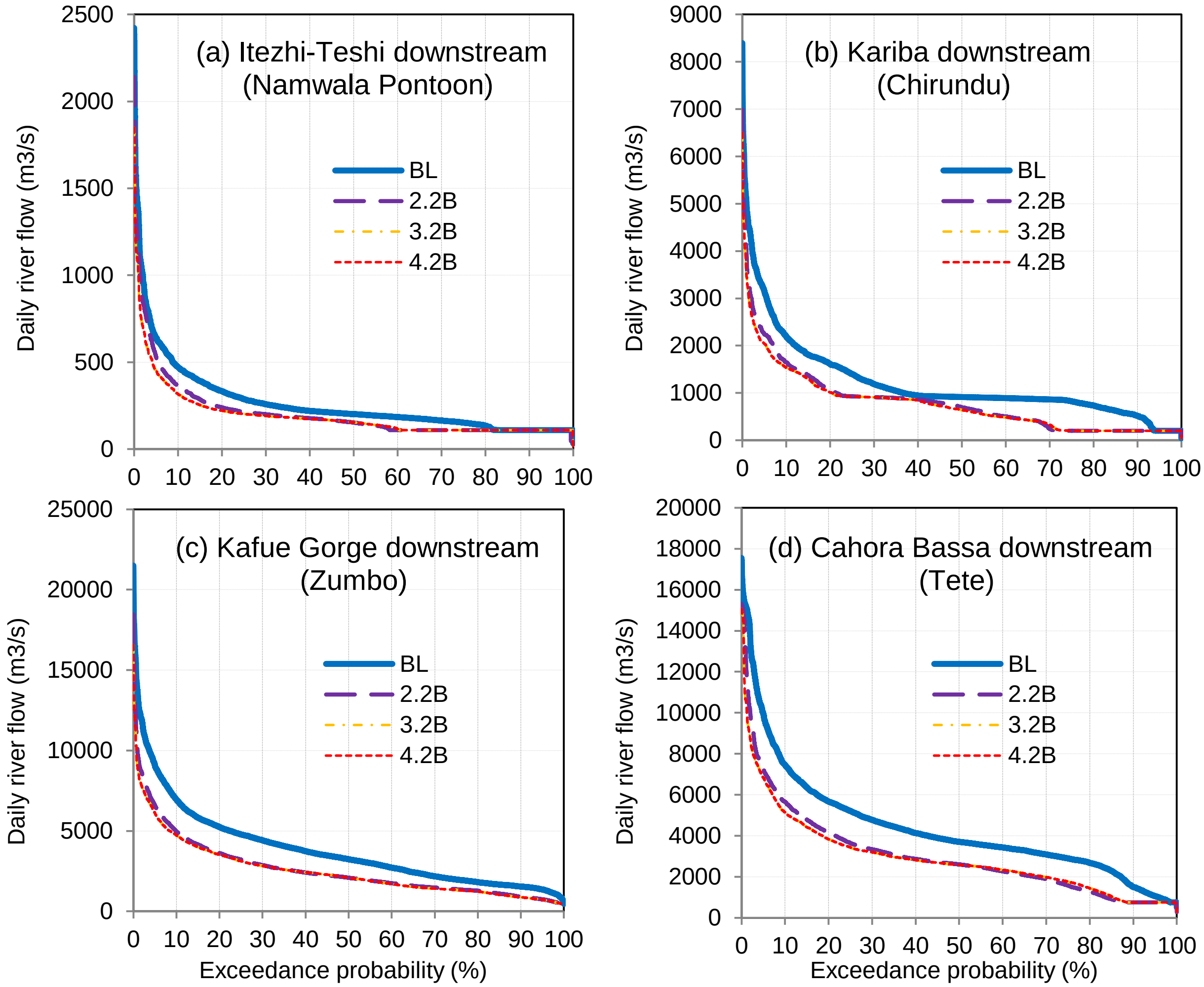
***Figure 2**. Mean monthly river flows downstream of dams. Vertical error bars represent one standard deviation from the baseline scenario.*





Despite differences in the relative changes from month to month, flow duration curves highlight that there could be a generalized net reduction in river flows for most of the time (Figure 3). At Itezhi-Tezhi, no major changes occur for large flows with an exceedance probability smaller than 5%, or for small flows with an exceedance probability greater than 80% (Figure 3a). At Kariba, no consistent changes are expected for very large flows (exceedance probability < 5%) and for small flows with an exceedance probability greater than 95%. Besides little differences in flows around the 40% exceedance level, flows downstream of Kariba are expected to decrease by up to 638 m^3/s. At Kafue Gorge, a consistent reduction is expected for flows with an exceedance probability greater than 1%, with flow reduction gradually decreasing from a maximum of 1657 at the 20% exceedance level. Most consistent reductions in flows are expected at Tete station downstream of Cahora Bassa, where flows could decrease by 1259-1854 m^3/s for the exceedance probability interval between 20 and 80%. Reduction of peak flows (occurring less than 10% of the time) downstream of Cahora Bassa is also expected, suggesting an overall reduction to flood exposure in this lower part of the river.

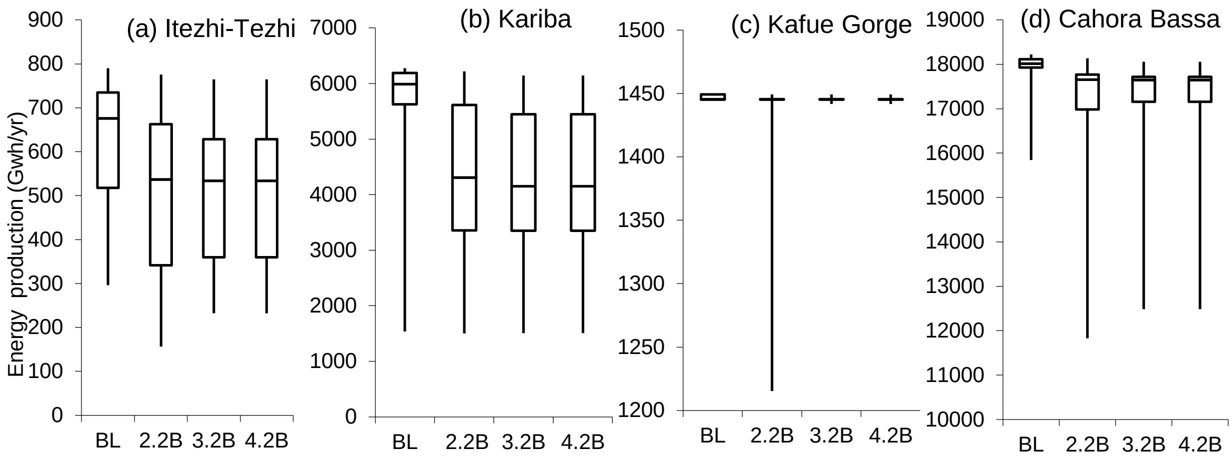
Figure 3. Flow duration curves of future scenarios for flows downstream of dams.



Effects of future scenarios on hydropower generation

Changes in water levels and flows could result in a negative to neutral effect on hydropower generation (Figure 4). At Itezhi-Tezhi, average annual hydropower is expected to change from 675 to 534-536 Gwh/yr, which is a reduction of 21% for all three future scenarios, though a larger increase in variability was estimated for the 2.2b scenario (Figure 4a). At Kariba, the largest dam in the basin in terms of installed capacity, annual generation is expected to change the greatest, from 5989 to 4152 Gwh/yr, which is a reduction of 28.1-30.7% (Figure 4b). At Cahora Bassa, which has the second largest installed capacity and receives the most river inflow from all dams, average annual generation (18017 Gwh/yr) is expected to decrease by 2% for all scenarios, and interannual variability is expected to increase significantly, in particular for the 2.2b scenario (Figure 4d). At Kafue Gorge, no significant changes were estimated for the mean annual energy production of 1445 kwh/yr. The main reason for this negligible change might be because most of the hydrological changes expected at this location are related to high flows during the wet season, which given the little storage (2.8E9 m^3) and low head (5 m) of this dam, means that most the high flows are discharge through the spillway. Overall, these mild decreases in hydropower generation are in agreement with previous findings for the Zambezi (Fant et al. 2013), and the increase in interannual variability is consistent with findings about future hydropower generation in other large dams around the world (Piman et al. 2015; Arias et al. 2020).

Figure 4. Effects of future climate change on total annual energy generation. Upper, middle, and lower divisions on boxplots represent the 75th, 50th, and 25th percentiles, respectively. Upper and lower error bars represent maximum and minimum annual energy production.



Conclusions and Recommendations

The objective of this study was to analyse the impact of hydropower operation on surface hydrology dynamics of the Zambezi river basin, and understand how such dynamics could be affected by future climate change. This study entailed the synthesis of existing GIS and monitoring data, hydrological data analysis, development of a model application of the Reservoir System Simulator (ResSim) for the Zambezi; verification of the model for historical conditions, and evaluation of the effect of future climate change scenarios on reservoir water levels, river flows, and hydropower generation. This study focused on four large hydropower dams located in the Kafue and Zambezi rivers: Itezhi-Tezhi, Kafue Gorge, Kariba, and Cahora Bassa. Results from data analysis and simulations for the baseline historical period showed dams have modified the natural flow regime of the Kafue and Zambezi rivers by increasing river flows during the drier months (July-November) and by decreasing flows during the wetter months (January-May). The combinations of these monthly changes have led to the flattening of the distinct seasonal pulse in this river system.

Major changes to the dynamics of the surface hydrology of the Zambezi are expected as a result of climate change. Future climate change could affect reservoir levels by decreasing reservoir inflows and by increasing evaporation. Results showed a mild decrease in mean annual water levels for all reservoirs, with largest changes expected at Itezhi-Tezhi (-1.3m), with minor (0.1-0.2 m) average values for the other three dams. Comparison of flows downstream of dams shows an overall negative tendency, with largest changes expected during the wet months. Flow changes are expected to be the largest at Cahora Bassa (-30 to -49%), followed by Kariba (-12 to -51%), Kafue Gorge (-25 to -42%) and Itezhi-Tezhi (-15 to -35%). Changes in water levels and flows could result in mild negative effects on mean average hydropower generation and significant increases in interannual variability; largest changes are expected at Kariba, where annual generation is expected to decrease from 5989 to 4152 Gwh/yr (-28.1 to -0.7%). At Itezhi-Tezhi, average annual hydropower is expected to change from 675 to 534-536 Gwh/yr (- 21%). At Cahora Bassa, average annual generation

(18017 Gwh/yr) is expected to decrease by 2%. At Kafue Gorge, no significant changes were estimated for the mean annual energy production of 1445 kwh/yr. Overall, no major differences in future projections were found among the three future climate change ensemble scenarios, with the exception of a greater increase in interannual variability for the 2.2b (1.5 degree of warming) scenario.

In terms of future studies, this study recommends a more rigorous model verification procedure to reduce the uncertainty associated with model prediction. Such procedure was compromised by the absence of basin-wide and continuous data. From a hydrology point of view, data gaps and discrepancies could be complemented with remote sensing (satellite) observations of water levels, evapotranspiration and flood extent. Also, this study recommends a closer look at the effects of climate change on specific dam outlet structures (turbines vs. spillways), as targeted guiding curves could greatly offset the effects of the changing hydrology. Once guiding curves are adjusted to offset the detrimental effects of climate change on hydropower, other aspects of the Water-Energy-Food-Ecosystem nexus could be quantified simultaneously. There have been recent scientific advancements in multi-objective optimization and robust decision making approaches in water resources and multi-sectorial studies which could be greatly informative in the Zambezi to understand tradeoffs and synergies between hydropower and other services in the fate of climate change.

From a management perspective, it is quite possible modification of reservoir operation will be necessary to offset the projected changes in hydropower generation. To what magnitude re-operations could offset future changes was not directly quantified in this study, but given the large capacity of the main reservoirs in the Zambezi, it is likely that the effects of re-operations (guided by optimization) will be significant.

Overall, this study projects a more water scarce Zambezi river, in which water available in reservoirs and downstream of hydropower dams could be more limited. An alternative operation schedule could help offset such losses, but it is important that such schedule also considers downstream environmental and human water needs, which will likely be even more compromised in decades to come.

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Characterisation of Current Agriculture Activities and Irrigation Potential in the Zambezi River Basin (ZRB)

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The Zambezi River Basin (ZRB), in Southern Africa, is a key transboundary water resource that sustains livelihoods of 30-40 million people. This report describes current agricultural activities, and current and potential future developments in irrigation in the ZRB. The study used various kinds of data including literature review, shapefiles from the Zambezi Water Information System (ZAMWIS), and climate and CROPWAT modeling. The results of the study show that rainfed food crop production is still the most important agricultural sub-sector in the ZRB, accounting for approximately 80% of the cultivated area. Maize and cassava are the major staples and other key food crops include rice, groundnuts, beans, sweet potatoes, sorghum, millet, and a wide variety of vegetables. In addition, livestock and aquaculture are an integral part of farming systems representing important alternative livelihood strategies. Despite considerable strides being made in improving productivity and environmental conditions in the basin, a great number of poor families still face poverty, hunger, food insecurity and malnutrition largely due to their overdependence on rainfed agriculture. Therefore, irrigation offers a viable alternative to meet the food needs for a growing population. Our study has established that water resources in the ZRB are not heavily committed, with only 21.2% of the total river discharge being consumptively used, mainly for irrigation and hydropower reservoir evaporative loses. The results show that only 25% of the total area with irrigation potential (674,230 ha) is presently under irrigation. However, most of this land is not properly equipped for intensive agricultural production. The remaining area with highest irrigation potential (470,107 ha) is mainly located in Malawi, Mozambique, Zambia and Zimbabwe. Our CROPWAT simulations suggest that irrigating this total area for production of various crops, will require an upper limit of about 370 m3s-1, against current mean Indian Ocean inflow of the Zambezi River of about 3500 m3s-1. The study therefore concluded that overall, the ZRB has a very high untapped irrigation potential capable of meeting food requirements of a growing population.

Keywords: Climate change; Economic livelihoods; Irrigation agriculture; CROPWAT, Water resources; Zambezi River Basin.

1 Introduction

The Zambezi River Basin (ZRB) is an important transboundary basin, being Africa's fourth largest and the largest river system in the Southern African Development Community (SADC). The basin is home to a total population of between 32 and 40 million, with 80% of these living in Malawi, Zambia and Zimbabwe. Agricultural production sustains the socio-economic livelihoods of about 80% of the total population, going up to 90% in some of the riparian countries like Malawi (World Bank (WB), 2008; IRC, 2008; AGRA, 2014). The sector also contributes to 24% of the riparian countries' GDP (World Bank, WB, 2010). However, most of the agricultural productivity is presently achieved through subsistence rainfed systems, with irrigation accounting for about 5% of the total. Climate change and variability is a key challenge to the already tenuous agricultural production systems, in addition to environmental degradation. The Zambezi is classified as a climate change hotspot (Midgely et al., 2011) and is among 11 major African river basins showing extreme responses to the effects of climate change and variability. In order to meet increasing food and water demands of a growing population and other competing water using activities, under a changing climate, there a need for an understanding of the current agriculture practices and the irrigation potential of the ZRB.

Therefore, this study aimed at characterizing current agriculture activities and irrigation in the ZRB in order to:

(i) understand baseline conditions in agriculture (including livestock and fisheries) by gathering and processing data and by-products (land use and coverage, local practices, seasonal patterns).
(ii) assess crops water demand, productivity and potential impact of irrigation expansion and scenario-based management practices.

2. Methods

In order to generate baseline information about the agricultural production systems in the ZRB, the study undertook a comprehensive desktop literature review, including databases such as FAO Aquastat (http://www.fao.org/aquastat/en/), the Zambezi Commissions Zambezi Water Information System (ZAMWIS,) by ZAMCOM (2016) and World Bank (2008 & 2010). Previous studies in the ZRB that were reviewed include those by Food and Agricultural Origination (FAO,1997), Euroconsult-Mott Macdonald (2008), World Bank (2008 & 2010), Amede et al. (2014), WWF (2003), Hoekstra et al. (2001) and Gomo et al. (2019). The data were extracted and summarized using tables and figures in Microsoft Excel. In addition, various maps on land use and land cover changes, water demands, aquaculture and livestock productivity in the ZRB were prepared from the ZAMWIS shapefiles using Arc GIS.

To assess the crop irrigation potential of the ZRB, the study applied CWR scenarios using the CropWat 8.0 program (Smith, 1992) by the FAO with climate and rainfall data files obtained from CLIMWAT (Smith, 1933). CropWat program employs the FAO Penman-Monteith method (FAO 56 PM; Allen et al., 1998) for the calculation of CWR and irrigation demand. The method is given as:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(\frac{900}{T+273}\right)u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}$$

where ET_o is the reference evapotranspiration (mm day^{-1}), which in this case is the daily CWR; R_n is the net radiation at the crop surface ($MJm^{-2}day^{-1}$), and Allen et al (1998) outline the estimation procedures; G is the soil heat-flux density ($MJm^{-2}day^{-1}$), normally assumed zero for daily calculations; T is the mean daily air temperature (°C) at a height of 2 m; u_2 is the wind speed at a height of 2 m (ms^{-1}); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa), which is based on relative humidity measurements; ($e_s - e_a$) is the saturation vapor pressure deficit (VPD) (kPa); Δ is the slope of the vapor pressure curve (kPa °C−1); and γ is the psychrometric constant (kPa $°C^{-1}$). Allen et al. (1990) presents procedures for the estimation of the rest of the variables. Eight stations within four countries with the largest irrigation potentials (Malawi, Zambia, Zimbabwe and Mozambique) were used as reference stations in the CropWat model.

3. Discussion

3.1. Current Agriculture Characterisation

The ZRB has a total cultivated area of about 52,050 km^2, with Malawi, Zimbabwe and Zambia accounting for most of this area. Out of this total area, only 4% is presently under irrigation whereas the rest is used for rainfed production of mainly staple crops such as maize and cassava, sometimes intercropped with others. According to the Food Productivity Index (FPI), overall food productivity across the ZRB was satisfactory (FPI>100) in the period between 2000 and 2013. However, most smallholder farmers in the ZRB have, in recent years, adopted other crops such as legumes (e.g. pulses), cereals (e.g. millet and sorghum) and root and tubers (e.g. sweet potatoes and cassava) owing to their tolerance of drought and soils with marginal fertility (Waldman, 2017). The rainfed agriculture production activities are further complimented by aquaculture in key fishing grounds of Lake Malawi, Lake Kariba, Lower Shire floodplains, Cahora Bassa, Lake Malombe, Zambezi Delta, Barotse floodplains Kafue Flats, Eastern Caprivi floodplains, Lukanga Swamp, Lake Lusiwashi, Lake Itezhi-tezhi. In addition, there is considerable high livestock productivity across the basin according to the Livestock Productivity Index (LFPI), with some riparian states like Malawi and Zambia registering very high productivity rates (LPI>20) between 2002 and 2013.

Presently, the ZRB has a total water commitment of about 21.2% of the total runoff (Table 1), most is due to evaporative losses from hydropower reservoirs (16.5%), followed by irrigation agriculture (3.13%) and environmental releases (1.16%). It can be noted in Table 1 that the water resources of the ZRB are not yet heavily committed.

Table 1. Water availability and commitments in the ZRM (Sources: Euroconsult Mott Macdonald (2008) & WB (2010))

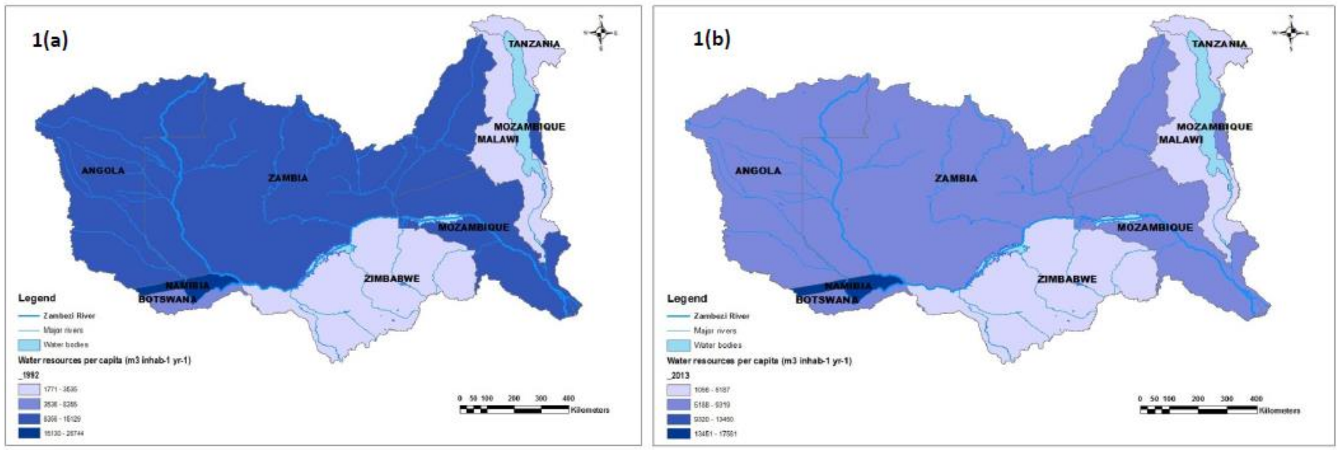
Available Runoff/Demands	km^3	%
Available Runoff	10,320	100
Hydropower	1,700	16.46
Agriculture	320	3.13
Urban(Domestic)	0.18	0.17
Rural (Domestic)	0.024	0.02
Industrial	0.025	0.02
Mining	0.12	0.12
Environmental Releases	120	1.16
Livestock	0.11	0.11
Total Water Demand	**2190**	**21.19**

Across the ZRB countries, there have been some changes in water availability between 1992 and 2013 (Figure 1). During this period, notable changes in water availability were observed in Zambia and Mozambique. Minimal changes were however noted in the land use/land cover change between 1992 and 2013.

Key deliverables from this part include: a detailed report on the ZRB agricultural activities (Ngongondo, 2019); comprehensive databases of ZAMWIS shapefiles and corresponding spatial-temporal maps on land use, land use/cover changes, water availability, food productivity, irrigated area, fisheries and livestock productivity; and excel files with data on cultivated area, available water resources and land used changes have been constructed.

Figure 1. Total amount of water available in the ZRB countries, (a) in 1992; (1b) in 2013

(Data Source: ZAMWIS (2016))



3.2 Current and Future Irrigation Potential

The amounts of abstractions for irrigation in the 13 sub-basins of the ZRB are shown in Table 2. Most of the irrigation withdrawals are taking place in the ZRB sub basins of Kafue, Kariba, Mupata, Shire/Lake Malawi and Tete, leaving a lot of room for expansion (Table 3). However, most of the irrigated area is not equipped for irrigation, with Zambia and Zimbabwe having the most equipped area (Figure 2).

Table 2. Irrigated areas in the sub-basins of the Zambezi River Basin (Source: World Bank, 2010)

Sub-Basins	Sub-Basin	Abstractions	Percent
Kabompo	13	4,817	0%
Upper Zambezi	12	37,623	1%
Lungue/Bungo	11	15,674	0%
Luanginga	10	14,203	0%
Barotse	9	3,491	0%
Cuando/Chobe	8	10,139	0%
Kafue	7	626,021	19%
Kariba	6	649,154	20%
Luangwa	5	120,498	4%
Mupata	4	308,562	10%
Shire River-Lake Niassa/Nyasa	3	648,649	20%
Tete	2	669,032	21%
Zambezi Delta	1	126,973	4%
Total		**3,234,836**	**100%**

Table 3. Potential Irrigated Area in the Zambezi River Basin for the year 2020 (Sources: World Bank (2010) & FAO AQUASTAT (2005))

Country	ZRB Population	Total Irrig. Area (ha)	Current Irrig. Area (ha)	Increase (Mm^3)	Water required (ha)
Angola	815,000	16,109	1,989	14,120	161
Botswana	13,000	280	4	276	3
Malawi	14,351,000	169,520	43,987	125,533	1,695
Mozambique	4,609,000	91,966	11,211	80,755	920
Namibia	84,000	1,544	139	1,405	15
Tanzania	1,991,000	26,128	9,070	17,057	261

Zambia	9,518,000	227,458	34,016	193,443	2,275
Zimbabwe	9,346,000	141,226	70,850	70,376	1,412
Total	**40,728,000**	**674,230**	**171,266**	**502,964**	**6,742**

Future irrigation crop water requirements in the ZRB were assessed in four riparian countries namely Malawi, Mozambique, Zambia and Zimbabwe. These were of particular interest as they have the largest current and planned share of agricultural land and hence the major crops grown in these countries.

Figure 2. Area equipped for irrigation in the ZRB as total per 1000ha (Source: ZAMCOM, 2016)

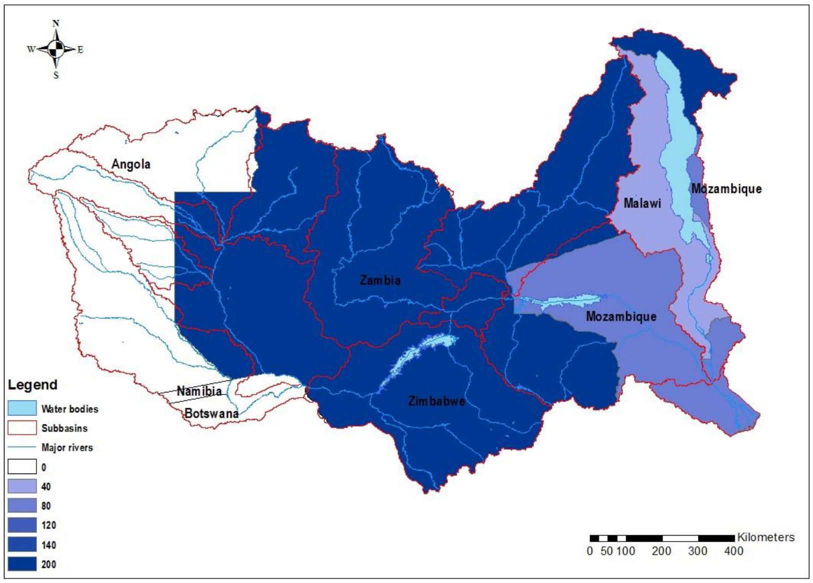


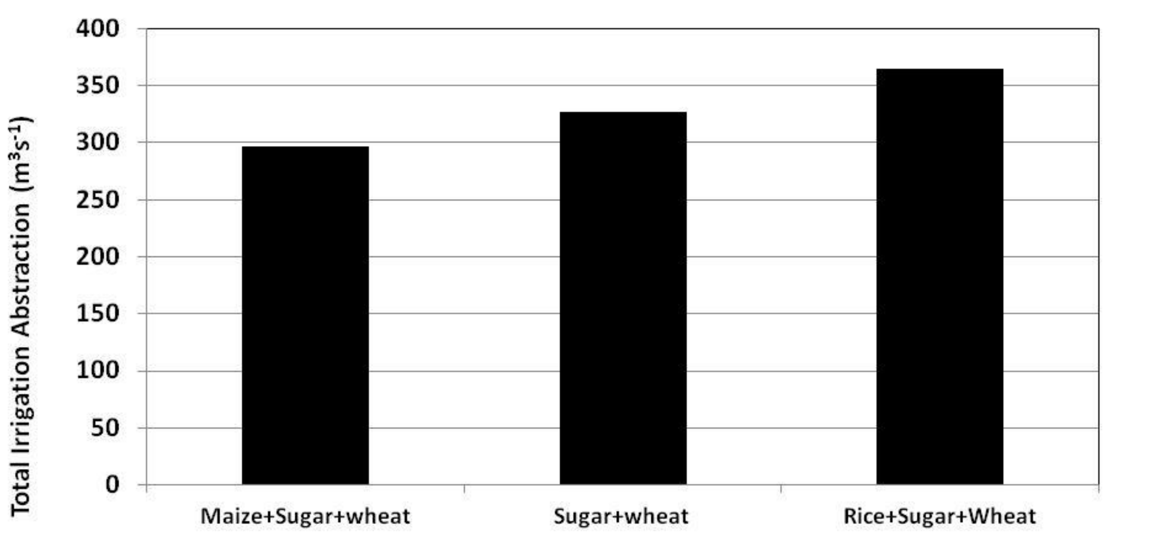
Table 4 presents CROPWAT outputs showing the upper limits of irrigation water abstractions in cubic meters per second (m^3s^{-1}) for selected crops and the total remaining potential irrigation area from Table 3. The assumption is that each crop takes the total remaining area in each country.

Table 4. Abstractions for various crop water requirements in 4 ZRB riparian countries

Country	Potential Irrigated Area (km^2)	Maize m^3s^{-1}	Sugarcane m^3s^{-1}	Rice m^3s^{-1}	Wheat m^3s^{-1}
Malawi	12,555.3	12.14	41.602	80	
Mozambique	80,755		73.9		
Zambia	1,934.43				75
Zimbabwe	70,376		135.9		

Figure 3 shows the upper limits of abstractions for various crops based on the remaining total areas with irrigation potential in Malawi, Mozambique, Zambia and Zimbabwe. The Zambezi River currently discharges an average of about 3500 m^3s^{-1} into the Indian Ocean. The abstractions in Figure 3 show an upper abstract limit of about 370 m^3s^{-1} to irrigate rice, sugar and wheat in the four countries. This would still leave the river with a lot of water (>3000 m^3s^{-1}) to cater for the environment and other water using activities. Various other crop combinations would of course vary the total amount of abstraction.

Figure 3. Upper limit scenario of CWRs abstraction for remaining irrigation potential area in ZRB



Key deliverable for the irrigation potential: CWRs estimated from the model CROPWAT. It is possible to apply the model CROPWAT model for the estimation of CWRs for other crops and site. In addition, a report (Ngongondo_MALAWI_AW_M4_clean_updated, 2019) was submitted.

4. Conclusions and recommendations

The Zambezi River Basin (ZRB) in Southern Africa is a key transboundary water resource that sustains the socio-economic livelihoods of a total population of between 30 and 40 million. The ZRB is classified as a climate change hotspot among 11 major African river basins showing extreme responses to the effects of climate change and variability. The following are the key conclusions and recommendations:

- The ZRB is largely underdeveloped, with forest and bush occupying 75% of the total area, followed by rainfed cropped land (13%), grassland (8%) and infrastructural developments (4%).
- Between 2000 and 2013, a large part of the basin experienced forest loss ranging between 0-20%, with some smaller parts registering losses of up 40-60% for those parts that experienced forest loss mainly due to conversion for agriculture and urban area.
- Agriculture is the main source of socio-economic livelihoods of communities in the ZRB.
- Food crop production, through subsistence rainfed agriculture, is the most important agricultural sub-sector in the ZRB, accounting for approximately 80% of the cultivated area.
- The ZRB has a total cultivated area under crop production of about 52,050 km^2 with Malawi, Zambia and Zimbabwe accounting for 36.56%, 26.28 and 22.17% respectively.
- The ZRB has a total available runoff of about 10,320 km^3 per year, of which only 21.2% is presently committed for evaporative losses (16.5%), irrigation agriculture (3.13%) and environmental releases (1.16%).
- Irrigation agriculture presently accounts for about 4% of the total cultivated area, mainly in Zimbabwe, Tanzania, Zambia and Malawi.
- Maize is the main staple crop across the basin, with cereals such as millet and sorghum and root and tubers such as sweet potatoes and cassava being alternatives due to frequent drought.
- The food crop production (FPI:100 being normal) in many parts of the ZRB as of 2013 can been considered to have been satisfactory ranging between 80 in the semi-arid parts of the basin in Zimbabwe and the Caprivi Strip in Namibia to 140 in Botswana, Mozambique and Tanzania, 200 in Zambia and 230 in Malawi and Angola. Cash crops, considered having better economic comparative advantage include tobacco, cotton, rose flowers, cashew nuts, spices, macadamia, coffee, tea and sugar are grown in the ZRB.
- Among the ZRB major irrigated crops, sugarcane covers the largest area of 95,000 ha (24.9% of the irrigated area), followed by rice (73,000 ha), wheat (68,000 ha) and vegetables (66,000 ha).
- The best equipped areas for irrigation are located in Zambia, Tanzania and Zimbabwe parts of the catchment with over 200 ha per 1000 ha of equipped area, whereas Malawi and Mozambique have less than 100 ha per 1000 ha that are equipped and the rest of the riparian countries have very low equipped areas.
- As of 2013, the whole basin has very high potential for expanding irrigation, as most of the irrigation commitments are presently in Malawi, Zambia and Zimbabwe.
- The ZRB irrigated area would need to increase by 29 per cent from 1995 in order to meet food and other nutritional requirements by 2025.
- The largest irrigation potential areas are in Mozambique, Zambia, Zimbabwe and Malawi parts of the ZRB for crops such as maize, wheat, sugarcane and rice.
- An upper limit of about 370 m^3s^{-1} would be needed to carter for a single cycle of irrigation CWRs for maize, wheat, sugarcane and rice in Mozambique, Zambia, Zimbabwe and Malawi.
- The ZRB accounts for one of the largest livestock productivities in the world, with Malawi and Zambia having livestock productivity indices above 240 (normal: 100) as of 2013.
- Aquaculture (fisheries) is an alternative source of livelihoods, with current key fishing grounds in Lake Malawi (over 64,000 metric tons per annum-mtpa), Lake Kariba (over 28,000 mtpa), Lake Malombe (over 10,000 mtpa), Kafue Flats (over 7,000 mtpa).

5. Study limitations and the way forward

- The study faced considerable data availability limitations. Effort were however made to collect data from as many sources as possible
- The irrigation potential parts of the study were delayed due to COVID-19 pandemic. However, reports were finally submitted.
- The irrigation potential used data for eight stations only in the ZRB and generalized to the total potential area in the 4 countries considered. There is therefore need for more detailed study to estimate CWRs using site specific climate data for other locations and sub-basins of the ZRB.

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Characterization of Current Agriculture Activities, Future Potential Irrigation Developments and Food Security to Face Climate Variability in the Zambezi River Basin

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Water and agriculture aspects focusing on irrigated and rainfed agriculture through appropriate agricultural water management practices were analysed in the transboundary Zambezi River Basin (ZRB), the fourth largest in Africa, and facing many challenges from the perspective of the Water-Energy-Food-Ecosystem (WEFE) nexus. Agriculture is the largest water consumer in the basin with more than 90% of the agricultural activity in the basin being based on flood plain cultivation and rain dependent agriculture, and sustaining the bulk of the rural population. Irrigation is important in the basin, but on a comparative basis estimates range from 147000 ha to 259000 ha only, but because it is water-use intensive, it factors significantly in the water use equation in the basin. Irrigation is estimated to consume 3235 million cubic meters of water currently amounting to 1.4% of the basin's renewable water resources. There is huge irrigation development potential in the basin, ambitious plans are afoot to triple the area under irrigation by 2025 which will increase the water for irrigation to 4.1% of the basins' renewable water resources. Smallholder irrigation practices are dominant in the Zambezi River Basin, consequently basic agricultural water management coupled with sustainable agricultural intensification is a key aspect of agricultural production. Typical practices in the basin include; gravity fed off-river and reservoir irrigation, dambo irrigation farming, motorized pumping irrigation, drip irrigation including drip kits, sprinkler irrigation and centre pivot irrigation. Since the Zambezi River Basin is transboundary and there is competition for natural resources by sector (water, energy, agriculture) and by country (ZRB riparian countries), the WEFE nexus presents itself as a viable tool for resources management. An exploratory WEFE nexus analysis of the ZRB was conducted based on selected water, energy, food and ecosystem goods and services indicators. Most of the WEFE indicators showed marginal sustainability.

Keywords: agricultural water management, irrigation development, renewable water resources, smallholder irrigation, WEFE nexus

Introduction

The Zambezi River Basin (ZRB) is the fourth largest river in Africa after the Congo, Nile, and Niger River basins. It is located in Southern Africa and is coordinated between 9°00'S to 20°30'S latitude and 18°20'E to 36°25'E longitude (Figure 1) (Schleiss and Matos, 2010). The Zambezi River Basin covers an area of 1.4 million km^2 and stretches approximately 2600 km. The basin is shared by eight riparian countries (Angola Botswana, Malawi, Mozambique, United Republic of Tanzania, Zambia and Zimbabwe), with Zambia having the largest share (41%), followed by Angola and Zimbabwe which have slightly less than half the Zambian portion (18.5 and 15.6%, respectively) (Schleiss and Matos, 2010). Three of the countries (Republic of Tanzania, Namibia and Botswana) have less than 2% of the river basin each. The ZRB is commonly split into three main regions: Upper Zambezi, Middle Zambezi and Lower Zambezi.

The average annual rainfall over the whole river basin is estimated to be 990 mm while the average annual evaporation is about 870 mm. The part of the ZRB which receives the highest rainfall (over 2000 mm per annum), lies in Tanzania (Cai et al., 2017). Land cover in the ZRB consists of rainfed farming, forest, bushland, grassland, open water and irrigated land. Forest and bushland take up 75% of land cover. Within the remainder 25%, rainfed agriculture occupies an estimated 13.2% of the land holding. Grassland and irrigated agriculture occupy 7.7 and 1.3% respectively (Euroconsult Mott McDonald, 2007). Agricultural activities have been the main driver of land cover changes. According to Gomo et al. (2018), approximately 16% of natural forests have been converted to crop area over the past decade.

Agriculture is the largest man-made land use around the ZRB. It is a large contributor to gross domestic product of riparian countries and livelihoods of its inhabitants. Malawi has the largest cultivated area within the ZRB (≈ 2 million hectares), followed by Zimbabwe and Zambia Angola, Botswana and Mozambique have the least area under cultivation within the basin (< 0.1 million hectares). With respect to renewable water resources, agriculture is the largest user in all riparian countries with countries such as Zimbabwe, Zambia, Tanzania, Mozambique and Malawi having more than 75% of renewable water resources being consumed by agriculture (World Bank, 2008). Despite this, there is not much information on agricultural water management (AWM) in the basin at different scales (Manzungu et al., 2017).

With respect to water and agriculture in the ZRB, questions arise include; how much land is available in the basin and of that how much is suited to agriculture and is being used thus, what typologies of agricultural practices exist in the basin and what are the key factors driving these, how much water is available in the basin and of that how much is allocated or available for agriculture, how much irrigation is taking place in the basin and what is the potential for further expansion with what water resources, what are the levels of agricultural water productivity in the basin, what options exist to improve agricultural water management, can there be trade-offs between rain fed and irrigated agriculture, and can the basin be eventually food secure? Within the context of the Water-Energy-Food-Ecosystem (WEFE) nexus, the questions are, can this be used as an approach or tool to better manage resources in the basin for sustainable energy and food production?

Methods

The research objectives were; to analyse the baseline conditions on agriculture (including livestock and fisheries) by gathering and processing data and by-products (land use and coverage, local practices, seasonal patterns) at ZRB scale; and to perform agriculture assessment (crops water demand, productivity and potential impact of irrigation expansion) and scenario based management practices. A mixed-method review approach, which included combining quantitative and qualitative research or outcomes of process studies was used to compile the review. Scientific journal articles, book chapters, technical reports, dissertations, SADC database and other forms of literature were used.

Discussion

Surface Water

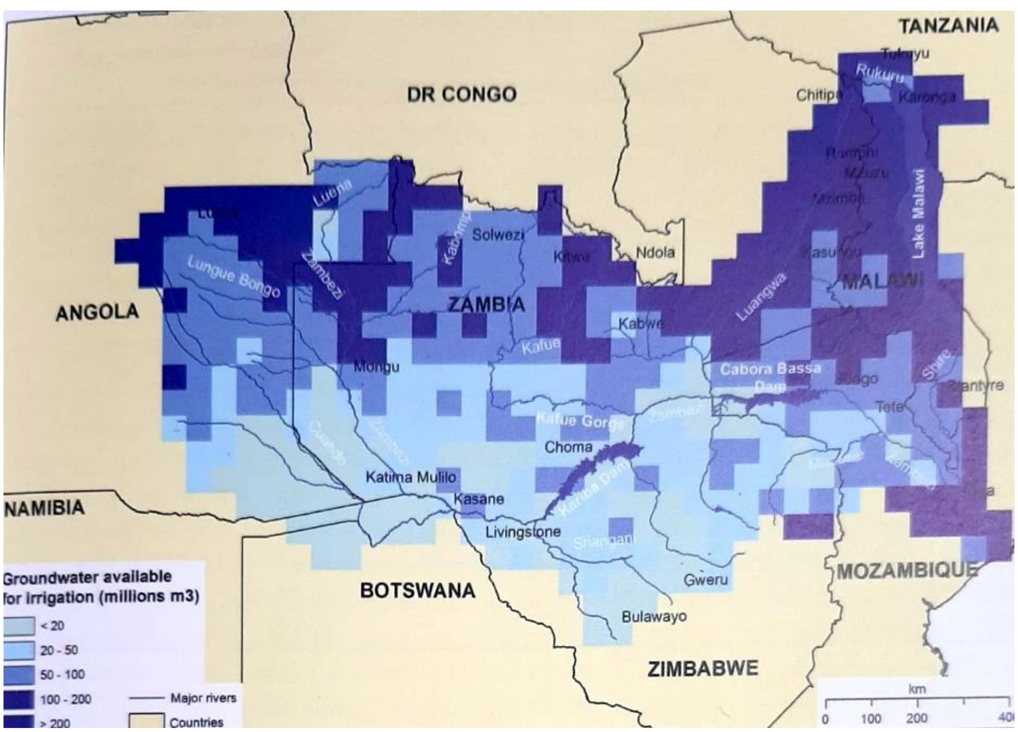
Mean annual precipitation is about 1 000 mm of which only 8% generates discharge and the remaining is lost via evapotranspiration. Rainfall throughout the Zambezi catchment is concentrated over the summer months (October to March) in response to the ITCZ. The rain cycle gives rise to the unique patterns of run-off in each sub basin (Schleiss and Matos, 2010; Kling et al., 2014; Zimba et al., 2018). Rivers draining the steep gorges of the Central Africa plateau peak rapidly with the rain, reaching their maximum discharge between January and March and decreasing to dry season flows in October. In the Kafue River and Shire basin, flood plain systems capture flood water and delay discharge until late in the rainy season or early dry season. Mean discharge at the outlet of the basin exhibits large seasonal and intra-annual variations though its average is estimated at ≈ 3600 $m^3 s^{-1}$. Seasonality in discharge is controlled by seasonality in precipitation, retention in large floodplains and swamps as well as artificial reservoirs (Pinay, 1988). The construction of Kariba, Cahora Bassa and other large dams in the Zambezi system has altered Zambezi runoff pattern.

Climate change forecasts show that ZRB will be affected by climate change, with runoff being sensitive to variations in climate. Rainfall is expected to decrease by 15% by 2050. Recent modelling efforts (Farinosi and Hughes, 2020) on climate change and water use scenarios showed that the relative impacts can be quite different across the whole Zambezi River basin, the greatest impacts being in the Lake Malawi/Nyasa sub-system, as well as other areas containing large open water bodies (natural and man-made), that are very sensitive to the combined effects of increased aridity. In addition, rainfall will be characterised by delayed onset with shorter and more intense rainfall events. This will have a negative impact on annual streamflow. This will ultimately affect agriculture, municipal, hydropower and ecosystems services at large (Beilfuss and Nhemachena, 2017).

Groundwater

The ZRB average annual groundwater recharge is estimated at 130 km^3. The International Groundwater Resources Assessment Centre (IGRAC) reports 10 transboundary aquifers; four which are located inside the ZRB perimeter and six which are partly located within the ZRB (Cai et al., 2017). Agricultural activities are the primary use of groundwater within the riparian states. Other ground water uses extend to fisheries and livestock watering. Ground water available for irrigation is estimated to be 38.5 km^3 (Altchenko and Villholt, 2015) (Figure 1) whilst the irrigation potential is an estimated 2.55 million ha.

Figure 1. Ground water available for irrigation



Agriculture

Land use in the ZRB is characterised by rainfed and irrigated agriculture rainfed agriculture. The WorldBank (2010) estimated that 70% of the riparian inhabitants are subsistence farmer. Stark rainfall variations are observed amongst ZRB member states with the lower parts of the basin receive approximately 500 mm in the extreme south and southwestern parts, whereas the upper sub basins such as Kabompo, Upper Zambezi, Lungue Bungo, Kafue, Shire, and Zambezi Delta receiving an estimated 1400 mm. The variations in rainfall consequently influence agricultural productivity, i.e., northern parts experience high yield as compared to the southern regions. Irrigated agricultural practices in the ZRB are informal irrigation by small-scale farmers, smallholder irrigation, and commercial irrigation schemes. Informal irrigators have an average landholding of 200 m^2 and they make use of conventional and traditional methods such as watering cans, bucket systems and hosepipes (Manzungu et al., 2017) whereas commercial irrigation is done on a large scale and it is characterised by advanced technology and heavy machinery. Riparian governments are heavily invested in smallholder irrigation schemes (SIS) to alleviate poverty. The SIS are characterised by a landholding of 1 ha and the farmers share common pool resources (Dirwai et al., 2019).

Fishing among the riparian inhabitants is done to either augment dietary needs or for small scale commercial (income generation). Fishing in the ZRB is also done on a commercial scale. The activity is also done for angling tourism. In 2016, African Union – Interafrican Bureau for Animal Resources (AU-IBAR) reported ≈ 100 fish species within the Zambezi River with the upper Zambezi boasting more species (> 85). Despite the importance of fishing in the riparian countries, there are still several reports of underutilized potential of fishing within the river basin and no increases in catch yields over the past decade (Table 1) (Interafrican Bureau for Animal Resources, 2016; Tweddle and Peel, 2015; Tweddle and Tweddle, 2010). The riparian countries have the potential to increase their catch yields, this will subsequently improve the livelihoods of the riparian population.

Table 1. Annual catch yields in the different regions of the Zambezi River Basin in the year 2000 to 2007 (Adapted from Tweedie and Tweedie, 2010).

Region	2000	2001	2003	2004	2005	2006	2007
	Tonnes						
Upper Zambezi	6 728	-	6 694	6 834	6 653	6 079	7 421
Kariba	8 863	9 306	8 818	9 003	8 768	8 008	9 776
Kafue	6 131	6 437	6 100	6 228	6 062	5 539	6 763
Lukanga	1 306	1 371	1 299	1 327	1 291	1 180	1 441
Itezhi-tezhi	2 221	2 332	2 210	2 256	2 196	2 007	2 450
Lusiwashi	2 139	2 246	2 128	2 173	2 115	1 933	2 359
Lower Zambezi	588	617	585	597	581	531	649
Total	29 976	24 374	29 837	30 422	29 671	27 283	32 866

Livestock farming is also an important aspect in the ZRB. According to Sadr (2015), the first livestock to enter Southern Africa was through the ZRB. Livestock farming consumes ≈ 120 million m^3 per annum, which is less than 1% of total consumptive use (Euroconsult Mott McDonald, 2007; World Bank, 2008). Cattle production dominates the livestock farming landscape. Cattle population within the basin is ≈ 42 million heads (ZAMCOM, SADC, SARDC, 2015). The number is still considered below potential. Small scale livestock production depends on natural grasslands, whilst at the commercial production level, the herd is given supplementary feed. Erratic rainfall patterns and droughts impose production penalties on farmers that rely on grasslands.

