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Wirtschafts- und Sozialwissenschaftliche Fakultät

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Forschungsvorhaben

Nachhaltige Ressourcenmanagement im Limpopo-Flusseinzugsgebiet: Eine Initiative für ein grenzüberschreitendes hydro-ökonomisches Modell (SusTraL)

TEIL II: EINGEHENDE DARSTELLUNG

Förderkennzeichen 01DG21054

Dezember 2021 – Februar 2023

II Detailed description of the project (SusTraL: Förderkennzeichen 01DG21054)

1 Use of the grant and the result achieved in detail, with comparison of the specified objectives

In the initial phase, the inter- and transdisciplinary project SusTraL, which deals with sustainable resource management in the Limpopo River Basin (LRB) focussing on Botswana, Mozambique and South Africa, was to provide an overview of a) the current situation with regard to water availability and quality in the LRB, b) identify options to address water availability and quality scarcity issues, c) identify the state of the literature on hydro-economic model (HEM) and computable general equilibrium models, d) develop a conceptual HEM for the Limpopo River Basin (LRB), and e) prepare the main proposal.

The research outputs outlined have been achieved through the funding of a research assistant position (January 2022 to February 2023; 9.7 hrs./week), subcontracts to the Okavango Research Institute at the University of Botswana, the Faculty of Agronomy and Forestry Engineering at the Eduardo Mondlane University in Mozambique, the School of Economics at the University of Cape Town in South Africa, the Kiel Institute in Germany and Dr. Jürgen Meyerhoff (HWR, Berlin) in addition to substantial contributions from Prof. Dr. Katrin Rehdanz (Professor at Kiel University; CAU).

Steps toward a conceptual hydro-economic model for the Limpopo River Basin

The main objective of the initial phase of the SusTral project was to discuss and evaluate components of a hydro-economic model (HEM) for the Limpopo River Basin. During the course of the project it was set that the HEM should cover the whole Limpopo River Basin, should cover both aspects of water quantity and water quality, should allow to assess the impacts of water scarcity and quality deterioration on the economies across the whole Limpopo River basin, and should be able to evaluate adaptations paths to climate change. The later focused especially on the potentials of technological adaptations by farmers and private households in the river basin.

The HEM was meant to provide decision makers in the four countries and at international institutions especially with the following information: a) Spatially explicit information about the availability and economic value of water across the river basin; b) Information about the potential adaptation behaviour by individual agents (farmers, households) as basis to develop policy instrument; c) information about aggregated potential water savings and potential quality improvements across the river basin conditional on adaptation behaviour; d) information about the economy-wide impacts on the national economies with a special focus on South Africa.

Figure 1 gives an overview of the overall structure of the HEM and the work packages required to implement it as a result of the initial phase of the SusTral project. Generally, work packages would span over the three main pillars to first record changes in water quality and quantity in the basin, second assess their impact on the economy, i.e. the four national economies present in the basin, and third to evaluate responses to the identified changes in water quality and quantity by key actors in the basin, i.e., farmers and private households as main water users. The various steps taken during the project are documented in the following below Figure 1.

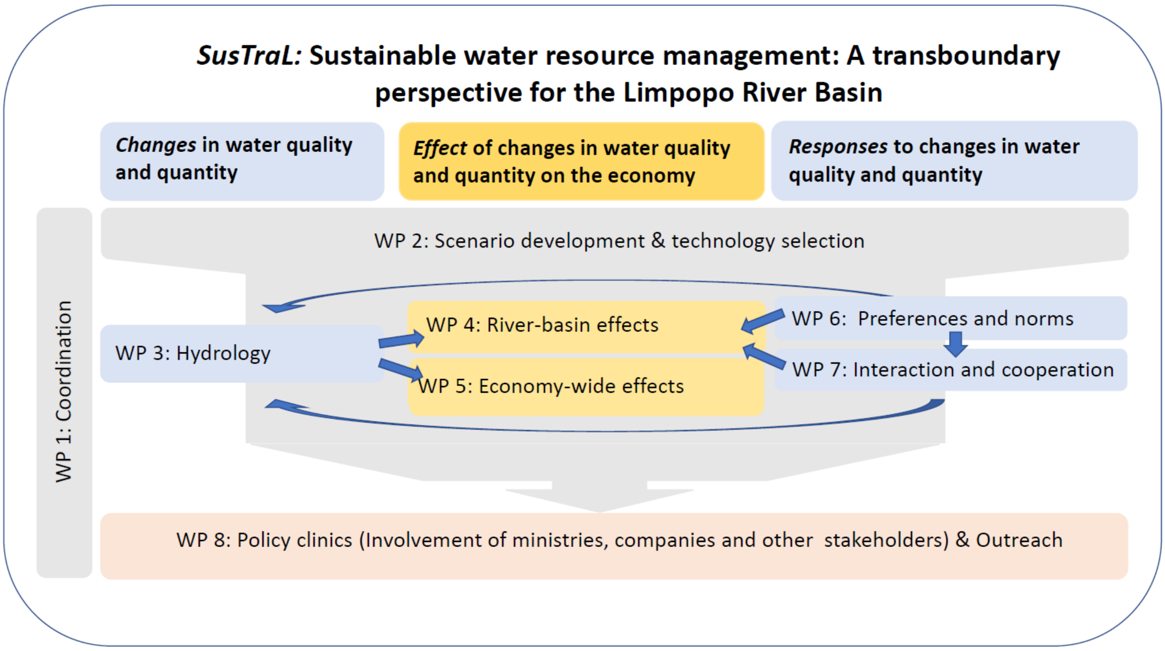

Figure 1: Conceptual frame for the development of a transboundary hydro-economic model for the Limpopo River Basin