Water-Energy-Food-Ecosystem Nexus

The WEFE nexus describes the close interlinkages of the water, energy, and food sectors, and how they rely on and impact ecosystems. Primarily it focuses on the interdependencies between achieving water, energy and food security for human well-being, i.e., basic services and economic development, while ensuring ecologically sustainable use of globally essential resources. In practical terms, the WEFE nexus helps to improve understanding and systematic analysis of the interactions between the natural environment and human activities in these three sectors. The pressure on natural resources (water, land and energy) and the need for harmonious development while sharing transboundary resources in the ZRB demand holistic approaches to the management of such resources. The WEF nexus is best placed as a tool for such resources' sustainable management. An exploratory WEFE nexus analysis for the ZRB was undertaken. The main reason for the WEFE nexus analysis are two-fold; first it allows for the inclusion of ecosystems goods and services (EGS) to the original WEF nexus. EGS are very important in the ZRB as water and other natural resources serve many purposes for the benefit of all life in the basin (more is discussed about this in the sections to follow). Secondly, the WEFE nexus, as discussed above, allows for the analysis of the water, energy, and food sectors, and their reliance on the ecosystems and the consequent impact on the same ecosystems. The WEFE nexus indicators for the Zambezi River Basin are presented in Table 2 for the 2018 base year, based on latest available data.

Table 2. WEFE nexus indicators for the Zambezi River Basin

WEFE nexus	WEFE Nexus Indicator	Status	Notes
Water	Proportion of available freshwater resources per capita (availability)	503.25 m^3/capita	(1)
	Proportion of crops produced per unit of water used – irrigated (productivity)	US$2.01/$m^3$	(2)
Energy	Proportion of the population with access to electricity (accessibility)	Very low	(3)
	Energy intensity measured in terms of primary energy and GDP (productivity)	0.23×10^{-6} MW/GDP 0.46×10^{-6} MW/GDP	(4)
Food	Prevalence of moderate or severe food insecurity in the population (self-sufficiency)	No data at ZRB level	(5)
	Proportion of sustainable agricultural production per unit area (cereal productivity)	1.16 tons/ha (maize) 1.13 tons/ ha (paddy rice)	(6)
Ecosystem	Proportion of ecosystems goods and service value per capita (value)	US$36.05/capita	(7)
	Water provisioning in ecosystems goods and service per capita	473100 m^3/capita 25 m^3/capita (excluding evaporation)	(8)
	Environmental flow requirements (sustainability)	1.16% MAR	(9)

NOTES: (1) From ZRB book Chapter 2 & EuroConsult Mott MacDonald (2007 - Table 2.4); (2) From ZRB book Chapters 1 & 6 in "ZRB – Water and Sustainable Development". In other reports the Agricultural GDP in the ZRB is given as US$14 billion (World Bank, 2010 – Table 3.57); (3) No data; (4) From ZRB book Chapter 5 & Table 5.1 Tilmant (2017); (5) Mixed data and none at ZRB level; (6) From World Bank (2010 – Table 3.69) derived from FAO (2008b); (7) From ZRB book Chapter 7 and McCartney and Nyambe (2017); (8) From ZAMCOM et al (2025) Table 7.4; (9) From ZRB book Chapter 2 & EuroConsult Mott MacDonald (2007) Table 2.4

The WEFE nexus analysis for the ZRB proved challenging to undertake because of data issues – both spatially and temporally, as well as conflicting data from different sources. Be that as it may, the following is deduced from the analysis. On average the available water resources per capita in the basin are on the lower side at (503.25 m^3/capita) and considered unsustainable since they fall below 1700 m^3/capita. The irrigated crop water productivity, similarly is on the lower side falling below US$10/$m^3$ and thus considered unsustainable. This is not surprising given the low levels of production by the smallholder irrigation projects in the basin typified by production for own consumption and some sale. With respect to energy, access to electricity was generally referred to a being low for the bulk of the basin population although the ZRB is considered one of the energy generation hubs of the region. Cereal productivity is considered marginally sustainable at 1.12 tons/ha for maize and 1.13 tons/ha for rice – the two cereals that constitute the base of food for the rural population. Again, these levels of productivity are not surprising given the dominance of small scale agricultural production based on small areas and low input of agro-chemicals and the lack of access to credit facilities for intensified production. By extension, such low levels of production coupled with high population increases in the region inevitable lead to food insecurity problems in the basin.

In terms of the economic value of EGS, these worked out at US$36.05 per capita, which when converted to a base of a day (so as to compare this to the concept of $/capita/day), comes out low. Although this measure is considered low, it is acknowledged that a large proportion of the basin population derives its livelihood from these EGS. In terms of water provisioning as an EGS, this seems healthy at 473100 m^3/capita but drops to 25 m^3/capita when evaporation is excluded, translating to about 70 l/capita/day. In terms of environmental flows, data from the ZRB is conflicting. Data base of river flows seem to indicate environmental flows of 15 to 20 % of the MAR, but when this is based on EGS, the environmental flows work out at 1.14% of the MAR. Considering the lower figure, sustainability of environmental flows is poor, but reality on the ground is something else.

Conclusion and Recommendations

Agriculture is the largest water consumer in the Zambezi River Basin. Irrigation is the key driver of the agricultural based economies of the basin countries with agricultural activities being dominant in Malawi, Mozambique, Tanzania, Zambia and Zimbabwe. Apart from cropping agriculture, the other agricultural activities practices in the ZRB include fisheries, livestock farming. With respect to fisheries, catch yields within the upper Zambezi are approximately 7 500 tonnes per annum and this approximately half of the potential annual yield (14 000 tonnes per annum). Livestock production only consumes about 120 million m^3 per annum (representing less than 1% of total consumptive use). 90% of the livestock in the basin is in Zambia, Zimbabwe and Malawi. Cattle population within the basin is approximately 42 million heads having risen from 35 million in 2005. The WEFE nexus analysis yielded some interesting results, but on the balance of issues, all indicators are marginally sustainable. This information can be used to plan for the future in a sustainable manner in the ZRB.

Study Limitations and the Way Forward

The transboundary Zambezi River Basin (ZRB), the fourth largest in Africa poses many challenges from the perspective of Water-Energy-Food-Ecosystem (WEFE) nexus. The report explored water and agriculture aspects in the Zambezi River Basin focusing on irrigated and rainfed agriculture through appropriate agricultural water management practices. The report was more inclined to discuss crop production in the ZRB as compared to other consumptive water uses because crop production in the ZRB is the biggest water consumer in the basin. The report highlights potential areas (fisheries and livestock production) were riparian member states can focus on for improved income generation for the riparian inhabitants. A more thorough and detailed WEFE nexus analysis is required with robust data sets to aid in the sustainable natural resources planning for the ZRB into the future.

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Water use estimation in Central Pivot Irrigation Systems in the Zambezi River Basin

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Centre Pivot irrigation systems (CPISs) represent a widely used type of irrigated agriculture in the Zambezi River Basin (ZRB). Mainly used for intensified sugar cane production, CPISs account for remarkable amounts of freshwater withdrawals, both from surface and ground water. This study aims to detect CPISs in the ZRB for year 2019 and to estimate related water demands and withdrawals for nine prevalent crop types such as cotton, maize, millet, potato, rape, rice, sorghum, sugar cane, wheat. A deep learning approach developed by Saraiva et al. (2020) is applied to Landsat imagery for automatic CPIS mapping while agricultural data on crop types and related water requirements is obtained from the GISEPIC AFRICA model (Pastori et al., 2011). The water source (surface water or groundwater) used for irrigation is assigned to each detected CPIS unit, allowing estimates for water withdrawals. In 2019, CPISs are present in 38 of the 76 ZRB sub-basins previously identified in the framework of a hydrological SPATSIM model setup (Hughes et al., 2020; Hughes & Farinosi, 2020), with major occurrence and water demands in Zambia followed by Zimbabwe. Assuming an average yearly water requirement of 750mm, as for sugar cane, estimated water demands of all ZRB CPISs amounts to 1032 million cubic meters. A proximity analysis of CPISs and surface water bodies reveals that freshwater is mainly withdrawn from surface water bodies (84%), compared to 16% groundwater used. Detailed estimates at CPIS site level provide an important basis for the CPIS water management both at small and large scale. Moreover, this data provides relevant information to be included in a currently developed groundwater flow model, aimed at assessing groundwater balance at regional scale and investigating the impacts of future scenarios on the surface water - groundwater exchanges. The successfully tested approach will be soon extended from static (year 2019) to inter-annual and -seasonal analysis of CPIS areas and related water demands and withdrawals for ZRB and other river basins, from 2000 to present. A case study on temporal evolution of CIPs in the Kafue plain is also shortly presented.

Keywords: Centre Pivot Irrigation Systems, water demand, irrigated agriculture, LANDSAT, Zambezi River Basin

1 Introduction

In the framework of the development of a groundwater flow model at ZRB (Zambezi River Basin) scale, the need to precisely estimate the spatial location and temporal evolution of groundwater withdrawal emerged. This includes analysis on:

i) the potential of automatic detection of Centre Pivot irrigation systems (CPISs) based on Landsat images at 30m resolution and
ii) the associated water demands for prevalent crop types.

Irrigated agricultural areas are relatively small in the ZRB when compared to total rainfed cultivated areas (World Wide Fund For Nature (WWF), 2003a), but have increased during the last years and contribute to remarkable freshwater withdrawals. According to Ngongondo et al. (in this volume) most of the irrigation withdrawals take place in the regions of Kafue, Kariba, Mupata, Shire/Lake Malawi and Tete. Sugar cane, rice, wheat and vegetables are major crops covering more than 80% of ZRBs total irrigated agricultural area (World Wide Fund For Nature (WWF), 2003b, 2003a).

CPISs as one type of irrigation systems are fully mechanized automated water sprinkler systems of circular shape and relatively large diameter (usually between 500-1000m). They are used for irrigation of most of field crops, cereals, legumes, forage, and vegetables. CPISs optimize the irrigation process and improve the growth of crops, relatively independent from location and climate (change), allowing agriculture even in less favourable but often ecologically sensitive areas. Water use efficiency increases with spatially and temporally precise water distribution and site specific water demands (Farg et al., 2017). The efficiency of central pivot irrigation in the ZRB is reported higher (50%) compared to gravity irrigation schemes with only 38% efficiency because water losses along the water way from CPIS scheme's intake to the crop are lower (World Bank, 2010).

Both surface water and groundwater are used for CPISs, depending on site location and availability of surface water in the proximity. The knowledge of the water availability and crop water demand is fundamental for a sustainable management of CPISs on the one hand and to protect groundwater and surface water bodies from over-exploitation and pollution on the other hand. Potential negative impact on surface water and groundwater needs to be investigated systematically over time, at local and regional scale which often lacks reliable and up to date data.

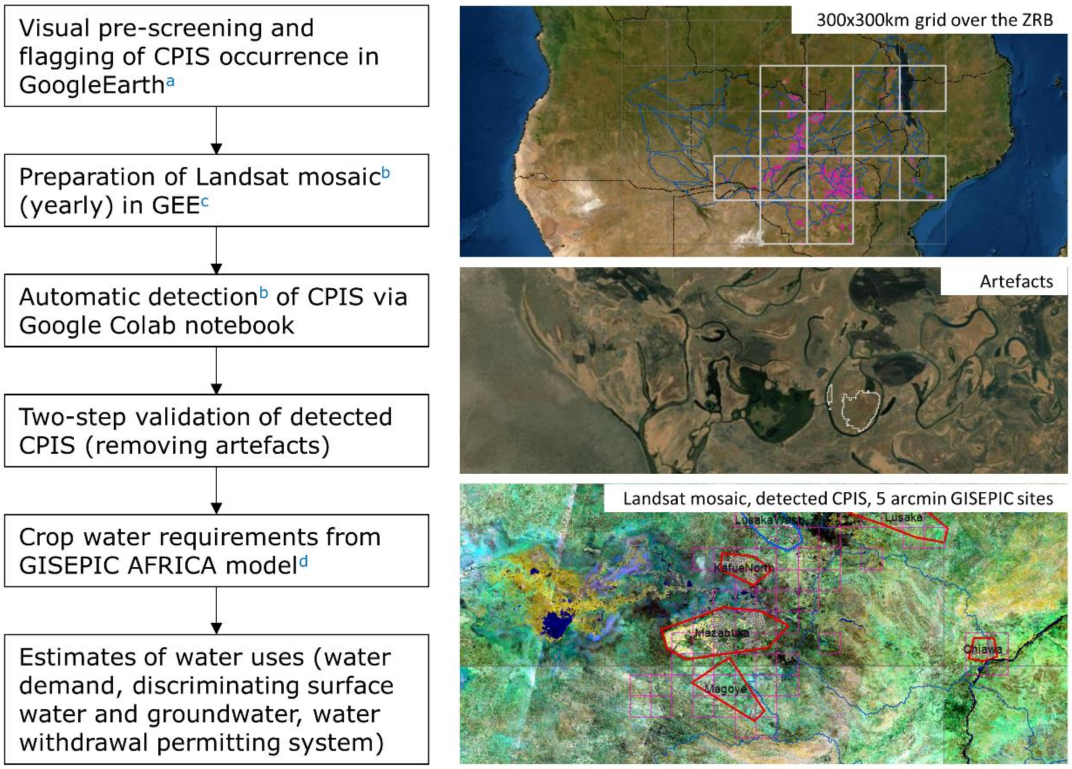
The analysis is performed for the entire ZRB for year 2019. The approach can be transferred from static to time-series analysis, monitoring the yearly and seasonal evolution of CPISs and other irrigated agricultural areas and related water demands. An example for CPIS evolution from 2000 to 2019 is provided for one region in the Kafue plain.

2 Methods

2.1 Automatic mapping of CPIS

Areas with CPIS occurrence in the ZRB are visually identified in Google Earth (Google, 2020b) and allocated to associated tiles of 300x300km extent covering the entire ZRB. For 13 tiles with CPIS occurrence, Landsat mosaics (Collection 1 Tier 1 TOA; 30m resolution; only images below 80% cloud cover considered) are generated in Google Earth Engine (GEE) (Gorelick et al., 2017) for year 2019, using scripts provided by Saraiva et al. (2020). Standard Landsat pre-processing steps (i.e., cloud mask, radiometric correction, TOA-correction, normalization) are applied. In addition, three NDVI based metrics are used to well distinguish CPISs in relation to other areas: i) 75th percentile of NDVI values for all images, ii) maximum value of the NDVI values of all images and iii) the standard deviation of the NDVI values for all images. The automatic mapping of CPIS is conducted by using the deep learning approach from (Saraiva et al., 2020), executed on Google Colab notebook (Google, 2020a). Detected CPISs are cleaned from artefacts afterwards. Small areas below 50,000 m² and wrongly classified circular structures, along meandering rivers or resulting from cloud mask voids, are removed. For 2019, the number of identified artefacts amounts only to 2% of total CPIS areas. CPISs not captured by the algorithm are not documented, but overall accuracy of CPIS detection is stated high in Saraiva et al. (2020). It is expected that the number of artefacts decreases towards more recent years due to better Landsat availability and quality.

Figure 4. Workflow for CPIS water demand analysis, using deep learning approach for CPIS detection (Saraiva et al., 2020)[b] and water requirement averages from GISEPIC AFRICA (Pastori et al., 2011)[d]; [a] Google (2020b), [c] Gorelick et al. (2017)



2.2 Modelling of crop water requirement

The biophysical-agronomic GISEPIC AFRICA model (Pastori et al., 2011) is used to derive the average water requirement (mm/year) for nine prevalent crops cultivated in ZRB CPIS, namely cotton (COT), maize (MAI), millet (PMI), potato (POT), rape (RAP), rice (RIC), sorghum (SOR), sugar cane (SUC) and wheat (WHE). The modelled crop management consists of planting, fertilization, irrigation, tillage and harvesting operations. The timing of management operations is implemented according to the heat units accumulated by crops (Arnold et al., 1998). The crop calendar is retrieved from the global dataset MIRCA2000 (Portmann et al., 2010). This dataset provides the start and end of the cropping period for 26 irrigated and rainfed crops on 402 administrative spatial units at global scale. The amount of manure, mineral fertilization, and irrigation is retrieved from Malagó et al. (2019) for the year 2005 and kept constant through the simulation. Daily data for the other atmospheric forcing variables (temperature, solar radiation, wind speed and relative humidity) are obtained from ERA-Interim (Dee et al., 2011). The simulation period covers 18 years from 2000 to 2017, in addition to 20 years of warm-up used to initialize model variables and allow processes to reach a dynamic equilibrium. Modelled information in GISEPIC AFRICA is provided at 5 arcmin (~10x10km) grid cells (so called "site"). For year 2019, detected ZRB CPISs are covered by 549 sites. The water demand is the product of the CPISs area and water requirement. Since the real portions of crop types cultivated in CPISs are not known, water demands are calculated for each site and each crop type, based on the site-specific CPIS area and crop water requirement. CPIS areas (sum), water requirements (mean) and water demand (sum) are aggregated for each sub-basin and entire ZRB.

Hughes & Farinosi (2020) simulated present and future water use scenarios over ZRB sub-basins assuming a fixed amount of required water for irrigated agriculture of 750 mm per year. This value represents a first rough and preliminary estimation of crop water requirement in the ZRB and is compared with the GISEPIC AFRICA derived average water requirement values for our selected crop types and sites (**Table 1**).

The availability of surface water (dams, reservoirs, rivers, lakes) in the proximity of CIPSs is assessed based on the S2 prototype land cover map of Africa (European Space Agency, 2017). In these cases, surface water withdrawal is assumed for CPISs, otherwise groundwater withdrawal. The resulting values were cross-checked with information provided by regional experts.

Table 1. Average water requirements (WR, mm * yr^{-1}) for nine selected crop types cultivated in ZRB CPIS (549 sites), complemented by the assumption (750mm) from Hughes & Farinosi (2020)

Crop type	COT	MAI	PMI	POT	RAP	RIC	SOR	SUC	WHE	Hughes & Farinosi (2020)
WR	604	391	158	324	404	338	413	724	373	750

3 Discussion

CPISs are detected in 38 of 76 ZRB sub-basins (**Figure 2**), covering an area of almost 1376 km² equivalent to 0.2% of total area of the 38 sub-basins and 0.1% of total ZRB area. Main occurrence is observed in Central Zambia and Northern Zimbabwe and low occurrence in Mozambique and Malawi **(Figure 3)**. 84% of CPISs in the ZRB rely on surface water and only 16% on groundwater, which is in line with percentages stated by regional experts. In Zambia, Mpongwe, Chisamba, Kabwe South and Lusaka West and portions of Lusaka East areas rely predominantly on groundwater **(Figure 2)**. All other areas rely on surface water, either from the Kafue, Zambezi (incl. Kariba), Munshibemba in Mkushi, or from storage dams. In Zimbabwe, CPISs are mainly located in the Mashonaland region, with dominance of surface water withdrawal. Few groundwater withdrawing CPISs are in the NW and SW of Harare, between Kadoma and Chegutu and in the NW of Bulawayo.

Crops with highest mean water requirements within the 549 sites of CPIS occurrence in the ZRB are sugar cane (725mm), cotton (604mm), sorghum (413mm) and rape (404mm) **(Table 1)**. The overall water requirement parameter of 750mm assumed by Hughes & Farinosi (2020) meets well the GISEPIC AFRICA derived mean water requirement for sugar cane, which represents one of the major crop types cultivated in CPISs in the ZRB.

Figure 2. CPIS water source at GISEPIC AFRICA site level (appr. 10x10km). Toponyms of sub-basins with CPISs occurrence indicated.

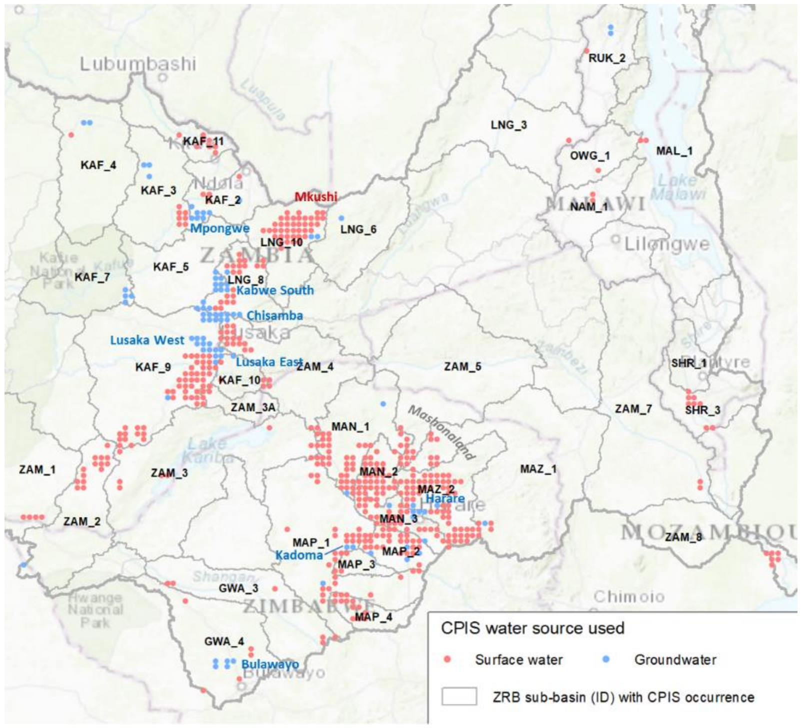
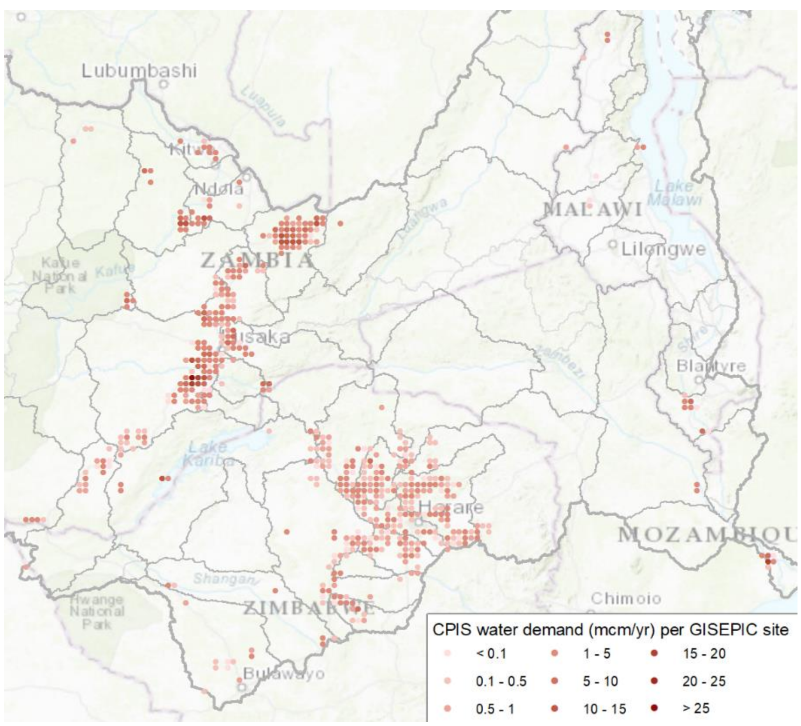


Figure 3. CPIS water demands at GISEPIC AFRICA site level (appr. 10x10km), based on average water requirement value from Hughes & Farinosi (2020) and Hughes et al. (2020).



However, for other important crop-types such as rice (338mm), wheat (373) or maize (391mm) water requirement values are remarkably lower compared to the 750mm. This shows the need for further analysis on crops distribution to further refine water requirements estimate. CPIS water demands are calculated for each sub-basin and for several crop types and compared with the value from Hughes & Farinosi (2020) and Hughes et al. (2020) in **Figure 4**. Assuming 750mm average water requirement the total water demand of all ZRB CPIS accounts to 1032mcm, of which 871mcm are withdrawn from surface water and 161mcm from groundwater bodies. Based on this, the sub-basins KAF_9 (230 million cubic meter (mcm)) and LNG_10 (179mcm) represent by far the highest CPIS water demands of all sub-basins, followed by ZAM_4 (58mcm), MAZ_2 (58mcm), and LNG_8 (50mcm) **(Figure 3 and 4)**. While CPISs in KAF_9 use surface (77%) and groundwater (23%) for irrigation, LNG_10 almost fully relies on surface water withdrawals **(Figure 4)**. CPISs in the sub-basins KAF_5, KAF_7 and LNG_6 fully rely on groundwater, while in BAR_6, GWA_3, KAF_11, LNG_3, MAL_1, MAN_2, MAP_3, MAP_4_NAM_1, OWG_1, SHR_1, SHR_3, ZAM_1, ZAM_3, ZAM_3A, ZAM_5, ZAM_7, and ZAM_8 surface water is used for CPISs. Regions of high CPIS water demands lacking surface water bodies in the proximity are supposed to have potential impacts on groundwater bodies, although most to be further assessed via local knowledge and groundwater flow modelling simulations. An initial analysis on the evolution of CPIS has revealed an increase of the number of commercial CPISs in the ZRB during the last 20 years. As demonstrated for one region near Mazabuka (KAF_9) in **Figure 5**, large extension of CPIS areas have occurred from 2010 onwards.

Figure 4. Estimates of water demands (sorted from highest to lowest) based on yearly water requirement averages (mm*y^{-1}) of nine prevalent crop types at sub-basin level, compared with water demands based on 750mm water requirement from Hughes & Farinosi (2020). In addition, CPIS areas subject to surface water and groundwater withdrawal are reported.

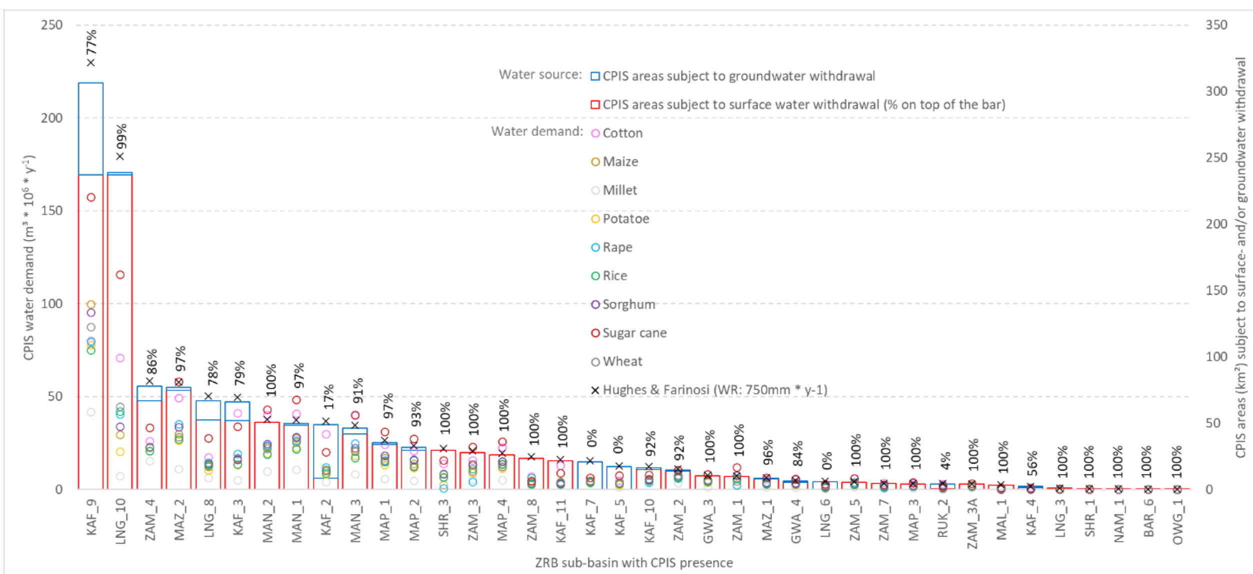
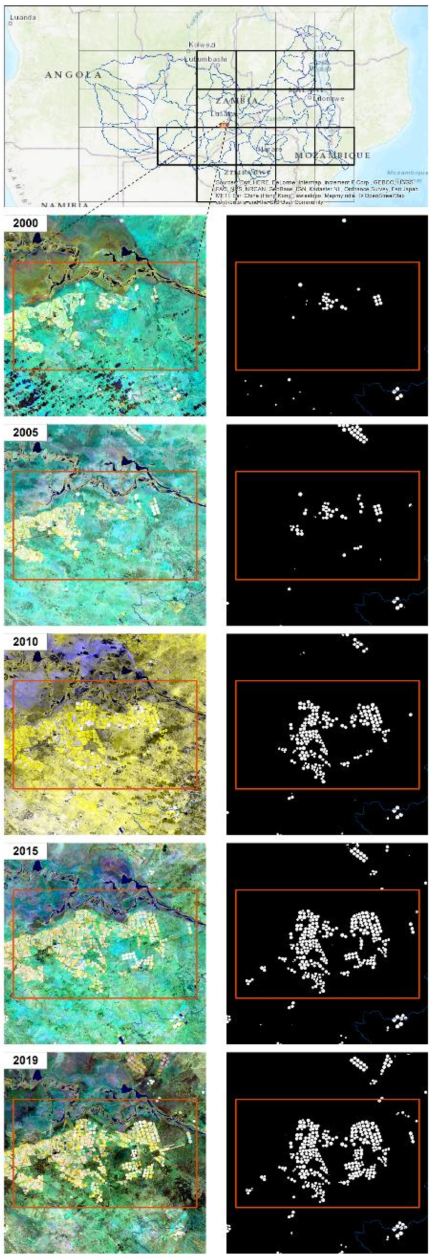


Figure 5. Quinquennial evolution of CPIS from 2000-2019 in the Kafue Plain (Mazabuka, KAF_9), subject to surface water withdrawals from the Kafue river. Pre-processed Landsat mosaic (left) and all detected CPISs (right).



4 Conclusions and recommendations

The presented semi-automatic approach is appropriate to estimate water used for CPISs at multi spatial- and temporal scale, based on deep-learning CPIS detection and agronomic data (i.e., crop types, water requirements, growing periods) as derived from the 5arcmin resolution GISEPIC AFRICA model.

The approach will be extended from CPISs to all types of irrigated and rainfed agriculture, using an adapted algorithm from Saraiva et al. (2020). On top of the static analysis for year 2019, the evolution of irrigated agricultural systems over time (2000-2019) will be monitored at yearly and growing season level, except for areas of poor Landsat image coverage and quality.

The assignment of the water source used by each detected single CPIS will be transferred from visual to automatic procedure through proximity analysis. Depending on the proximity to open water bodies (river, lake, pond, dam reservoir), agricultural units will either be assigned to surface or groundwater withdrawal. It is expected that the portion of groundwater used for CPISs increases with greater distance to surface water bodies unless surface water supply is ensured through piping systems, assumed to be rather rare in the ZRB. Yearly water class layers will be derived from Sentinel 2 imagery for years from 2016 (20m resolution, European Space Agency (2017)) and LANDSAT imagery for years before 2016 (30m resolution, as from Pekel et al. (2016) and EC JRC/Google (2020)). The water use ratio (surface vs. ground water) for irrigated agriculture is an important indicator for water management and protection. Results will be validated and approved by regional experts for each site.

A NDVI analysis will be conducted to automatically monitor growing periods within agricultural clusters (irrigated and rainfed). Differences between NDVI values in areas of rainfed agriculture, irrigated agriculture and non-agricultural land will be analysed over time, at monthly scale. Obtained data will be used to validate and eventually update information provided by GISEPIC AFRICA.

Ground truth data is crucial for complementing and validating information derived from models like GISEPIC AFRICA. It is recommended that regional experts provide the following information on a regular and standardized basis, for each region, or in best case for each 5 arcmin GISEPIC AFRICA site of irrigated and rainfed agriculture:

- crop types cultivated (percentage of occurrence of each crop type);
- crop growing period (start and end month, number of days);
- withdrawn water source (portion (%) of groundwater and surface water withdrawn);

- location of small dams and reservoirs;
- water withdrawal permitting system (how much water is legally allowed to be abstracted).

Precise estimates of water demand and water withdrawal over time for CPIS and other irrigated agricultural areas will serve as input for both surface and groundwater models.

Acknowledgments

Our deepest gratitude to Marciano Saraiva/Agrosatélite Applied Geotechnology Brazil for his exhaustive and direct support regarding the implementation of his developed scripts and algorithms for automatic mapping of CPIS in the ZRB. Special thanks go to Guido Ceccherini/EC-JRC, Susann Günther/Arhs Italy and Fernando Fahl/GFT Italy for their valuable scientific and technical support, to Kawawa Banda/Un. of Zambia, Aidan Senzanjie/Un. of KwaZulu-Natal, Ash Seetal/CSIR, Cosmo Ngongondo/Un. of Malawi and Denis Hughes/Rhodes Un., for their relevant contributions in the framework of the ACEWATER2 deliverables and subsequent discussions. A special thank goes to Doug Lawrence/Imagen Consulting, who provided guidance and ground-validated information on CIPSs and relevance of groundwater vs. surface water use.

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Hydrogeology and Groundwater Quality Assessment of the Zambezi River Basin (ZRB)

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Objectives

The main nexus of the groundwater resource and quality assessment scientific group are:

- Collate, document and review of all existing geological, hydrogeological, water quality, physiography data on a basin scale
- Compile, configure and generate geological and hydrogeological maps with descriptions having consistent and uniform attributes throughout the ZRB
- Compile basin-scale salinity map as a proxy for water quality as well as aquifer productivity, estimated groundwater reserve and aquifer suitability maps
- Archive all spatial data in such a manner that it is accessible to the public
- Provide limitations and recommendations for follow up investigations

Implementation Process

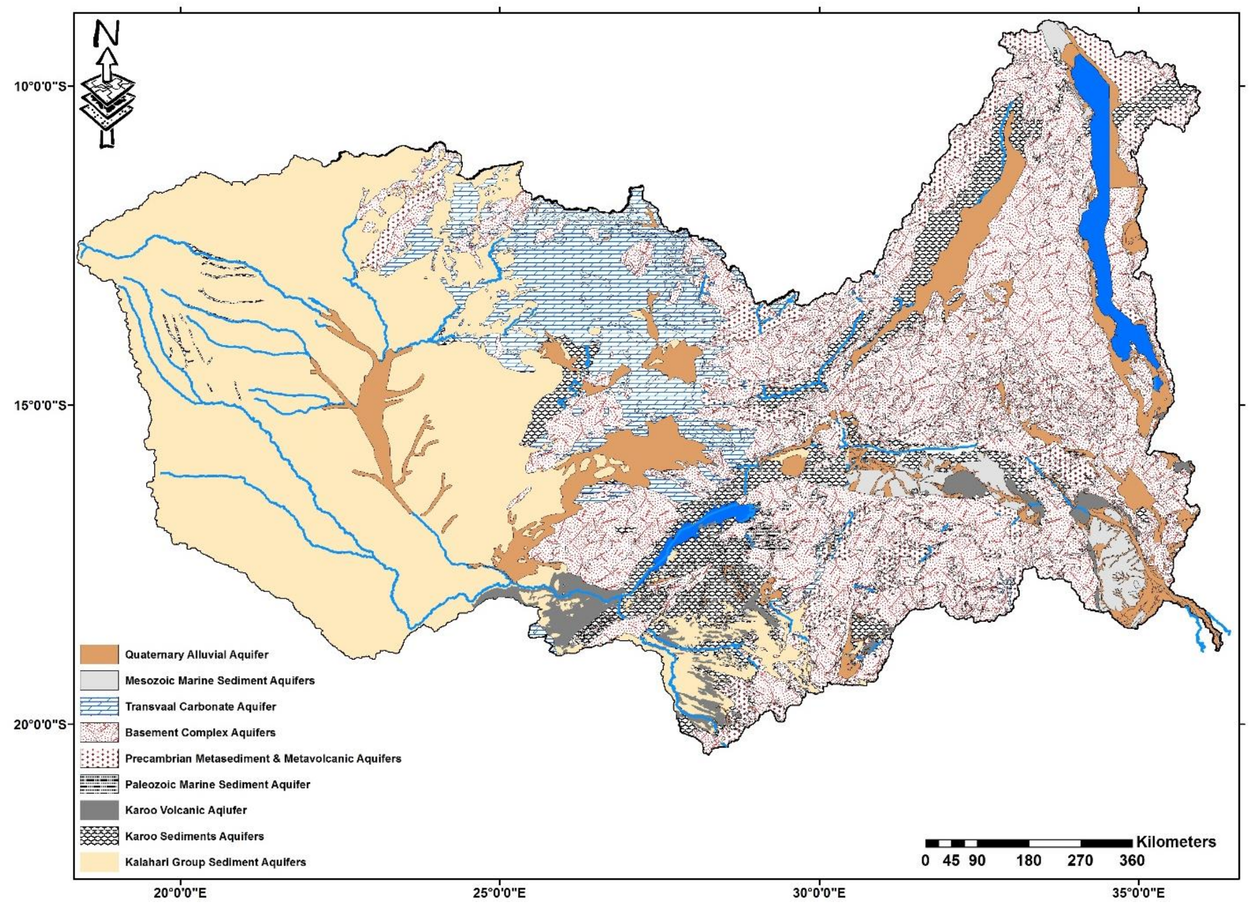
The main tool extensively used for different maps compilation is ArcMap 10.3™ Geographic Information System (GIS) platform. The process begins by loading existing geospatial data of geology from various sources (The Southern Africa Development Community-groundwater management institute (SADC-GMI), The National University of Science and Technology (NUST) Zimbabwe, Waterbase and WaterShed domains from the United States Geological Survey (USGS)). On a GIS platform, manual editing and optimization of the attributes of local and regional geological nomenclature are implemented to homogenize the formation names. Spatial merging and renaming of basin-wide geological units are executed to generate a modified geological map of the ZRB. Data gaps and inconsistencies are refined by scanning hardcopy maps and subsequent georeferencing followed by spatial comparison of existing maps. A revised hydrogeological map of the ZRB is produced by taking the geology map units and incorporate aquifer productivity, storage and storage coefficients of each geological unit and conduct reclassification and layover operations on a GIS environment to produce new aquifer units by taking into account previous aquifer classification on regional scale.

Groundwater quality map is done by taking electrical conductivity data as a proxy salinity. It is relevant to point out that there is low confidence in the groundwater salinity data of the ZRB considering the data comes from a small portion of the river basin and that the low level of analytical data quality. The electrical conductivity data was obtained in a spreadsheet format and new salinity map is produced in SURFER 9.0™ which was then imported as a shape file to ArcMap platform for mapping. Aquifer productivity map is produced by overlaying aquifer yield and aquifer units whereas aquifer development suitability map incorporates aquifer yield with depth to water level, closeness of suitable irrigation lands and groundwater salinity map.

Relevant outcomes

- Modified basin-scale geological map is generated for the entire ZRB comprising of nine
- Modified hydrogeological map is produced that identifies nine major aquifer units namely Quaternary Alluvial, Kalahari Group Sediment, Mesozoic Marine Sediment, Karoo Volcanics, Karoo Sediments, Paleozoic Marine Sediments, Transvaal Carbonates, Precambrian metasediment and metavolcanics and Basement Complex Aquifers (Fig. 1).
- Aquifer productivity map with Quaternary alluvial and Transvaal carbonate aquifers having the highest rating amounting to 22% of the ZRB, aquifer development suitability and groundwater salinity maps are also created indicating high salinity in three areas (two in Kalahari and one in Sire River catchment) and high groundwater suitability in 25% aquifers of the ZRB.
- Aquifer potential storage estimation is made on a basin scale per each aquifer unit leading to the total estimated groundwater reserve of all aquifers to 43 billion m^3.
- Proper documentation and archiving of a large spatial database of geology, hydrogeology, aquifer productivity, storage and suitability as well as groundwater quality was generated and made accessible to the public.

Figure 1. Revised hydrogeological map of the ZRB



Study limitations and the way forward

One of the most obvious limitation of the project is data availability and data access. In many instances raw data in several countries are managed by government entities with poor record of archiving raw data and therefore make data generally non-existent or not accessible. Many government organizations possess large record of reports without any raw data, which is usually retained by consultancy firms. Some private and nonprofit organizations simply refused to share data or in some cases not willing to share data unless the entities are part of the project team. In many instances, raw data (salinity data) does seem to have low reliability in terms of the data quality as no information on data quality control and assessment is available. Another important limitation is the uneven distribution of available data making the accuracy questionable because of data extrapolation to fill data gaps during spatial data analysis. Aquifer storage and transmissivity data is very scarce and assumption was made to uniform value, which makes storage and productivity estimations to be less reliable.

One of the most relevant aspect of the project is producing database that can easily be modified as new information becomes available on a continuous basis. Future projects should continue provide hands-on training on basic field data collection, development a uniform data quality control and quality assessment protocols as well as provide a platform that can be used to archive all raw, semi-processed and processed data. It is also recommended to conduct the resource assessment activity on selected secondary, tertiary and quaternary catchments within the ZRB.

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Zambezi River Basin groundwater flow model: Exploratory spatial analysis based on freely available data sources

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A groundwater flow model was implemented over the Zambezi River Basin using the state-of-the-art DHI-WASY finite element code Feflow, in the framework of the EU funded project ACEWATER2 (African Centers of Excellence in WATER, phase 2). Based upon freely available BGS (British Geological Survey) quantitative hydrogeological maps, the regional hydrogeological SADC-GMI database and the outcomes of new scientific research on groundwater and surface water hydrology conducted by the regional Centers of Excellence and other key leading experts in surface and groundwater hydrology (Un. of Western Cape, Un. of Zambia, NUST/Zimbabwe, Rhodes Un.) at basin and country scale (Zambia, Zimbabwe), the model implementation aimed at: i). investigating and discussing challenges and limitations in applying groundwater flow modelling at the basin scale in a data poor region, in the light of the high geological, tectonic and hydrogeological complexity of the basin; ii. to conduct exploratory spatial analysis relevant to the assessment of effective recharge, return flow to surface water bodies, and climate change scenarios impact on groundwater hydrology. The later assessment was largely based on the outcomes of the calibration of the spatsim hydrological model and scenarios simulation. The study showed that freely available regional groundwater datasets tend to capture the key differences and trends at regional scale. However, this tends to invoke high uncertainty in properly capturing the hydrological and hydrogeological parameters and their local variability; relevant aquifer bodies or hydro features exercising a major control over the groundwater flow can eventually be masked out when aggregating the hydrogeological bodies. This study demonstrates the use of freely available datasets in generating a groundwater flow model for the Zambezi Basin. Groundwater management interventions at basin level can use this model to support sustainable integrated resource utilization.

Keywords: Groundwater flow modelling; groundwater hydrology; hydrogeology; Zambezi River Basin

1 Introduction

Groundwater in Africa can be considered a strategic resource for regional growth and development with an estimated storage of 100 times the continent's annual renewable freshwater (MacDonald et al., 2012). Many believe that this seemingly high annual GW replenishment has the capacity to buffer vulnerability induced by climatic variability (Chebud and Melesse, 2009) and enhance human development linked to the water, food, and energy nexus (Gaye and Tindimugaya, 2012). Lack of detailed information and knowledge (data scarcity) on the availability and sustainable use of GW resources, however, has constrained integrated development initiatives in the basin. The availability and subsequent use of free open source datasets in modelling the groundwater regimes has not been explored in this basin. A groundwater flow model was implemented over the entire river basin, using the DHI-WASY finite element numerical code Feflow (V. 6.2; Diersch, 2014). The choice of the code was motivated by the extent of the study area and by its geological and tectonic complexity, that require a flexible discretization scheme to follow up local details, where needed as along rivers and at major geological discontinuities, while minimizing the overall number of elements by using a rough resolution in the most remote and unknown regions. Sources of free spatial data on recharge and transmissivity was from the BGS database. Existing databases from SADC GMI over southern Africa and scientific research on groundwater and surface water hydrology conducted by the regional Centers of Excellence and other key leading experts in surface and groundwater hydrology (Un. of Western Cape, Un. of Zambia, NUST/Zimbabwe, Rhodes Un.) at basin and country scale (Zambia, Zimbabwe) was used for calibration and validation of the analysis. This work therefore provides a brief recall of model formulation and key parameters, and discusses the details of the uncertainty analysis. The objectives were: i) to develop a critical reasoning on groundwater hydrology model calibration and system behaviour, based on spatsim estimated recharge and related uncertainty. The issue is exacerbated by the high degree of generalization of geological formations and the prevalence of groundwater circulation along fractures in the basement rock outcropping in the eastern part of the basin, ii) to assess the setup of alternative calibration scenarios and the related hydrogeological water balance components, while taking all the above limitations in mind.

2 Method

The groundwater system extent was setup in the same way as the surface drainage basin; although this assumption does not necessarily hold true everywhere - both the extent of the study area and the lack of detailed aquifer geometry at local scale justified the choice. Confined aquifer conditions over the entire domain were assumed; a simplification, that, given the extent and complexity of the groundwater system, was justified by the need to limit the potential instability of the numerical solution process and to speed up the model convergence. No flow BCs (Boundary Conditions) were setup along the outer limits of the model; potential occasional inflow occurring along the southern boundary of Barotse plain and upstream of Victoria falls as a consequence of precipitation and recharge of the Kalahari aquifer system was neglected. Furthermore, highly refined discretization mesh, in the order of 1500 - 2000 m, was setup along the surface drainage network, at lakes and at humid areas, as derived from different datasets, including Hydrosheds, the Hydrolakes and the JRC global surface water (Pekel et al., 2016). Lower resolution discretization mesh was setup in the most remote and unknown regions, to minimize the overall number of elements. Model nodes along major perennial rivers, at lakes and humid areas (e.g. Barotse and Kafue plains) were setup as 1st type Dirichlet Boundary Conditions (BCs). Elevations at nodes were inferred from the SRTM 90 m and the HydroLakes datasets. Where neighboring water bodies exist at sensibly different elevations, as is the case for the many subparallel valleys in the western part of the basin, unrealistic simulated local flows occurred. Inflow generated at the higher elevation BCs are immediately drained, at downstream nodes or simply at lower elevation nodes, as a consequence of the generalization of hydrogeological properties that does not generally capture the local hydrogeological complexity (e.g. transmissivity variability, perched aquifers, multi-aquifer systems). In order to discard such anomalous local artifacts, otherwise impacting on the overall final water balance, nodes inflow at 1st type BCs was finally inhibited, converting them to draining conditions only. In addition, transmissivity (T) and effective recharge BGS estimates (Figure 5 and 6) were transferred to the elements of the discretization mesh.

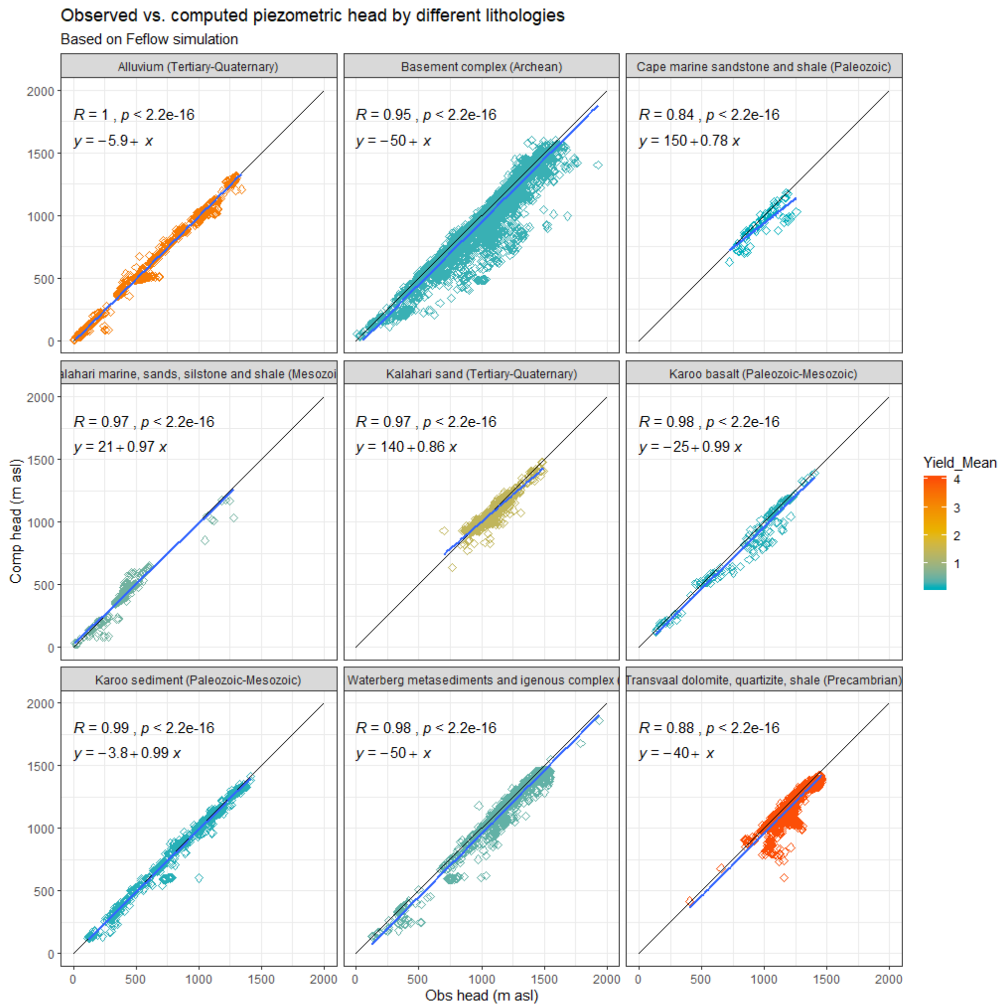
3 Results and Discussion

Freely available world and African scale topographic and hydrogeological datasets can be used to setup a large scale basin, as the specific case study of the transboundary Zambezi River Basin clearly documents. Both finite difference and finite elements codes, as the USGS

MODFLOW and the proprietary DHI-WASY Feflow, can be used to setup this kind of models. Even in the face of complex large scale geological, hydrogeological and tectonic settings, the finite element formulation provides a higher discretization flexibility, by closely defining the drainage network and the relevant features at hydrogeological discontinuities (e.g. faults, fractures, contact between formations). The finite element formulation can generate a rough mesh resolution in the most remote or unknown regions, optimizing the overall number of elements and improving the effectiveness of the numerical solution. The groundwater flow model initial setup, based on the freely available datasets, clearly reveals some major shortcomings. However, these datasets capture the key differences or trends at regional scale ; this is the case for the Zambezi River Basin, that has reducing rainfall rates (and aquifers' recharge) from the N to the S, and a clear distinction between the high transmissivity thick porous media alluvial deposits in the western part of the basin vs. the large outcrops of fractured basement rocks with much lower transmissivity in the eastern basin (Figure 1).

Nevertheless, the highly simplified hydrogeological conceptualization at large scale implies a high uncertainty in properly capturing the hydrological and hydrogeological parameters and their local variability; relevant aquifer bodies or hydro features exercising a major control over the groundwater flow can eventually be masked out when aggregating the hydrogeological bodies. In the Zambezi river basin case study, overestimation of effective recharge, underestimation of transmissivity, or the concurrence of both conditions were clearly highlighted in the eastern part of the basin.

Figure 1. Observed vs. computed piezometric head at calibration



4 Conclusions and recommendations

A groundwater flow model over the Zambezi River Basin aquifer system was developed with the DHI-WASY finite element code Feflow, addressing two distinct objectives: (a) to investigate the challenges in using the freely available African scale hydrogeological datasets compiled by the British Geological Survey (MacDonald et al., 2012) to capture the key hydrogeological parameters (drainage network, recharge, transmissivity); (b) to investigate the groundwater hydrology behavior, based on estimated parameters and related uncertainty in the framework of the spatsim hydrological model calibration of the river basin. The study showed that freely available regional groundwater datasets tend to capture the key differences and trends at regional scale. However, this tends to invoke high uncertainty in properly capturing the hydrological and hydrogeological parameters and their local variability; relevant aquifer bodies or hydro features exercising a major control over the groundwater flow can eventually be masked out when aggregating the hydrogeological bodies. In the Zambezi river basin case study, overestimation of effective recharge, underestimation of transmissivity, or the concurrence of both conditions were clearly highlighted in the eastern part of the basin. The basin therefore seems to have much less recharge but higher transmissivity originally captured by regional estimates. Furthermore, this study highlighted the need for further improvement/refinement of model as data becomes available and the integration of withdrawal into the groundwater model.

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Zambezi River Basin Groundwater Hydrology Characterisation in Zimbabwe

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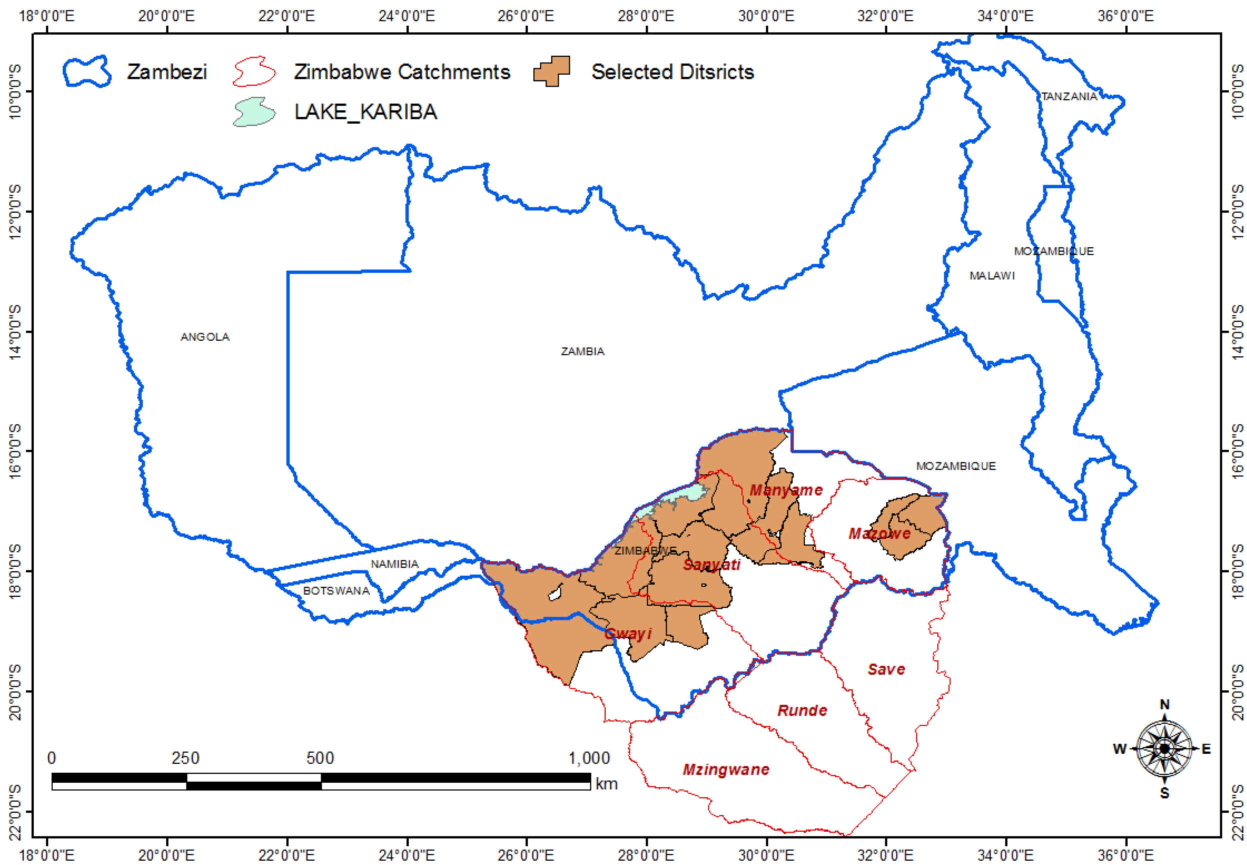
The project "Zambezi River Basin Groundwater Hydrology Characterisation in Zimbabwe" was a contribution to the "Water and Cooperation within the Zambezi River Basin (ZRB)" case study project for Southern Africa Centres of Excellence (CoEs) in the framework of AU/NEPAD ACEWATER2 project. The general objective of the case study project was to assess Water-Energy-Food-Ecosystem (WEFE) interdependencies across the ZRB. Scientific activities such as literature review and spatial data analyses were conducted on the ZRB in Zimbabwe. The scientific activities resulted in the compilation of a baseline report; a spatial database for groundwater hydrology in the ZRB in Zimbabwe; spatial database on water availability represented by re-charge and borehole yields in the ZRB in Zimbabwe and a report on the state of the art aquifer vulnerability assessment and a groundwater vulnerability map for the ZRB in Zimbabwe. It was concluded that the water-energy-food-ecosystem nexus has implications on the demand for groundwater for various uses in the basin and the availability of groundwater in the basin to meet the demand. The nexus is also affected by availability of surface water in the Zambezi River and climatic conditions that allow for recharge of groundwater and generation of energy to access the groundwater for use.

Keywords: Aquifer vulnerability; groundwater hydrogeology; water availability; water demand; water-energy-food-ecosystem nexus

1 Introduction

The Zambezi River Basin is home to over 40 million people and is projected to be 51 million by 2025 (ZAMCOM 2019). Zambia and Zimbabwe have the biggest area shares inside the basin (Fig 1), therefore, their populations in the catchment are also substantial.

Figure 1. Extent of the Zambezi River Basin showing the location of Zimbabwe in the basin (generated from DEM data)



The population for Zimbabwe in the Zambezi River Basin (ZRB) is estimated to be 10.5 million (ZAMCOM 2019).

The combined mean annual surface run-off from the Zimbabwean sub basins is estimated to be 50mm (Sanchez, 2018). The sub basins in Zimbabwe form four of the seven hydrological zones in Zimbabwe. Studies of rainfall records such as by Tumbare (2004) in the basin covering two centuries reveal that droughts were recorded in 60 years out of the 200 years. Studies have also revealed that during the drought years the demand for groundwater for food production increases, demonstrating the interdependencies of Water, Energy, Food and the Ecosystem (WEFE). Droughts are expected to become more frequent and more intense due to climate change (Tumbare, 2004). The general objective of the case study project was to assess Water-Energy-Food-Ecosystem (WEFE) interdependencies by developing and testing a Spatial Decision Support System (SDSS) on Water Cooperation, across the Zambezi River Basin. To contribute to the development of the Spatial Decision Support System on Water Cooperation, the following specific objectives guided the scientific activities related to the groundwater hydrology and quality:

1. To provide a multi-scale groundwater hydrology baseline database at ZRB and selected countries level, based on literature review, available data sources and existing country/regional scale studies of major relevance to WEFE nexus;

2. To provide baseline conditions database on groundwater hydrology and water demand versus availability for few shared regional case studies, by gathering and processing data and by-products and to perform groundwater assessment.

3. To perform vulnerability assessment to contamination of selected aquifers across the ZRB.

2 Methods

The methods employed in the scientific activities involved desktop study of baseline data accessed from the Zambezi Watercourse Commission (ZAMCOM), Southern African Development Community- Groundwater Management Institute (SADC-GMI) and RURAL WASH Information Management System (RWIMS) database as well as from literature. The data was analysed for the following thematic areas:

- Groundwater hydrology

  In this section an analysis of the state and spatial distribution of aquifers in the ZRB in Zimbabwe was made based on the available data and literature review.

- Groundwater availability and quality

  Groundwater availability in the ZRB in Zimbabwe was analyzed in the form of spatial distribution of boreholes and the respective yields of the boreholes found in the river basin.

- Water demand and water use patterns

  Water demand and water use patterns in the ZRB in Zimbabwe were analyzed according to the selected districts in the different catchments.

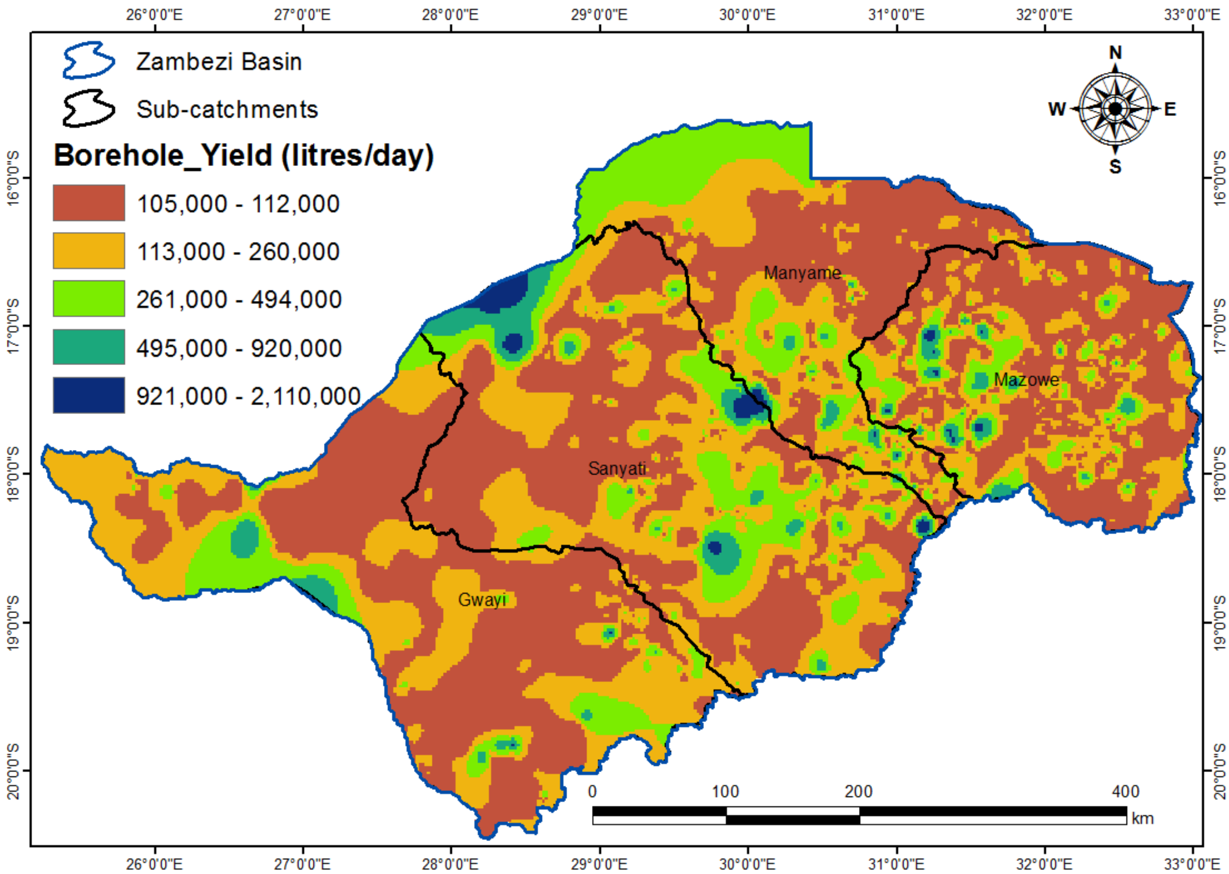
An assessment of the vulnerability of the groundwater to contamination was carried out using the ArcGIS- based model DRASTIC. Inference to the landuse in the different sections of the ZRB in Zimbabwe was done to explain the spatial variations in groundwater vulnerability to contamination.

3 Discussion

Access to water, food, energy and ecosystem (WEFE) services are the four crucial elements for human well-being and they are intrinsically linked (Nhamo et al., 2018). When studying river basins, understanding the interactions between these elements is vital in ensuring that different and often competing needs are met in a coherent manner. Generally, the demand for water, energy, food and ecosystems services and goods is expected to increase in the whole ZRB due to demographic changes, economic growth, as well as changes in climate ZAMCOM (2017). The productivity of the ground water sources in the basin depend very much on the geology in the area and hence vary across the different catchments of the river basin as the geology varies. This is helpful for analysis of WEFE inter-dependences in the river basin. Understanding the hydrogeology of the river basin is crucial in determining the groundwater available in the basin to meet the requirements of the population for food production and other uses. The hydrogeology of the basin also informs the energy input required to access the groundwater at particular locations in the river basin. For example, different technologies and energy are required to access ground water from crystalline and metamorphic rocks with low groundwater potential, and groundwater from Karoo sediments.

An analysis of the availability of groundwater was surrogated by borehole yields which are dependent on the recharge of the aquifers. The yield of boreholes in the ZRB in Zimbabwe was estimated as ranging from 105 m^3 per day to 2110 m^3 per day as shown in Fig 2.

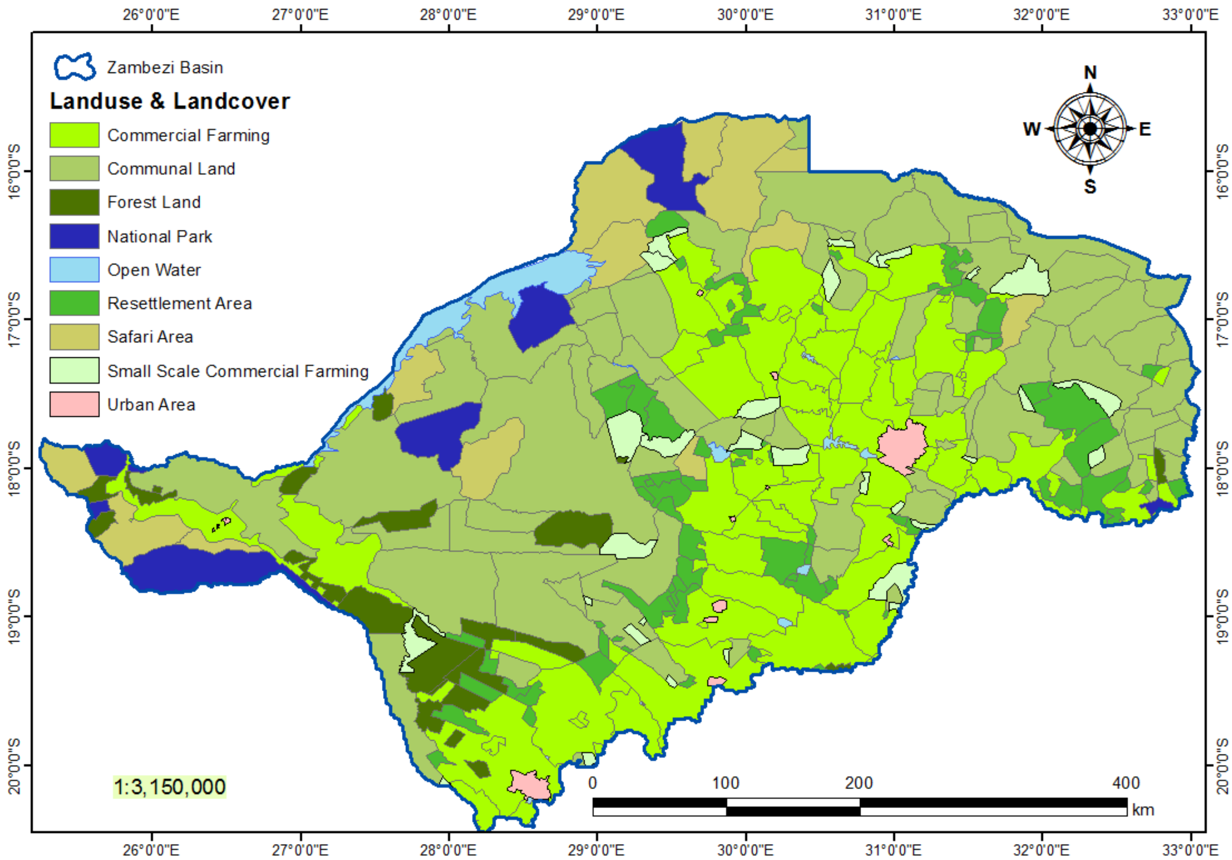
Figure 2. Borehole Yields in the Zambezi River Basin in Zimbabwe (Data Sourced from SADC-GMI, 2010)



The analysis of demand for groundwater was estimated using population distribution in the ZRB in Zimbabwe and was estimated to range from 92 m^3 per day to 135 815 m^3 per day depending on the population in the area. Comparison of the borehole yields and the estimated demand show that the available groundwater is not adequate for the needs of the population in the ZRB in Zimbabwe.

Water demand was analysed in relation to the different land uses in the basin. The different land use patterns in the river basin in Zimbabwe is shown in Fig 3. These land uses are urban land, communal land, small scale commercial farming area, large scale commercial farming area and recreational and national parks. As shown in Fig 2, communal lands are dominant in all catchments. Based on these land uses multiple water demands in the basin can broadly be classified as domestic, industrial, mining, agricultural and recreational water demands.

Figure 3. Land use patterns in the Zambezi River Basin in Zimbabwe (Source of the data: SADC-GMI 2010)



The analysis of primary water sources in selected districts of the ZRB in Zimbabwe revealed that ground water can be accessed through boreholes, deep wells, shallow wells, springs and sand abstraction. The estimated quantity of available groundwater was only from the yield of boreholes and groundwater can be accessed by other means and be available to satisfy the demand.

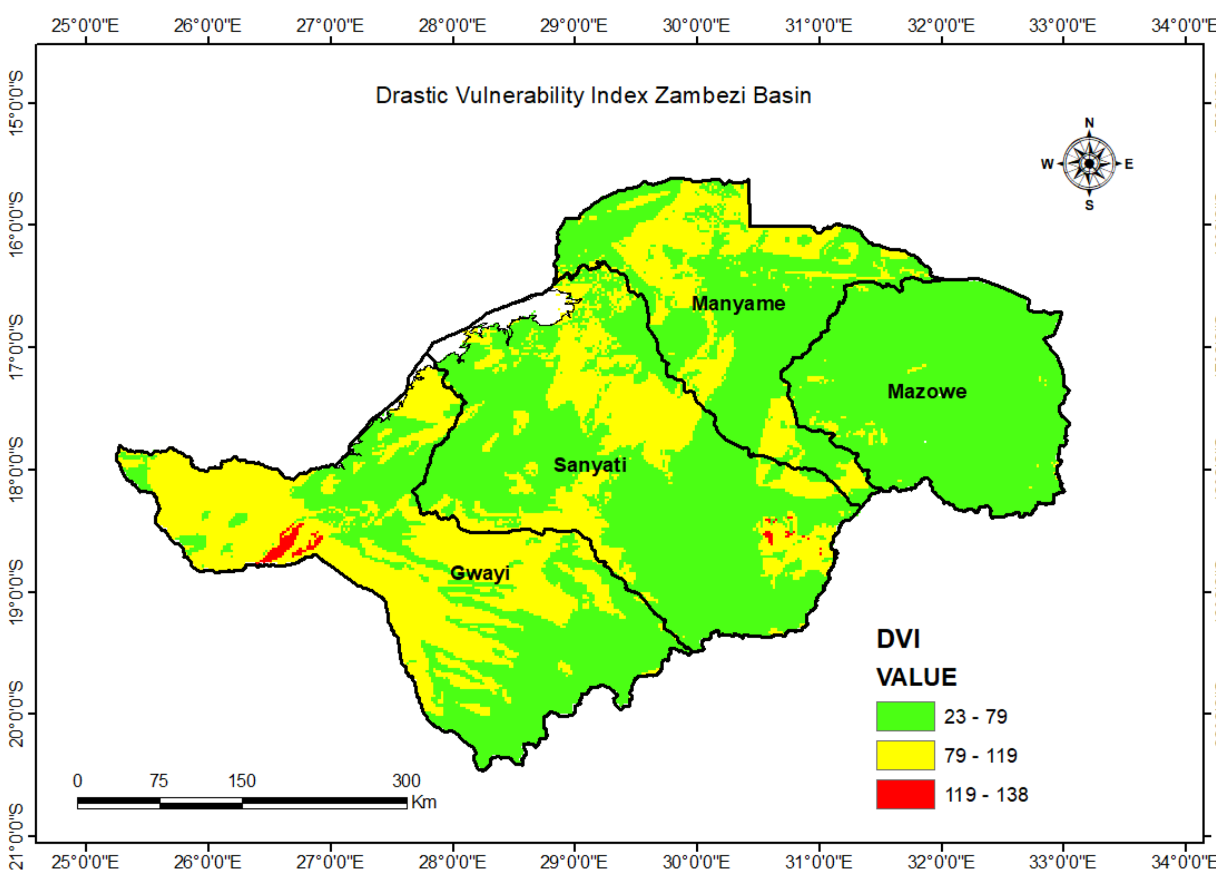
From a Water-Energy-Food-Ecosystem nexus perspective, availability of groundwater is related to the modes of accessing the groundwater as energy is required to access the groundwater. Most rural communities use boreholes, deep wells, springs (where available) and shallow wells for primary water as the technology of accessing the water only requires mechanical energy of the person accessing the water. For sand abstraction to yield reasonable amounts of water there is need for more sophisticated pumping systems requiring energy sources such as electricity or fuels, therefore this method of accessing water is only restricted to communities who can get funding for such technologies.

In the ZRB in Zimbabwe, water has multiple uses which include the generation of electricity at the Kariba Dam. Recent periodic droughts that hit the basin in the past few years had an impact on the generation of electrical energy at the dam. According to Hamududu and Killingtveit (2016) hydropower generation declined in 2015 in the basin due to drought. With a specific focus on the Kariba Dam, the potential annual electrical power generation was reduced by more than 50 percent in 2015 (ZAMCOM 2017). The droughts have made the Zambezi River Authority (ZRA) to reduce water allocations to the Zimbabwe Power Company

(ZPC) from 19 billion cubic metres to 16 billion cubic metres for 2019. In light of this, it can be noted that recurring droughts in the ZRB in Zimbabwe have a negative effect on water availability in the basin's reservoirs which in turn influence energy production. Reduced electrical energy production at Kariba Dam has an effect on food production which is a component of the WEFE nexus. Food production primarily through agriculture is hampered due to the lack of electrical energy that is required for irrigation. Groundwater for irrigation has to be pumped from the source and onto the fields. The crops at risk are the winter crops such as wheat which sorely rely on irrigation. In the basin, electrical energy is also required to produce agricultural inputs such as seed, fertilisers and agrochemicals (ZAMCOM 2017). Industries in the ZRB in Zimbabwe currently (2019), are not able to produce these agricultural inputs at their full capacity due to the long load shedding periods. Therefore, the availability of groundwater in the ZRB in Zimbabwe for food production and other community needs depends on the availability of energy which in turn depends on availability of water resources.

The quality of the groundwater resources should render the water suitable for domestic, agriculture and other uses. The generalized vulnerability assessment shows that the groundwater in Zambezi River Basin in Zimbabwe is low to moderately vulnerable to contamination as shown in Fig 4. The areas of moderate vulnerability such as Hwange in the Gwayi catchment are characterized by mining activities which are potential threats to the quality of the groundwater resources. The vulnerability assessment informs the WEFE nexus in that water for food and domestic use must be of acceptable quality and when this quality is compromised energy is required in treating this water to acceptable standards.

Figure 4. DRASTIC Vulnerability Index of the ZRB in Zimbabwe



In the ZRB Zimbabwe, natural ecosystems play an important role in the fresh water supply to population, hence their inclusion in the nexus. However, due to a number of anthropogenic activities in the basin the natural ecosystems are under threat. Rapid urbanisation in major cities such as Harare have resulted in the construction of houses and industries on wetlands. This is against the background that wetlands are crucial in ensuring the capacity of ecosystems to purify water and reduce the vulnerability of the groundwater to contamination. In a study done by Mucheriwa (2016), Deka River in Hwange was severely impacted by AMD which affects the availability of surface water by aquatic ecosystems, industries as well as domestic users as well as the increased vulnerability of the groundwater to contamination by infiltration.

Unsustainable harvesting of wood fuel resources in the ZRB Zimbabwe also has disrupted the natural ecosystem. According to FAO (2014) disruptions to ecosystems, through unsustainable harvesting of wood fuel resources, will consequently impact the local availability of water. At the same time, a decreasing availability of water contributes to a decrease in wood fuel resources, therefore have multiple impacts on the nexus. Therefore, under the WEFE nexus, there is need for suitable energy schedules and planning from hydropower facilities that cooperate with improved irrigation techniques and smart crop arrangements together with efficient energy use by industries and a holistic approach in planning and management of ecosystems in the ZRB Zimbabwe.

4 Conclusions and recommendations

4.1 Major baseline findings in ZRB in Zimbabwe

- The productivity of the ground water resources in the basin depend very much on the geology in the area and hence vary across the different catchments of the river basin as the geology varies.
- The ZRB in Zimbabwe is generally rich in ground water resources.
- There is a high demand of groundwater in the ZRB in Zimbabwe as the communities in the basin are predominantly rural. An analysis of selected districts in the ZRB in Zimbabwe reveal that on average 82.5% of the households in the selected districts rely on groundwater as a primary source.
- Generally there is not enough data on groundwater quality in ZRB in Zimbabwe to inform suitability for human consumption and promote food production in the basin.
- Access to the groundwater resources is through boreholes and mechanical pumps are used in most cases in the rural communities (54% usage in the selected districts) except on commercial farms, National Parks and private urban homes where energy sources such as solar energy, fossil fuels (diesel, petrol) and electricity are used.
- The type of energy used to pump the ground water as well as its availability have a direct bearing on the amount of food produced from irrigated agriculture in the small scale and large scale commercial farming areas in the ZRB.

4.2 Assessment of vulnerability of the groundwater to contamination

- The generalized vulnerability assessment shows that the groundwater in Zambezi River Basin in Zimbabwe is low to moderately vulnerable to contamination.
- The areas of moderate vulnerability such as Hwange in the Gwayi catchment are characterized by mining activities which are potential threats to the quality of the groundwater resources.

4.3 Water-Energy-Food-Ecosystem (WEFE) nexus across the Zambezi River Basin in Zimbabwe

- Generally access to water, food, energy and ecosystem (WEFE) services are the four crucial elements for human well-being and they are intrinsically linked in the ZRB in Zimbabwe.
- The demand for water, energy, food and ecosystems services and goods is expected to increase in the whole ZRB due to demographic changes, economic growth and climate change.

From a WEFE nexus perspective, availability of groundwater in the ZRB in Zimbabwe is related to the modes of accessing the water from the aquifers as energy is required to access the groundwater.

5 Study limitations and way forward

The major limitation of the study was data scarcity:

- Groundwater quality data in the ZRB in Zimbabwe is very scarce, a generalised assessment of groundwater vulnerability was used for water quality assessment.
- Recharge estimation data was also scarce, and this was accomplished by employing a model that takes into account physical and empirical relationships of spatial patterns of groundwater recharge, surface runoff and evapotranspiration.

The way forward is to coordinate studies on groundwater quality as well as quantity and groundwater recharge in the ZRB to create a comprehensive, sound and accurate up-to date database for planning and future reference.

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WEFE Nexus in the Zambezi Watercourse: A Proposed Governance Implementation Framework

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The wealth of natural and human resources, coupled with its water resource development opportunities, made the Zambezi Watercourse ideal for assessing current governance approaches and its effectiveness to support sustainable socio-economic development impact, particularly community and livelihoods scales, through implementing the WEFE Nexus. There were three phases to the study: firstly, a collation and assessment of the Zambezi Watercourse Commission (ZAMCOM) governance documents and approaches; secondly, evaluating the risks identified in the scientific assessments of the study; and lastly, to support existing ZAMCOM initiatives through practicable interventions that would enhance WEFE Nexus implementation, using the findings from Phases 1 and 2. The study established that there was a wealth of information available about various aspects of the Zambezi Watercourse, including the WEFE Nexus. At a macro level, the ZAMCOM Agreement and the Strategic Plan for the Zambezi Watercourse 2018-2040 address the governance framework and related high-level enabling structures. However, implementation of the governance framework across different geographical scales in the watercourse, particularly at the community and household scales for livelihoods benefits was unclear, as were any tangible WEFE Nexus benefits. The key issue from the scientific assessments was the lack of data on the one hand; and secondly, the quality of the available data could be questionable. This would negatively affect objective scientific assessments that were an important basis for governance intervention decisions. The WEFE nexus governance implementation framework proposed in this study took into account these factors including the unique socio-technical and socio-political dynamics of the watercourse. Consideration of indigenous knowledge systems and traditions and the severe resource constraints that are typical of many African situations were a key factor in the implementation framework configuration. The emphasis of the proposed governance implementation framework is not theoretical or academic, but rather a practitioner perspective that is catalytic, practical and realistic.
Keywords: Zambezi Watercourse WEFE Nexus governance; Practical WEFE Nexus implementation; Evidence-informed policy-making and governance.

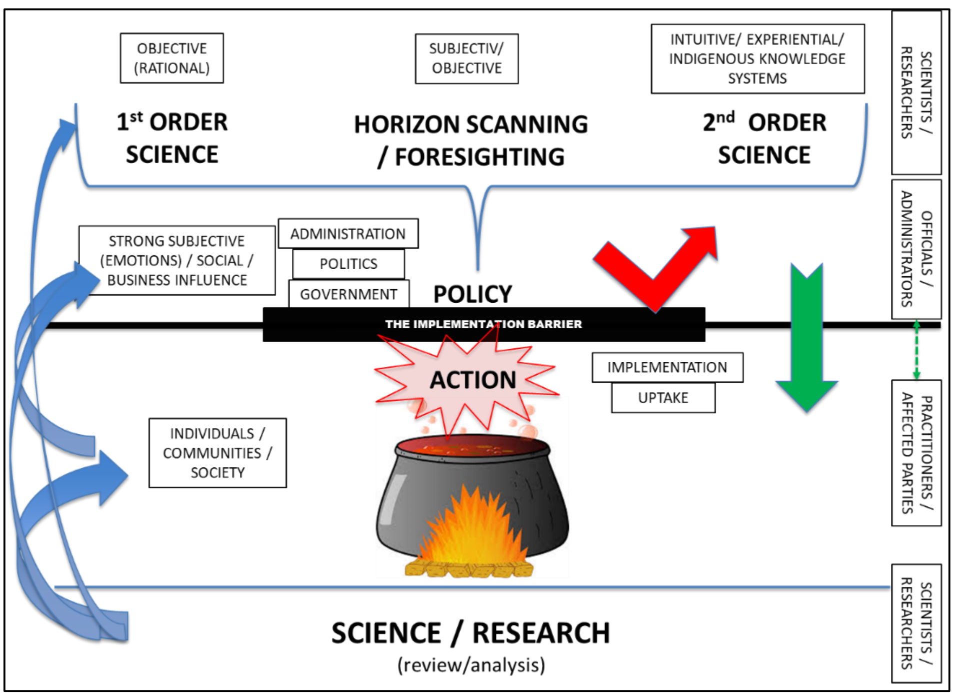
1. Introduction

The transboundary Zambezi Watercourse, the fourth largest one in Africa (after the Nile, Niger and Congo) and second largest in the SADC Region, has a wealth of natural and human resources and tremendous socio-economic development potential that is currently not fully harnessed. It also presents many challenges from the perspective of Water-Energy-Food-Ecosystem (WEFE) nexus issues. Among others, these include hydropower; reservoir multipurpose optimisation and release management; rain-fed and irrigated agriculture development; the impact of land use and agricultural practices; the role of ecosystem services; population increase and rapid urbanisation; and, climate variability/change and extreme events risks (drought and flooding).

These issues pose a significant challenge at various scales within the watercourse, in particular relating to African socio-politics, socio-economic development dynamics and the implementation of integrated concepts and programmes, here termed the "African Conundrum" (Figure 1). Left unattended, these would be a potential cause of water disputes. Conversely, well-formulated and proactive interventions to address the issues can also become a good basis for cooperation among the various role-players, in a manner that benefits all affected parties. That the watercourse is relatively under-developed makes it ideal to demonstrate the practical implementation of WEFE at various geographical scales from a governance perspective, and particularly to realise grassroots livelihoods benefits.

The Africa Centres of Excellence in Water Sciences (ACEWater) Phase 2 project, in collaboration with the Southern African Network of Water Centres of Excellence (SANWATCE), the Zambezi Watercourse Commission (ZAMCOM) and other partners, undertook scientific assessments and the preparation of a manual in support of water governance, cooperation and information systems in the watercourse. This study presents a proposed governance implementation framework for the WEFE nexus in the Zambezi Watercourse, as one of the work package outputs from the project.

Figure 1. The "African Conundrum" depicts the science-policy-action relationship in many country situations (blue arrows). The intended translation of science and policy into action with tangible community grassroots and livelihoods benefits (green arrows) is currently often not realised (red arrow) beyond the policy domain. The WEFE Nexus is an example where there is considerable resource allocation for policy formulation, analysis and research, there is no equivalent or proportionate resource allocation for the implementation of these policies.



2. Methods

The study commenced as a desk-top level assessment, but progressed into a more detailed desktop analysis. There were three phases to the study:

Phase 1 – the initial brief was the collation and assessment of information from ZAMCOM. This was then expanded to include other current and past projects undertaken in the watercourse relating to a range of environmental and water resources management issues and WEFE nexus considerations.

Phase 2 – evaluating risks from the scientific assessments of the ACEWater2 Project and examining other factors including: governance models and theories; managing complexity and uncertainty; trans- and inter-disciplinary science; adaptive management; futures planning and back casting; indigenous knowledge systems; and, second-order science. Other WEFE governance frameworks and models for the Zambezi Watercourse were also analysed for relevance and impact; and,

Phase 3 – configuring an appropriate WEFE nexus governance framework from a practitioner's perspective, contextualised against selected frameworks of relevance including the science-policy interface; policy, institutions and governance; complexity and uncertainty; and, adaptive management. The focus is on implementation for grassroots community and livelihoods benefits and impacts, using the findings from Phases 1 and 2.

3. Discussion

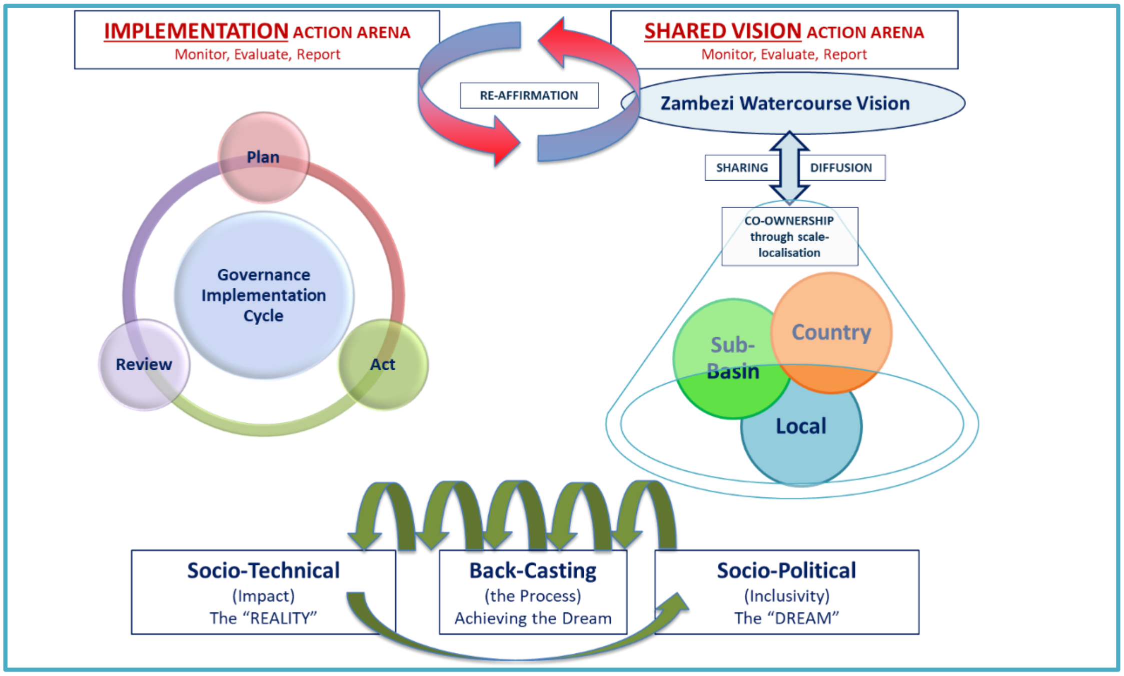
The study established that there was a wealth of information available about various aspects of the Zambezi Watercourse, including studies and assessments not commissioned by ZAMCOM. A comparative analysis of these studies was not undertaken as part of this study.

The key issue emanating from the ACEWater2 Project scientific assessments was the lack of data on the one hand; and secondly, where data was available, its quality could be questionable. The data impact manifested in the quality of the modelling outputs and the level of confidence of the modelling assessments. Related to the availability of data was the issue of poor watercourse monitoring for a number of indicators and parameters required for the different models used in the scientific assessments. This affected the level of confidence that ascribed to the modelling outputs and watercourse assessments.

At a macro level, the governance framework and related enabling structures are contained in the ZAMCOM Agreement and the Strategic Plan for the Zambezi Watercourse 2018-2040. The challenge is the implementation of the framework across different geographical scales in the watercourse, particularly at the community and household scales. In essence, the WEFE nexus had little demonstrable and tangible benefit to the majority population within the Zambezi Watercourse.

In order to address this gap, the proposed WEFE nexus governance implementation framework, shown in Figure 2, was developed taking into account the unique socio-technical and socio-political dynamics of the watercourse including factors described in the Phase 2 methodology, as well as selected frameworks deemed to be relevant, as discussed below. While anchored in the relevant theory, the framework is primarily a practitioner's perspective based on direct experience.

Figure 2. Zambezi Watercourse WEFE Nexus Governance Implementation Framework. Back casting is a process to affirm and realise the shared vision of the watercourse, followed by performing key incremental actions that lead to its progressive realisation. Even though they may be self-standing processes, visioning and implementation are inextricably linked, both addressing socio-political and socio-economic ambitions at appropriate geographic scales. Reaffirmation is a critical 3 to 5-year cyclical action to assess achievements and address changing dynamics.



3.1 Evidence-Informed Policy Making

The role of science in policymaking is an important starting point for all governance and cooperation initiatives. However, the science policy interface is often shrouded in uncertainty regarding the nature of the interplay between them; there is first-order empirical science, second-order experiential and intuitive science and future science. The question of which science is more relevant is a moot point, although there is no reason why all three should not have relevance, particularly in the African policy and governance context which has a strong traditions base.

Hodgson (2010) indicated that the current policy formulation required more than knowledge from scientific evidence to improve its effectiveness and that other aspects such as ethics, aesthetics or a view of the future were also required. In particular, futures thinking is not part of normal science. Thus, unless there was a clearer understanding of the interplay between objective science and subjective human judgement, the contradiction between evidence-based and practical policymaking would remain. The manifestation of this contradiction has been evident from the suspicion and approach taken by some governments where in extreme cases, the science-policy interplay becomes undiscussable since policy is about power and agendas (hidden or obvious).

More recent indications by Hodgson and Leicester (2017) are that evidence-based approaches of policy and decision-making used in government were increasingly falling short of the complexity, uncertainty and urgency of needed decision-making. This is also the view of practitioners in policy and facilitators of change in society, whose intellectual concepts are strongly grounded in experience.

It is clear that the question of decision-making and policy formulation in practice is underpinned by factors which are all equally important: rational (*first-order, empirical science*), those which cannot be reduced to rationality (*second-order experiential/intuitive science*) as well as future perspectives in the form of *horizon scanning and futures thinking*. While the latter two may not conform to the definition of conventional science, all three must nevertheless be treated in a scientific manner.

In the African situation, Fourie (2018) showed that there is now an understanding that the use of research evidence in the implementation of development goals and agendas is not merely a technical process. This applied to the millennium development goals and relate to the current sustainable development goals and water-energy-food-ecosystem nexus. He noted six barriers that make it difficult for African states to use research for policy:

- The **complexity of evidence** where researchers regard scientific papers as the most important form of evidence whereas policy-makers rely on practical knowledge and political understanding. Furthermore, comparative scientific evidence on the same subject may often be contradictory and with different methodologies, perspectives and ideologies;
- An **absence of personal relationships or direct engagement between researchers and policy-makers**. This is identified as a key barrier, since strong personal relationships are important for the uptake of research evidence. Furthermore, the use of technical and scientific terminology would exclude non-academic partners by excluding them from the knowledge creation process;
- **Different timeframes between research and policy-making**. Long and extended timeframes for peer-reviewed research do not synchronise with the urgency of policy formulation responding to sometimes pressing societal challenges and are often a barrier to research uptake;
- The **perceived absence of research relevant to policymakers** resulting in irrelevant research. This ties in closely with the manner in which the research is communicated where scientific norms, conventions and language may detract from the practical relevance of the research, as well as its implementation.
- A number of policy-making institutions, particularly government, lack **the analytical capacity to analyse, interpret and support the uptake of research evidence**. This is exacerbated when there are time pressures and excessive volumes of evidence available to them; and,
- **Policy makers often have budget constraints** and evidence-based policy interventions can be very expensive.

Notwithstanding these six barriers, Fourie (2018) has indicated that building relationships between policymakers and researchers based on expertise and mutual respect is a good response to overcoming the barriers. He further notes, "*it is now understood that the use of research evidence isn't merely a technical process*" which is why the United Nation's 2030 Agenda emphasises the importance of creating partnerships.

3.2 Policy, Institutions and Governance

The Ostrom Institutional Analysis and Development (IAD) framework and Rational Choice Model relating to governance effectiveness was deemed relevant by the manner in which the framework disaggregates and examines the various components relating to policy, institutional formulation, structure and performance (Mcginnis, 2011; Ostrom, 2009). The original framework was adapted for this study to reflect an African perspective.

Its value to the Zambezi Watercourse is in specifying institutional performance in complex environments, particularly relating to action and impact or outcomes. Simplistically put, as shown in Figure 2, the "actor" (a decision-maker at any particular institutional level) analyses possible outcomes from collective choice situations in the "action arena" and implements these. In such situations, institutional arrangements, the socio-economic conditions and the biophysical environment influence the "actor".

3.3 Complexity and Uncertainty

The notion of complexity and uncertainty in dynamic systems is an irrefutable facet of natural systems and existence. This has become more apparent and is increasingly acknowledged with the recognition of the inter-connectedness and uncontrollability of many systems in modern society, irrespective of whether the situation is in the developed or developing world. The water-energy-food-ecosystem (WEFE) nexus and its inward and outward linkages are an excellent representation of this complexity. When coupled with climate change predictions, this complexity has the added and increased dimension of uncertainty.

Existence and co-existence requires unconventional attitudes and measures in order to engage and live in such situations of complexity and uncertainty. The Zambezi Watercourse is no exception and holds much promise in shaping and defining practical approaches to dealing with inherent and imminent dynamic complexity and uncertainty within the watercourse. This must manifest in a manner that provides benefits and security to the overall population within the basin. For the purposes of this manual, the manner in which complexity, ambiguity and uncertainty are addressed become important from the perspective of practical governance to provide the much needed benefits and security.

Systems thinker and complexity activist Wahl (2017) states that the linkages between individual and collective responses to deal with complexity and complex systems are multifaceted and include a number of scientific sub-fields addressing different aspects of complex systems. Several of these disciplines and approaches have already been applied in the Zambezi Watercourse. Wahl (2019) further states that the purpose of science should be to improve our ability to understand the dynamics and relationships of systems rather than to attempt to predict and control them, which would make our participation more appropriate.