Step 1: Overview of the current situation in the three focus countries about water availability and quality and identification of technical options to address water issues

The aim of this part of the project was to get an overview of the situation of the three partnering countries to the project in relation to the most urgent water availability and water quality issues. The information is compiled in country reports and attached to this report (see Annexes A to C). In addition, we used workshops in South Africa and Botswana not only to present the SusTraL project, but more importantly to discuss water issues and potential solutions.

The reports and the feedback from stakeholders in the workshops (see also below) showed that overuse of the water resource is a major problem in the three partner countries, caused on the one hand by changing rainfall patterns and exacerbated by climate change. In addition, illegal use in particular (mainly in agriculture), which is difficult to control, causes conflicts between the different users of a region, but also conflicts between upstream and downstream regions. This problem is also evident on a transnational level between the riparian states of the Limpopo.

In addition to the overexploitation of the resource, the poor quality of the surface waters and groundwater also poses a threat to humans and the environment. Table 1 gives an overview of the three main issues related to water quality in the three countries. In South Africa, acids and heavy metals are the main problem, while Botswana is more affected by high sediment loads and Mozambique by salt intrusion due to groundwater exploitation. Acids and heavy metals from mining in Botswana also affect water quality here, while Mozambique has to deal with water contamination from mining in the upstream countries. There is no mining in Mozambique. This demonstrates the importance of transboundary assessments and strategies. Further contaminations originate from agriculture (nutrients and pesticides) and from domestic wastewater, which contains nutrients, pharmaceuticals and bacteria.

The stakeholder workshops were also used to identify technical options to address these water issues. Different techniques were identified and discussed. As an example, Electro-Molecular Activated Direct Oxidation was introduced from a company to clean wastewater from domestic areas and agriculture with an ultrasonic technique.

Table 1: Main issues related to water quality in the three countries

	South Africa	Botswana	Mozambique
Contaminant 1	Acids, heavy metals from mining	Sediments from agriculture	Salt intrusion from groundwater exploitation
Contaminant 2	Pesticides, herbicides, nutrients from agriculture	Acids, heavy metals from mining	Acids, heavy metals from mining in South Africa and Botswana
Contaminant 3	Bacteria, nutrients, pharmaceuticals from waste water/- treatment plants	Nutrients from agriculture	Bacteria, nutrients, pharmaceuticals from waste water/- treatment plants

Source: Annexes A-C (country reports).

Step 2: Hydro-economic models and water quality issues

Generally, HEMs provide a powerful approach to influence and improve the interaction among hydrologic, economic, and institutional frameworks in the context of water scarcity and quality degradation as they allow different water problems to be mapped simultaneously at the river basin level (Expósito et al. 2020). However, a review of the literature revealed that HEMs have so far focused on the general overview of its origins, principles, and applications to inform water allocation decisions. This is reflected by several hydro-economic modelling reviews that have been conducted in the recent past (e.g., Bekchanov et al. 2017). However, while water resource planning is often limited to water quantity only, water quantity and quality are interdependent. In contrast to early reviews, in this project we conducted an extensive review of literature that integrate water quality aspects in the hydro-economic modelling of river basins. We find that even though in the present decade, a growing number of studies have incorporated water quality dynamics in HEMs compared to previous decades, the available studies are still very limited in terms of application and development. Hence, studies on river basin-scale modelling need to pay more attention to water quality issues. The literature review, compiled by the University of Cape Town, is available upon request from Prof. Djiby Thiam (djiby.thiam@uct.ac.za).

Step 3: Hydro-economic models and accounting for ecosystem services

Water systems create vital ecosystem services (ES) like water provision, disease control, recreation, fisheries, aquatic habitat provision, and other cultural services (Vollmer et al., 2022). The indispensability of ES, as provided by hydrologic processes, to the maintenance and fulfilment of human life is evident. A problem, however, is the non-market nature of most of these services, and due to the missing price signal the potential overuse of a service. To account for the fact that these non-market services are valuable to society and have been mentioned as important during the stakeholder workshops, we conducted a second review of the literature (Meyerhoff and Dreyer, 2023), included as Annex D in this report. In the overview, we describe the type of non-market valuation studies that have been conducted in relation to water issues. When focusing on HEM studies that consider ecosystem services, there are hardly any. Here, we have identified a large research gap that would be worth exploring.