3.4 Adaptive Management

Since the late 1990's adaptive management has been gaining recognition as a method having merit for water sector governance. This was primarily because of the complexity of water ecosystems and the absence of certainty regarding the eventual or possible outcomes and impacts of choices and decisions made in managing water resources, particularly in the medium- to long-term. Furthermore, at this time, the potential for climate change impacts on water resources started to emerge and added another layer of complexity and uncertainty. From a practical perspective, the likelihood of water sector management and performance "paralysis" was a highly likely consequence of this increasing complexity and uncertainty, including the desire for "research over-analysis" and "integrated management" of the resource because of its crosscutting role in all systems – this is the practitioners', or implementation, "analysis-paralysis syndrome".

Currently, the DAFNE (Decision-Analytic Framework to explore the water-energy-food NExus) model is being implemented in the Zambezi Watercourse to explore options for sustainable and integrated future management together with stakeholders. This multi-step process enables the quantification and comparative analysis of the WEF nexus with respect to trade-offs between conflicting objectives and facilitates a social understanding of the impacts (van Bers *et al*, 2018).

According to Salmoral *et al* (2019), while the DAFNE Model has not explicitly addressed the degree of certainty relating to climate change complexities or political choices, nor the consensus of decisions made in the participatory process, it has encouraged collaborative adaptive management. Importantly, these relate to Nexus governance in a transboundary context having to overcome the technical and 'most-rational solution' approach paradigm. It must capture political contexts and power constellations by including politics and dealing with normative questions, for example on resource (water and energy) allocations. Salmoral *et al* (2019) also support the view taken in this manual that further, on-the-ground experiences and collaboration between researchers, policymakers and the private sector are needed to demonstrate and realise the complementarities of nexus governance and water diplomacy to achieve the outcome of promoting cooperation in the management of resources at a transboundary level.

4. Conclusions and Recommendations

Overall, considerable effort has been expended to analyse the various issues prevailing in the Zambezi Watercourse, mainly by a number of external/international role-players and funding agencies. The watercourse member states and ZAMCOM welcome this support. However, this also exposes two significant weaknesses that directly affect effective governance and implementation actions – inadequate financial and human resources; hence the dependence on external agencies. These may not be insurmountable impediments if the main governance parties in the watercourse engage more proactively with institutions in their respective countries and within the Southern African Development Community (SADC) region. Current socio-political developments in the SADC region and on the continent favour this course of action.

Notwithstanding the above, listed below are four equally important recommendations considered to be "critical success factors" or enablers of effective governance and WEFE Nexus implementation. Conversely, left unattended these become "fatal flaws":

1. A detailed comparative analysis of the findings from similar studies should be undertaken in the Zambezi Watercourse, particularly in the examination of similar issues using different research and analysis methodologies. Such an exercise would validate findings and ascertain what information and which models (hydrological, economic, decision support, etc), approaches and methodologies would be appropriate and relevant to the Zambezi Watercourse given the data limitations in many parts of the watercourse;
2. The need for better and more monitoring using established and standardised protocols for a range of different indicators is essential, as established from the scientific assessments. The importance and value of good quality data at the appropriate scale for effective WEFE management and governance purposes is unequivocal. In this regard, it is recommended that a watercourse-monitoring framework be established, that would include appropriate indicators and parameters to ascertain changing trends using reliable data and information;
3. A thorough audit of all water use is required to establish a baseline of who the water users are in the watercourse, where they are located, what volumes of water are being used and for what purpose. The monitoring and reporting of all resultant water quality and environmental impacts forms part of this audit. This inventory becomes a basis for all other aspects of water resources management, use and allocations, protection,

conservation, development and control. A universal system of authorisations and allocations administered by a watercourse agency is a strong recommendation; and,

4. In order to effectively penetrate the policy-action barrier, there should be consideration for the establishment of WEFE Extension Service Facility/Centres comprising a cohort of trained and competent personnel in multiple disciplines to support the local implementation of practical WEFE Nexus techniques and interventions. These extension service facilities/centres must be located at strategic points throughout the watercourse for ease of access to communities, preferably working within communities. Facility staff should also be sourced from local communities, in this way creating local job opportunities and contributing to local economies.

Lastly, the approach to the configuration of the governance implementation framework and the four recommendations above in support of it, was predicated on three key elements for the framework operationalisation:

1. **catalytic** at its scale of application and universally throughout the watercourse;
2. **practical**, allowing for ease of application at all levels; and,
3. **realistic** in addressing the key current and future issues in the watercourse.

The framework was the crystallisation of a range of factors, all of which have a bearing on the current intricacies related to WEFE nexus governance implementation. It is intended for universal application within the watercourse, irrespective of the geographical scale being considered; and inclusive of the diversity of intended target stakeholder groupings.

5. Study Limitations and the Way Forward

The current study was initiated at a desktop level and later expanded to include a more detailed assessment. However, these initial assessments have brought to light an excellent opportunity to showcase WEFE Nexus Governance and Implementation at a transboundary scale and in a capacity and resource poor environment.

This manual is NOT an attempt to provide an exhaustive or comprehensive analysis of water cooperation and governance theories and frameworks. Neither is it an academic or theoretical treatise on cooperation and conflict and the respective impacts of each. At this stage, it is also not an analysis of the current status of cooperation and conflict at various/different scales (geographical and temporal) within the watercourse.

Notwithstanding the above and based on the lessons learned, should the proposed recommendations be initiated in a following phase to this study, the prospects are good for commencing WEFE Nexus implementation at grassroots community levels for impact and, in particular, livelihoods benefits. Pilot areas can be selected in each the respective member states to reflect different situational circumstances of the watercourse.

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Urban growth: buildings under construction in Addis Ababa, Ethiopia (February 2020).
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WEFE NEXUS: CONTINENTAL SCALE AND CROSS-CUTTING TOPICS

This chapter covers both thematic and geographic cross-cutting topics relevant to the WEFE nexus assessment, mostly at continental scale. The objective is to complement the scientific research conducted in the selected river basins and to contribute to refine the overall framework.

Most of the contributions arise from activities that have been specifically designed and implemented in the framework of the ACEWATER2 project, thanks to a joint effort of WATER4DEV JRC staff, leading sector experts, and African key stakeholders (AMCOW, RECs, RBOS, research institutions). Project annual and regional meetings, and the constant coordination with the CoEs in shaping effective scientific research relevant to policy making, contributed to inspire these additional efforts. Among the different topics addressed: the HCD and water priorities, in the framework of the energy and agriculture debate; the role of geothermal energy along the EARS (Eastern Africa Rift System); the interlinks among climate variability, water availability and dams impact (evaporation) on water cycle; the current status in groundwater management. Specific contributions arising from Institutional JRC activities complement the analysis, addressing relevant topics related to energy (African Power Pools), urbanisation and connectivity, in view of the expected strong energy demand increase, human settlements expansion and need for good connections to promote economy.

A dedicated space is devoted to the water cooperation atlas. Based on data-driven analysis, the activity has beeing largely debated with all the African partners since the early phases of the project and led to the implementation of a user-friendly GIS tool, aimed at visualizing analysis outcomes and conducting scenarios-based assessments.

A short review of the Aquaknow JRC water portal Knowledge Management Platform concludes the report. It has been actively used to support project documents/data management and dissemination.

Human Capacity Development priorities in the Water Sector in Africa

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The demand for human capacity development (HCD) in the water sector is defined by the role water plays in Africa's ambitions for socio-economic development. Those aspirations are encapsulated by the African Union (AU) Agenda 2063, which emphasises water security as a key priority area. Capacity constraints in the water sector are well documented as posing grave implications for the realisation of Africa's development agenda. The review, thus, analysed the relevant policies and strategies to develop human capital to actualise both the AU Vision; and the Africa Water Vision 2025. There are derivational linkages between the AU's call to a skills-driven revolution to economic transformation; and the vitality of water to the advent of sustainable development. These are used to deduce four broad categories of HCD priorities for the water sector. The first being to encourage technological empowerment, e-education and adaptive learning in fostering opportunities for development and water knowledge sharing across all AU Member States. Second, to integrate flexibility, adaptability and continuous learning in the Technical and Vocational Education and Training (TVET) sector. Requisite reforms include an urgent need to establish officially recognised vocations for water and wastewater management; and, facilitate an image make-over for sanitation related occupations. Third, use of space science and technology to generate sorely needed information to support decision making for the sustainable utilisation of water and related resources. Fourth, recognition of competences from non-formal and informal education and training to – among others – mainstream indigenous water and pollution management knowledge into lifelong learning systems. The relevant key institutional actors – outside the AU-NEPAD African network of centres of excellence in water sciences and technology (CoEs) – are identified. An implementation, monitoring and evaluation framework is also defined and delineates partners' roles and responsibilities. They span leveraging of political and financial commitment; resources mobilisation; coordination; planning and reporting; and project management oversight and accountability for resources and results.

Keywords: water knowledge, human capacity development

1. Introduction

The report on the Human Capacity Development (HCD) priorities in the Water Sector in Africa is prepared as one of the outputs of the ACE-Water project. It is based on an analysis of information gathered by the European Commission Joint Research Centre; and strategic documents of project partner institutions and organisations.

1.1 Objectives

Implementation of the ACE WATER II project was geared towards achieving the following objectives:

i) establishing a human capacity development programme to addressing junior professional and technician level capacity challenges; and,

ii) establishing common sector priorities for higher education institutions at regional level.

Within this context, a desk review of the relevant strategic documents of the mandated institutions in Africa, and the outputs from the project activities was carried out to meet the following requirements:

1. identify actors and sector needs at regional level relevant for water and related sectors, including mapping the most relevant partners and stakeholders;
2. identify priorities with regional counterparts from the documents and discussions available and other strategy documents;
3. propose a draft of an implementation framework together with a Monitoring and Evaluation (M&E) framework; and,
4. summarise conclusion and recommendations to be addressed to AMCOW and the RECs.

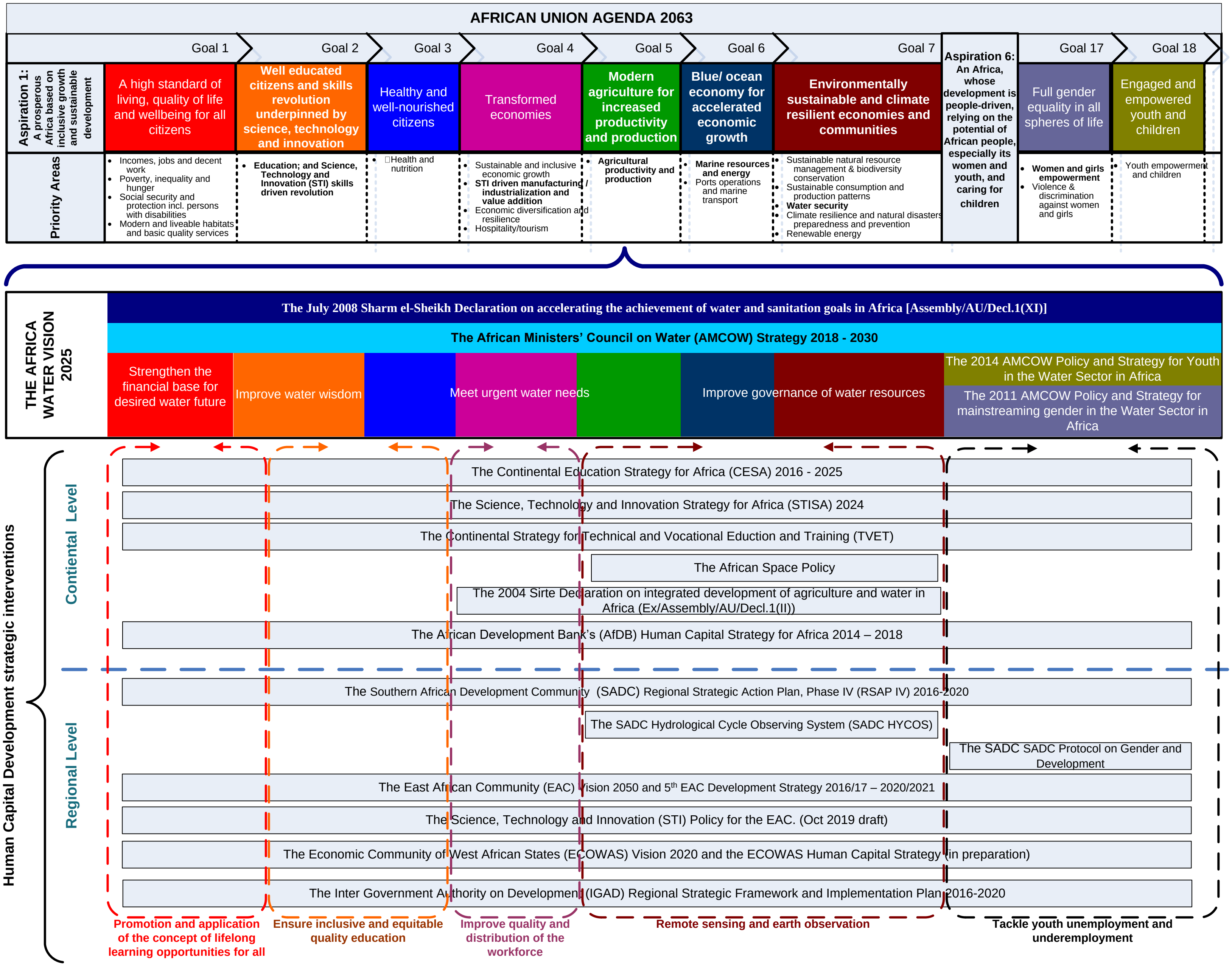
1.2 Methods

The report documents the insights into the water sector HCD priorities gained from the study. The priorities are inferred from expectations of action to respond to the urgent need to implement Africa's development agenda. Macro-level socio-economic development objectives – at continental and regional level – are distilled into specific scientific, technical and institutional priorities for action at national level. Framed by the pillars of the ongoing education reforms to transform society and economies in Africa, the analysis highlights the water sector-related and/or impacting objectives within the macro goals. The specific priorities, thus, derive from the necessary strategic interventions to bolster efforts to improve water wisdom, and – in turn – realise the Africa Water Vision 2025.

The analysis is extended to the related policy instruments and tools designed to foster regional integration; social inclusion; and labour mobility. In this respect, the spotlight is shone on the strategic goals of the RECs that deal with human capital development; gender mainstreaming and social inclusion; education reforms; and water resources assessment, monitoring and management.

A schematic representation of the interlinkages is presented in **Figure 1** below.

Figure 1. Schematic representation of HCD relevant policies and strategies



2. Discussion

The demand for human capacity development in the water sector is defined by the role water plays in Africa's ambitions for socio-economic development as elaborated in Agenda 2063. To the extent that every sector of the economy is influenced by water[6], the realisation of sustained economic growth and social transformation in Africa is dependent on ensuring water security.

The observed trends in Africa's population growth; urbanisation and lifestyle changes have implications for water demands. The anticipated impacts of climate variability and climate change will ravel the form, intensity and timing of water demand; affect water availability; and increase the risk of water-related hazards. A high level of technical ingenuity is, therefore, required to develop the requisite water infrastructure base to release Africa's development potential. A similar level of social ingenuity is also required to adjust to water scarcity and prepare for the adverse impacts of climate change.

Ergo, the need for improved water wisdom. First, to cope with and compensate for the consequences of the anticipated changes in water demands in all economic sectors. And, more importantly, to reliably satisfy those demands to deliver robust, competitive and climate resilient economies; and inclusive socio-economic development and livelihoods improvement.

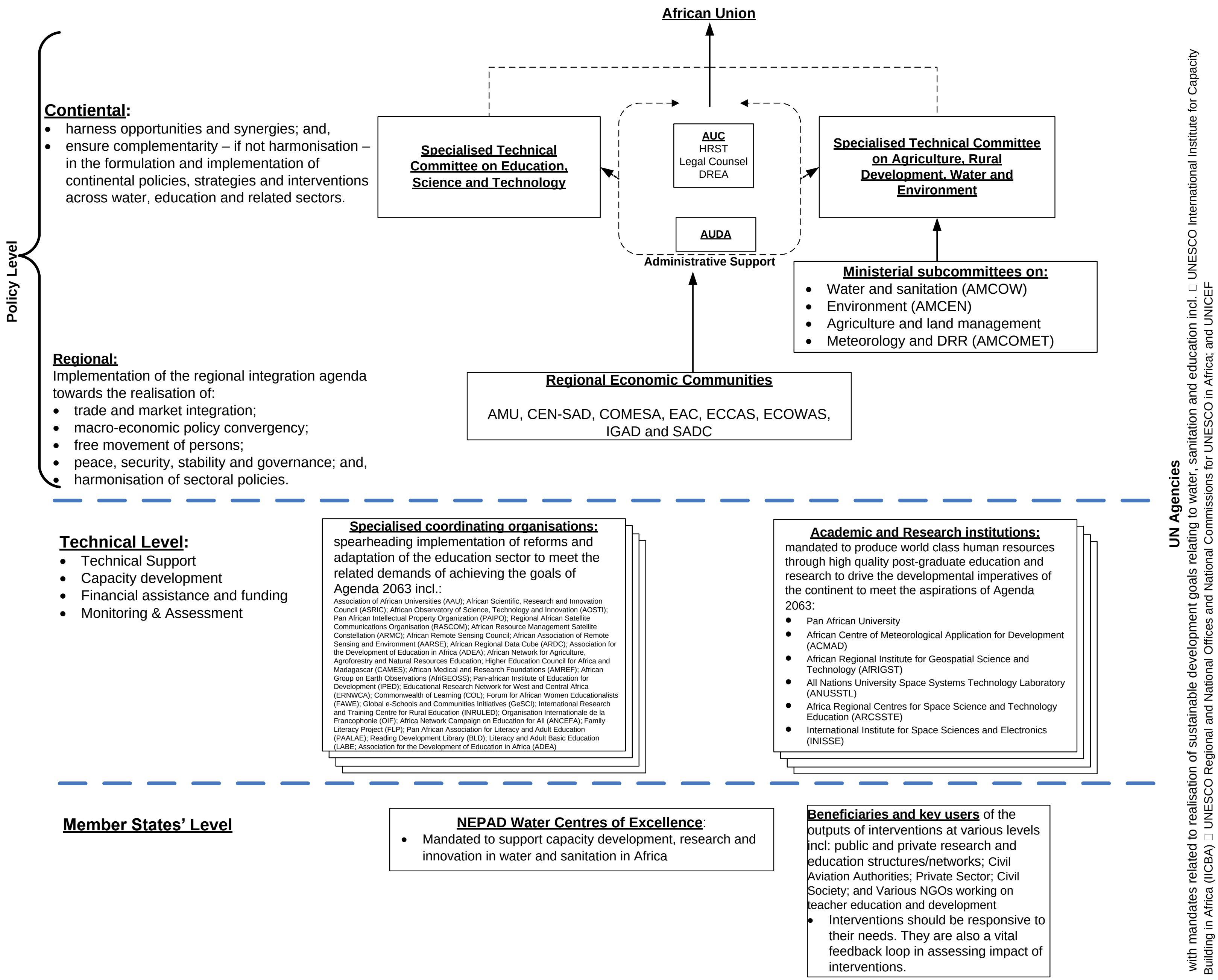
Implementation of the decision of the Executive Committee of AMCOW – EXCO/11/2013/CAIRO/17 – to *"…develop a Human Capacity Development Programme aimed at addressing junior professional and technician level capacity challenges in the water sector"* reflects the broad continental sentiment to underpin aspirations of a prosperous Africa on a skills-driven revolution. The African Union Specialised Technical Committee on Education, Science and Technology (STC-EST) is mandated to develop the requisite human capital to sustain the vision of an integrated, prosperous and peaceful Africa. To this end, the STC-EST is spearheading implementation of strategic reforms in the education and training sector as highlighted in the preceding chapter. These are broadly categorised into:

1. science, technology, innovation and skills development;
2. application of space science and technology;
3. technical and vocational education and training (TVET); and,
4. non-formal and informal education and training (NFET).

The HCD programme – and the overall drive to improve water wisdom – represent one of the facets of the STC-EST's mandated revolution to a knowledge-based and productive society. And as such, the water sector HCD priorities presented in the report are identified within the framework of the strategic reforms in the education and training sector. The report also provides a list of key partners and stakeholders contributing to and or influencing implementation of specific reform themes. The specific roles of key strategic partners in the reform process are summarised in **Figure 2**.

[6] According to Kenessy (1987), direct use of water in the extraction sectors (agriculture, forestry, mining, energy) creates a ripple effect in the processing (utilities, manufacturing, and construction); delivery (transportation, trade); and information (finance, insurance, real estate, public administration) sectors as goods and services are produced and transferred through supply chains until they reach the final consumer.

Figure 2. Roles of key strategic partners in the pursuit of water sector HCD priorities



3. Conclusions and Recommendations

There are derivational linkages between the AU's call to a skills-driven revolution to economic transformation; and the vitality of water to the advent of sustainable development. These are used to deduce four broad categories of HCD priorities as recommended below.

3.1 Skills, technological empowerment, e-education and adaptive learning

These elements should underlie implementation of the Water Sector HCD priorities. The focus should be to build critical skills – vis-à-viz sustainable development, utilisation and management of water and related resources – to enhance economic growth and social transformation.

It is, thus, imperative to grow and strengthen the AU-NEPAD African Network of Centres of Excellence in Water Sciences and Technology (CoEs). It should be transformed into a fully functional, Africa-wide knowledge and excellence network fostering opportunities for development and water knowledge sharing across all AU Member States. The CoEs should, in turn promote innovation to tackle challenges of labour market skills mismatch; and low productivity. They should equip African youth with flexible skills needed for tomorrow's job market. A key focus area should be facilitating the development of such new skills profiles as digital water management specialists and green/smart water use technologists.

3.2 Foster transformation in Technical and Vocational Education and Training (TVET)

Invariably, all continental and regional policy and strategy documents reviewed for the study emphasise the need to integrate flexibility, adaptability and continuous learning in education and training supply. As such, transformation of the TVET sector is necessary to make it suited to impart skills in all areas of training and learning, be they formal, informal or non-formal. This is vital to improve employability, relevance and distribution of the workforce.

Key first steps for the water and sanitation sector include:

1. Developing and instituting officially recognised vocations for the water and wastewater sectors.
2. Raising the level of prestige and attractiveness of sanitation related occupations in particular (waste disposal, wastewater management), as well as eliminating gender inequities.
3. Review of curricula to facilitate water sector skills development from the basic level to the higher education level.

3.3 Support space science and astronomy research, teaching and outreach

Potential abounds for the application of space science and technology to improve the quality of life and the create wealth for all in Africa. This includes:

- i) monitoring and conducting assessments of the environment;
- ii) managing the use of natural resources;
- iii) providing early warnings of and managing natural disasters; and,
- iv) providing education and health services in rural and remote areas.

In essence, space-based solutions are necessary for the effective management of resources such as water, land, forests, marine ecosystems and their productive utilisation. Indeed, many of the space-derived services and products currently used in Africa are imported.

To actualise the vision of "*an integrated, prosperous and peaceful Africa, driven by its own citizens and representing a dynamic force in the global arena*", the development of indigenous capacity to operate and maintain core space capabilities cannot be overemphasised. For the water sector, the implications are clear and germane. Developing remote sensing and earth observation capabilities will enhance the effectiveness of early warning systems. In turn, this will

i) improve related disaster risk preparedness;

ii) assure water, energy, food and ecosystems security; and, therefore,

iii) ensure climate resilient development.

Against the background of the foregoing, the NEPAD-CoEs should – through the HCD Programme – champion:

i. the development of skills and expertise in earth observation and remote sensing applications, and their use;
ii. the development of earth observation services and products;
iii. development of specialised curricula, materials and teaching aids to introduce:
    - space science teaching and research at universities; and,
    - space science and astronomy teaching and outreach at primary and secondary education level;
iv. awareness raising among the public, users, and policy and decision makers; and,
v. knowledge sharing among African experts, users and stakeholders

3.4 Recognition of competences from non-formal and informal education and training (NFET)

There is an urgent need to mainstream indigenous water and pollution management knowledge into lifelong learning systems through:

i. adopting a competence-based approach to curriculum reform within a lifelong learning framework;
ii. improving understanding of, and responding to the demands for individual, community and societal core skills and competences;
iii. creating more opportunities for adult education and community learning opportunities (including NFET schools); and,
iv. tapping into existing technological preferences, cultural practices, local values and traditions of community learning and imparting of life skills.

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Development Priorities of the Water Sector in Africa placed in the context of Agri-Energy sectors

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Reliable satisfaction of water demands is a determining factor of the extent to which Africa's economic growth and social transformation agenda will be realised. The political agenda is dominated by the urgent need to industrialise as a first step to alleviating persistent poverty. The ambition is to build robust, competitive and climate resilient economies; accelerate employment and labour productivity growth; and deliver inclusive socio-economic development and livelihoods improvement. These aspirations – coupled with rapid population growth and urbanisation – translate into multi-fold increases in demands for water for food, energy, economic production, health and the environment. Adding to the complexity are the anticipated impacts of climate change and climate variability. They will change the form, intensity and timing of water demand; affect water availability; and increase the risk of water-related hazards such as floods and droughts. These challenges have been further exacerbated by the COVID-19 crisis. Frequent washing of hands with soap is a key protective measure against the virus. By contrast though, available information indicates that majority of the urban population cannot wash their hands due to constraints in accessing basic water services. Focus is, therefore, on developing and operationalising delivery mechanisms at a scale required to assure water, food, energy and ecosystems security for the people of Africa. Similarly, ensuring the availability of safe water for all is vital to keep up the fight against the spread of COVID-19 and future pandemics. The fundamental development priorities of the water sector are thus inferred as, first, addressing challenges of weak institutional capacities. And, secondly addressing the absence of a compelling business case for investments in water that can catalyse sustained financing commensurate with Africa's development ambitions.

Keywords: water, energy, food and ecosystems security.

1. Introduction

The report synthesises the development priorities of the water sector in Africa. This is done within the context of the express plans for productive use of water in the sectors of energy and agriculture.

1.1 Relevance of Water, Food and Energy Nexus perspectives to EU-AU Cooperation Priorities

The EU Water, Energy, Food and Ecosystems for Development (WEFE4Dev) work programme implements initiatives on WEFE Nexus assessment in relevant river basins in Africa. The integrated multi-sectoral approach to water management at river basin level is combined with proactive and all-inclusive cooperative dialogues. The dialogues draw participation from the policy organs and decision makers of African institutional partners – including the AU-NEPAD Water Centres of Excellence (CoEs).

Among the ongoing areas of cooperation are:

i) developing regional knowledge management systems and decision support tools to support institutions and policy-makers in Africa;

ii) encouraging collaborative research to understand and quantify the inter-linkages between WEFE resources; and,

iii) building the capacity of existing institutions and decision-makers to implement such an integrated approach.

1.2 Water for Africa's economic growth and transformation: a situation analysis

Agenda 2063 describes the vision of Africa, in 50 years' time from 2013, with respect to different aspects of human wellbeing and socio-economic development. The vision comprises seven key aspirations of the people of Africa for the year 2063 with set quantitative targets. The aspirations are, namely:

Aspiration 1: A prosperous Africa based on inclusive growth and sustainable development.

Aspiration 2: An integrated continent; politically united and based on the ideals of Pan-Africanism and the vision of Africa's Renaissance.

Aspiration 4: A peaceful and secure Africa.

Aspiration 5: An Africa with a strong cultural identity, common heritage, shared values and ethics.

Aspiration 6: An Africa, whose development is people-driven, relying on the potential of African people, especially its women and youth, and caring for children.

Aspiration 7: Africa as a strong, united, resilient and influential global player and partner.

Source: (AUC, 2014a)

An indication of the challenges to achieving the goals of Agenda 2063 is summed up by the facts reported here below.

Text Box 1: Situation Analysis of the water sector in Africa

a) Floods, droughts, and water pollution are the greatest threats to water resources in Africa. In only the 8 most prone countries in Africa (Algeria, Egypt, Ethiopia, Gabon, Madagascar, Morocco, Nigeria and Tunisia), flooding is projected to cause direct losses of an estimated US $1.4 billion per annum (UN, 2015)[*].

b) Information available from the African Water and Sanitation Sector Monitoring and Reporting (WASSMO) System indicates Africa's installed hydropower capacity as ranging between 45,936 and 90,696MW out of a reported economically and technically feasible hydropower potential of 304,350 MW (AMCOW, 2016).

c) Water use in the agricultural sector was reported as 275 km^3, in 2016, accounting for about 73.4% of the total water withdrawals in Africa (AMCOW, 2016). Coupled with a generally continuing trend of a diminishing contribution of the sector to GDP in Africa, significant challenges and limitations are noted in efforts to achieve the targets of the Africa Water Vision 2025 relating to increasing agricultural water productivity; and increasing the size of the area under irrigation in Africa.

d) Member States that provided data to the *2014 Africa Water and Sanitation Sector Report* indicated having satisfied, in 2013, just 26.05% of the minimum economic, social and environmental water demands, which in turn gives an indication of the extent to which Africa's water infrastructure is underdeveloped. Similarly, as an indicator of the long-term sustainability of Africa's socio-economic growth and transformation, the figure raises major concerns for Africa's development aspirations especially when it is considered that the underdevelopment of water infrastructure accounts for up to 2% of Africa's lost annual GDP growth (AUC - AMCOW, 2016)!

e) Rainwater harvesting to, on the one hand, augment supply for domestic and agricultural uses, and, on the other hand, manage storm water, is yet to be fully capitalised on by Member States. The continent reported that the contribution of rainwater to the total municipal water consumption accounted for only 1.49% in 2013, compared to the set target of 10% by the year 2015 (AUC - AMCOW, 2014).

f) More than 340 million Africans are still lacking potable water – let alone access to sufficient water to satisfy their basic daily needs – while more than 547 million Africans lack access to basic sanitation (AMCOW, 2016)! The failings in this respect are shown to contribute significantly to: (i) a significant number of the 5,000 people that die each day due to water and sanitation diseases that are easily preventable being from Africa; (ii) estimates of annual losses of 5% of the continent's GDP being due to inadequate provision of basic sanitation services, and, (iii) reductions in household incomes and savings, as well as school attendance – due to the impacts of ailments related to poor sanitation on the labour force – which, in turn, adversely affect economic productivity and the pursuit of poverty eradication goals (AUC - AMCOW, 2014).

g) These challenges have been further exacerbated by the COVID-19 crisis. Frequent washing of hands with soap is a key protective measure against the virus. By contrast though, World Bank figures show that 63% of the urban population in sub-Saharan Africa cannot wash their hands due to constraints in accessing basic water services (Ndaw, 2020). It is noteworthy that urban centres are the main clusters of the virus. It, therefore, goes without saying that ensuring the availability of safe water for all is vital to keep up the fight against the spread of COVID-19 and future pandemics. Improving access to water, sanitation, and hygiene systems holds promise for bringing down the overall disease burden; and reducing the number of deaths to disease.

h) In Eastern Africa, the COVID-19 pandemic is one aspect of a triple crisis that includes the worst locust outbreak in 70 years; and disease outbreaks associated with flooding due to exceptionally high rainfall in 2019 and 2020 (Marsham, et al., 2020). In 2018/19, the impacts of climate variability over the Indian Ocean; the Arabian Peninsula; and Eastern Africa contributed to a locust outbreak (Gilliland, 2020). Combined, the two factors – climate variability and a locust outbreak – underlie the growing hazard of acute food insecurity in the Eastern Africa region. The result is increased COVID-19 vulnerability given the reduced capability of the population to engage in social distancing and to practice basic hygiene!

i) 153 million individuals, about 26% of the population above 15 years of age in sub-Saharan Africa, suffered from severe food insecurity in 2014/15 (FAO, 2017)**

j) Moreover, Africa's water and environmental resources, which are critical to the release of Africa's development potential as well as sustaining growth and development, are faced with severe degradation in part due to inadequate sanitation. Whereas it is yet to be covered within the scope of data collection of the Africa Water and Sanitation Sector Report, information from the Member States indicates that about 90% of wastewater is discharged directly into rivers and lakes without any treatment!

k) The total domestic expenditure in the water and sanitation sector in Africa for 2013 was reported as US $18.48 billion, falling way short of the annual requirement of US $50 billion determined by the AfDB and AMCOW as the minimum required to assure the actualisation of the Africa Water Vision 2025 (AUC, AMCOW, AfDB, GWP, 2019). That, in turn, threatens Africa's aspirations for social progress and productivity of its population.

Sources: *The African Water and Sanitation Sector Monitoring and Reporting (WASSMO) System, http://www.africawat-sanreports.org/IndicatorReporting/report?view=overview&category=fact&level=region*
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1.3 The underlying policy environment for Africa's water development in a WEFE nexus context

The continental policy environment for fostering development within a WEFE nexus context includes the following AU Decisions and Declarations:

1. Ex/Assembly/AU/Decl. 1(II): Sirte Declaration on the Challenges of implementing integrated and sustainable development of agriculture and water in Africa. Second Extraordinary Session, 27 February 2004. Sirte, Libya;
2. the 2008 Tunis Ministerial Declaration on Accelerating water security for Africa's socio-economic development;
3. Assembly/AU/Decl.1(XI): Declaration: Sharm El-Sheikh Commitments for Accelerating the achievement of Water and Sanitation Goals in Africa, Eleventh Ordinary Session, 30 June – 1 July 2008, Sharm El-Sheikh, Egypt;
4. the 2008 Sirte Declaration on Water for Agriculture and Energy in Africa: the Challenges of Climate Change; and,
5. the 2010 Maputo Declaration (AU/MIN/Energy/Decl.) that resolved *"to promot*[e] *cross-border river basins development and regional electric energy production and*

exchange networks" and *"…the Programme for Infrastructure Development in Africa (PIDA)…".*

Deriving their mandate from the policy framework in the foregoing, the mandated institutions are supporting in-country implementation of the declarations. Key among the related initiatives have been:

1. the ***Africa Food Crisis Response*** and the ***Comprehensive Africa Agriculture Development Programme (CAADP)*** to enhance access to agricultural water and irrigation, as well as improving rural infrastructure as part of activities to intensify agricultural production and productivity;
2. the ***20-point Action Plan on Economic Growth*** through water and energy of the African Ministerial Conference on Hydropower and Sustainable development. It focussed on planning and construction of water infrastructure, including 130 dams, to support Africa's growth aspirations. In collaboration with the AfDB, a target was set to increase Africa's water storage capacity by at least 8.5km^3 in the period 2008 - 2013;
3. ***Regional Strategic Action Plans*** for integrated water resources development and management in the SADC and ECOWAS regions; the ***Nile Basin Initiative (NBI)***; the ***World Hydrological Cycle Observing System (WHYCOS)*** project; the ***TIGER (Technology Informatics Guiding Education Reform) Initiative***; the ***Water, Climate and Development Programme (WACDEP)***; and the ***Climate for Development Initiative for Africa (ClimDev-Africa)***. All have been developed with the overarching goal of improving day-to-day water management. In turn, they are contributing to the delivery mechanisms for economic, social and environmental change;
4. the ***Programme for Infrastructure Development in Africa (PIDA)***, the Priority Action Plan of which includes nine transboundary water infrastructure projects; and,
5. the ***African Water Resources Management Priority Action Programme 2016 - 2025 (WRM-PAP).*** It prioritises targeted interventions to achieve four broad goals, namely: i) ensuring water security in Africa; ii) enhancing resilience to climate change and water related disaster risks; iii) strengthening information systems for water resources monitoring and assessment; and iv) improving environmental integrity through wastewater and water quality management.

Additional relevant EU-AU policy initiatives framing the demand for the WEFE nexus approach to water development in Africa include:

1. **the Sustainable Development Goals:**
    a. SDG 2: *End hunger; achieve food security and improved nutrition; and promote sustainable agriculture*
    b. SDG 6: *Ensure availability and sustainable management of water and sanitation for all*
    c. SDG 7: *Ensure access to affordable, reliable, sustainable and modern energy for all*
    d. SDG 9: *Build resilient infrastructure; promote inclusive and sustainable industrialisation; and foster innovation;*
    e. SDG 13: *Take urgent action to combat climate change and its impacts*

f. SDG 15: *Protect, restore and promote sustainable use of terrestrial ecosystems; sustainably manage forests; combat desertification; and halt and reverse land degradation; and halt biodiversity loss*

2. **The Framework for Action to actualise the Africa Water Vision 2025**, of *'an Africa where there is an equitable and sustainable use and management of water resources for poverty alleviation, socio-economic development, regional cooperation and the environment'* sets clear targets for all elements of the WEFE nexus as follows:

Table 1. WEFE related targets of the Africa Water Vision 2025

Actions	Targets for 2025
1. Proportion of people without access • to safe and adequate water supply • to safe and adequate sanitation	Reduce by 95% Reduce by 95%
2. Water for achieving food security • Water productivity of rain-fed agri. and irrigation • Size of irrigated area	Increase by 60% Increase by 100%
3. *Development of water for agriculture, hydropower,* *industry, tourism & transportation at national level*	Increase by 25%
4. Conservation and restoration of environment, in *biodiversity, and life-supporting ecosystems* • Allocation of sufficient water for environmental sustainability. • Conserving and restoring watershed ecosystem	Implemented in 100% of river basins

2. Discussion

Africa's development largely depends on goods and services derived from its environment and natural resources. As Africa pursues rapid and sustainable growth pathways via structural transformation, the management of natural capital, especially water resources, is critical. Water is at the core of the Sustainable Development Goals given its vitality to nearly every aspect of generating social, economic, financial and other wellbeing related benefits.

There are challenges, though, facing AU Member States. The population is growing rapidly. And by 2050, more than 60% of Africa's population will reside in urban areas. The population is also young. More than 40% of the population in most countries is below 15 years old: a large proportion of which is unemployed (AUC, 2014a). Migration within Africa and across the Mediterranean to southern Europe has reached crisis levels. This is – in part – due to political instability in some regions of Africa, but also due to a general lack of economic opportunities (AUC, AMCOW, AfDB, GWP, 2019).

Over the last decade, Africa has recorded sustained and impressive economic growth on the back of rising commodity prices. A dip in commodity prices during 2015 combined with droughts in the Horn of Africa and part of southern Africa, revealed structural challenges in African economies. For most countries, the combined effect of lower commodity prices; limited economic diversification; and over-dependency on mineral resources has been mounting debts and low absorption capacity. Notwithstanding average growth rates of 7% or more among some of the countries, future sustained growth will need to be diversified and inclusive.

It will also have to build on Africa's natural capital endowments especially agriculture – the largest employer on the continent (AfDB, 2018).

The limiting factor is undeniably water insecurity, exacerbated by complex hydrology and climate change.

The economies of many countries in Africa are extremely vulnerable to climate variability and climate change as they are largely based on natural resources (water, land, energy, forests/ecosystems). Inadequate investments to enhance human and institutional capacities; build infrastructure; and improve information systems to support water management exacerbate the difficulties. Just within the scope of this study, only 15 – 30% of Africa's hydropower potential is tapped (AMCOW, 2016). Neither is the huge irrigation potential in its 64 shared river basins being harnessed to assure food and nutritional security.

Also deserving of specific mention are the challenges to the attainment of sustainable development by Africa's Small Island Developing States (SIDS). These challenges are particularly exacerbated by exposure to global environmental issues. Concerted efforts are required for African SIDS to combat climate change; promote sustainable development; and address their environmental and natural resources related vulnerabilities.

In order to achieve rapid, sustained growth in a climate change context, strategic partnerships for water infrastructure development; institutional strengthening; and political leadership are urgently required. Coupled with measures to assure inclusivity of the vulnerable, especially women and youth, resilience to the shocks caused by climate risks will be enhanced. And nowhere more so than in Africa's SIDS where building resilience is integral to deriving full benefit from their often limited resource base. In turn, climate resilient development will lead to sustainable growth and improved livelihoods.

To achieve the SDGs, it is imperative for the African Union and AMCOW to champion a paradigm shift in the approach to developing, utilising and managing Africa's water and related resources. The urgency and need for governments, societies and the private sector to fully embrace the concept of environmental security cannot be overemphasised.

3. Conclusions: emerging water development priorities vis-à-vis the energy and agriculture sectors

In the above context, water sector development should foster an appreciation of the vitality of water in economic growth; job creation; and industrialisation. It should also raise the business case and profile of water in national and regional development. Indeed, aggressive efforts are required to:

i) promote water development as a means to providing a service – which is water for food, energy, industrial production – to the economy in order to enable growth and development to happen;

ii) improve the level of appreciation of the economics of water in development planning at all levels; and,

iii) facilitate investment in strategic water management solutions with transboundary, if not regional, benefits.

From a WEFE nexus perspective, the emerging water sector development priorities can be summarised as presented in Table 2 below.

Table 2. Summary of water sector development priorities from a WEFE nexus perspective

Priority for the water sector	**WEFE nexus synergies and opportunities**		
Water	**Food**	**Energy**	**Environnent**
Strengthening the business case for water investments in Africa	Aspirations for increased agricultural production and productivity, espoused by the CAADP are dependent on commensurate and reliable water access. Its thus imperative that investments into land for agricultural production factor in water development.	Projections of an African population of 1.6 billion by 2030 translate into, at least, a tenfold increase in water needs for energy production to support modernisation of economies and social progress. Implementation of the 19 PIDA water and energy projects (see Appendix 1) is vital not only to increase energy production and access, but also to improve navigation and irrigation development.	Water investments are a precursor to environmental security and, in turn, climate resilient – and therefore – sustainable development
Application of the UNHigh-Level Panel on Water (UN-HLPW) Principles on Valuing Water	Create incentives for water users, including irrigated agriculture, to not waste or pollute water, and to promote its reuse	Prioritise investment in innovative development of energy infrastructure to serve multiple purposes including reducing water related disaster risks and economic shocks.	Value environmental contributions to water management; prevent degradation and pollution of watersheds, rivers, lakes and aquifers; and, where necessary, restore and maintain acceptable environmental conditions and water quality
A new narrative: *"Investing in Water is investing in Jobs"*	Utilise the water-energy-food-ecosystem nexus approach to: i) position water better in the economy; ii) accelerate the pace of water infrastructure investments; and, iii) increase awareness of water's critical role in enhancing job creation; economic growth; and industrialisation.		
Development of water as a means-to-an-end	Pursuit of the Africa Water Vision targets of: i) realising, by 2025, at least 25% of the development potential of water for agriculture; hydropower; industry; tourism and transportation ii) putting in place and fully implementing mechanisms and measures for the conservation and restoration of environment, biodiversity, and life supporting ecosystems		
Investment-led transboundary management and governance of water and environmental resources	i) cross-sector financing/investment to assure viability of investments in water dependent productive sectors (municipal water supply, energy, agriculture, agri-processing, mining, tourism) ii) identifying and quantifying water flows and their relationship with both climatic variables and economically valued inputs – if not limiting factors – to domestic supply, agriculture, industry, mining, energy production and various service industries;		

Priority for the water sector	WEFE nexus synergies and opportunities
	iii) supporting strategic planning processes for use of land and related resources so that water resources utilisation and environmental conservation are optimised; and iv) providing instruments to support public and investor confidence in the amount of water being traded, extracted for consumptive use, recovered and managed for environmental and other public benefit outcomes v) capacity development vis-à-vis valuing ecosystem services, trade-offs and payment for ecosystem services at regional and sub-regional levels vi) managing demand and improving efficiency in the production, supply and utilisation of water in agriculture – including use of waste as a resource in agriculture vii) promoting and facilitating multifunctional "green" basin development centred on natural and built infrastructure to provide a continuum of water storage solutions viii) instituting tariff systems targeted towards better cost recovery in wastewater collection and treatment, while at the same time safeguarding affordability; ix) facilitating safe use of wastewater in urban farming; and, x) bio-gas energy production.

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Analysis of the water-power nexus in the African power pools

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1. The West African Power Pool

1.1 Introduction

The water-energy nexus is the term used to refer to the complex interactions between the water sector and the energy sector. On the one hand, water is needed for energy production, fossil-fuel extraction, transport and processing, or irrigation purposes. On the other hand, energy is needed for extraction, treatment, and distribution of drinking water, and for wastewater treatment and desalination. One aspect of this conundrum is the link between water and electric energy (also known as water-power nexus or water-electricity nexus) when it comes to its quantification within the electric power system.

Within the electricity sector context, the operation and economics of the power systems are constrained by the availability and temperature of water resources since thermal power plants need water for cooling and hydropower plants are fuelled by water to generate electricity. Regarding the thermal power plants, the largest amount of freshwater withdrawals for cooling purposes can be found in North America and Europe representing 86% of the global water withdrawals, whereas the water used for cooling represents 43% of the European Union's water demand. Due to water shortages or high river water temperatures, 'the number of days with a reduced useable capacity is projected to increase in Europe and USA' according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). In fact, water impacts on European power systems have recurrently occurred in the last years and they led to monetary losses, power curtailments, temporary shutdowns, demand restrictions, and ultimately increased wear and tear of the power plants. On the other hand, the operation of the power system may impact on the quantity and quality of the water resources.

The combined effect of increased water consumption, for energy and non-energy purposes, with lower availability of water resources due to climate change is expected to lead to similar problems in Africa. According to the World Bank[7], electricity and water demands are projected to grow significantly up to 2050 in Africa, by 700% and 500% respectively, with respect to 2012. In most African energy systems hydropower is the dominant renewable energy source. Other salient characteristics of these systems are their small sizes, the low electrification rates, the high shares of oil in the power generation mix, and the lack of significant power and gas interconnections.

The Joint Research Centre of the European Commission (JRC) has developed a fruitful cooperation with the African Union and its institutions, in line with the EU-Africa Strategic Partnership[8]. This cooperation aims to provide evidence-based scientific and technical support to decision makers, as well as to universities, research institutes and the scientific community at large, thus also contributing to the fulfilment of the objectives defined at the Rio+20 United Nations Conference on Sustainable Development[9]. Water and renewable energy feature among the key priority areas for cooperation.

African energy issues have received increased attention on the European policy agenda and this focus has been further elevated with the recent communications on the European Green

[7] World Bank's Thirsty Energy Initiative: http://www.worldbank.org/en/topic/water/brief/water-energy-nexus.
[8] See https://www.africa-eu-partnership.org/en and http://www.aeep-forum.org/en/home.
[9] https://sustainabledevelopment.un.org/rio20.

Deal (European Commission, 2019), which stresses that 'climate and environmental issues should be key strands in relations between the two continents', and the communication on a comprehensive strategy with Africa (European Commission, 2020).

Africa is currently confronted with a variety of challenges in the electricity sector. According to the International Energy Agency (IEA, 2017) close to 600 million people are still without access to electricity in sub-Saharan Africa (SSA). Those who have access to electricity often suffer from supply interruptions. World Bank data (The World Bank, 2019) shows that countries in SSA experience annual electricity outages ranging from 50 up to more than half of all year's hours per year. Different reasons tend to cause the blackouts and brownouts in the electricity grid; chief among them are infrastructure failures and capacity shortages when the expansion of the generation fleet cannot keep up with demand growth. Since in many African countries hydropower accounts for a large fraction of the total generation capacity, periods with low water inflows are another major thread for generation inadequacy and thus supply disruptions. These supply disruptions go along with negative economic and health consequences. When electricity is not available either load has to be shed, triggering for instance economic processes to be put on hold, or diesel-generators have to be ramped-up. The latter response also negatively affects air-pollution levels and can be three times more costly than grid-electricity according to a study (Farquharson, Jaramillo, and Samaras, 2018).

Recognising the benefits of cooperation across countries to confront the energy challenges dating back since the late 1980's, power pools have gradually emerged in Africa. Today five power pools are established in Africa that comprise the Central, Eastern, North, West and Southern African Power Pool respectively. Each mainland African country is member in at least one power pool and few countries are members in or more pools. The aims of the power pools are to jointly plan and operate the power systems across the countries, which is reflected in growing levels of interconnections and the gradual establishment of a market-based coordination approach. There are also plans to establish interconnections between power pools.

The report **"Analysis of the water-power nexus in the West African Power Pool" (JRC115157)** describes the modelling framework developed by the JRC for analysing the water-power nexus, in the framework of the Water-Energy-Food-Ecosystems project (WEFE). WEFE is an internal JRC project that supports the design and implementation of cross-sectoral policies looking to improve the resilience of water-using sectors and the preservation and sustainability of freshwater resources.

This first report focuses on the West African Power Pool[10] (WAPP). for several reasons[11]:

— The WAPP region[12] has a significant rate of economic growth, with demand for water, food and energy on the rise.

— The WAPP member states are also considered highly vulnerable to climate change and are already experiencing impacts on their agricultural productivity, food, water, and energy security.

— The area is rich in water resources (approximately 27% of Africa's internal renewable water resources), but suffers from chronic water deficits because of uneven distribution

[10] http://www.ecowapp.org/.

[11] http://www.ecreee.org/sites/default/files/ecreee_policy_briefpolicy_brief_managing_resources_for_sustainable_devel.pdf

[12] Consisting of Benin, Burkina Faso, Cape Verde, Ivory Coast, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo. All the analysis has been made at national level, considering each country of WAPP as a node of the system (except Cape Verde which is disconnected from the rest of the system).

of rainfall and flows in time and space, insufficient knowledge about water resources, low allocation of potential resources, and poor resource management.

— The region has plenty of energy resources but they are also unevenly distributed, and the renewable energy potential is underused. Electrification rates are low and there is a high dependence on biomass. The power generation mix has a significant share of gas and oil power plants and the interconnections between countries are very limited.

— The goal of WAPP is to integrate the national power systems into a unified regional electricity market with the ultimate goal of providing in the medium and long term, a regular and reliable energy at competitive cost, under the auspices of the Economic Community of West African States[13]. For that pourpose there exists an ongoing cooperation to promote and develop power generation and transmission infrastructures as well as to coordinate the exchange of power among the WAPP member states.

The overall objective of this report is to show that the proposed modelling framework may be used to analyse the water-power nexus in large areas, such as the WAPP, with a high temporal and spatial resolution and with the most accurate data. Specifically, this work aims to:

— Present the methodology for the analysis of the water-power nexus.

— Describe the available public data sources used for modelling the WAPP case study.

— Validate the proposed approach comparing the outcomes of the model with the available historical data and testing the behaviour of the model in a near-future scenario. This is accomplished by applying a framework that combines the use of the Dispa-SET and LISFLOOD models. Then, the reservoir levels are passed on to the Dispa-SET Unit Commitment and Dispatch (Dispa-SET UCD) module, which runs for one year at hourly time steps.

This study also serves as a basis for possible future capacity building activities by providing a set of open source tools and data that can be used by researchers or practitioners across the region. In particular, this study is expected to:

— Serve as a proof of concept of a methodological approach for analysing scenarios with high penetration rates of electricity from renewable energy sources (RES-E) in African power systems. This methodology, based on open models and data, could be used by policy makers, regulators, transmission system operators and investors taking informed decisions.

— Produce a good estimation, using new methods applied to publicly available data, of key data currently missing needed for analysing the water-power nexus, in particular i) time series with hourly load profiles, ii) time series of wind and solar availability factors, and iii) gaps in power system infrastructure and reservoir datasets. All those data are the minimum inputs needed for addressing storage and flexibility needs in African power systems.

— Lay the foundations for carrying out studies on geographically and technologically optimised high RES-E systems for the African continent.

1.2 Conclusions

The modelling framework presented in this study provides a tool able to simulate with a very high level of detail the water-power nexus in the Western Africa Power Pool.

This level of detail and complexity is needed to carry out an in-depth analysis of the impacts of the availability of water resources on the operation of the WAPP power system.

[13] http://www.ecowas.int/

The model can quantify the economic impacts, the emissions, the water withdrawn and consumed, and the detailed operation of the power system (scheduling and use of interconnectors) under current and future assumptions on climate conditions, energy demand, etc.

The study rests on an extensive review of data and information sources, and also provides a method to deal with the lack of detailed information on the electricity demand and the generation from renewable energy sources. The analyses of future policy cases of the WAPP will be able to build on these data, available at the JRC Data Catalogue[14].

One of the main objectives of this study has been to explore the validity of our modelling framework. We find that the Dispa-SET model behaves soundly, despite the data-related limitations, replicating the available statistics up to a great extent, and the outcomes of the simulation are robust since they are based on long time-series of climate data. Therefore the data and the model presented in this study can be used to support the design and the monitoring of energy- and water-related policies.

Even though the focus of this analysis has been on testing the validity our analysis also reveals some planning / policy related conclusions. We show that the future operation of the WAPP power system significantly depends on the availability of water resources, which is however outside the control of policy planning. This dependence translates into a high volatility of the system cost. We show that the thermal capacities scheduled to be commissioned in the WAPP master plan can mitigate this volatility to a certain extent. This however goes along with an in average higher electricity bill and increased emissions. Future policy scenarios should therefore explore which technology portfolios would be most suitable to achieve low volatility, low cost and low emissions simultaneously.

Moreover, on the technical side there are several possible improvements that could be added to the modelling framework described in this report in order to obtain more accurate results and better insights:

— Better data on the demand of electricity and water.

— Better data on the operational conditions and constraints of the power plants, thermal and hydro, the cross-border exchanges, and the national networks.

— More information about the river network and the reservoirs in order to implement cascading constraints.

— Analysis of future climate scenarios wherein the consequences of water scarcity would be exacerbated and the vulnerability of thermal power plants would be higher.

— Implement constraints on the water stress and the temperature of the water in order to better analyse extreme conditions and the vulnerability of key individual power plants (usually the ones with the highest capacity).

— Stochastic modelling to produce a more robust mid-term hydrothermal scheduling for the unit commitment model.

— Better representation of the demand of water for non-energy purposes.

In addition to the enhancements listed above, the extension of the analysis to other African power pools would allow studying the options for large-scale integration of renewable energy sources, by testing future scenarios assuming more interconnection capacities within and between the African power pools, and analysing in more depth (e.g. impacts on water

[14] JRC Data Catalogue https://data.jrc.ec.europa.eu/collection/id-00134, as well as https://github.com/energy-modelling-toolkit/Dispa-SET (model code), and https://zenodo.org/deposit/3839756 (databases).

temperatures) the consequences of the interactions between the water and power system in wider areas.

2. The Southern African Power Pool

2.1 Introduction

The study **"Analysis of the water-power nexus in the Southern African Power Pool" (JRC121329)** focusing on the Southern African Power Pool (SAPP) is the second of a series of JRC studies investigating the water-power nexus in Africa. Historically, the Southern African mainland has been weakly electrically interconnected, allowing only for very small volumes of electricity exchange. The first exchanges took place between the Democratic Republic of Congo, Zambia and Zimbabwe in the 1960s' followed by an interconnection between Mozambique and South Africa in the 1970s' (Wright and Coller, 2018). This resulted in two distinct (northern and southern) interconnected systems in Southern Africa. With the Cahora Bassa Dam in Mozambique finished in 1974 the interconnection with South Africa provided a window into how pooling the large coal resources in the southern part (South Africa, Botswana) with the hydro rich North (Congo and Zambezi basins) could be beneficial for the whole region. It was in 1995 when the northern and southern systems were interconnected through a 400 kV link between Zimbabwe and South Africa. This year marked the establishment of the Southern African Power Pool under the Southern African Development Community (SADC). Its coordination centre was set-up in Harare, Zimbabwe, and its twelve member countries comprise all mainland members of the SADC. At the time of writing, Angola, Malawi, and Tanzania do not have connections yet with another member, but new electricity lines are in the planning and expected to be operational within a foreseeable time-span.

In terms of market development the SAPP is regarded the most advanced among the African power pools (Infrastructure Consortium for Africa, 2016), having been the first among the pools to establish a competitive day-ahead market in 2009 and intraday and forward market segments subsequently. The SAPP member countries though are quite heterogeneous when it comes to population size and status of economic development.

Power generation in the SAPP largely relies on two types of energy carriers: coal from the fields in South Africa and Botswana and water stemming from the Congo, Orange and Zambezi rivers and their branches. These two forms of power generation are both water intensive, exposing the electricity generation in the SAPP region to water scarcity risks through for instance heat waves or competition over water resources. Coal, as is the case for all thermal plants, requires water to cool down plants' high temperatures, so that a water shortage or too warm water can impede this process. Hydropower plants convert running/falling water – mechanical energy – into electrical energy – without water there is no energy source to convert (Wang, Schleifer, and Zhong, 2017).

Particularly in recent years diminished and late or irregular rainfall together with long-term temperature increases have affected the supply of water for hydropower generation (Lara, 2018; ESCOM; Carson et al., 2018; UNECA, 2018):

- "In late 2015, the Tanzanian government was forced to shut down all its hydroelectric plants following droughts that dried up many of the country's dams, or left them with dangerously low water levels. As a result, the country generated only 12% of the power it regularly consumed leaving millions of people in the dark" (Lara, 2018).
- "In 2016, the largest hydroelectric plant in sub-Saharan Africa, Mozambique's Cahora Bassa, also found itself in trouble. Two years of drought conditions brought water levels to record lows, down to 34% of full dam capacity. The impact went well beyond

Mozambique, as about two-thirds of power generated at the facility is sold to South Africa and Zimbabwe" (Lara, 2018).

- "Also located on the Zambezi river is Zambia's largest hydroelectric plant, the Kariba is located upstream of Cahora Bassa and supplies roughly 40% of Zambia's power demand. Unsurprisingly, in the same year of Cahora Bassa's record lows, power generation at Kariba fell by a whopping 75%. Currently, Lake Kariba, stands at historically low water level just barely above the amount need to keep the hydro power pants running" (Lara, 2018).
- Low water levels in Lake Malawi have reduced the water flow on the Shire River causing a capacity short-fall of 150 MW in Malawi's hydro power generation (about 35 % of peak demand). A similar situation occurred in Namibia where available hydro capacity became as low as 90 to 160 MW instead of the nominal capacity of the Rucana power plant (ESCOM).
- In 2008 South Africa experienced a significant drop of more than 20 percent in it electricity generation (Carson et al., 2018). Rather than by drought, South Africa was affected by heavy rainfall which flooded and muddied the coalmines and silos, which affected the coal supply for the power plants (UNECA, 2018). In the end of 2019 coal mines were flooded again by heavy rains triggering another series of power cuts on top of an already challenging situation.

These examples illustrate that essentially all of the SAPP countries are affected by water-related impacts on their electricity generation and in conjunction with other causes experience extended periods of electricity supply interruptions. The economic costs of these power outages are high and have been estimated at 5–7% of the GDP for Malawi, South Africa and Tanzania (Conway et al., 2017). The water related risks for the SAPP could become even stronger in the future. With the new hydro project currently in the pipeline there will be a growing concentration of hydropower generating capacity in a single basin - the Zambezi basin - from about 70% now to around 85% in 2030 (Conway et al., 2017).

2.2 Conclusions

The countries in the SAPP, albeit heterogeneous in terms of their economic development including the maturity of their energy systems, face the joint challenge of having to expand and transform their electricity infrastructure. This is on the one hand driven by the need to serve demand that is expected to grow sharply in order to provide for electricity access, and to keep up with projected population growth and economic convergence. In particular, the Democratic Republic of Congo, Malawi and Mozambique are countries with low GDP per capita and low energy access rates that can be expected to contribute to future rising demand. On the other hand, changing climatic conditions have immediate implications for the electricity generation in the SAPP. A large share of countries (Angola, Democratic Republic of Congo, Lesotho, Mozambique, Malawi and Zambia) rely on hydropower as their primary generation option and already today major rivers, such as the Zambezi or the Congo, feeding The countries in the SAPP, albeit heterogeneous in terms of their economic development including the maturity of their energy systems, face the joint challenge of having to expand and transform their electricity infrastructure. This is on the one hand driven by the need to serve demand that is expected to grow sharply in order to provide for electricity access, and to keep up with projected population growth and economic convergence. In particular, the Democratic Republic of Congo, Malawi and Mozambique are countries with low GDP per capita and low energy access rates that can be expected to contribute to future rising demand. On the other hand changing climatic conditions have immediate implications for the electricity generation in the SAPP. A large share of countries (Angola, Democratic Republic of Congo, Lesotho, Mozambique, Malawi and Zambia) rely on hydropower as their primary generation option and already today major rivers, such as the Zambezi or the Congo, feeding the water storage reservoirs in the region, are subject to significant variability of their mean annual discharge. This variability, which is particularly high in the fall season, has been confirmed through the analyses carried out for this report where the discharge variability of 39 climatic years has been analysed for all larger hydro power plants (>50 MW) in the SAPP. In recent years below-average discharge levels have caused electricity supply interruptions in many of the SAPP countries and it can be assumed that climate change could exacerbate such a tendency. In conjunction with the changing climate also the occurrence of extreme events, such as the floods in South Africa, which reduced the operation of the coal fleet with impacts on several SAPP countries, has to be considered. These dimensions have to be taken into account when assessing the challenges and opportunities of operating and developing the power system in the SAPP in the context of the water-power nexus.

Recognising that addressing all these aspects is beyond the scope of this work, the main contributions of this report focus on the following three objectives:

— First, to provide a knowledge base for analysing and understanding implications of climate-driven water availability for the power system operation and planning in the SAPP. To achieve this we have compiled, cross-validated and analysed a large amount of relevant datasets as well as the pertinent literature. Based on these data we calibrated the open-source power dispatch model Dispa-SET to the situation that has been characteristic for the SAPP in 2016/2017. This allowed us to validate and better understand the current situation in the SAPP that is characterised by an insufficient availability of generation capacity – caused by a lack of installed capacity in some countries, technical outages and variable availability of hydropower - to consistently meet increasing electricity demand. This situation is in general more pronounced in those SAPP member countries that are not yet connected to the interconnected electricity network, namely Angola, Malawi and Tanzania, whereas in the Democratic Republic of Congo the deficit of generation adequacy is most severe. This is reflected in increased levels of unserved energy that differ by country, but in our simulations can reach up to 25% of yearly demand in Malawi. The simulations of the climatic conditions experienced in the SAPP over a large range of historic climatic years also reveal that a higher availability of water can substantially alleviate the negative economic consequences of unserved electricity on electricity price levels and hampered economic activity (not quantified in this study).

— Second, the datasets, modelling tools and insights derived from the situation that has been characteristic for the SAPP in 2016/2017 provide a suitable reference case against which hypothesis through sensitivity analyses can be tested or upon which future policy scenarios can be developed. Future work with this framework serving the needs of policy partners could put a more granular focus on specific assets, e.g. valuation of specific power plants or interconnection projects, or look at the benefits of pan-Africa or Africa-EU cooperation, e.g. by linking different pools and power systems. To facilitate work at this end we make all the relevant files accessible open source through the JRC Data Catalogue under the WEFE collection[15].

— Third, in terms of policy-relevant questions two themes that have been shown to be of critical relevance in framing the analysis of the SAPP are explored further in this report through dedicated sensitivity analyses. These are the impacts of realising increased inter-connections between the SAPP countries, by implementing all currently considered candidate projects and the consequences of supply interruptions in South Africa both within the country and for the other SAPP countries. Our results show that capacity shortage in South Africa would negatively spill-over to other SAPP countries in terms of increased levels of unserved energy and electricity prices. Contrary, an increased interconnectedness of the SAPP power system allows the currently unconnected countries

[15] https://data.jrc.ec.europa.eu/collection/id-00134

to participate in the gains of pooling resources and overall, by providing more flexible paths for the electricity to flow, increases the resilience against electricity supply interruptions. By comparing the capacity factors of interconnectors for a broad range of hydro-climatic conditions, we identify promising candidate projects for new interconnection capacity additions or expansions respectively that can be assessed further in more detailed analyses. In terms of socio-economic impacts increased interconnectedness is reflected in an overall significantly reduced and smoothed distribution of electricity price and unserved electricity levels. A comparison of total system costs for the whole SAPP across the climatic years in the four scenarios also reveals that these can differ by about 20% depending on how much water is available for hydro generation. A similar order of cost reduction can be achieved through a better interconnection of the SAPP countries which places an emphasis on grid expansion policies as only the latter one can be (directly) controlled through policy decisions.

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3. The North, Eastern and Central African Power Pools

3.1 Introduction

The study **"Analysis of the water-power nexus in the North, Eastern and Central African Power Pools" (JRC121098)** complements similar analyses of the water-power nexus in African power pools and focuses only on three power pools, namely:

— the Central African Power Pool (CAPP)[16] Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of Congo (DRC), Equatorial Guinea and Gabon;

— the East African Power Pool (EAPP)[17], DRC, Djibouti, Egypt, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, Libya, Uganda and South Sudan; and

— the North African Power Pool (NAPP)[18] Algeria, Libya, Mauritania, Morocco and Tunisia.

The renewable and fossil potentials vary significantly between the power pools. NAPP is mostly dominated by fossil while CAPP and EAPP are dominated by water. Most diverse, by per country basis is EAPP where some countries are either entirely fossil or almost entirely renewable powered.

The overall objectives of this final study are to:

— Propose a methodology for the analysis of the water-power nexus.

— Describe the available data sources used for modelling of the three African Power Pools.

— Investigate synergies between the water and power sectors by assessing the hydro potential in the proposed region through several what-if scenarios with regard to the availability of water for energy purposes in dry and wet seasons.

— Examine the potential for and relationship between current and future electricity situation and power trade between countries in selected power pools, by increasing the temporal and technological granularity of the previously-developed model TEMBA – OSeMOSYS (The Electricity Model Base for Africa)[19].

[16] CAPP Geographic Information System: https://www.peac-sig.org/en/
[17] East African Power Pool: http://eappool.org/
[18] Comité Maghrébin de l'Electricité (COMELEC): https://comelec-net.org/index-en.php
[19] TEMBA – the open source model of African electricity supply that represents each continental African country's electricity supply system and transmission links between them. http://www.osemosys.org/temba-the-electricity-model-base-for-africa.html

— Identify areas where grid extensions would be beneficial for the African electricity supply system.

Significant effort has been made to obtain the best possible data for the modelling and scenario analyses. The demand forecasts are uncertain and have significant impact on the modelling results. A number of scenarios and projections regarding the hydro inflows and other key parameters have been made in this analysis, and the accuracy of the results is function of the uncertainty linked to these projections, especially regarding the cross-border interconnection lines, technical and costs assumptions of the power plant fleet as well as fuel prices.

When data was unavailable or obviously erroneous, corrections had to be performed and best-guess assumptions had to be formulated to fill the gaps. In order to ensure full traceability in the data processing, all the scripts used to process the raw data are documented and provided as electronic annex to this report.

3.2 Conclusions

This third study provides an open modelling framework and input dataset for the analysis of the water-power nexus in three of the five African power pools. It considers both the current (or near-future) situation and long-term scenarios constrained by climate-related CO_2 limitations.

In the Reference scenario, capacity additions varying between 573–589 GW are anticipated by year 2045, for an overall demand which is expected to grow by 16 % by 2025, 89 % by 2035 and 216 % by 2045. To ensure the adequacy of this system, it is of primary importance to increase the transfer capacities between countries. Results indicate that load shedding and curtailment can be significantly reduced by a higher degree of interconnection, both in the current and in the future (long-term) scenarios. The existing grid configuration, where several countries are isolated and do not share any cross-border lines with the neighbours, is not adequate and load shedding is necessary, especially in the Central African Republic and South Sudan, where a lack of generation capacity is stated.

The simulations highlight the dependence of the power sector on the availability of freshwater resources in the three power pools. Variations between wet and dry years significantly impact the final energy mix: the share of electricity coming from hydro units can vary up to 5.2%. Consequently, they also impact the total operational costs: the difference between the wet and dry seasons is around 1.4 billion EUR, or 3.28 EUR/MWh. CO_2 emissions vary by around 15 million tons per year between wet and dry years. It is important to note that the impact of the power fleet on the water sector is mainly related to water withdrawals, water consumption remaining marginal in the most vulnerable countries. This is due to the large share of once-through cooling systems in NAPP, whose main effect is to increase the water temperature, but do not limit the quantity of water available for other usages.

A highly interconnected grid reduces water consumption by 50% in NAPP and 2% in EAPP. Withdrawals are reduced by 50% across the three power pools when compared to the existing system configuration. Interconnections also influences the average price of electricity, which is 2.7% lower in extremely wet, and 3.9% lower in extremely dry seasons. Furthermore, a well interconnected grid also reduces the need for VRES curtailment and water spillage in HROR and HDAM units, allowing higher integration from renewable sources, as well as reduced needs for load shedding, which are only observed in extremely dry seasons.

The analysis further shows that simultaneous system integration and new VRES capacity additions can reduce the potential carbon emissions by more than 32% compared to the reference scenario. Congestion in the proposed interconnection lines might cause serious VRES curtailment by limiting the energy flows from southern (hydro-abundant) countries, and energy flows from the northern (VRES-abundant) countries. As the primary energy generation from thermal units in future low carbon scenarios is significantly lower, lack of flexibility and load shifting resources can lead to curtailment in time periods with high availability and load shedding in time periods with low renewable availability. Despite this, excess capacity in NAPP combined with a well-developed transmission network is sufficient to cover all potential mismatches between the supply and demand in EAPP and CAPP.

From a methodological point of view, the results suggest that long term planning models such as TEMBA - OSeMOSYS can usefully be complemented by a more detailed dispatch model to ensure the feasibility of the proposed scenarios. Further steps of this work include a bi-directional soft linking between the two models, which would provide a more insightful global economic optimum for the analysed power pools.

Finally, it is worthwhile to note that in order to ensure transparency and reproducibility of the work, all the proposed models, methods, and data are released under open licenses and can be freely downloaded from the JRC Data Catalogue[20].

[20] JRC Data Catalogue https://data.jrc.ec.europa.eu/collection/id-00134, as well as https://github.com/energy-modelling-toolkit/Dispa-SET (model code), and https://zenodo.org/deposit/3839756 (databases).

Status of Geothermal Industry in East African Countries

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The role and potential of geothermal energy in 11 countries crossed by the East African Rift System (EARS), geographically extending from Eastern to Southern Africa, has been reviewed. The focus is on geothermal resources aimed at generating electric power by using either flashing or Organic Rankine Cycle (ORC) plants with geothermal fluids extracted from medium to high temperature hydrothermal systems.

The business models implemented are discussed, in relation with the peculiar features of the geothermal energy which is characterized by important initial investments and limited operating and maintenance expenditures, as most of the renewable energy sources, but having peculiar remarkable mining risks mainly related to the exploration drilling phase. Constraints delaying a more widespread use of geothermal energy for electric power generation in East Africa are analysed, together with the role of international and financial institutions in providing funds and risk mitigation opportunities, support in capacity building and the development of national legal frameworks needed for an improved and faster development of geothermal resources in East Africa. A review of the present status of geothermal development initiatives underway in each of the 11 countries is presented, looking at the possible role of geothermal resources within the electric energy market in each country.

Keywords: Geothermal resources, EARS, Eastern Branch, Western Branch

1 Introduction

In the light of the debate on energy production and on renewable energy in Africa, a decision was taken to integrate the ACE WATER2 overall framework by investigating the role and potential of geothermal energy, that looks like promising in several countries along the East African Rift System (EARS), geographically extending from Eastern to Southern Africa. The general objective of the study was to present the state-of-the-art on the geothermal resource development in East African Countries (Eritrea, Djibouti, Ethiopia, Kenya, Uganda, Rwanda, Burundi, Tanzania and Comoros) and in two Southern African countries (Malawi and Zambia), for the sake of simplicity all collectively referred to as "East African countries".

The focus of the study is on geothermal activities aimed at generating electric power by using either flashing or Organic Rankine Cycle (ORC) plants with geothermal fluids extracted from medium to high temperature hydrothermal systems.

Geothermal energy is a renewable energy characterized by: low environmental impact and greenhouse emissions when compared to energy generated using fossil fuels; quite constant generation output independent from weather conditions, which makes it particularly suitable for base load electric generation; high initial capital costs and low operating and management expenditures; remarkable mining risks mainly related to the results of exploratory drilling phase.

Geothermal resources, consisting in the heat contained in the Earth crust, are presently exploited for both electric power generation and for direct uses. Favourable geodynamic environments allow founding exploitable geothermal systems at economic and technical feasible depths. Apart for the utilization of low temperature resources (<100°C) only made for direct uses, the generation of electric energy is made from medium (between 100°C and 200°C) and high (>200°) temperature geothermal systems. Almost all the high temperature fields exploited today are hydrothermal systems from which heat is extracted by means of wells producing fluids contained in a permeable reservoir. According to thermodynamic conditions, the reservoir can be either vapour or liquid dominated depending on the fluid phase controlling the reservoir pressure distribution.

Geothermal power development requires a long project execution cycle, which the IGA (2014) guide divides into eight key phases: 1) Preliminary survey; 2) Exploration; 3) Test drilling; 4) Project review and planning; 5) Field development; 6) Power plant construction; 7) Commissioning and; 8) Operation. The three first phases (which could be broadly called the exploration stage) are seen as the riskiest part of the project development, because either confirm the existence of a geothermal reservoir suitable for power generation or not. According to Gehringer and Loksha (2012), it may take approximately seven years (usually between 5 and 10 years) to develop a typical full-size geothermal project with a 50 MW turbine as the first field development step. Therefore, it could not be regarded as a quick fix for any country's power supply problems, but rather should be part of a long-term electricity generation strategy.

2 Method

The technical report (Battistelli et al., 2020) is the result of a desk-based work, consisted in a review of selected documents and news approximately from year 2005, searched on the web and dealing with geothermal resources development in East African countries. The review includes published papers, official reports and documents that are available through the World Wide Web (WWW) mainly looking at institutional sites of involved stakeholders, both at the national and international levels.

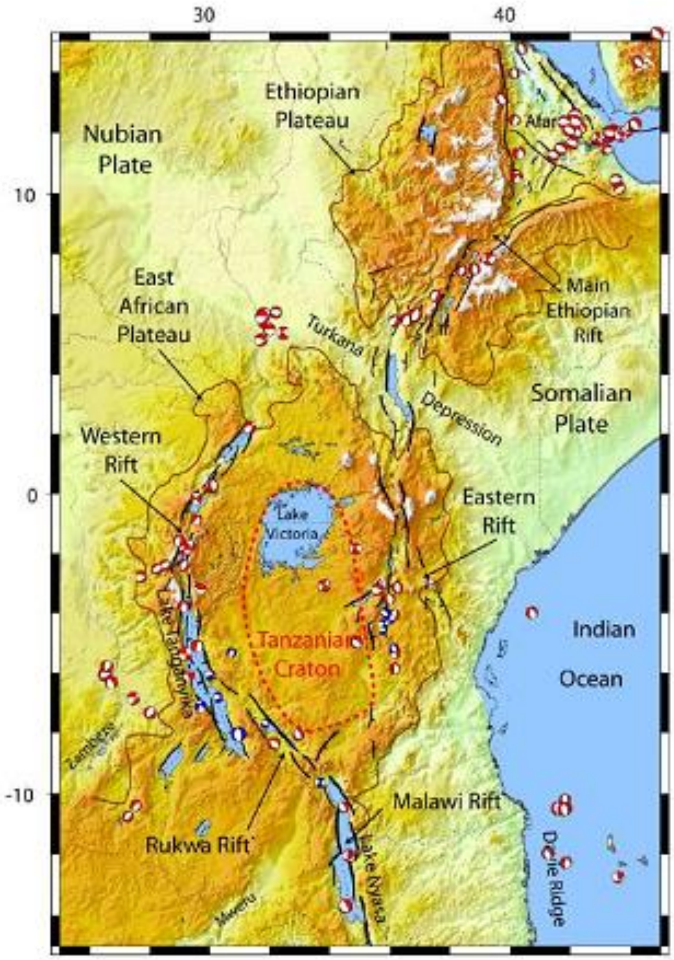
The role and the activities performed by main international stakeholders have been summarized, highlighting both the results achieved in promoting the geothermal industry in East African countries and the needs for further efforts in specific fields.

As far as the status of geothermal energy development in each country is concerned, the analysis includes an overview of the energy sector in each country, with specific focus on the electric market and the present and planned resources used for electric power generation in order to highlight the possible role of geothermal resources utilisation. In this context, the activities performed for geothermal resource exploration and development in each country are reviewed and summarized looking at the stated development plans of national stakeholders. Details on the activities performed and achieved results in studied geothermal prospects are given in order to highlight the actual status of each prospect and compare achieved results with stated development plans.

3 Discussion

East Africa is characterized by the presence of the EARS with the Eastern branch, extending from Eritrea to Tanzania and crossing Djibouti, Ethiopia and Kenya, and the Western branch extending from Uganda to Mozambique and crossing Burundi, Rwanda, Zambia, Tanzania and Malawi (**Figure 1**). While this geodynamic context creates high favourable conditions for the existence of geothermal resources at economically and technically drillable depths, at present only Kenya has developed its geothermal resources with an installed electric power of 865 MW, representing about 30% of total installed power, against estimated resources amounting to some 7,000 MW.

Figure 1. The East African Rift System (Source: Omenda, 2018)



Currently, it appears to be evident that the countries crossed by the Eastern Branch of EARS have a definitely higher geothermal potential, mainly concentrated in the Afar depression and the Ethiopian and Kenyan Rift Valleys. Even if not huge on an absolute scale, the resources inferred in Eritrea, Djibouti and the Comoros (the latter not actually pertaining to the Eastern Branch of EARS), if developed, would almost satisfy their present and future electric network base loads. In the case of the countries crossed by the Western Branch, they have a lower geothermal potential, mostly related to medium, rarely high, temperature fault controlled geothermal systems, whose utilisation for electric power generation would require ORC power plants. As a consequence, about 95% of EARS estimated potential amounting to some 22,400 MW belongs to geothermal areas located along the Eastern Branch.

The role of geothermal energy in the energy mix of the East African countries depends on the present status of the energy sector of each country, on the potential of indigenous energy sources, including geothermal energy, and strategic choices taken by each government. There are several reasons for the delay of geothermal resources development experienced so far by these countries, such as:

- Lack of clear and coherent legislative frameworks, regulating the activities of both public and private investors in several countries.
- Lack of local technical and managerial skills, able to conveniently support the exploration and exploitation of geothermal resources.

- The remoteness of many East Africa geothermal areas from developed O&G regions, where most of the drilling contractors and service providers are based, and then the absence of infrastructures and logistic facilities supporting the drilling activities characterising well developed O&G regions.
- Inadequate financing of the early stages of geothermal projects; commercial banks reluctance to participate in the exploration phase and the need for more risk reduction opportunities, which facilitate the investment by both public and private operators.
- Competition from other renewable energy sources, such as hydropower, solar and wind, which creates a challenging environment for geothermal projects in the region.
- The issue of remunerative price for the generated electric power in still poor developed national electric markets.

In order to help East African countries to overcome the above issues, international organizations and financial institutions, such as WB, AU, EU, IRENA, NDF, AFD, AfDB, JICA, USAID, etc., are actively collaborating with national governments to create the necessary legislative framework in each country. They have facilitated the capacity building with the organization of dedicated courses and conferences and the creation of the Africa Geothermal Centre of Excellence (AGCE) in Kenya, taking advantage of the existing training facilities of GDC and KenGen. On the other hand, financial and international institutions are providing both grants and low interest loans to help public and private operators in the various steps of geothermal resource development, from the exploration surveys to the construction of power plants.

In fact, geothermal power plant development involves substantial capital requirements due to exploration drilling costs, for which it can be difficult to obtain bank loans. Since geothermal exploration is considered high risk, developers generally need to obtain some type of public financing. This risk is derived from the fact that capital is required before confirmation of resource presence or exploitability, and therefore before project profitability can be determined.

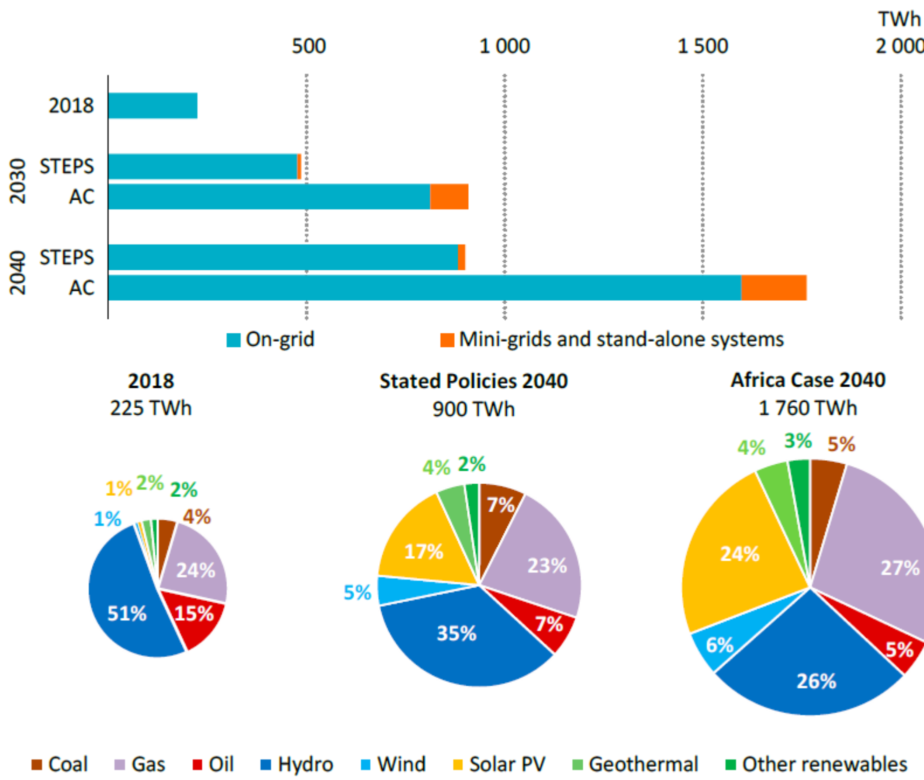
Some of the Governments (Djibouti, Kenya, Uganda, Tanzania) have decided to reduce this risk and the cost of capital for private developers by creating public companies in charge of initial exploration activities and in some case also of exploitation of geothermal resources to provide private companies (that install power plants and supply electricity to their customers) with the required steam. An important risk mitigation opportunity is represented by the Geothermal Risk Mitigation Facility for Eastern Africa (GRMF) which is providing grants covering a variable costs fraction for infrastructure construction, surface exploration surveys and exploration drilling, the latter being the phase characterized by the higher mining risks. After 5 GRMF Application Rounds, grants have already been awarded to 30 projects located in Djibouti, Ethiopia, Kenia, Uganda, Tanzania and Comoros. The opening of the expressions of interest for the 6th Application Round was done on August 3, 2020. In addition, several international stakeholders are actively supporting all the phases of geothermal field development, from exploration to power plant EPC, with grants and soft loans and providing technical assistance and consultant support to national institutions and geothermal operators.

Historically, reconnaissance and preliminary surface studies on geothermal prospects in East Africa where performed by public institutions or companies supported by international donors and consultants. Often, this approach has been characterized by a discontinuous performance of exploration phases separated by long periods of inactivity, sometime accompanied by the switch of operations from one institution to another one, with loss of skilled personnel and know-how. More recently most of the countries have developed regulatory environments in which both public and private operators, as well as private-public initiatives, are allowed to develop the geothermal resources.

The example of Kenya, with an institutional setup of its energy sector similar to that of the most advanced geothermal countries in the World, testifies that the opening to private investors and operators, as well as to the collaboration between public companies in charge of the exploration and field management and Independent Power Producers (IPP), allows an accelerated and more effective development. Other countries are following Kenya in establishing a clear regulatory environment and accelerating the initial prospects exploration by both dedicated public companies and private developers.

Regarding the forecasted role of geothermal energy in the generation of electricity, the scenarios developed by IEA (2019) (**Figure 2**) show the electricity supply by type, source and scenario in sub-Saharan Africa, excluding South Africa, in 2030 and 2040.

Figure 2. Electricity supply by type, source and scenario in sub-Saharan Africa (excluding South Africa), in 2018, 2030 and 2040 (IEA, 2019)



The situation in 2018 is compared to two different scenarios, namely the IEA's Stated Policies and the Africa Case, foreseen for year 2040. The IEA's Stated Policies scenario is based on current and announced policies, while the Africa Case scenario is a new scenario built by IEA around Africa's own vision for its future. It incorporates the policies needed to develop the continent's energy sector in a way that allows economies to grow strongly, sustainably and inclusively.

In 2018 geothermal power accounted for 2% of electricity generation and is expected to represent in 2040 4% by both IEA's scenarios. The two scenarios foresee an increment of electric generation in 2040 of about 4 and 7.8 times, respectively, with respect to the present generation capacity, which implies an increment of geothermal generated electricity of about 8 and 15.6 times, respectively. Thus, geothermal energy is expected to double its contribution share in 2040, but still representing a small fraction of electricity generation, in particular if compared to the important increment of Solar PV, which will compensate for the reduction of hydropower contribution. On the other hand, both scenarios suggest that even if most of the investments on renewable energies will be drained by Solar PV, geothermal will anyway experience a large increment of generated energy and then of installed power.

4 Conclusions and recommendations

In order to help East African countries to overcome the identified barriers to the development of geothermal resources utilization, international organizations and financial institutions are actively collaborating with national governments to create the necessary legislative framework in each country, to facilitate the capacity building with the creation of excellence centres and the organization of dedicated courses and conferences.

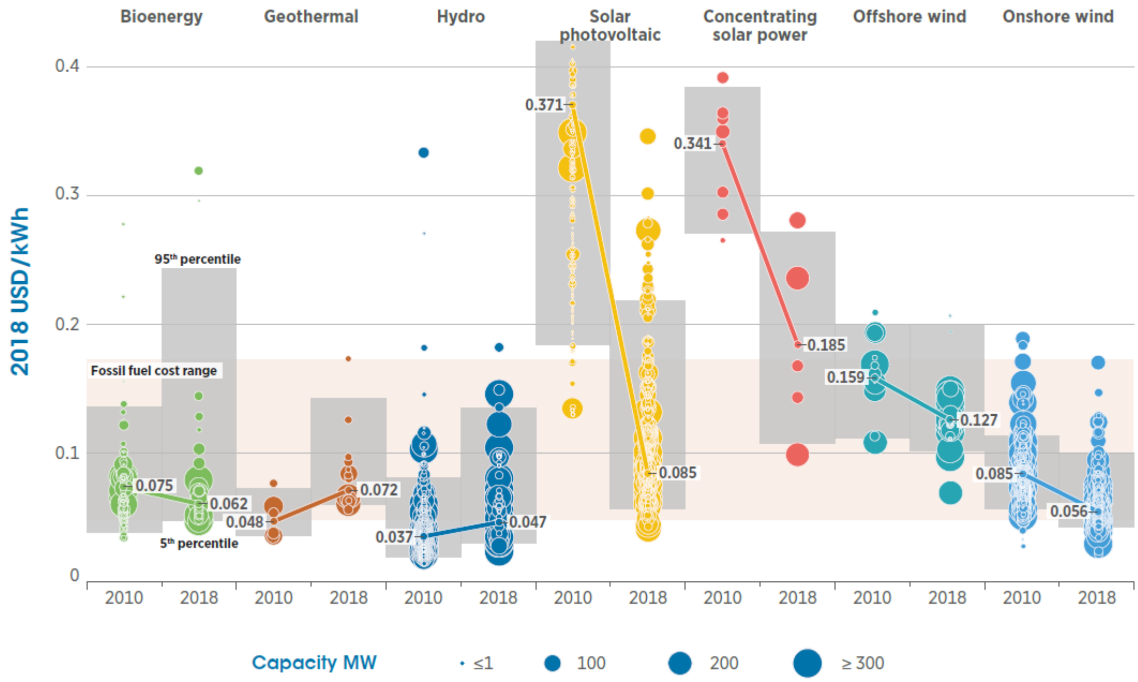
On the other hand, financial and international institutions, such as WB, AU, EU, IRENA, NDF, AFD, AfDB, JICA, USAID, etc., are providing both grants and low interest loans to help public and private operators in the various steps of geothermal resource development, from the exploration surveys to the construction of power plants.

In addition, the following technical approaches, derived from experiences and lessons learned, are believed to reduce risks and improve the bankability of geothermal projects (IRENA, 2018):

- Sound exploration for high-quality geological data.
- Linking technical and commercial analyses to the development of realistic prefeasibility studies prior to making major investments.
- Generating early revenues through wellhead generators. Actually, installing wellhead power plants is advantageous when an early electric generation can be obtained during a long-term field development in quite large fields, and when the wellhead power plants can be relocated on another field or field sector when the final power plant starts its operations.
- Supplement project revenues through direct use applications and sale of other by-products such as lithium, CO_2, silica, etc.

In any case, geothermal energy shall be competitive in relation to other energy sources, either other renewables or fossil fuels. According to IRENA (2019), most of the plants allows a levelized cost of electricity (LCOE) lower than about 0.08 USD/kWh, which is competitive with electricity generated with fossil fuels (**Figure 3**). It is reasonable, that cheaper renewable energy sources like Solar and Wind not affected by the mining risks of geothermal energy may likely be preferred by many international and national investors. The important foreseen development of electric energy market in East African countries allows anyway to expect a corresponding development of geothermal resources to diversify the use of indigenous renewable resources and take advantage of the peculiar advantages of geothermal energy generation (stable production, low GHG emissions, low operating and maintenance costs).

Figure 3. Global LCOE evolution of utility-scale renewable power generation technologies in the 2010–2018 period. Real weighted average cost of capital is 7.5% for OECD countries and China and 10% for the rest of the World. (IRENA, 2019)



The countries that at present show the best geothermal perspectives, mainly located along the Eastern Branch of the EARS, are Djibouti, Ethiopia, Kenya and Tanzania, while the limited resources inferred in Eritrea and the Comoros would anyway be able to cover the present electric base load in both countries.

In conclusion, thanks to the efforts of both national governments and international stakeholders, the geothermal energy in Eastern Branch countries of EARS seems to be at a turning point in particular in Ethiopia and Djibouti, with Kenya going on in an accelerated way along an already established successful path. On-going exploration in the Comoros has also good perspectives with geothermal potential to be confirmed, but largely exceeding the present base load of the country.

The geological settings and the exploration activities performed so far suggest that the countries crossed by the Western Branch of EARS have a lower geothermal potential, mostly related to medium, rarely high, temperature fault controlled geothermal systems whose utilisation for electric power generation would require ORC power plants. Experiences recently gained with the exploration of fault-controlled systems in the Western Branch and related new achieved understanding, have implications for both tailored geological exploration approaches and the identification and prioritization of prospects in the Western Branch countries, which will likely allow to identify new promising prospects.

5 Study limitations and the way forward

The focus of the study was on geothermal activities aimed at generating electric power by using either flashing or Organic Rankine Cycle (ORC) plants with geothermal fluids extracted from medium to high temperature hydrothermal systems. Thus, direct uses of geothermal energy such spas, cooking, space heating and cooling, greenhouse heating, crop drying, aquaculture and heat for industrial processes, as well as the possible selling of by-products (lithium, silica, CO_2) were not addressed in the related report. Direct uses represent the natural utilization of low temperature resources, but can also complement the exploitation of medium and high temperature resources for electric power generation to improve the heat recovery and the project rentability.

The final report is the result of a desk-based work, consisted in a literature review of selected papers and news approximately from year 2005, searched on web resources. The review includes published papers, reports and documents that are available through the World Wide Web (WWW). While any reasonable effort has been assured to collect the relevant information within the time constraints of the study, of course the literature review cannot be exhaustive because of the so many projects underway and so many international and national stakeholders acting in the 11 African countries considered. In addition, while most of the general information is available to the public through the WWW, the details on specific initiatives are often not readily available and, on the other hand, the published information is not always updated.

The outcomes of the study could be updated and improved by contacting the various stakeholders, both national and international, actively involved in the development of geothermal resources in the countries crossed by the EARS.

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Urban development and regional connectivity in Africa

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Africa is experiencing rapid urbanization and continuous socio-economic changes and this trend will likely continue towards the future. While urbanisation exacerbates many of the challenges in cities that we also see in the EU (inequality, congestion, housing shortages, etc.), many African cities have seen enormous economic growth recently, and are gaining competitiveness at the global scale. Yet, in Africa, urbanisation is happening in a context of slow structural transformation, pervasive urban poverty and inequalities that might compromise sustainable urban futures. The functioning of urban centres and the way the systems of cities are interconnected are crucial aspects in addressing bottlenecks in a continental and regional perspective.

JRC is working on the understanding of urbanisation and development processes in Africa applying a territorial approach, based upon a multi-scale and integrated methodology that allows analysing local phenomena – at high spatial granularity – while simultaneously capturing continental and regional trends.

Mimicking the methodologies applied within the EU borders21, the approach consists of two pillars:

a) The compilation of a harmonised Reference Territorial Database for Africa;

The database includes **country-level data** (such as Trade flows, economic sectors analysis, etc.) and indicators based on **localised (grid level) data** (such as population and demographic characteristics, Circular economy and energy efficiency, Land uses, Natural resources, Education and health services, etc.)

b) The development and application of the LUISA4Africa modelling platform;

LUISA4Africa consists of a **population model integrated in a doubly constrained land-use optimisation model**.

First simulation runs have been computed according to the Shared Socio-Economic Pathway 3 (SSP3)[22] whereby economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time; population growth is low in industrialized and high in developing countries; and a low international priority for addressing environmental concerns, which leads to strong environmental degradation in some regions. Reference (or baseline) year of simulation is 2015 (Figure 1 – Population density), target year is 2050 (Figure 2 - projected population density).

[21] *The LUISA Territorial Modelling Platform and Urban Data Platform: An EU-Wide Holistic Approach (2020) in Territorial Impact Assessment- Advances in Spatial Science - Springer Nature Switzerland AG https://doi.org/10.1007/978-3-030-54502-4*

[22] *O'Neill, B.C., Kriegler, E., Kristie L.E., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W. 2017. The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st century. Global Environmental Change 42: 169-180*

Figure 3 shows simulated population growth in Nigeria from 2015 to 2050. At national level, Nigeria is expected to reach 400 Million people in 2050, hence doubling its current population. The simulation (Figure 4)**Errore. L'origine riferimento non è stata trovata.** captures the spatial granularity of that growth, which is for example particularly evident around the city of Kano. The city itself is projected to grow from 12.5 million to above 30 million inhabitants, with density increasing from 620 inhabitants per squared kilometres in 2015 to almost 1500 inh/sqkm in 2050. Capital Lagos observes a relatively contained increase, likely due to saturation of the inner urban areas.

Figure 1. Population density for year 2015

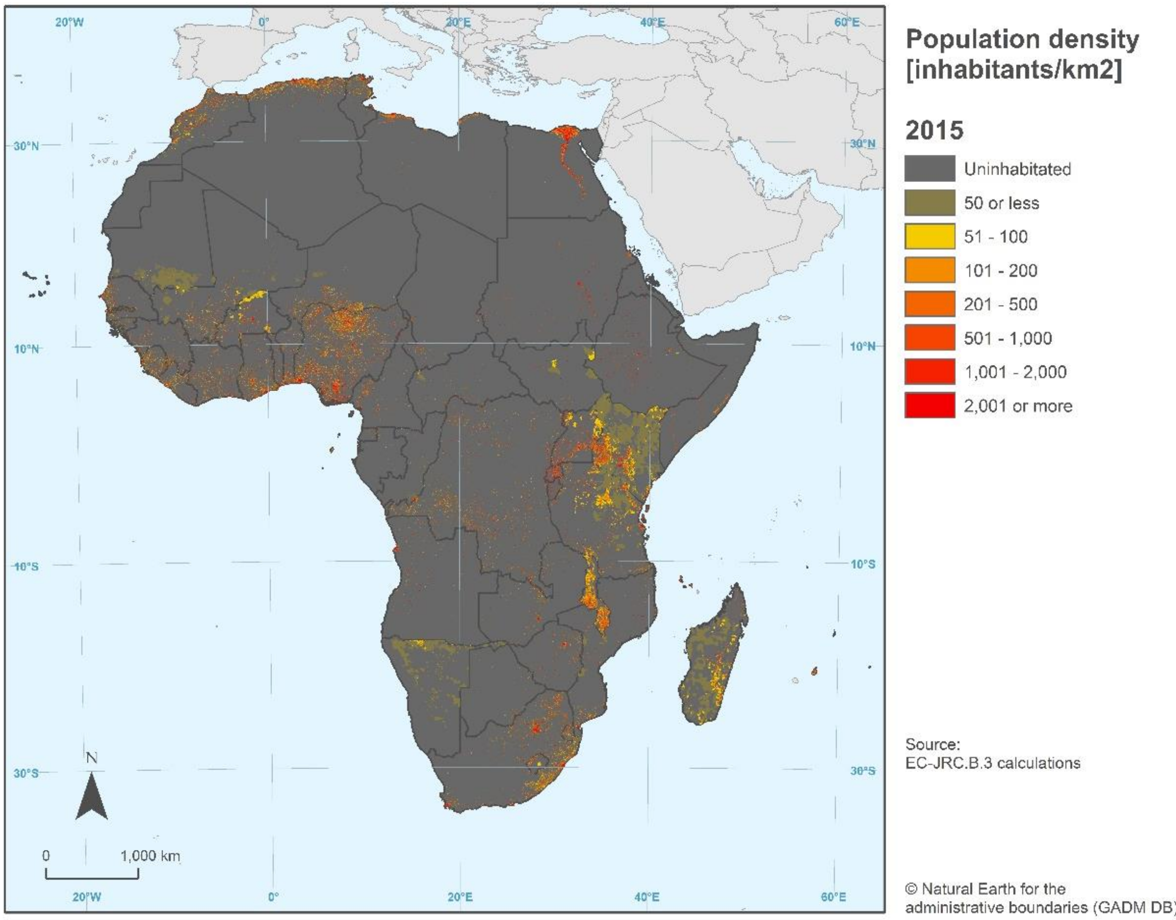


Figure 2. Projected population density for year 2050.

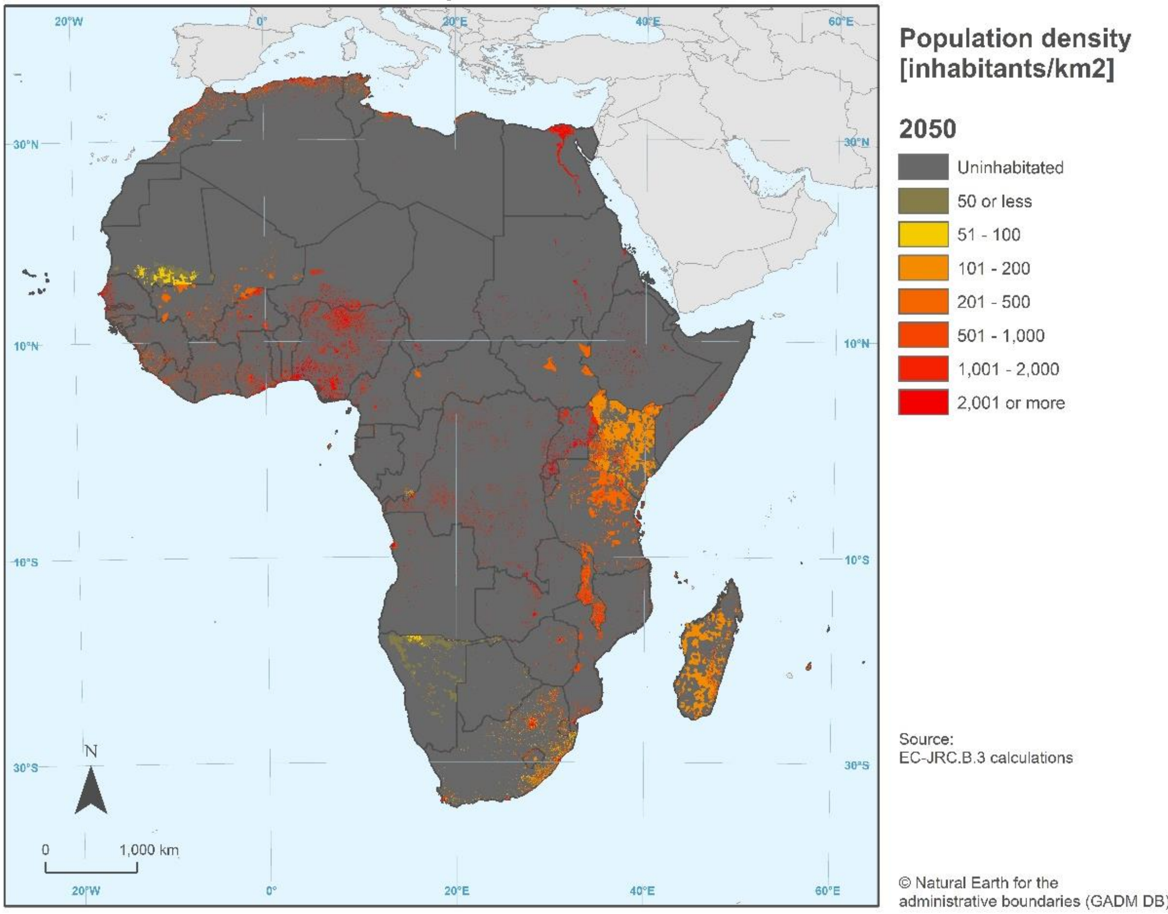
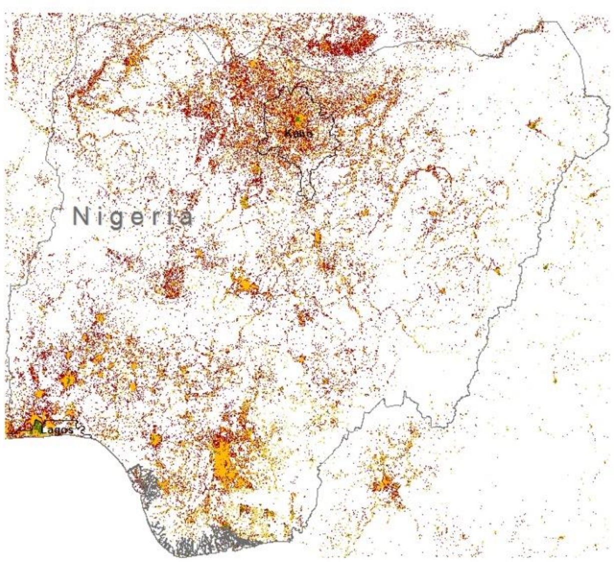


Figure 3. Nigeria Increase (%) in population from 2015 to 2050. Red = above 300%, Yellow: 10-300%, Green: below 10%



When comparing Kano to other cities in central Africa (Figure 4, also indicating expected population growth in Lagos, Luanda, Kinshasa City, Dar es Salaam, Abidjan, Nairobi and Addis Ababa), Kano is the leading city in terms of total population, while Luanda is the city with the highest growth rate (Figure 5).

Figure 4. Urban total population for 8 African cities for 2015-2050, according to modelled SSP3 scenario.

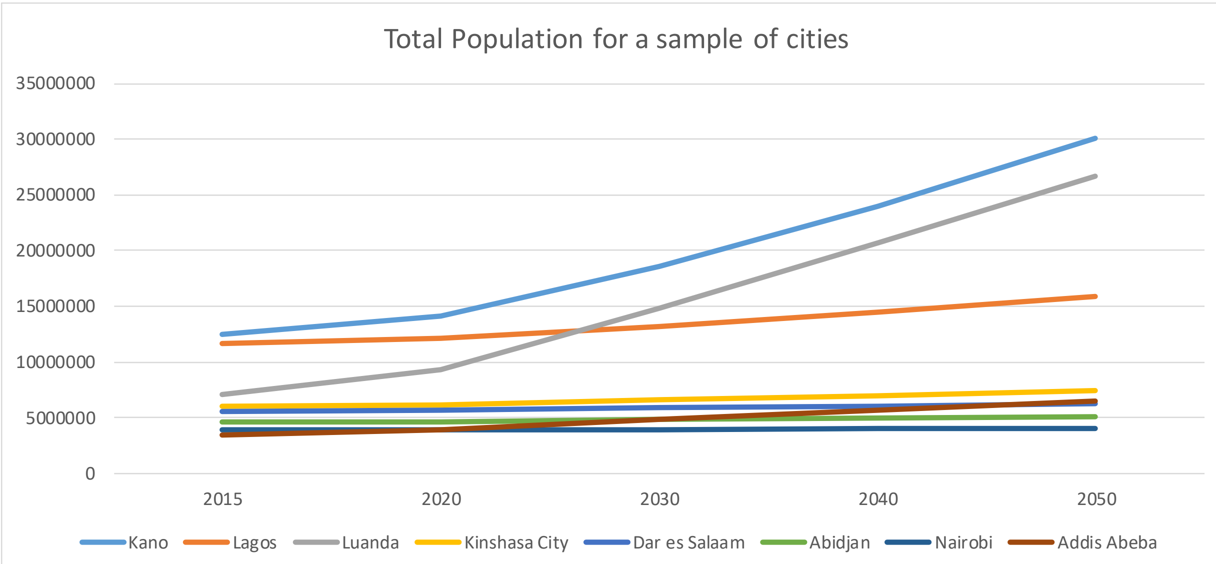
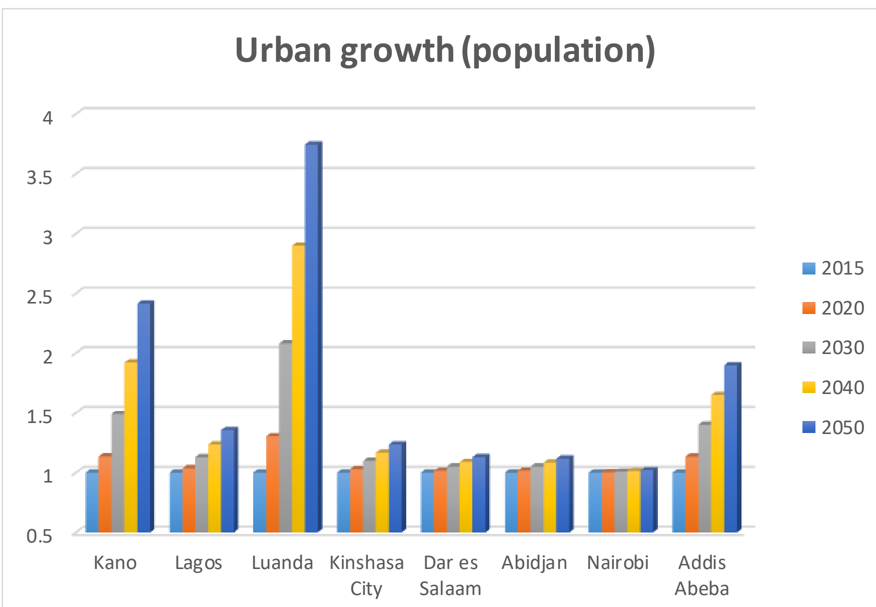


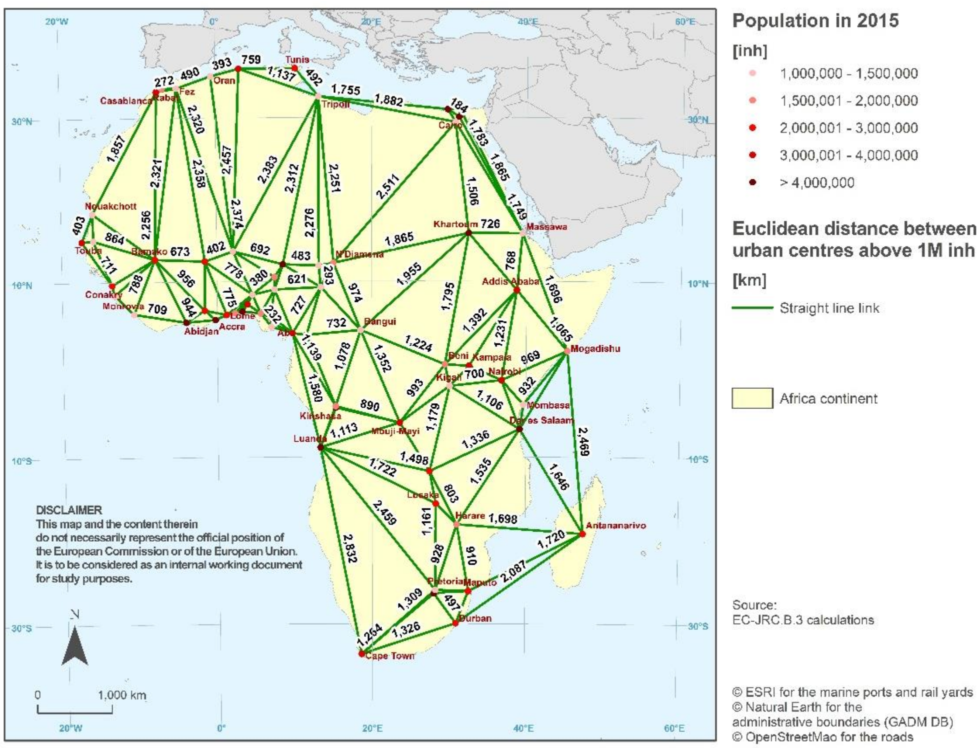
Figure 5. Urban population growth for the period 2015-2050 in 8 cities with population for 2015= 1, according to modelled SSP3 scenario.



A further application of the LUISA4AFRICA platform and underlying reference database is the analytical identification and characterisation of **strategic corridors**. The final purpose of this exercise is to **enhance sustainable connectivity**, to develop more diversified value chains and facilitate intra-Africa and Africa-Europe trade. In this context, the development of a strategic corridor is meant to support territorial development (both rural and urban) through reliable networks and services, including the deployment of digital and energy related infrastructure.

Data and methods from the LUISA4AFRICA platform have been used to identify strategic corridors spatially in a way that is objective and reproducible. The first step in this analysis of 'corridors' is the identification of 'nodes' to be connected. Typically, linking cities or urban agglomerations is of primary importance to enhance regional connectivity. Figure 6 presents the Euclidean distances (e.g. straight line) between urban centres with population above 1 million inhabitants.

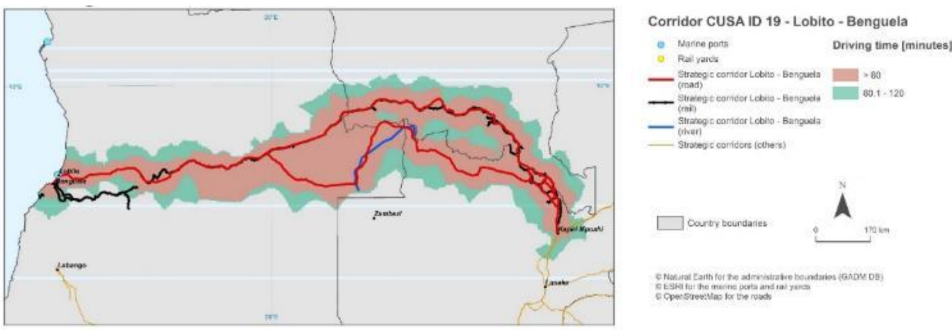
Figure 6. Distance between urban centres with population above 1 million inhabitants.



The second step towards the characterisation of a strategic corridor is the delineation of a **buffer** (or area of interest) around the set of links (e.g. roads, railways or waterways) connecting the two geographic nodes. The width of the buffer is computed on the basis on 'driving-time' from the closest link (see figure 7 for an example).

Further steps of the analysis involve the computation of indicators and the characterisation of each corridor according to a set of criteria, in order to define investment priorities.

Figure 7. Example of buffer for a strategic corridor.



The overall aim for the project is the development of a tool to perform multi-dimensional analysis of territorial developments related to urbanisation and regional connectivity. Once completed, the tool can be use by stakeholders and policy-makers to evaluate and eventually select the location of investments and measures.

Data and indicators are gradually made available in the Urban Data Platform Plus (urban.jrc.ec.europa.eu), once the validation exercise is completed.

Framing the state-of-the-art on the use of software and digital tools for sustainable groundwater resource management in the African continent

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Groundwater is a resource of increasing prominence in Africa whose potential has still to be developed in full capacity. While it is clear that data gathering is of outmost importance to achieve a certain level of knowledge for many African aquifer systems, Information and Communication Technology may support and boost efficient data management. This way, more technically sound and even community-based decisions may be made. In this context, we attempted to frame the state-of-the-art on the use of digital tools for supporting sustainable groundwater management in the African continent. By means of a comprehensive literature review and performing investigations via a structured questionnaire on ongoing practices at institutional/private sector level, the results allow a clear view on the present level of knowledge and on the diffusion of such tools.

At present the use of digital tools/groundwater numerical models is deemed to be an occasional activity, mostly applied for large engineering projects or basic modelling studies, rarely used for planning and management of the resource. All in all, their use in the period 2000-2020 can be considered low, with a clear difference between North Africa and Sub-Saharan African countries. Digital tools are recognised as needed tools by African institutions at national/regional level. However, skills and capacities are largely missing: the need for capacity building is (extremely) high. Commercial software solutions still dominate the market, while open source ones appear in increasing trend of usage in the last years.

Finally, main barriers in the use of digital tools are: i) scarcity of data, ii) inadequate resources (lack of computing resources), and iii) missing capacities (lack of computing skills). In addition to these, the lack of adequate and well-functioning Internet connection is considered one of the main bottleneck in favouring the spread of new technologies. Capacity building and knowledge transfer has then to be on top of the agenda for a digital groundwater governance in Africa. In particular, training should be directed to favour the use (and re-reuse) of open-source applications and the often huge amount of information and contents available. A generation of experts with a sounding interdisciplinary background should be able, in five to ten years, to properly manage ICT applications.

Keywords: Africa, groundwater resource management, digitalisation, groundwater modelling

1. Introduction

Groundwater is a resource of increasing prominence in Africa whose potential has still to be developed in full capacity as the natural storage is high, the water quality is often good, and infrastructure is more affordable to poor communities (Adelana and MacDonald, 2008). MacDonald et al. (2012) produced the first quantitative maps of groundwater resources in Africa and described this resource as the largest and most widely distributed store of freshwater in Africa, while at the same time being resilient to drought of several years. Cobbing and Hiller (2019) reported that for most Sub-Saharan African (SSA) countries current groundwater use remains under 5% of national sustainable yield. At the same time, they suggest to support SSA countries in increasing internal technical capacities on groundwater development and management. However, data on groundwater systems are sparse and the current state of knowledge is low, hence constituting a serious limitation to the sustainable development of groundwater resources (Xu et al., 2019).

While it is clear that data gathering in order to achieve a certain level of knowledge is of outmost importance for many African aquifer systems, there is at the same time the need of technologies that may help in managing this data effectively, and, consequently, planning the use of this resource. Information and Communication Technology (ICT) may provide several tools to this aim. Standardized and digitally referenced groundwater data is required to enable the detailed analysis of local, regional, and country-wide and transboundary groundwater needs and trends, to prioritize issues, areas and techniques to focus limited resources on, to enable the prediction of future scenarios of groundwater conditions, and to investigate the linkages of groundwater to other environmental issues. We here refer as digital tools to all those ICT tools that may support groundwater data gathering, archiving and analyses, spanning from digital ground- and remote- sensors, to Geographical Information Systems (GIS), to groundwater numerical modelling up to advanced artificial intelligence methods for data-based groundwater resource planning and management. Their diffusion is nowadays facilitated by two main factors: availability of computing resources at low cost and of open source and free software.

As it is unrealistic to perform a search and analyses on all the above-mentioned digital tools without incurring in biases, we looked at a proxy that can provide reliable output to our search. The adoption of groundwater flow numerical modelling is still recent and may provide better evidence of the recent trends in the level of digitalisation in the groundwater sector, particularly in low income countries. As such, we attempted to frame the state-of-the-art on the use of software and digital tools for groundwater resource management in the African continent. The multifaceted objective of this research is that of deriving ideas and actions for supporting the diffusion of digital tools in Africa, as a relevant asset for achieving sustainable groundwater management with reference to the specific African context.

2. Materials and methods

To achieve our goal, we used two independent approaches:

- 1) a dedicated literature review on scientific/technical documents with specific reference to groundwater flow numerical modelling;
- 2) by mining 220 replies by African experts in groundwater resource management to a dedicated questionnaire constituted by 83 questions.

During the analyses, we cross-validated the results of the literature review with those gathered through the questionnaire. Our research focused on the trends over the period 2000-2020 in the use of groundwater flow numerical models.

A desktop analysis on groundwater flow modelling experiences in the African continent over the last 20 years (2000-2019) and in 2020 was carried out. We searched both technical/scientific peer-reviewed papers and not peer-reviewed technical reports or academic documents (i.e. conference proceedings, PhD thesis, MSc thesis). The peer-reviewed papers search was carried out using scientific databases such as Science Direct, Scopus, Web of Science and so on. Different searches were performed with specific keywords, which included either Africa or the name of African countries. Once a document was retrieved, a detailed analyses of the reference section was undertaken. Further documents were collected by contacting individuals in our research network.

We then based our analyses only on the scientific papers detailing numerical modelling experiences as a proxy of the level of digitalisation. The spatial extension of each modelled domain was georeferenced (Figure 1). The following information were analysed for scientific papers i) produced in the last 20 years (2000-2019) and ii) with first author a scientist from an African institution:

- number of scientific papers (and comparison with papers with first author not from an African institution);
- spatial distribution and comparison between North Africa and Sub-Saharan Africa;
- type of numerical codes used in modelling exercises;
- use of Graphical User Interfaces (GUIs).

We structured a questionnaire in four sections. The first section aimed at characterising the respondent, while the second provided background information on the issues dealt. The third section provided information on groundwater monitoring and sampling practices, while the fourth and last brought us into the perspective on the use of modelling and digital tools for groundwater resource management. We submitted about 750 requests to compile the questionnaire in a dedicate web form. We received about 230 completed questionnaires; after validation, we ended up with 220 valid and completed questionna

3. Results and discussion

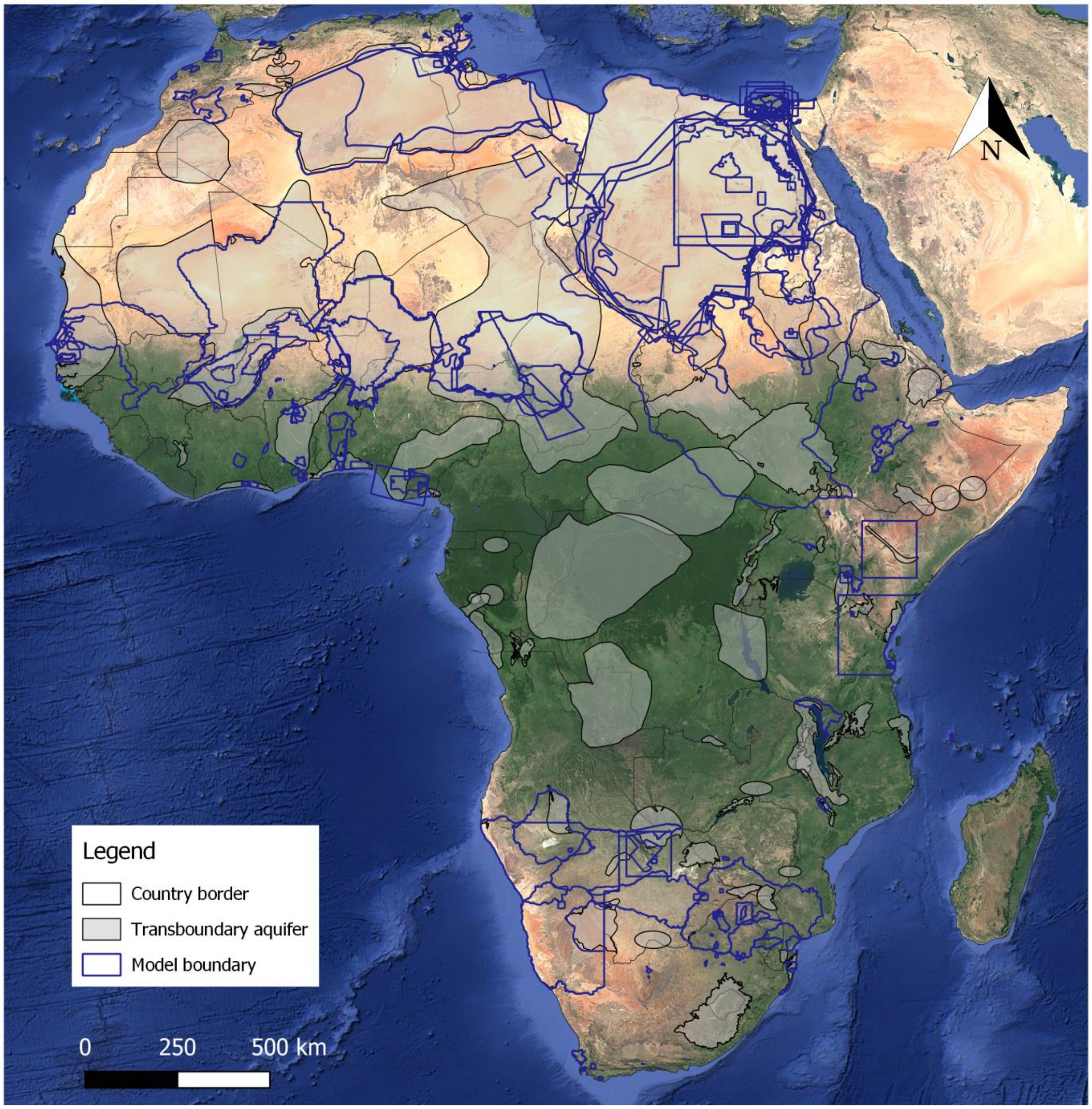
A total of 394 documents produced within the period 2000-2020 (to date) were retrieved in the literature review. Table 1 sums up the type of documents retrieved and the number for each type of document; only about 8% of the retrieved documents are in French, all of the others are in English. Figure 1 shows the boundaries of the modelled domains retrieved during the literature review plotted against the limits of transboundary aquifers.

Table 1. Type and number of retrieved documents.

Type of document	Total number	Language	
		English	French
Research paper	280	272	8
Conference proceedings	34	32	2
MSc Thesis	16	11	5
PhD Thesis	21	11	10
Book chapter	13	13	-
Book	2	2	-
Technical report	27	22	5
Research paper in book	1	1	0
Total	394	364	30

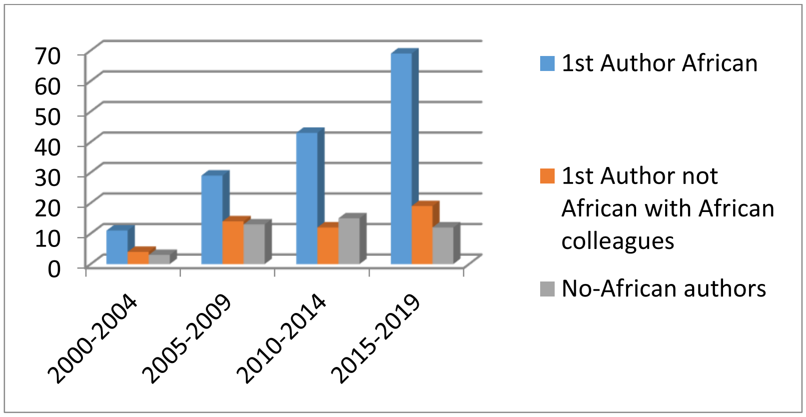
As a considerable number of studies (38%) has been led in 2000-2019 by scientists non-affiliated to African institutions, we focused on the scientific papers with first author being an African scientist affiliated to an African institution. Figure 2 shows the number of papers with first author from an African institution versus those not from an African institution, and those without African co-authors. To this regard, the African lead papers increased about six times, passing from 11, in the period 2000-2004, to 69 in 2015-2019. We noticed a sharp divide between North Africa (NA) and Sub-Saharan Africa (SSA), as in NA five countries barely contributed to the whole scientific production on the topic in about the same amount than all countries in SSA. African led studies are mostly run in Egypt, Ghana, Tunisia, South Africa, Morocco, Niger, Nigeria and Algeria.

Figure 1. Boundaries of the modelled domains retrieved during the literature review. In the image the African transboundary aquifers are also represented (source IHP-UNESCO, 2015 modified).



The analysis was expanded through the answers to the structured survey, to get an insight on the software currently used in public and private African institutions. The investigated sample comes mainly from the academic/research sector (about 78%) with a high academic degree (PhD for 66% of the respondents). The 90% of the sample declared to use digital tools for groundwater resource management daily and 94% declared an area of expertise related to groundwater modelling/data analysis, with main areas of interests related to groundwater exploration, integrated water resource management and water quality issues. The respondents' digital skills are stronger first in GIS, then in numerical modelling.

Figure 2. Number of scientific papers with a scientist from an African institution as first author versus those with first author not from an African institution.



As a representative example of the information we gather in this research, we present the results we obtained for the Senegalo-Mauritanian Basin, a large transboundary aquifer (TBA) shared among Senegal, Mauritania, Guinea-Bissau and Gambia. This TBA is found in a transitional zone between NA and the SSA. It represents an average example inheriting environmental and socio-economic characteristics of the two regions. The spatial distribution and the list of modelling efforts retrieved for the Senegalo-Mauritanian Basin are presented in Figure 3 and Table 2 respectively. We retrieved all in all 20 modelling studies (scientific papers (6), conference proceedings (1), technical reports (4), PhD and MSc thesis (4, and 5 respectively). Seven studies were performed before 2010 and thirteen between 2012/2020. All of the technical reports were prepared in the years 2017 and 2018.

These studies, when dealing with spatially distributed problems, were conducted using mostly the MODFLOW code. HYDRUS 2D and SUTRA were used to exemplify research questions at local 2D cross sectional scale. The HYDRUS code was used in four studies dealing with local research topics in one dimension. Aside from what is presented in one scientific paper ([376][23]), simple distributed modelling applications are generally shown and little or no information is provided on the calibration process. Ten studies are related to groundwater management (evaluating seawater intrusion, assessing potential areas for withdrawal, assessing groundwater supply for sustainable mining activities), while five have purely descriptive hydrological objectives (i.e. increasing understanding on the system hydrodynamics or evaluating the impact of climate change on groundwater). Nearly all studies (18) are led by Senegalese authors. The others are about the application of groundwater modelling for paleobotany/paleoclimate analysis in the Niayes area [376], while [404] is simulating the whole water budget of the Senegal river basin. The spatial relevance of the modelling efforts varies from local (6) to sub-regional (7). The areas most interested by the modelling activities (Figure 3) are the northern coastal aquifers, the Dakar region and the horst of Diass, and the Saloum and Casamance hydrological systems.

[23] [376] and following numbers in brackets: unique identifier for each piece of documents retrieved and archived, and numbered in Fig. 3, during the literature search (excerpt for the SMB reported in Table 2). For more info see Rossetto and Veroli 2020.

Figure 3. Boundary of the Senegalo–Mauritanian Basin, location and extension of the retrieved modelled areas.

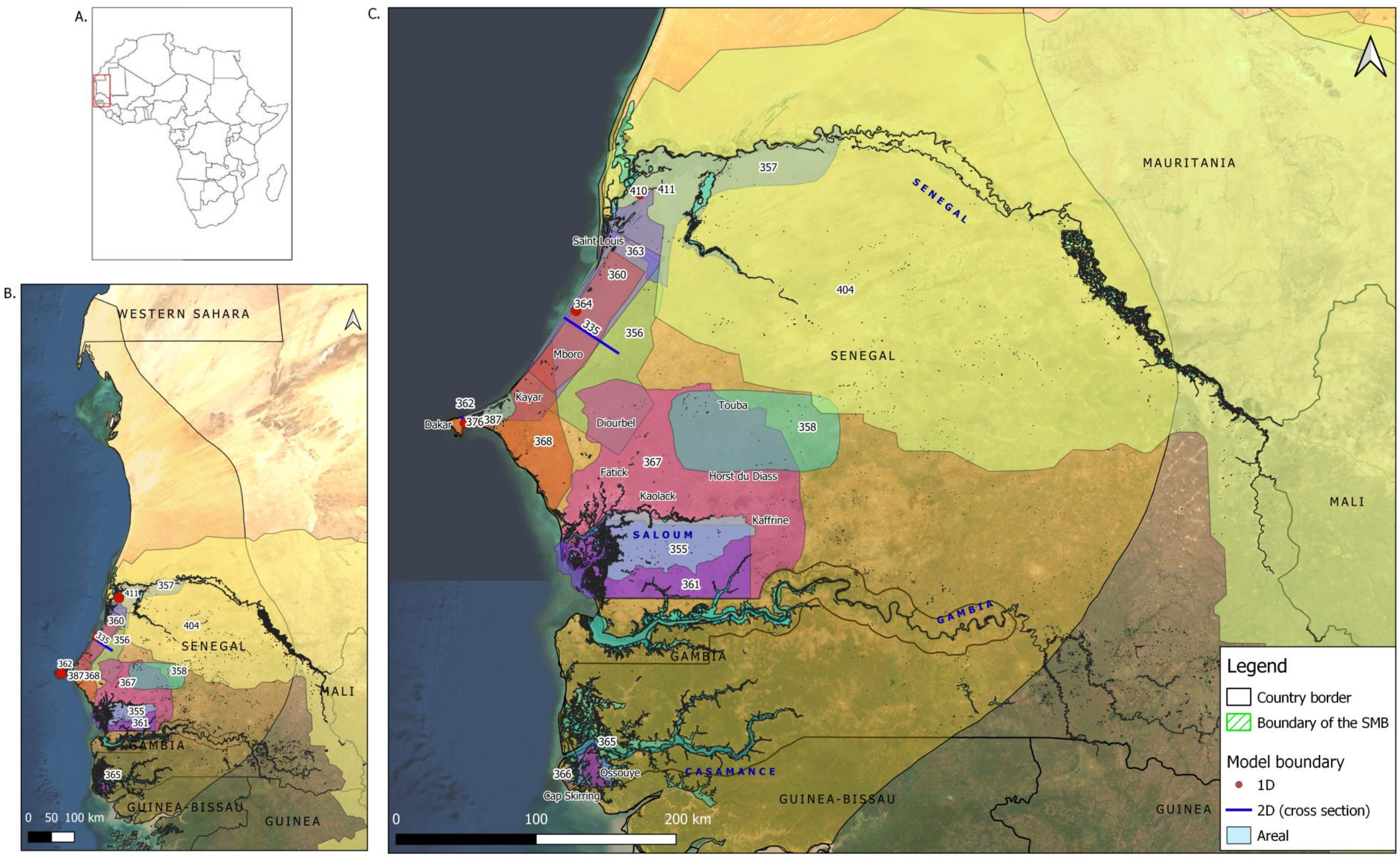


Table 2. Table summary of the models retrieved for the Senegalo - Mauritanian Basin.

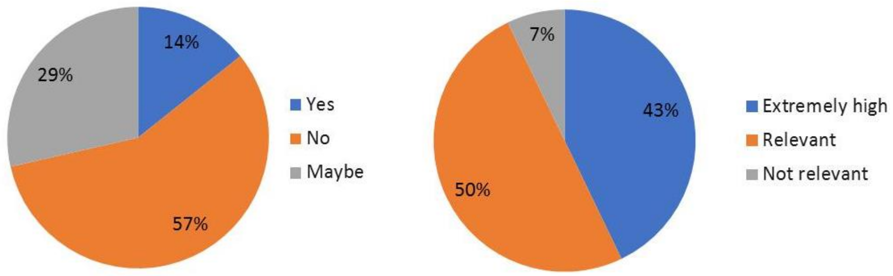
ID	Year	Document Type	Objective short	Country	Model name	Main investigated aquifer	Watershed	Code used for simul.	GUI
387	2000	PhD Thesis	Groundwater management	Senegal	Thiaroye aquifer	Coastal aquifer	Senegal	MODFLOW	PMWIN
404	2001	Research paper	Understanding hydrology	Senegal, Guinea, Mali, Mauritania	Senegal River Basin	Senegalo-Mauritanian	Senegal	MIKE-SHE (modified)	MIKE-SHE (modified)
356	2002	MSc Thesis	Groundwater management	Senegal	Niayes area	Niayes aquifer	Senegal	MODFLOW -96	Not specified
355	2002	PhD Thesis	Groundwater management	Senegal	Saloum hydrologic system	Continental terminal	Saloum	MODFLOW	GMS
357	2005	MSc Thesis	Groundwater management	Senegal	Delta of the Senegal river	Coastal aquifer	Senegal	MODFLOW	Visual MODFLOW
358	2006	MSc Thesis	Groundwater management	Senegal	Touba	Maastrichtiaan aquifer	Saloum	MODFLOW	Visual MODFLOW
411	2006	MSc Thesis	Understanding hydrology	Senegal	Senegal river delta	Quaternary sand aquifer	Senegal	HYDRUS 1D	HYDRUS 1D
362	2012	Conference proceeding	Understanding hydrology	Senegal	Quaternary sands aquifer of the northern littoral	Quaternary sand aquifer	Senegal/Saloum	SUTRA v.2.1	Not specified
360	2012	MSc Thesis	Understanding hydrology	Senegal	Quaternary sands aquifer of the northern littoral	Quaternary sand aquifer	Senegal/Saloum	MODFLOW	GMS
361	2014	Research paper	Understanding hydrology	Senegal	Saloum aquifer	Continental Terminal	Saloum	MODFLOW	Visual MODFLOW
410	2015	PhD Thesis	Understanding hydrology	Senegal	Senegal River Delta	Superficial aquifer	Senegal	HYDRUS 2D	HYDRUS-2D
364	2016	Research paper	Groundwater management	Senegal	Niayes area	Niayes aquifer	Saloum	HYDRUS 1D	HYDRUS-1D
359	2017	PhD Thesis	Understanding hydrology	Senegal	Horst of Diass	Paloecene/Maastrichtian	Saloum	Not specified	Not specified
365	2017	Technical report	Groundwater management	Senegal	Plateau of Oussouye	Continental Terminal	Casamance	MODFLOW	Visual MODFLOW
366	2017	Technical report	Groundwater management	Senegal	Cap Skiring	Maastricthian/CT	Casamance	MODFLOW	GMS
363	2018	Research paper	Groundwater management	Senegal	Quaternary aquifer of Dakar	Quaternary sand aquifer	Senegal/Saloum	FEFLOW	FEFLOW
367	2018	Technical report	Groundwater management	Senegal	Arachidier basin	Upper (Quat./CT/Oligo-Mioc.) and intermediate (Éoc./ Pal.) aquifers	Saloum/Gambia	MODFLOW	Visual MODFLOW
368	2018	Technical report	Groundwater management	Senegal	Horst of Diass	Paloecene/Maastrichtian	Saloum	MODFLOW	Visual MODFLOW
335	2019	Research paper	Understanding hydrology	Senegal	Niayes area	Quaternary sand aquifer	Saloum	MARTHE	Not specified
376	2020	Research paper	Understanding hydrology	Senegal	Dakar region	Quaternary sand aquifer	Saloum	HYDRUS 1D	HYDRUS-1D

From the countries of the SMB we received 14 completed valid questionnaires (10 from Senegal, 2 from Mauritania and 1 each from Guinea and Gambia), mainly respondents from the academic/research sector (about 77%), with a high academic degree (64% PhD), from ten institutions. The 86% of the sample declared that his/her area of expertise is related to groundwater modelling or groundwater data analysis (with expertise in GIS and use of spreadsheets), and main areas of interests in groundwater exploration and water quality issues. The sample suggests the main priorities to be addressed in groundwater management are: i) achieving hydrodynamic and hydrochemical characterisation of groundwater bodies; ii) achieving sustainable groundwater management; iii) define most productive areas of the aquifers. Experts in GIS are present in all of the institutions, while experts on groundwater modelling only in three out of ten institutions. Four institutions have staff trained in programming. The 85% of the sample knows the meaning of the OS term. The ESRI ARCGIS (ESRI, 2011) is the most commonly used GIS application, challenged by the free and OS QGIS (QGIS Development Team, 2009) and the commercial MapInfo GIS (Pitney Bowes Software Inc., 2008) applications. MODFLOW (McDonald and Harbaugh, 1988) is the most common code for groundwater flow simulations for all the respondents, and, it is used by means of commercial GUIs. The usage of the two identified free and open source GUIs (ModelMuse; Winston, 2009) and FREEWAT (Rossetto et al., 2018)) is still far in number respect to the commercial ones. Unfortunately, when asked about the average computational capacity at their institutions, the respondents did not provide useful replies.
Digital tools are recognised as needed tools for groundwater resource management at national/regional level by 86% of our sample. Respondents believe groundwater numerical modelling are used for research purposes (36%), and about 30% each for professional work and in public authorities. Although 50% of the respondents do not know how many groundwater flow numerical models were implemented in their own country in the last ten years, 40% of the sample reports a number (less than 10) which is fairly in agreement with the results of the literature review. number. Still 50% of the sample also replied the use of groundwater numerical models is deemed to be an occasional activity or mostly applied for large engineering projects (50%). These models are not regularly updated or, once built and used for a specific question, they are abandoned.
Reasons for groundwater modelling not being routinely used are identified in inadequate resources to develop and maintain a model (36%), scarcity of data (29%), and finally missing capacities (18%). To this, other factors are identified in lack of computing resources and the time required for implementing reliable applications. Data are reported to be available for few areas, with limited parts of the SMB countries well covered: barely 95% is convinced that prior to any modelling exercise starts a robust data collection effort should be undertaken. Nonetheless, 60% thinks groundwater models, even built with scarce data, are valuable tools to drive hydrogeological investigations and to get initial insights on resource availability. About 60% believes their country has not reached the skills and capacities for dealing with groundwater management using digital tools; the 95% thinks the need for capacity building on the use of digital tools is from relevant to extremely relevant.

4. Conclusions and recommendations

Groundwater is a critical resource for people and ecosystems. Digital tools may support and boost efficient data management so that more technically sound and even community-based decisions may be made. The research run allowed a detailed overview of the usage and diffusion of digital tools for groundwater resource management in Africa. Both the literature review and the survey run show that digital tools have entered and are progressing in the African context, and this increasing trend is still ongoing in 2020. However, out of this data, we may say that the present usage of digital tools in general is still low.

Figure 4. Percentage of responses on achievements of competencies on groundwater modelling (left) and on the need for specific training (right) in countries of the SMB.



Several scientific papers and many of the retrieved documents deal with basic applications by means of commercial GUIs, providing the idea of use driven by software availability on the market, rather than a digested methodology. This is also confirmed by the fact that when asked about available computing capabilities a large part of the interviewed sample was not able to provide such information. The only example of active development is mentioned in in Lyazidi et al. (2019) with the development of a tool to facilitate the use of a database and the visualisation and management of spatial and temporal data related to the study of the Gareb-Bouareg aquifer (Morocco).

However, this progress in digitalisation is faster in NA than SSA. Within SSA differences also exist, for example, South Africa and Ghana seem to be more advanced, while in other countries we do not have this evidence. At the same time, not in all the countries of similar areas the level of advancement is noticeable (i.e. in Western Africa Senegal seems to be more advanced compared to Mauritania, Gambia and Guinea Bissau).

A particular focus was dedicated to review the use of Open Source tools in groundwater-related data management, analysis and modelling. At present the digital groundwater management is still dominated by commercial applications. Anyway, the declared use of free and open source GIS applications and the appearance of free and open source GUIs for modelling shed a light on an increasing trend of usage of these software.

Only 22% of the whole sample consider that, on average, skills and capacities for dealing with groundwater management using digital tools are available in their own country, while it is the opinion of 50% that these are not reached. The three key elements identified as barriers in the use of digital tools are: i) scarcity of data, ii) inadequate financial resources to develop and maintain a model (lack of computing resources), and iii) missing capacities (including lack of computing skills). On data scarcity, only about 50% of the respondents declared that digital archive of groundwater-related data exists in their country. In this sense, 67% of the respondents stated that sufficient data to build models are only available in few areas of their country. Finally, the lack of adequate and well-functioning Internet connection is considered one of the main bottleneck against the spread of new technologies.

Capacity building on the use of digital tools for groundwater management is deemed to be extremely high by 60% and high by 35% of our sample, respectively (Figure 4). Undertaking cooperative international research projects is considered the most relevant action to create capacity, followed by training and national projects. Capacity building and knowledge transfer has then to be on top of the agenda for a digital groundwater governance in Africa. As highlighted by the respondents to the questionnaire, building capacities even on basic applied topics is an issue. Starting from this, we suggest to introduce applied courses on hydroinformatics, at university level (both in BSc/MSc and in PhD in engineering, earth science, and environmental science degrees) where fundamentals of programming are taught and then move to more applied contents (i.e. sensor's data acquisition and management). Following, we suggest to introduce numerical methods theory and example applications. This will allow young professional/researchers to be aware of the methods independently from commercial software, able to choose among the solutions that fit best, and eventually to modify and tailor them for their own purposes. In particular, training should be directed to favour the use (and re-reuse) of open-source applications and the often huge amount of information and contents available. A generation of experts with a sounding interdisciplinary background should be able, in five to ten years, to properly drive digital and data-based groundwater governance in Africa.

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Water loss through evaporation from hydropower production in Africa

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Hydropower plays an important role in the African energy mix besides fossil fuel, non-hydro renewable, nuclear and waste heat energies, to cope with increased energy demand due to fast population and economic growth. This study estimates gross water loss through evaporation from hydropower reservoirs of 159 associated hydropower plants above 5MW installed capacity, representing 95% of the total hydropower installed capacity in Africa. Evaporation losses for the year 2016 are calculated for each reservoir using the FAO approach for open water sources. Reservoir extents are extracted from JRC Landsat based Global Surface Water data (30m resolution), reference evapotranspiration data is obtained from the LISVAP pre-processor and information on shared uses of reservoirs is collected from several databases. In 2016, estimated gross water loss from hydropower reservoirs amounts to 42.2 billion cubic meters (bcm) compared to 1.2 bcm from all the other fuel types combined (Gonzalez Sanchez, Seliger, et al., 2020). The four biggest hydropower reservoirs in the continent, Akosombo (Ghana), Aswan High (Egypt), Kariba (transboundary reservoir with Zambia and Zimbabwe) and Cahora Bassa (Mozambique) cover an area of 17,954 km² and account for almost two thirds of the total water loss from hydropower reservoirs in Africa. The performance of a hydropower plant is favourable when higher energy production meets lower water consumptions, and vice-versa., as the case for most hydropower plants in Morocco, Ethiopia and South Africa. New hydropower developments need to be carefully pre-assessed especially in regions characterized by severe water scarcity.

Keywords: Hydropower, water loss, Africa, Global Surface Water

1 Introduction

Hydropower production in Africa is widely expanding due to an increased need for electricity. Considering other energy types used in the African energy mix such as fossil fuels (coal, oil, gas), non-hydro renewables (solar, wind, biomass, geothermal), nuclear and waste heat energy, many African countries highly depend on hydropower production. Often, hydropower plants and associated reservoirs are located in regions prone to droughts or floods, causing electricity cuts due to lack of water (Reuters, 2016; The Guardian, 2017) or decrease of dam capacity due to siltation (Loisulie, 2010). Moreover, reservoirs can cause recession of agriculture downstream the river while at the same time they can contribute to flood control, by managing the alterations of the water cycle, aggravated by climate change. Reservoirs used for multiple purposes can contribute to agricultural production, water supply, navigation and recreation in proximity to the reservoir. Hydropower related water losses occur through plant operation as well as seepage and evaporation from hydropower reservoirs, with evaporation being the biggest contributor to water consumption (Gonzalez Sanchez, Hidalgo Gonzalez, et al., 2020) often several magnitudes higher compared to other fuel types (Macknick et al., 2012). Water losses through evaporation for energy production are influenced by a pool of factors, mainly climate, reservoir size (terrain), shared uses of reservoir water and reservoir management practices.

In the frame of the overall study about "Freshwater use of the energy sector in Africa" (Gonzalez Sanchez, Seliger, et al., 2020) which estimates the energy sector's water consumption and withdrawal in African countries including fuel extraction, processing, power plant construction and operation, this short paper analyses the gross water loss through evaporation from African hydropower reservoirs compared to the energy production rates of associated hydropower plants, for the year 2016. Water loss through hydropower plant operation is negligible and thus not further investigated. Since seepage water usually remains in the water basin, it is not seen as real loss and, thus, not further analysed, neither. However, annual seepage losses can account up to 5% of the reservoir volume (Gleick, 1994). Water loss estimates of year 2016 provided in this study are based on high resolution spatial and temporal data and, thus, the real situation of hydropower reservoirs extents affected by regulation (storing, retaining and releasing water), region-specific meteo-climate drivers (heat- waves, droughts, precipitation, wind speed, evaporation) and number and intensity of shared uses (Busker et al., 2018; Herath et al., 2011) is reflected. Morphological conditions and overall stored reservoir volume are not considered in this study.

2 Method

159 hydropower plants out of 529 operational hydropower plants in Africa are considered in our study, which represents 95% of the total hydropower installed capacity in Africa in 2016 (30.2 GW). The selected hydropower plants are characterized by installed capacities above 5MW and an evident water accumulation in the reservoirs caused by the dam operation. Information on African hydropower plants is obtained from S&P Global Platts (2016). Reservoir extents of year 2016 are derived from the JRC Yearly Water Classification History, v1.1 (EC JRC/Google, 2019b), which bases on the JRC Monthly Water History, v1.1 (EC JRC/Google, 2019a). The monthly and yearly history are core of JRC Landsat based Global Surface Water data set and refer to a period from 1984 to present, at 30m resolution (Pekel et al., 2016b, 2016a). The JRC LISVAP pre-processor for the LISFLOOD water balance and flood simulation model (Alfieri et al., 2020; Burek et al., 2013) is used to obtain reference evapotranspiration data, based on ERA5 data (Copernicus Climate Change Service, 2017). Evaporation losses from reservoirs are calculated using the FAO methodology for open water surfaces (FAO, 2015):

$$Ev\ (m^3) = \frac{ET_0(mm) * A\ (m^2)}{1000}$$

where ET_0 (mm) is the LISVAP reference evapotranspiration and A (m²) the reservoir area from the Yearly Water Classification History. Regarding multi-purpose reservoirs, shared uses are identified from GRanD (Lehner et al., 2011), ICOLD (ICOLD, 2013) and FAO databases (FAO, 2016). A ranking-based approach is used to allocate evaporation water losses to hydropower. If electricity generation is the primary use in a reservoir, water loss is fully (100%) allocated to hydropower. If hydropower is secondary or tertiary use among competing reservoir uses, only 50% and 33% is allocated to water loss related to hydropower (Mekonnen et al., 2015; Scherer & Pfister, 2016). If no information about hydropower use is provided in the above-mentioned databases, but the associated hydropower plant is listed in Platts (S&P Global Platts, 2016), a minimum allocation of 10% is assigned for electricity generation in the reservoir. Annual electricity production for each power plant is estimated by using capacity factors at country level based on data from the International Renewable Energy Agency (IRENA) (2018), International Energy Agency (IEA) (2018) and United Nations (UN) (2016)

$$CF_{ij} = \frac{Total\ Generation_{ij}(MWh)}{Installed\ Capacity_{ij}(MW) * 24 * 365}$$

The capacity factor and installed capacity of each plant is used to calculate the generated electricity per hydropower plant.

$$Electricity\ generated_k(MWh) = CF_{ij} * Installed\ Capacity_k$$

with κ referring to the power plant and CF_{ij} as capacity factor corresponding to the country and fuel type (here: hydropower) where power plant κ is located. Total hydropower production per country is obtained by summation of electricity production of all associated hydropower plants.

3 Discussion

The 159 African hydropower plants analysed in this study are mainly located along a NW-SE striking arc and in Western Africa **(Figure 1, Figure 2**, first row**)**. In 2016, hydropower capacity represented 15% of the total installed power generation capacity, ranging between fossil fuels (higher capacities) and non-hydro renewable energies (lower capacities) **(Figure 2,** second row**)**. In Central Africa hydropower accounts for 58% of the total installed capacity, followed by Eastern Africa (54%) and Western Africa (30%). In Northern and Southern Africa, less than 10% of total installed capacity is produced by hydropower (Gonzalez Sanchez, Seliger, et al., 2020). Eight countries (Lesotho, Congo Dem. Rep., Zambia, Malawi, Ethiopia, Mozambique, Burundi, Central African Republic) highly depend on hydropower, exceeding 70% of their total installed capacity. Hydropower production causes with 42.2 bcm the highest water consumptions in the African energy mix exceeding other energy types by several orders of magnitudes **(Figure 2,** third row**)**. The four largest African hydropower reservoirs, namely Akosombo (Ghana), Aswan High (Egypt), Kariba (Zambia and Zimbabwe) and Cahora Bassa (Mozambique) cover an area of 17,954 km² which accounts for almost two thirds (27 bcm) of the total water loss from hydropower on the continent (**Figure 1 and Figure 3**). Countries like South Africa, Morocco, Ethiopia, Congo D.R. or Angola are dominated by reservoirs of smaller size with relatively low water losses but relatively high installed capacities **(Figure 3)**. The performance of a hydropower plant is favourable when high energy production meets low water consumptions, and vice-versa. In this context, hydropower sites with unfavourable water loss / energy production ratios above 2 mcm/GWh are Mansour Eddahbi (Morocco), Nyumba Ya Mungu (Tanzania), Jebel Aulia Dam (Sudan), Kompienga (Burkina Faso), Mtera (Tanzania), Akosombo (Ghana), Baneah (Guinea), Bagre (Burkina Faso), Lagdo (Cameroon) and Buyo (Cote d'Ivoire), of which Akosombo, Lagdo, Mtera and Jebel Aulia Dam represent very big or big reservoirs greater than 500 km² in surface **(Figure 1)**. In this size category, reservoirs Merowe (Sudan), Roseires (Sudan) and Cahora Bassa (Mozambique) show rather good ratios below 0.5 mcm/GWh.

Figure 1. Distribution of the African hydropower plants with installed capacity greater than 5MW, associated reservoir sizes and reservoir water loss through evaporation in 2016. The ratio of water loss vs. energy production indicates the performance of the hydropower site.

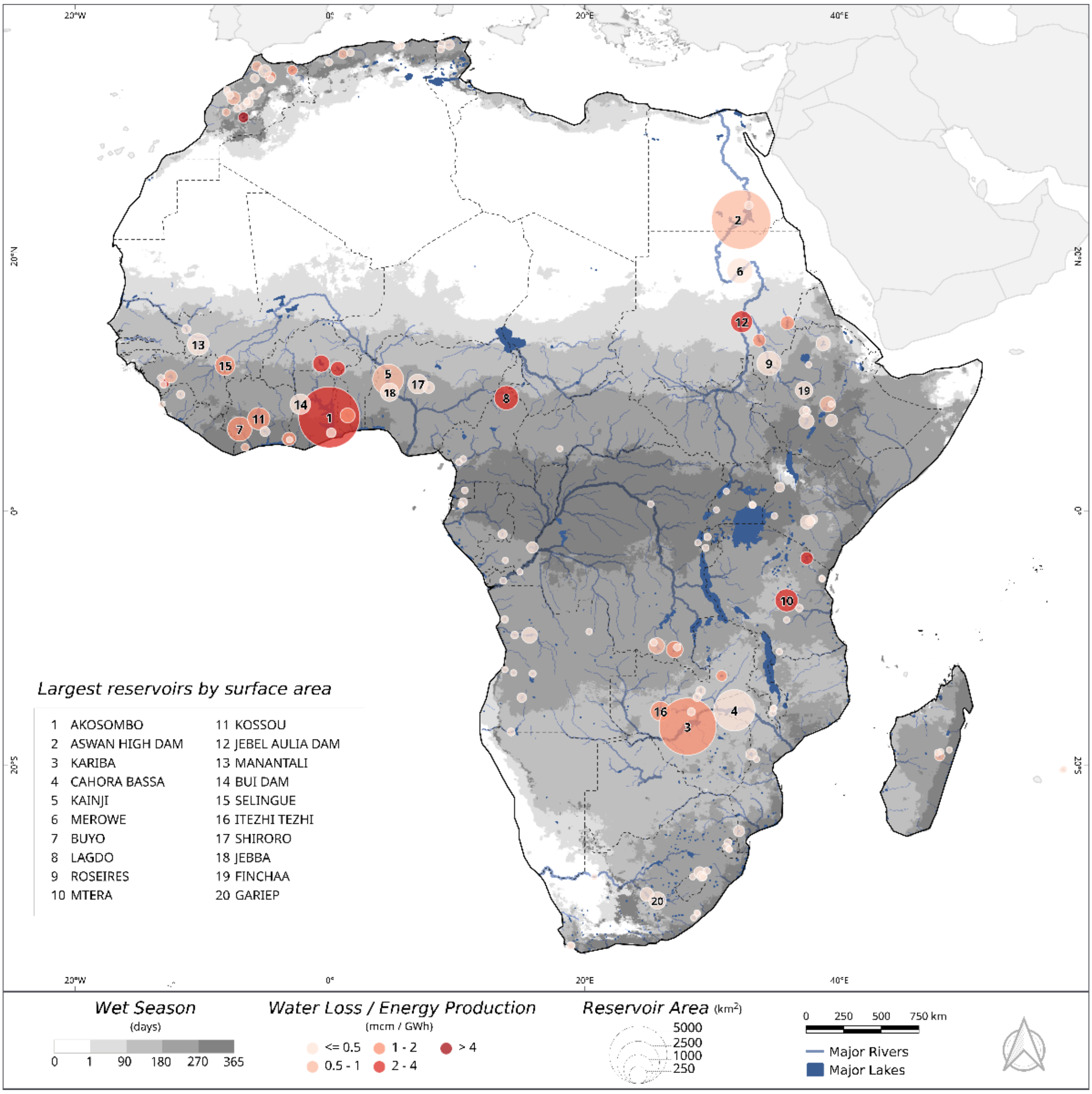
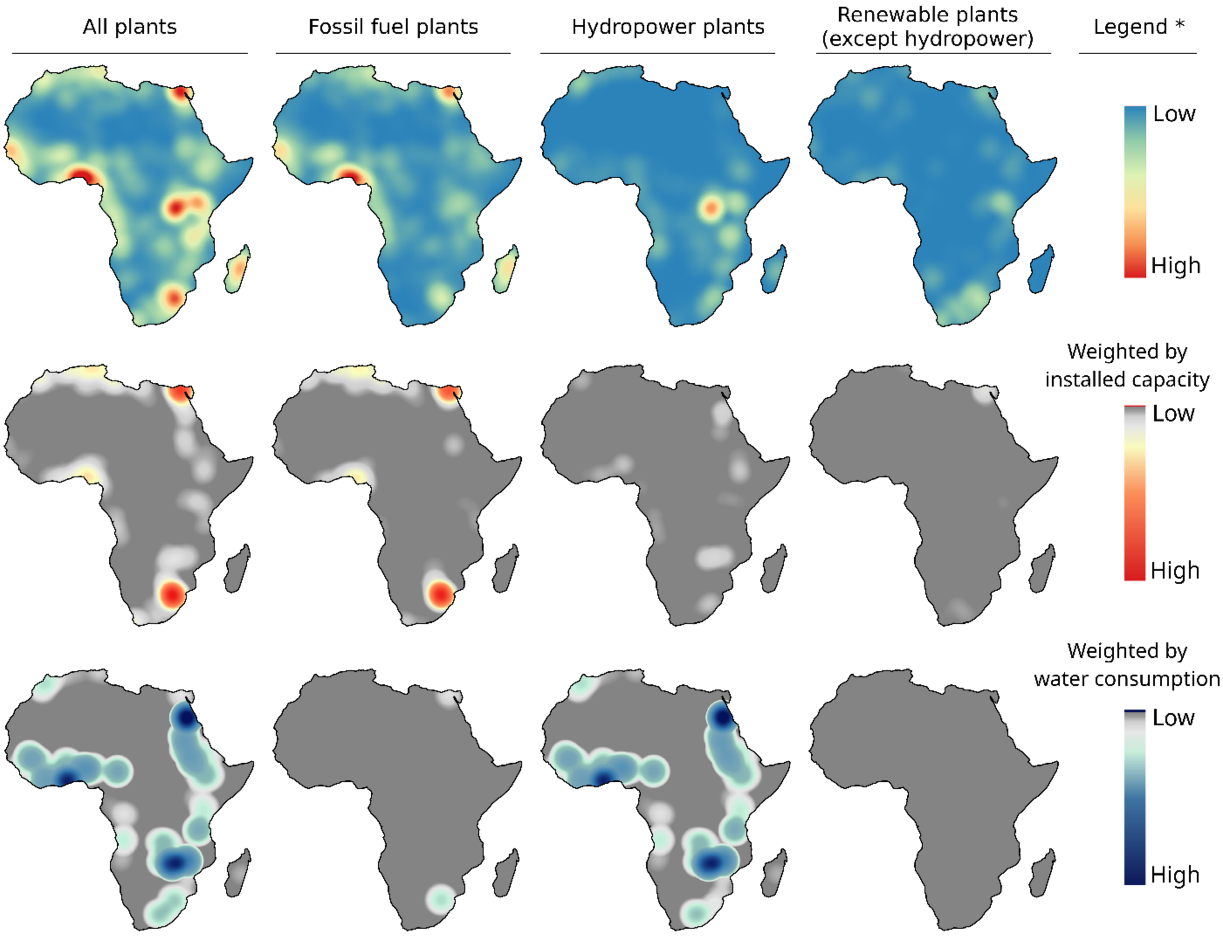


Figure 2. Density maps of African power plants (fossil fuel, hydropower, non-hydro renewable plants) in 2016. Row 1: power plant location; Row 2: power plant location weighted by installed capacity; Row 3: power plant location weighted by water consumption.



* Density of plants: the maps were created using the Kernel Density Estimation (KDE) algorithm based on the quartic kernel shape. Weights were applied in the second and third rows to visualize the density of plants when considering the installed capacity and water consumption.

4 Conclusions and recommendations

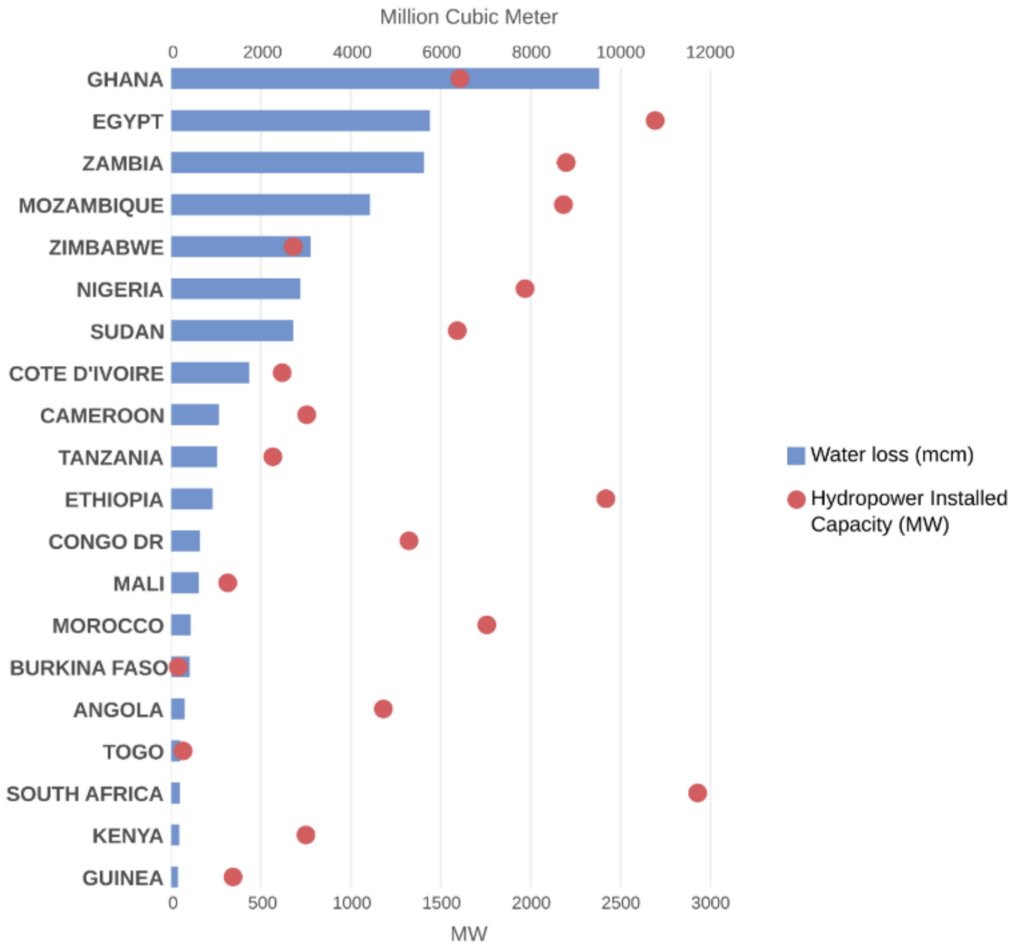
The presented study provides a consistent approach to estimate gross water loss through evaporation from hydropower production in Africa, considering reservoir extents and climate conditions of a specific year (here 2016). It overcomes bottlenecks of many global databases which partly lack details regarding the accuracy of the measurements, the moment in which the data have been gathered or any information on the temporal evolution of the reservoir extents (Gonzalez Sanchez, Hidalgo Gonzalez, et al., 2020).

The discrimination of shared uses of reservoirs allows allocation of water losses through evaporation exclusively to hydropower production. However, the applied method of shared use allocation could be further developed by integrating not only aspects on priority of uses but also information on regulations and economic and social valuations. Ground-truth data and regional expert knowledge could substantially contribute here, even though it is challenging to obtain sound information for many reservoirs all over Africa.

The analysis of gross water loss from reservoirs tends to overestimate, because water course extents prior to dam construction and reservoir impounding are not considered in the analysis. Therefore, a net water loss analysis could refine the estimates, although early water course information prior to dam construction is not always easy to retrieve from satellite imagery. Water loss estimates through evaporation from reservoirs could be further improved by considering also morphological conditions, overall stored volume of the reservoirs and more detailed information on dam and reservoir management.

The here presented study for year 2016 is currently being complemented by a temporal variability analysis of hydro-generation characteristics for 50 selected African reservoirs of good spatial (representing entire Africa) and temporal quality (at least 30 years of time series length), linked to climate oscillation patterns. Based on a set of statistical methods (e.g. change detection, change of variance, empirical mode decomposition), reservoir extents, climate history and its interdependences are analysed in order to find suitable predictors for future water availability for hydropower production and to support future hydropower management.

Figure 3. Water loss through evaporation vs hydropower installed capacity for the top 20 countries with the highest water loss in the year 2016.



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Climate Variability Analysis: Precipitation and Temperature in Four African Basins

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Climate Variability plays a key role in the context the integrated management of water resources and WEFE (Water-Food-Energy) nexus. This study, in the framework of ACEWATER2 project, analyzes spatio-temporal gridded monthly and daily datasets for precipitation and temperature to retrieve information on climate variability for an historical reference period (1981-2017) in the ACEWATER2 project selected basins (Senegal, Niger, Nile and Zambezi river basins). Analysis outcomes provide an overview of the precipitation deficit expressed as function of different return periods and the number of years with high heat wave magnitude index. Higher precipitation deficit associated with lower return periods means high precipitation variability. Results highlight: higher precipitation variability for areas with lower precipitation, generally the poorest and driest ones, strongly dependent upon rainfall for both water supply and rainfed agriculture; spotted heat waves with relevant impacts on people life and health, hence being particularly critical in densely populated areas.

Keywords: Climate Variability, Precipitation, Drought, Temperature, Heat Waves

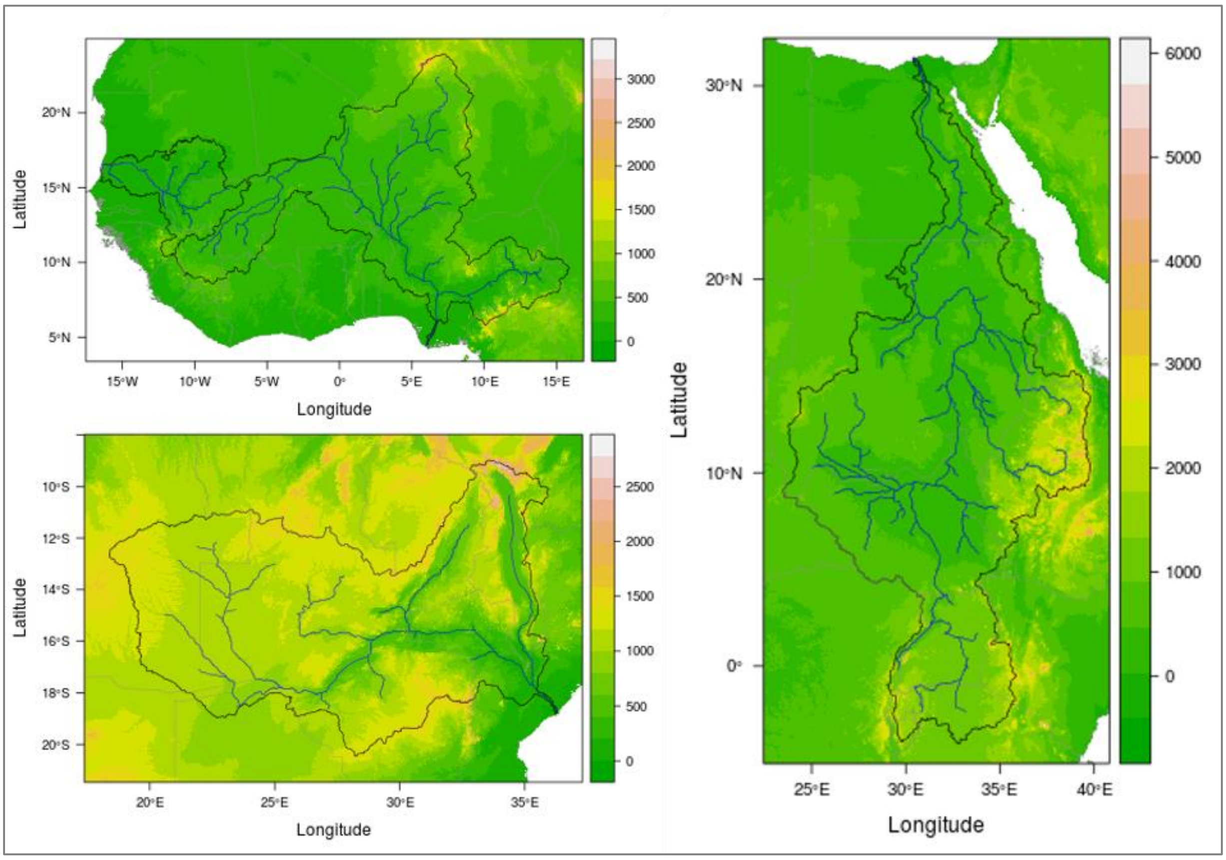
1. Introduction

Climate variability refers to the way climatic variables, as precipitation and temperature, fluctuate yearly, above or below a reference average value, typically computed on the basis of a long term data series of at least three decades. The climate variability analysis is based on the statistical analysis of the time series data. Climate variability affects socio-economic activities and the assessment of probability of given events, as estimated after the climate variability analysis, supports stakeholders in taking appropriate measures to reduce risks and impacts.

Climate variability clearly differs from the climate change, that refers to the numerical simulation of long-term climate dynamics based on RCPs (Representative Concentration Pathways) scenarios (i.e. climate projections).

Traditional statistical methods can be used to perform the climate variability analysis. In this work, maps of precipitation deficit associated to different return periods and maps of heatwave magnitude for the ACEWATER2 project selected basins (Senegal, Niger, Nile and Zambezi river basins, see Figure 1) are presented. Analysis was implemented in R (R Core Team,2020, Cordano, 2017a,2017b; Cattaneo et al., 2017,2019), based on freely available datasets, as detailed in Crestaz at al. (2019).

Figure 1: DTM (Digital Terrain Model) over the four river basins (Senegal, Niger, Nile, Zambezi)



2. L-Moment and precipitation deficit (drought)

L-moments statistics have been calculated for precipitation, based on the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) at monthly scale over the period 1981-2017. CHIRPS is a gridded 30+ year quasi global rainfall dataset with a resolution of 0.05 degrees (Funk et al., 2014). The L-moments are combinations of probability weighted moments and based on difference of expected values of sub-samples. Their interpretation is similar to other statistical moments, but with the advantage of being less susceptible to the presence of outliers and performing better with smaller samples (Hosking and Wallis, 1997).

The 1st L-moment (L-mean) corresponds to the conventional statistical mean and is plotted in Figures 2, 3a, 3b and 4 (left column) to represent monthly mean precipitation. The 2nd L-moment (L-cv) measures random variable's dispersion. The 3rd and 4th L-moments (L-skewness and L-kurtosis) are measures relating to the shape of the sample distribution. The L-skewness quantifies the asymmetry of the sample distribution, and the L-kurtosis measures whether the samples are peaked or flat relative to a normal distribution. A strict mathematical formalism on L-Moments is given by Hosking and Wallis, 1997.

Based on estimated probability function of monthly precipitation at each pixel, various deficit/excess indexes and return periods can be mapped. The deficit/excess indices highlight the divergence with respect to mean climatology. In particular, the relative deficit D, that's the deficit rescaled to the mean, is defined as:

$$D = \frac{E[P] - P}{E[P]}$$

Where P is precipitation and E[P] is the mean or the expected value of precipitation. Relative excess is the opposite of relative deficit.

Deficit increases if precipitation decreases.

Figures 2, 3a, 3b and 4 show the mean precipitation for each month of the year, and the relative deficit associated to different return periods (5, 10, 20 and 50 years), per each month.

Deficit values for different return periods depend on the shape of probability distribution. The return periods depend on precipitation/deficit cumulative probability and corresponds to the average time, expressed in years, between two events with the same magnitude (or higher). Return periods of deficit provide an indication on the variability of precipitation in the actual climate. Whereas events with higher return periods (50 years) are to be considered as extremes, events with lower return periods (i.e. occurring every 5 or 10 years in average) are a measure of precipitation variability. If a 60% deficit has a return period of 5 years, i.e. precipitation lower than 40% of the mean expected value, it can be considered relatively frequent. However, in many cases this happens during the dry season, i.e. low values of mean precipitation.

Precipitation expected values and deficit values for different return periods for Niger and Senegal river basins are plotted in Figure 2. The area of the two basin cover all Western Africa. The relative deficit increases in areas with lower mean precipitation, above all during the rainy season (approximately June to September).

Precipitation expected values and deficit values for different return periods for Nile river basin are plotted in Figures 3a and 3b. Nile river basin extends in a south-north direction, over the two terrestrial hemispheres. Rainy zones are, in the northern hemisphere, tropical areas from June to September and, in the southern part, from September to June. In the southern part of the basin, the precipitation variability (given by the deficit values with a return period of 5 and 10 years) does not present any strict dependency with precipitation expected values and is higher respect to the northern part where climate is arid.

Monthly precipitation average values and deficit values for different return periods for Zambezi river basin are plotted in Figure 4. The basin is located in Southern Africa and covers different climatic areas. The northern part is rainier than in southern part. During the rainy season (approximately December to March) deficit values at the given return periods are higher, especially in the southern part of the basin with lower mean precipitation.

Figure 2: Monthly mean precipitation [mm](left) and relative deficit values [%] associated to the return periods of 5, 10, 20 and 50 years in the Niger and Senegal river basins

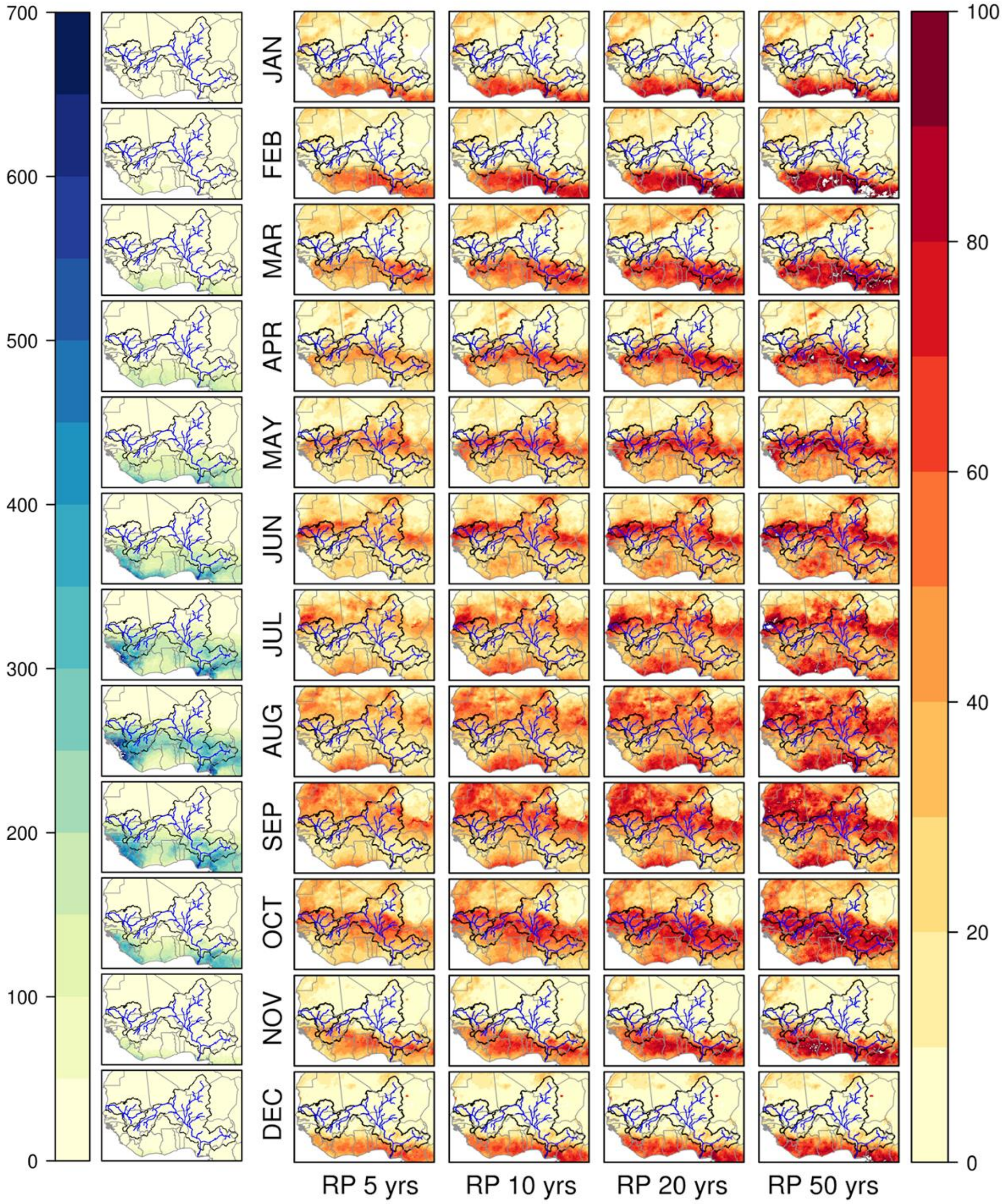


Figure 3a. Monthly mean precipitation [mm](left) and relative deficit values [%] associated to the return periods of 5, 10, 20 and 50 years in the Nile river basin (JAN to JUN).

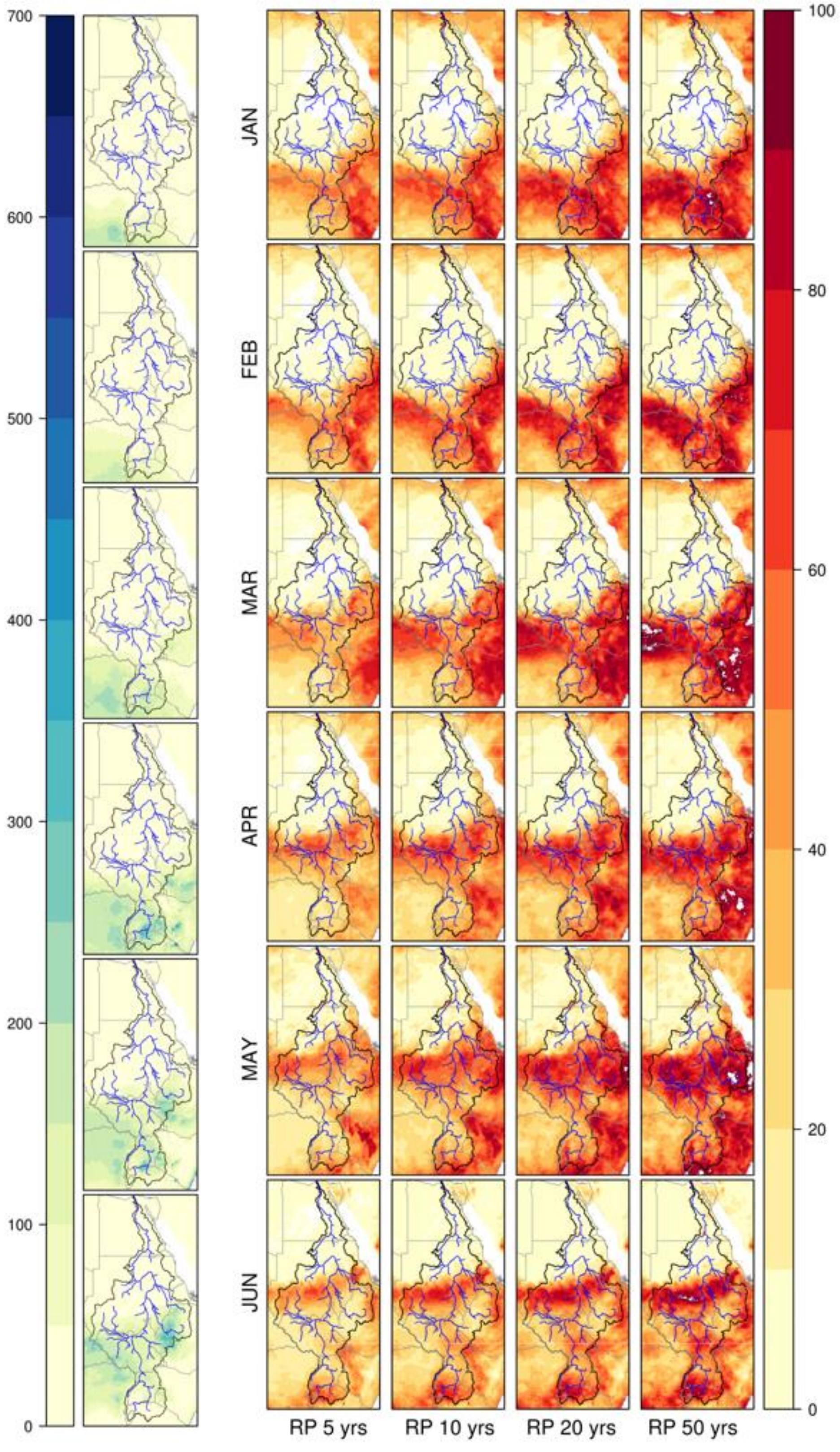


Figure 3b: Monthly mean precipitation [mm](left) and relative deficit values [%] associated to the return periods of 5, 10, 20 and 50 years in the Nile river basin (JUL to DEC).

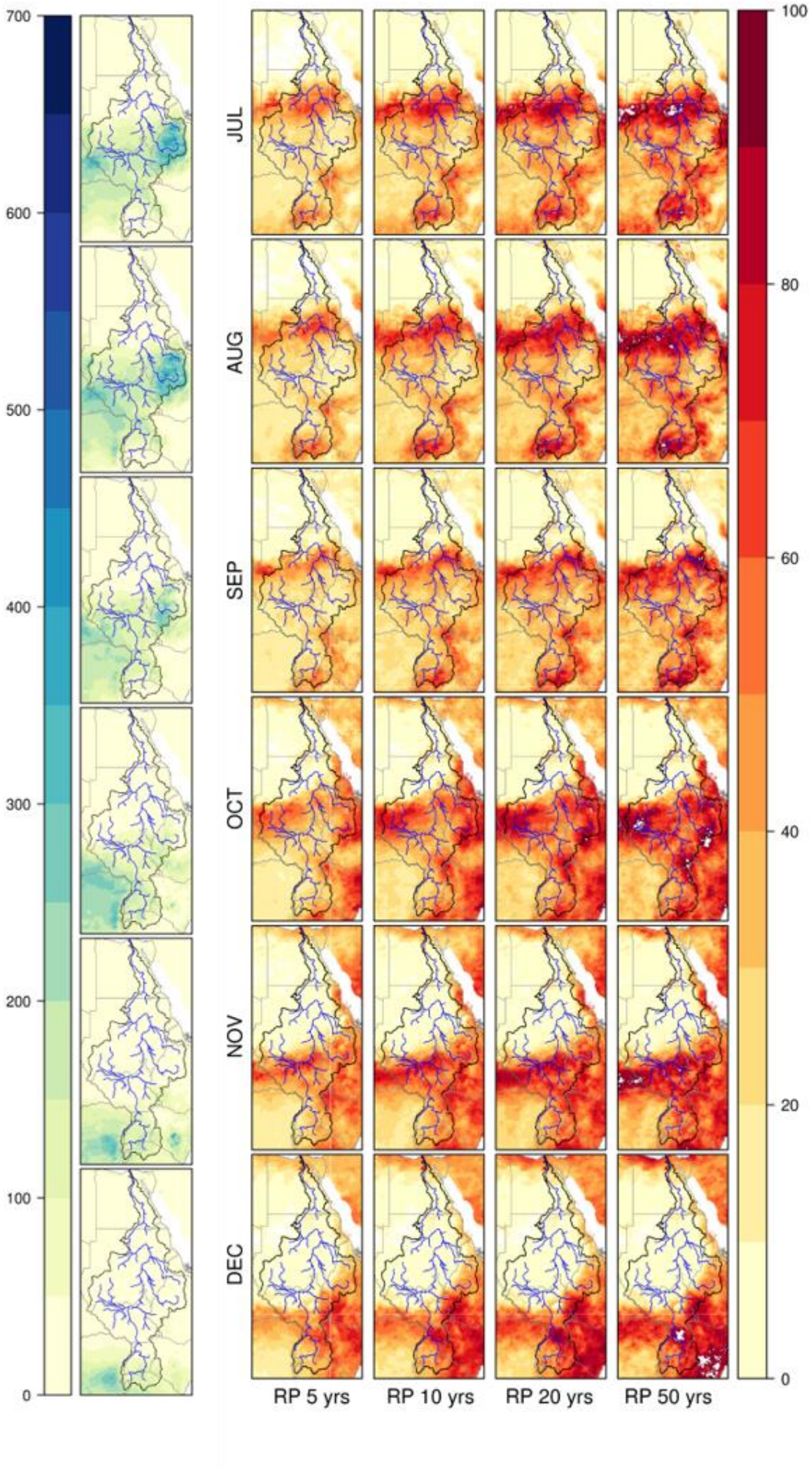
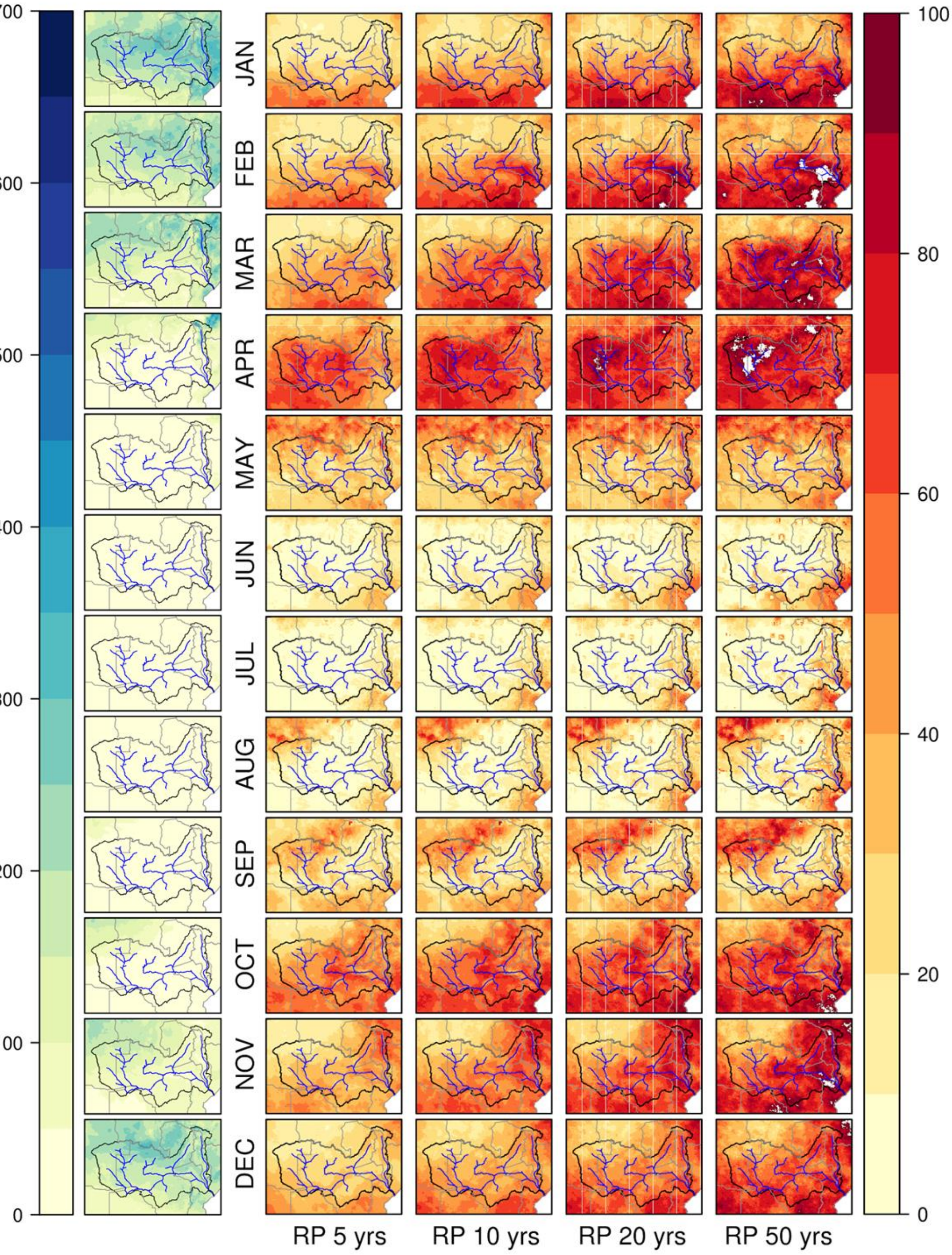


Figure 4: Monthly mean precipitation [mm](left) and relative deficit values [%] associated to the return periods of 5, 10, 20 and 50 years in the Zambezi river basin



3. Heat waves

Heat waves are defined as a period of at least three consecutive days for which daily maximum temperature exceeds a threshold value, which is defined as the 90th percentile of daily maxima temperature, centered on a 31 days long window. Detailed mathematical formulation and possible alternative definitions of the magnitude of a heat wave are discussed in Russo et al. (2014, 2015). Further to this, a magnitude heat wave index has been defined by the authors as the sum of the magnitude of the consecutive days composing a heatwave.

Spatial gridded datasets of daily temperature can be used to calculate annual heat wave magnitude index, using specific software tools, as the Extremes R Package (Gilleland and Katz, 2016).

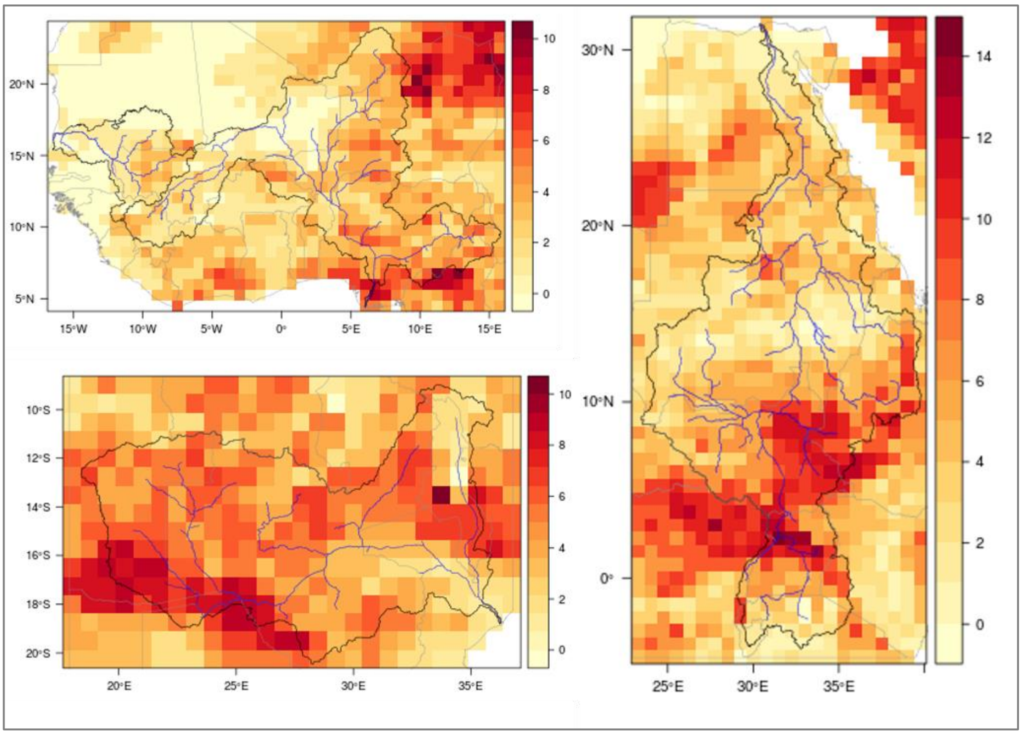
In order to complement the climate variability analysis conducted at the four basins of interest (Niger, Nile, Senegal and Zambezi), heat wave magnitude indices have been computed over the reference period 1981-2017. ERA-INTERIM (Dee et al, 2011) has been used as reference data.

Maps are provided for the four basins (Figure 5), reporting the number of the years over the reference period for which the magnitude heat wave index is greater than 4 (Ceccherini et al,2017). Roughly speaking, the maps can be used to highlight areas characterized by extremely severe hot conditions.

According to Ceccherini et al. (2017), the most impacted areas at continental level include an elongated region spanning through Algeria up to South Sudan, Congo, Angola and Southern Africa. These results find confirmation in current analysis (Figure 6), where the north-western part of the Niger River Basin; the White Nile area between South Sudan and Congo and the southern part of the Zambezi River Basin are reported as the most critical ones.

It is worth to stress that spotted heat waves can have relevant impacts on people life and health, hence being particularly critical in densely populated areas.

Figure 5: Number of years with HWMId>4. Reference Period 1981-2017



4. Conclusions and the way forward

An analysis of climate variability, focused on rainfall and heat waves, was implemented based on freely available CHIRPS (rainfall) and ERA-Interim (temperature) datasets (Funk et al., 2015; Dee et al., 2011). The geographic scope was on few of the major African transboundary river basins, as selected in the framework of the ACEWATER2 project: Gambia and Senegal in Western Africa; Blue Nile and Lake Victoria (further extended to cover the entire Nile river basin) in Eastern Africa; and Zambezi in Southern Africa.

The analysis highlighted that, in most cases, higher precipitation variability concentrates in areas with lower precipitation, that, by the way, are also the poorest and driest regions, strongly dependent on rainfall for both human and livestock water supply, as well as for sustaining rainfed agriculture and pastureland. The analysis, performed at monthly frequency, clearly informs also about the temporal dimension of the phenomena, as related to dry and wet seasons.

Of course the interpretation of the rainfall variability maps cannot be made in isolation from other key spatio-temporal environmental and socio-economic information, further to the mean local rainfall conditions. For example, extremely dry desertic areas can be subject to high variability, as influenced by occasional to rare rainfall, still leading to limited added value (except for pointing at risks of flash floodingalong the wadis). On the other hand, as the focus shifts towards semi-arid areas, with increasing population and livestock density and role of rainfed agriculture becoming key to food sustainability, spatial and temporal distribution of climate variability becomes fundamental to the assessment of risks and vulnerability. Estimates of water requirements, as a function in agriculture on crop type and the different stages of the phenological cycle, have to be assessed against the impact of climate variability, in order to highlight any potential criticality. At the other extreme, humid areas can turn to be much more resilient, also face to relatively large rainfall variability.

As concerns temperature, analysis outcomes, based on heat waves magnitude index computation, reveal the north-western part of the Niger River Basin; the White Nile area between South Sudan and Congo and the southern part of the Zambezi river basin as the most critical ones. Spotted heat waves can have relevant impacts on people life and health, in both country side and densely populated areas.

Finally, further joint analysis of heat waves, precipitation patterns, estimated variability, and water requirements (e.g. human supply, livestock, rainfed agriculture) is needed and future research and developments will address such an integrated view.

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Analysing hydro-political risk to enhance cross-country water cooperation: the African Water Cooperation Atlas

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One of the tasks of the ACEWATER2 project was represented by analysis of the relation between the water management issues and the episodes of political instability. The activities conducted in this field were summarised in the African Atlas of Water Cooperation. Main scope of the project was "to create a dynamic tool addressed to policy-makers to stress hotspots and cues on the potential disequilibrium in the different Water-Energy-Food-Ecosystem components under different climate variability scenarios, natural resource supply, socio-economic and human demand at River Basin scales in Africa". By analyzing the interaction between water availability and uses at river basin scale, the tool was designed to provide assistance to the efforts in the EC-Cooperation in Developing countries, and contribute to the development of the EU Migration Inclination Index. This chapters summarized the main activities developed under this task.

1 Introduction

Within the activities of the African Networks of Centres of Excellence on Water Sciences (ACE WATER) phase 2 project, the Joint Research Centre was involved in the analysis of the dynamics of cooperation and conflict about water management issues at global and Africa level. The work conducted produced four technical reports (F. Farinosi, Gonzalez Sanchez, et al., 2018; F. Farinosi, Gonzalez-Sanchez, Carmona-Moreno, et al., 2017; F. Farinosi, Gonzalez-Sanchez, Crestaz, et al., 2017; Fabio Farinosi et al., 2019), a scientific publication (F. Farinosi, Giupponi, et al., 2018), and a digital tool (available at https://aquaknow.jrc.ec.europa.eu/maptool/atlas) that is aimed at being developed as a decision support system (DSS) to support decision makers in the management of large river basins, in particular in Sub-Saharan Africa.

The work conducted in this field started from the analysis of the dynamics related to the hydro-political risk in transboundary basins at global scale. The second phase of the project focused on the specific dynamics of the African continent and aimed at understanding how water resources management, jointly with natural variability and different levels of governance are likely to exacerbate civil unrest, particularly in terms of protests and violent episodes caused by issues related to water resources. The analysis identified episodes of violence induced by lack of water, studied the availability of water in relation to water uses, and assessed the correlation and causal relations between water availability and the episodes of violence, while accounting for the possible "mitigating effect" brought by the institutional quality.

The final scope of this work is to offer the policy maker at local and regional levels a tool able to help in formulating policy scenarios towards a more efficient and effective water resources management in the different African river basins. The logical framework characterizing the analysis is linked with the belief that a correct water management and an enhanced institutional efficiency could push towards the optimal use of resources boosting economic and social development in a WEFE perspective.

1.1 Water cooperation and hydro-political risk analysis

The Water Cooperation atlas refers to an empirically based tool thought to analyse the interactions between biophysical and socio-economic factors able to influence cooperation or tensions over water in shared watersheds. The idea was to develop a tool able to monitor availability, uses and abuses of water and water-stressed hot spots at national and regional scales. This is not only directed at analyzing water supply and demand, as for a water stress indicator, but also the socio-economic, institutional, legal, and cultural context evolutions that are likely to influence the hydro-political tensions or cooperation.

Competition over limited water resources is one of the main concerns for the next future. In this context, transboundary waters, with more than 280 watercourses shared between almost 150 countries, are to be considered of critical importance in the global politics. Climate change and population growth are expected to heighten hydro-political tensions, leading to increased water disputes in transboundary river basins. The study of past hydro-political interactions, involving either tensions or cooperation, allowed to better understand the dynamics that push countries sharing the same watershed towards more cooperative or confrontational transboundary water issues.

The tool introduces an analysis assessing the factors that are more relevant to determine water related management issues independently from their consequences in terms of cooperative or confrontational dynamics. The outcomes of the conducted assessment will then be used to map the distribution of hydro-political risk beyond the transboundary scale, with the possibility to identify water management hotspots in the areas where knowledge about water dynamics is limited or not available.

The aim of this product is to provide the policy maker with a flexible instrument able to capture historical and current trends of factors relevant for water related issues, but also the possibility to interactively construct future scenarios and eventually simulate different sets of policy options and strategies. The first step of this project consisted of a global analysis based on the global assessment of water related issues and their correlates in the interactions between countries sharing transboundary watersheds (F. Farinosi, Giupponi, et al., 2018). This analysis required information about the bi-lateral interactions of the countries sharing the existing 276 international river basins (IRCC database). On a second step, the project focused on a regional scale, creating a database with the available information related to water, energy and food cooperation to support a regional African Atlas, and integrating it into a GIS to analyze the impacts of water-related disaster and water availability on water quality, health, access to water and energy/agriculture production.

The designed graphical tool is organized to interactively display: maps, map controls, operation widgets, layers panels, and charting tools. The instrument is designed to be extremely flexible and user friendly. The information is visualized at the river basin level or at raster level when available. Data about biophysical and socio-economic variables are displayed as either raster or vectorial layers. The tool provides the controls needed to display the evolution on the data over time (Figure 1) and allows specific analyses for the African main transboundary basins (Figure 2).

Figure 1. Likelihood of hydro-political interactions (F. Farinosi, Giupponi, et al., 2018)

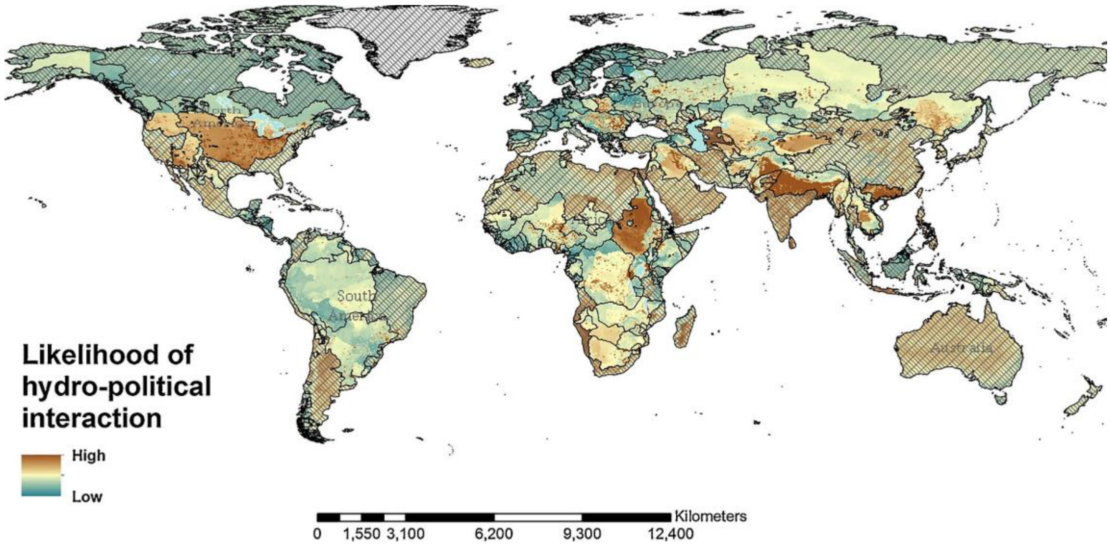
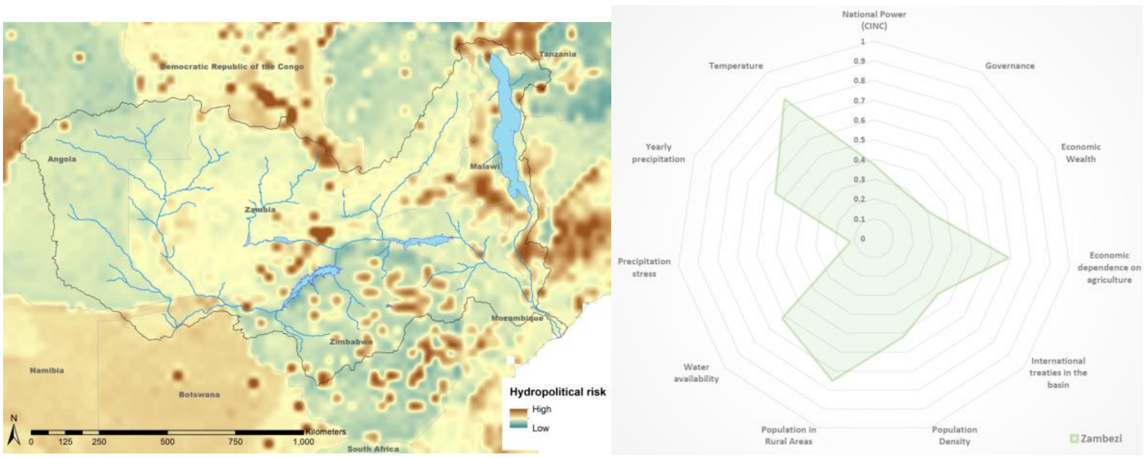


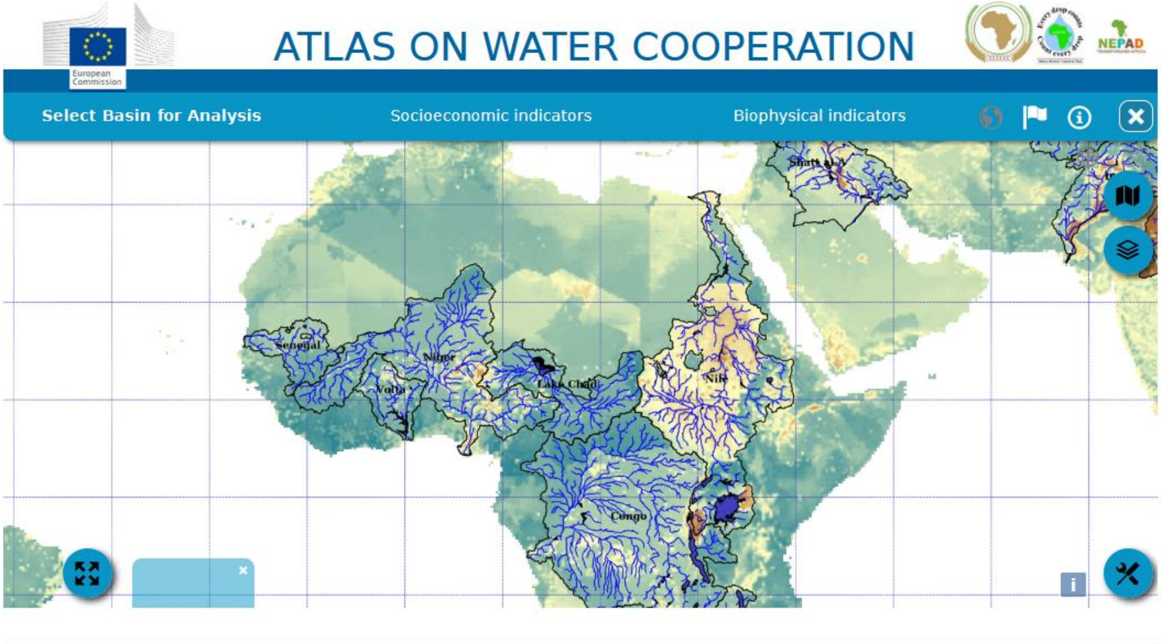
Figure 2. Hydro-political Risk and Need for Water Cooperation in the Zambezi River Basin (left). Average normalized values of the main factors determining the Basin's hydro-political risk (right) (F. Farinosi, Giupponi, et al., 2018)



2. Graphical visualization tool

The visualization of the spatial information for both, the Water Cooperation Atlas and its African development, was made available through a graphical tool structured with the combination of a geoServer to maintain the geographic data, a PostGIS database to store geodata on the server side, some pieces of server code, and a client web-based tool designed to display and manipulate the stored information. In the client side, the tool proposed is a reusable component, programmed with Javascript and several libraries (geographic –openLayers- and other programming frameworks) that could be incorporated in any website that might need a geographic component. The designed graphical tool was organized to interactively display: maps, map controls, operation widgets, layers panels, and charting tools. The instrument was designed to be flexible in its functionalities and user friendly. The information is visualized at the river basin level or at wider raster level when available. Data about biophysical and socio-economic variables are displayed as either raster or vectorial layers. The result is a collection of data time series with the data sampled at a detailed spatial and temporal resolution. The tool provides the controls needed to display the evolution on the data over time if necessary. The component of the tool allowing the user to design specific scenarios, updated following the feedback received from the African partner institutions (Figure 3).

Figure 3. African water cooperation atlas visualization tool (available at https://aquaknow.jrc.ec.europa.eu/maptool/atlas)



3. Conclusions and recommendations

Competition for limited water resources is one of the main concerns for the coming decades. Scarce water resources may generate or exacerbate political tensions, and increase regional instability and social unrest.

We used, for the first time, a machine-learning approach for investigating the probability of occurrence, the intensity and the factors leading to water issues across political boundaries. The index and the model developed allow for the timely identification of world areas at high hydro-political risk in the coming years.

Hydro-political interactions - episodes of either political cooperation or tension in transboundary river basins - are mainly determined by water availability, population density, power imbalances, and climatic stressors.

The results reveal that, globally, the combined effect of climate and population growth dynamics could increase the likelihood of water interactions in transboundary river basins by between 74.9% and 95%, depending on the specific scenario.

Overall, changing socioeconomic and climatic factors is likely to increase the pressure over water resources worldwide and this is likely to increase water competition among countries.

At global level, the Nile, the Ganges/Brahmaputra, the Indus, the Tigris/Euphrates and the Colorado rivers are world ‘water hotspots’ where ‘hydro-political interactions’ are more likely to occur, since in these areas, which are already under water stress, future demographic and climatic conditions are expected to exert particular pressure.

The global specifications of the analysis was then used to characterise the hydro-political risk within the African transboundary basin, in particular the ones taken as case studies in the ACEWATER2 project: Zambezi, Senegal, Lake Victoria, Blue Nile, and Niger basins.

This project task presented an exploratory analysis about the connections between the spatio temporal variation of water resources and the episodes of civil unrest related to mismanagement of water resources. The activities included the screening of:

- Violent events data subset;
- Water use characterization in Africa;
- Water resource distribution and use in relation to the violent episodes;
- Institutional assessment.

The research also provided a newer indicator for monitoring hydro-political dynamics under Target 6.5 – Water Resources Management of the 2030 Agenda for Sustainable Development. So far, the only existing indicator was the 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation, which captures mainly institutional resilience, with no consideration for the other factors mentioned above.

The proposed index and model can help policymakers identify areas at greatest hydro-political risk, allowing for the prompt design and implementation of strategies to encourage cooperative behaviours among countries.

This could help prevent the occurrence or exacerbation of political tensions over water resources.

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Aquaknow Knowledge management system and its contribution to the ACEWATER2 project

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KMSs (Knowledge Management Systems) are largely used by private and public organizations to collect and share information and to promote collaborative and state-of-the-art management practices. Aquaknow, a Drupal-based KMS implemented and hosted at the JRC to address the specific needs of the water sector, is operationally used to support many different water-related projects; among them, the ACEWATER2 project, focused on scientific analysis of WEFE (Water-Energy-Food-Ecosystem) nexus and Human Capacity Development over a large part of the sub-saharan Africa. The project, involving a large number of stakeholders and a complex set of scientific and HCD deliverables, resulted to be an optimal candidate for exploring and improving the system capabilities. The specific strategy of information organization, covering different deliverables as reports, datasets, databases and models' setup files, is presented here, complemented with a review of the facilities to access global and regional data, through their related metadata.

Keywords: Knowledge Management System, Aquaknow, document, dataset.

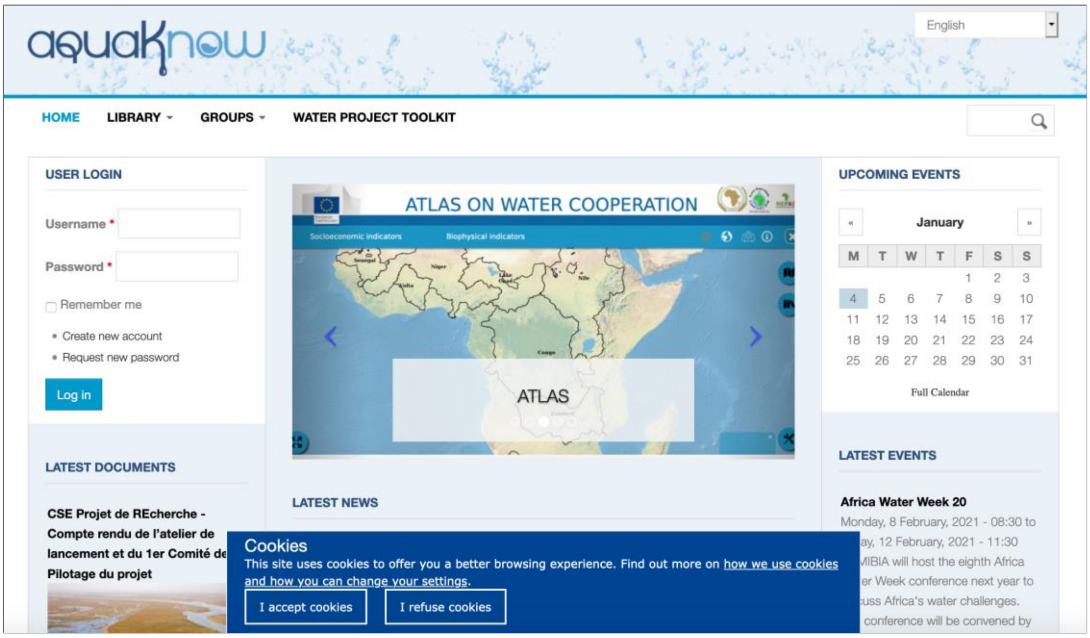
INTRODUCTION

As new information (i.e. reports, papers, datasets, databases, models' setup, analysis outcomes) is produced, the need for the adoption of efficient practices for knowledge management and sharing becomes more and more evident. Among main objectives, the need to avoid or minimize duplication risks, to be more effective in sharing information (i.e. among different Organizations, within and among different Working Groups), in promoting collaborative efforts and protecting sensitive and confidential products. A KMS (Knowledge Management System) is a tool (Mayer, 2007), today typically web-based, used by organizations, as public Institutions and private companies, to help organize documents, data and any other relevant information (e.g. discussions, FAQs) into easily accessible and standardized formats. Using KMS software can help keep documentation up to date, assist stakeholders in sharing, accessing and managing knowledge effectively, while protecting confidential information through dedicated user groups. It's a valuable tool, whether for small or large global organizations, addressing the needs to communicate through a wide variety of audiences.

All above issues are of course relevant to large projects, where complex tasks must be addressed and a large number of Institutions and stakeholders are involved. AquaKnow (http://aquaknow.jrc.ec.europa.eu/), a KMS implemented in the framework of an European Union Water Initiative (EUWI) and managed by the Joint Research Centre, addresses the specific needs of the water community and, as such, it has been used to support the ACEWATER2 project implementation (Crestaz et al., 2019).

Current contribution briefly introduces the key features of the Aquaknow platform (user interface in figure 1) and the further implementation in the framework of the ACEWATER2 project, addressing the objective to highlight the platform benefits and promote its use.

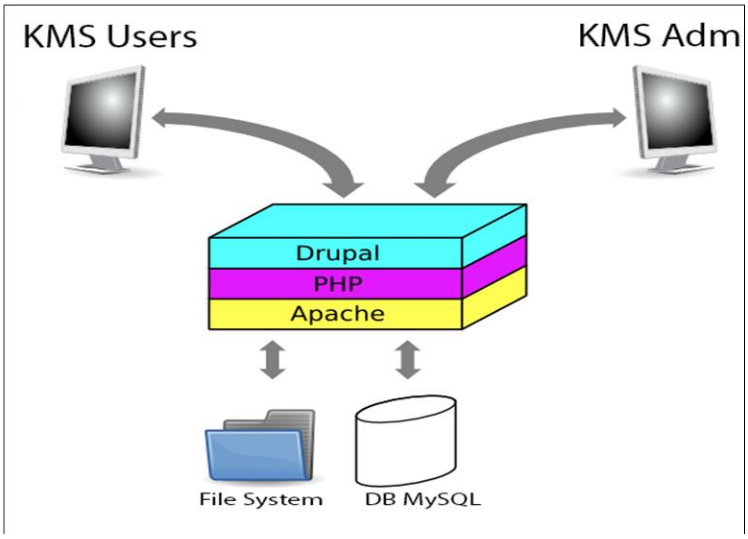
Figure 1. Aquaknow main user interface



AQUAKNOW

As most KMSs, Aquaknow supports the management of both public and private contents, the accessibility rules for the latter being under the full control of the contents' creator. System user can setup his/her profile, login, generate contents (e.g. documents, events, news) publicly or within dedicated working groups. The latter can be set as public or private, depending upon sensitivity of the hosted content.

Figure 2. Aquaknow architecture



Aquaknow has been originally developed in Drupal[24] (Catalina, 2018) version 6, later migrated to the version 7, while a major reimplementation using version 8 (Todd, 2017) is currently under analysis. Drupal, an open-source framework based on PHP, became one of the most used tool for developing PHP applications within the European Commission. The scheme of the Aquaknow KMS architecture (figure 2) highlights the key layers, enabling users and system administrator to interact with the information stored to the file system or to the database.

AQUAKNOW IN THE ACEWATER2 PROJECT

ACEWATER2 is a huge project funded by DG-DEVCO, managed by the JRC in collaboration with UNESCO, and run through the period 2016-2020. The project addressed both scientific

[24] Drupal documentation is available here: drupal.org

research on WEFE nexus assessment and Human Capacity Development, with a geographic scope ranging through most of the sub-saharan Africa.

With its large base of stakeholders, from Institutions as AU, AMCOW (African Ministers' Council on Water), RECs (Regional Economic Communities), RBOs (River Basin Organizations) and more than 20 CoEs (Centers of Excellence) from Western, Central-Eastern and Southern Africa, project deliverables (reports, manuals, datasets, databases, models' setup) are conceived to be freely available. In line with project objectives, the deliverables address multiple objectives, including that of contributing to the advancement of the scientific and water management community.

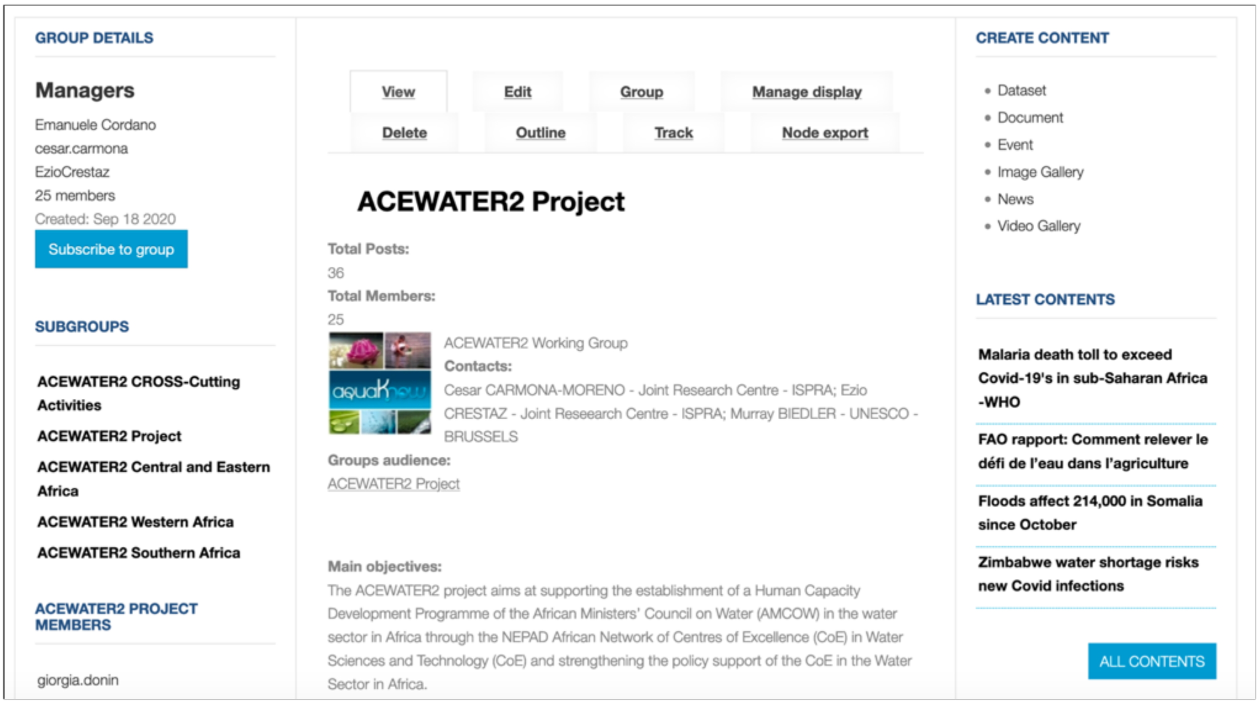
Still few resources have to remain confidential, as is the case of databases made accessible by third-parties, under specific agreements and outside of any contracting agreement. This is the case of the databases provided by ZAMCOM and SADC-GMI, respectively on the hydrology of the Zambezi river basin and on the groundwater hydrology in Southern Africa; both databases were released to specific CoEs, following a MoU (Memorandum of Understanding) and the signing of a NDA (Non-Disclosure Agreement) with the specific Institution. In few cases, data had to be purchased by the CoE from national public Institutions (e.g. ministries), being subject to restrictions with respect to any further dissemination. This has been the case for the daily hydrological data in Sudan. Where raw data or detailed time series could not be delivered, if possible aggregated data have been provided.

Further to the above, access to the project resources was restricted to contributing CoEs only, on a network-basis, during the implementation phase, when most of the documentation was still in draft.

Given the stated framework and constrains, a main group named '*ACEWATER2 project*' (figure 3) was setup, acting as the parent for four subgroups, namely:

- three subgroups, dedicated to each one of the main regions of interest; 'ACEWATER2 Western Africa', 'ACEWATER2 Central and Eastern Africa' and 'ACEWATER2 Southern Africa'; and
- a fourth group dedicated to cross-cutting topics, mainly of continental relevance (e.g. water governance, energy, hydropower, groundwater modelling in Africa) or spatially extending through different regions (e.g. geothermal energy along the EARS, Eastern Africa Rift System, from Eritrea down to Zambia).

Figure 3. ACEWATER2 project main page



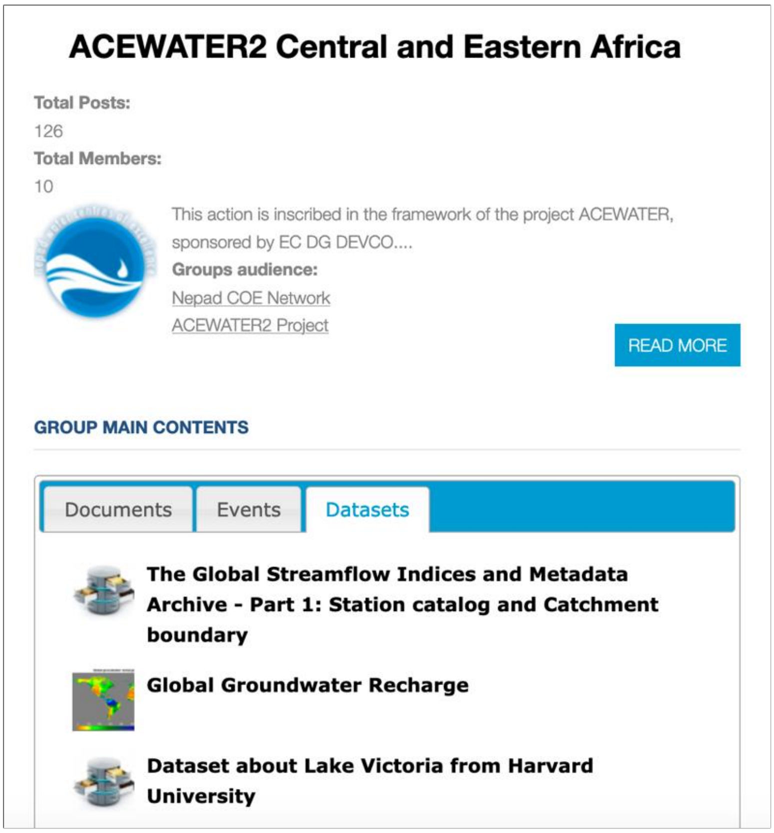
A list of private groups' members is maintained centrally by the group administrator, who is responsible for managing members' invitation and removal. Any Aquaknow registered user creating his/her own public or private group turns to be the group administrator, being able to grant proper users' access permissions. Access to private groups is by invitation. In the specific case of ACEWATER2 group, access request can be directed to the authors of current contribution.

Users can access existing information/data or upload their own resources, in formats as MsWord or MsExcel, up to a maximum file size of 512 Mb. Spatial and temporal datasets (e.g. location shape files and related time series text files) can be zipped and uploaded to the system as well (figure 4). Confidentiality constrains are setup and data shared publicly or privately, through the members of the same group only.

Spatial data are complemented with metadata, as from the details in table 1. Users can search for and filter spatial datasets by assigned categories and navigate the metadata, to access detailed information, links to the original resources or download locally the zipped files.

Analogously to other data, spatial data can be private or public, depending upon visibility or confidentiality constrains that can impose dissemination restrictions by the legitimate owners. Data subject to confidentiality constrains are not exposed publicly. Metadata, on the other hand, are public and can be optionally integrated with the datasets themselves.An example of how ACEWATER2 subgroup members can access data and metadata is reported in the below figure 4.

Figure 4. ACEWATER2 Central and Eastern Africa sub-group



An example of how data are presented in the Aquaknow interface is reported here below in figure 5, and details on the metadata fields in table 1.

Figure 5. Spatial metadata: an example for CHIRPS dataset

climate::chirps::Monthly CHIRPS Precipitation Dataset

By admin 0 Comments

Dataset Category:
climate
Dataset name:
chirps
Dataset Type:
raster
Dataset Format:
geotiff
Dataset Keywords:
RAIN
Dataset Short Description:
Monthly CHIRPS Precipitation Dataset
Dataset Extended Description:
Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a 30+ year quasi-global rainfall dataset. Spanning 50°S-50°N (and all longitudes), starting in 1981 to near-present, CHIRPS incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring.
Dataset URL:
http://chg.geog.ucsb.edu/data/chirps/
Dataset Credits:
Funk, Chris, Pete Peterson, Martin Landsfeld, Diego Pedreros, James Verdin, Shraddhanand Shukla, Gregory Husak, James Rowland, Laura Harrison, Andrew Hoell & Joel Michaelsen. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Scientific Data 2, 150066. doi:10.1038/sdata.2015.66 2015. http://chg.geog.ucsb.edu /data/chirps/index.html
Dataset Availability:
FREE
Dataset Spatial Extent:

Dataset Region of Interest:
World
Dataset Spatial Resolution Description:
about 5 km
Dataset Spatial Resolution Degree:
0.0500000000
Dataset Temporal Extent:
Thursday, 1 January, 1981 to Tuesday, 31 January, 2017
Dataset temporal frequency:
monthly
Dataset Source:
ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/global_monthly/tifs/
Dataset Last Access:
Friday, 25 August, 2017
Dataset JRC Contact Info:
cesar.carmona-moreno@ec.europa.eu
Dataset Path:
climate/CHIRS/data/montlhly/tif
Groups audience:
ACEWATER2_JRC
NEPAD SANWATCE
NEPAD CEANWATCE
NEPAD WANWATCE

Table 1. Metadata for spatial resources

Metadata Fields	**Metadata Field Description**
TITLE	Title of the dataset appeared on Group page
CATEGORY	Category of the data set (agriculture, climate, demography, geology, ecosystem, energy, hazard, health, hydrology, land, politics, infrastructure, miscellaneous, socio-economy, soil, topography, transport)
NAME	Identification name of the dataset
TYPE	Type of the data set (if specified) (e.g. raster, vector)
FORMAT	Format of the files contained the dataset that can be downloaded (e.g. tif,shp,txt,xls,zip,...)
KEYWORDS	Keywords of the data set
SHORT DESCRIPTION	Short description of the data set
EXTENDED DESCRIPTION	Extended description of the data set
URL	URL reference for datasets downloading
CREDITS	Credits and references to peer-reviewed publication where the dataset was published.
AVAILABILITY	Brief summary on the availability of the data set (i.e. «FREE», «REGISTRATION REQUIRED», «PRIVATE», «PAID ACCESS» or «NOT ACTUALLY AVAILABLE»)
USE LIMITATIONS	Terms and conditions of use of the data set.
REGION OF INTEREST	Textual description of the area covered by the data set (spatial extent) (e.g. «Africa», »Southern Africa», «Africa and Europe», «World»).
DATASET SPATIAL EXTENT [deg]	Area covered by the data set expresses as a geospatial extent with longitude and latitude coordinates (for instance.« -180, 180, -90, 90 (xmin, xmax, ymin, ymax) (W, E, S, N)» if the region of interest is «World»). The coordinate reference system is EPSG 4326 (+proj=longlat +ellps=WGS84 +datum=WGS84 +no_defs).
SPATIAL RESOLUTION [deg]	Spatial resolution expressed in degrees (deg) when available.
SPATIAL RESOLUTION DESCRIPTION [text]	Human-readable textual description of the spatial resolution.
TEMPORAL EXTENT - START DATE	Temporal extent – start date of the data set (if the data set is dynamic). Date format must be in ISO 8601

TEMPORAL EXTENT - END DATE	Temporal extent – end date of the data set (if the data set is dynamic). Date format must be in ISO 8601
TEMPORAL FREQUENCY	Temporal resolution of the data set (i.e. «static», «none», «not specified» «multi-year», «yearly», «multi-month», «monthly» , «multi-day», «daily», «sub-daily«).
SOURCE	Source of the data set (in most cases it is the URL of the web page where the data set can be directly downloaded).
RESOURCE LAST ACCESS	Date of the latest day when the URL of data set was visited and verified.
GROUPS AUDIENCE	The name of the group of users that can access the dataset
DATASET FILE	Compress archive file for the dataset containing all data and related metadata
DATASET IMAGE	Representative image which has the functions of the icon of the Dataset in Aquaknow.

CONCLUSIONS AND THE WAY FORWARD

Aquaknow, a web-based Drupal KMS specialized in water and related issues developed by and hosted at JRC, has been used to operationalize the implementation of ACEWATER2, a large multi-year (2016-2020) sub-Saharan project involving a large number of stakeholders and deliverables. Based on the platform facilities, working groups have been structured so as to enable effective access to project resources, while protecting confidential information. Being one of the project objectives that of addressing the WEFE (Water-Energy-Food-Ecosystem) nexus scientific assessment, also the need for organizing information on both freely available and project specific datasets has clearly emerged. Simplified metadata have been designed and the Aquaknow platform customized to access such information.

Project deliverables, including reports, manuals, datasets, databases and models' setup files can now be accessed, except for confidential information provided by third-parties under specific agreements explicitly excluding any further dissemination.

The migration of the Aquaknow platform to the new Drupal standard (version 8) is under consideration. Above structures and information resources will be migrated consistently and their access guaranteed in the newer version.

The new platform will come with new challenges and opportunities, few of them having already been discussed at a certain depth. For example, the opportunities arising from the adoption of a more advanced database backend to support spatial data management (e.g. PostgreSQL/PostGIS) will certainly be investigated.

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LIST OF ABBREVIATIONS AND DEFINITIONS

AAU	Addis Ababa University
ACEWATER	African networks of Centres of Excellence on WATER Sciences
AFD	Agence Française de Dévelopment
AfDB	African Development Bank
AGCE	Africa Geothermal Center of Excellence
AGHRYMET	Centre Regional de Agro-Meteorology
AMCOW	African Ministers' Council on Water
AMCOST	African Ministerial Council On Science and Technology
ARC2	African Rainfall Climatology version 2
AU	African Union
AUC	African Union Commission
AU-IBAR	African Union – Interafrican Bureau for Animal Resources
AWM	Agricultural Water Management
BC	Boundary Condition
BCM	Billion Cubic meters
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geosciences and Natural Resources)
BGS	British Geological Survey
BL	BaseLine
BNB	Blue Nile Basin
BORBA	Benin-Owenna River Basin Authority
BRIDGE	Building RIver Dialogue and Governance
CAADP	Comprehensive Africa Agriculture Development Programme
CAPP	Central African Power Pool
CDF	Cumulative Distribution Function
CEANWATCE	NEPAD Central-Eastern African Network of Water Centers of Excellence
CHG	Climate Hazard Group
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CIP	Central Irrigation Pivoting system
ClimDev-Africa	Climate for Development Initiative for Africa
CN	Curve Number
CoE	Centre of Excellence
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRU	Climate Research Unit
CSAG	Climate System Analysis Group, at University of Cape Town
CSIR	The Council for Scientific and Industrial Research
CV	Climate Variability
CWR	Crop Water Requirement
DAFNE	Decision-Analytic Framework to explore the water-energy-food NExus
DEM	Digital Elevation Model
DG-DEVCO	Directorate-General-for international DEVelopment and Cooperation (now INTPA)
DHI	Danish Hydraulic Institute
DPSIR	Driver-Pressure-State-Impact-Response
DRASTIC	Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, Hydraulic conductivity model
DSS	Decision Support System
DSSAT	Decision Support System for Agrotechnology Transfer
DTM	Digital Terrain Model
EAPP	Eastern African Power Pool
EARS	East African Rift System
EC	European Commission
ECOWAS (CEDEAO)	Economic Community of West African States
EGS	Ecosystems Goods and Services
EIWR	Ethiopian Institute of Water Resources, Addis Ababa University

EL	Evaporation Losses
ENSO	El Niño Southern Oscillation
EPC	Engineering Procurement & Construction
ERA-Interim	ECMWF Re-Analysis
ESA	European Spatial Agency
ESCOM	Electricity Supply Corporation of Malawi (Ltd)
ESMAP	Energy Sector Management Assistance Program
ET	EvapoTranspiration
ETS	Equitable Threat Score
EU	European Union
FAO	Food and Agriculture Organization
FAR	False Alarm Ratio
FPI	Food Productivity Index
FREEWAT	FREE and open source software tools for WATer resource management
GCM	Global Climate Model
GDC	Geothermal Development Company (of Kenya)
GDP	Gross Domestic Product
GEFC	Global Environmental Flow Calculator
GERD	Great Ethiopian Renaissance Dam
GEV	Generalized Extreme Value
GHA	Greater Horn of Africa region
GHG	GreenHouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GIS	Geographical Information System
GLO	Generalized LOgistic
GOF	Goodness Of Fit
GPA	Generalized PAreto
GRMF	Geothermal Risk Mitigation Facility (for Eastern Africa)
GSOD	Global Surface summary Of the Day
GUI	Graphical User Interface
GW	GroundWater
HCD	Human Capacity Development
HDAM	Hydro DAM
HDI	Human Development Index
HEC	Hydrological Engineering Center from the US Army Corps of Engineers
HJKYRB	Hadejia-Jama'are-Komadugu-Yobe river basin
HMS	Hydrologic Modelling System
HYDROSHED	HYDROlogical data and maps based on SHuttle Elevation Derivatives at multiple scales
HROR	Hydropower Run-Of-River
HWSD	Harmonized World Soil Database
KGE	Kling-Gupta Efficiency
KMS	Knowledge Management System
IAD	Ostrom Institutional Analysis and Development
IAEA	International Atomic Energy Agency
ICPAC	IGAD Climate Prediction and Application Centre
ICT	Information and Communication Technology
IEA	International Energy Authority
IIASA	International Institute for Applied Systems Analysis
IFC	International Finance Corporation
IFPRI	International Food Policy Research Institute
IGA	International Geothermal Association
IGAD	Intergovernamental Authority on Development
IGRAC	International Groundwater Resources Assessment Centre
IIASA	International Institute for Applied Systems Analysis
INRS-ETE	Institut National de la Recherche Scientifique, Canada
INTPA	Directorate-General-for INTernational PArtnership

IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPPs	Independent Power Producers
IRCC	International River Cooperation and Conflict database
IRD	French Institute for Research for Development
IRENA	International Renewable Energy Agency
ITCZ	InterTropical Convergence Zone
ITD	Inter-tropical discontinuity
IWEGA	International Centre for Water Economics and Governance in Africa
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
JRC	Joint Research Centre of the European Commission
KenGen	Kenya Electricity Generating Company
KNUST	Kwame Nkrumah University for Sciences and Technology
LCOE	Levelised Cost Of Electricity
LDCs	Least Developed Countries
LGAs	Local Government Areas
LUISA	Land-Use based Integrated Sustainability Assessment
LULC	Land Use and Land Cover
LVB	Lake Victoria Basin
MADI	Mean Absolute Deviation Index
MAE	Maximum Absolute Error
MBE	Mean Bias Error
MNID	Middle Niger and Inner Delta
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
MW	MegaWatt
NA	North Africa
NAPP	North African Power Pool
NBA	Niger Basin Authority
NBI	Nile Basin Initiative
NCAR	National Center for Atmospheric Research
NCL	NCAR Command Language
NDA	Non-Disclosure Agreement
NDBRA	Niger Delta River Basin Authority
NDF	Nordic Development Fund
NDVI	Normalized Difference Vegetation Index
NEPAD	The New Partnership for Africa's Development
NIHSA	NIgeria Hydrological Service Agency
NIMET	NIgeria Meteorological Agency
NFET	Non-Formal and informal Education and Training
NRB	Niger River Basin
NSE	Nosch-Sutcliff Efficiency
NUST	Namibia University of Science and Technology
NUST	National Univeristy of Science and Technology (Bulawayo, Zimbabwe)
NWRI	National Water Resources Institute
OECD	Organization for Economic Co-operation and Development
O&G	Oil and Gas
OMVG	Organisation pour la Mise en Valeur du fleuve Gambie
OMVS	Organisation pour la Mise en Valeur du fleuve Sénégal
ORC	Organic Rankine Cycle
OS	Open Source
OUM	Overall Unified Metric
PAUWES	Pan African University – Institute of Water and Energy Sciences
PERSIANN-CDR	Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Climate Data Record
PET	Potential EvapoTranspiration

PHP	PHP Hypertext Preprocessor (recursive acronym)
PIDA	Programme for Infrastructure Development in Africa
POD	Probability of Detection
PV	PhotoVoltaic
PWMs	Probability Weighted Moments
RBO	River Basin Organization
RCM	Regional Climate Model
RCMRD	Regional Centre for Mapping of Resources for Development
RCP	Representative Concentration Pathways
REC	Regional Economic Community
RES-SIM	REServoir system SIMulation
REV	Risk of Environmental flow Violation
RMSE	Root Mean Squared Error
RRMSE	Relative Root Mean Square Error
RSS	Risk of irrigation Supply Shortage
RURAL-WASH	RURAL WASH Information Management System
SAPP	Southern African Power Pool
SADC	Southern African Development Community
SADC-GMI	Southern African Development Community, Groundwater Management Institute
SAF	Systems Approach Framework
SANWATCE	NEPAD Southern African Network of Water Centres of Excellence
SARDC	Southern African Research and Documentation Centre
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
SDGs	Sustainable Development Goals
SDSS	Spatial Decision Support System
SESF	Social-Ecological Systems Framework
SIDS	Small Island Developing States
SIS	Smallholder Irrigation Schemes
SMB	Senegalo-Mauritanian Basin
SPAM	Spatial Production Allocation Model
SPATSIM	SPAtial and Time Series Information Modelling
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SRB	Senegal River Basin
SSA	Sub-Saharan Africa
SSP3	Shared Socio-Economic Pathway 3
SSTA	Sea Surface Temperature Anomaly
STC-EST	African Union Specialised Technical Committee on Education, Science and Technology
SUTRA	Saturated-Unsaturated, variable-density ground-water flow with solute or energy TRAnsport
SWAT	Soil and Water Assessment Tool
T	Temperature
TAMSAT2	Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations version 2
TEMBA	OSeMOSYS (The Electricity Model Base for Africa)
TIGER	Technology Informatics Guiding Education Reform
TVET	Technical and Vocational Education and Training
UCAD	University of Cheikh Anta Diop
UKZN	University of KwaZulu-Natal
UM	Unified Metric
UN	United Nations
UNDP	United Nations Development Program
UNEP	United Nations Environmental Program
UNESCO	United Nations Educational, Scientific and Cultural Organization

UNZA	University of Zambia
USAID	United States Agency for International Development
USGS	United States Geological Survey
VRES	Variable Renewable Energy Sources
WACDEP	Water, Climate and Development Programme
WACOZA	Water and Cooperation over the Zambezi river basin
WANWATCE	NEPAD West African Network of Water Centres of Excellence
WB	World Bank
WEAP	Water and Evaluation And Planning system
WEFE	Water-Energy-Food-Ecosystem nexus
WEP	Water-Energy Productivity
WHYCOS	World Hydrological Cycle Observing System
WHO	World Health Organization
WMO	World Meteorological Organization
WRC	Water Research Center (Univeristy of Khartoum, Sudan)
WRM-PAP	African Water Resources Management Priority Action Programme 2016 - 2025
WWF	World Wide Fund for Nature
WWW	World Wide Web
ZAMCOM	ZAMbezi water course COMmission
ZAMWIS	ZAMbezi Water resources Information System
ZPC	Zimbabwe Power Company
ZRA	Zambezi River Authority
ZRB	Zambezi River Basin

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