Step 4: Hydro-economic models and computable general equilibrium (CGE) models

Water policies that aim for instance at a more efficient use of the resource are likely to have repercussions that go beyond the water sector. While HEMs are well suited to determine the impact of a water policy on the water sector, they miss the impact on (i) other sectors such as farming; (ii) on the economy as a whole; and on the welfare of private households. Therefore, the SusTraL project discussed ways to integrate an economy-wide model that fully describes the funds flowing between production sectors – e.g. payments for water use by the agricultural sector – and from production sectors to private households – e.g. the consumption of food – with the HEM model to determine the direct and indirect impacts of water policy.

As concerns the economy-wide framework, we discussed to develop single-country, multi-sectoral dynamic computable general equilibrium (CGE) models along the lines of Diao and Thurlow (2012). Single-country models – possibly linked to each other for example via trade flows – have the advantage of allowing for much greater detail than the main alternative, multi-country GTAP-based models. Our preferred type of single-country CGE model is particularly well-suited for the research question at hand as it provides a highly disaggregated representation of the agricultural sector, rendering it possible to analyse the differential impact of water availability and water policies on the cultivation of crops with different water intensities.

Step 5: Hydrological models: SWAT

For the main phase of the SusTral project, we considered the use of the process-based ecohydrological Soil and Water Assessment Tool (SWAT). The model was developed to assess the influence of agricultural land use on the water and matter balance for largescale watersheds (Arnold et al., 1998). It is used to model spatially differentiated environmental and anthropogenic impacts on water quality (Neitsch et al., 2005) and to evaluate sustainable land use options (e.g., Lam et al., 2011). In the SWAT model, the watersheds are subdivided into two spatial subunits: (i) the hydrological feature of subbasins and (ii), for the consideration of subscale processes, the hydrological response unit (HRU), which is derived from a combination of land use, soil, and slope class. The hydrologic cycle is divided into terrestrial and aquatic phases. Terrestrial processes are controlled by climate, soils, agricultural management, plant growth, while water is calculated as matter balance. Water and agrochemicals are routed to the channel at each subbasin outlet, and in-stream transformation processes are simulated (Neitsch et al., 2005).

We considered a number of sub-catchments in the LRP for a detailed analysis in the main phase. In particular sub-catchments with intensive agricultural were considered exemplarily relevant to describe the current status in terms of water quantity and quality with the SWAT model. Next, we considered measures to enhance water harvest during the rainy period and to improve the efficiency of irrigation which would be simulated with the model to inform decision makers. Further scenarios with measures to improve the water quality could include e.g. buffer strips at river banks, improved field management to reduce surface runoff. Based on these simulations, the efficiency of the strategies would be calculated in m^3 of river discharge and nutrient loads and compared to other regions and mitigation strategies.

Coordination of the project and stakeholder engagement

Project meetings

Regular digital meetings (total of 15) of all project partners were organized to discuss and agree on planning and further steps within the project and to ensure the success of the project and compliance with the project objectives. Furthermore, the selection of the models to be used in the main phase, their set-up as well as the acquisition of necessary input parameters were discussed during these meetings.

Project meeting and stakeholder-workshops in South Africa/Botswana 27/04-05/05/2022

Project meeting with stakeholders in South Africa:

Representatives from the regional Dep. Of Water and Sanitation, Companies offering technical solutions for various contaminations, an NGO and Limcon participated in the meeting.

Project meeting with stakeholders in Botswana:

Participants were from the Water and Sanitation Department, from a nursery using waste water treatment effluent for irrigation and from the tourism industry.

Project meeting with stakeholders in Mozambique:

Due to weather conditions (extreme rainfall events and impassable/blocked roads), the workshop had to be cancelled.

Both workshops showed that the interest of the stakeholders was very high and that active participation was appreciated. The objectives of the project as well as their planned implementation were commented and discussed by the participants. Depending on the stakeholder group, hydrological extremes, water scarcity or lack of water use efficiency and poor water quality were addressed as the most urgent problems.

Project meeting in Kiel (12/2022):

The objective of this meeting was to elaborate the frame for a four year research project of sustainable water management in the Limpopo catchment. Work packages for the main proposal were elaborated and potential scenarios for the HEM, CGE and SWAT simulations discusses. Linkages and coupling of the different models were defined.

Prepare the main proposal

The proposal submission planned in this part of the project had to be abandoned because the call for proposals had not been published by the end of the project. Figure 1 above shows the content and objectives of the main components of the proposed project.

2 Main items of the financial statements

The most important items of the financial statements can be found in Table 2.

Table 2: Financial statements

	Personell	Travel	Awarding contracts	Other administrative expenses	Total
2021	0 €	0 €	0 €	0 €	0 €
2022	24,859 €	2,482 €	65,103 €	265 €	**92,710 €**
2023	8,092 €	1,082 €	21,714 €	0 €	**30,888 €**
Total	**32,951 €**	**3,565 €**	**86,817 €**	**265 €**	**123,598 €**

3 Necessity and appropriateness of the work

The course of the project's work essentially followed the planning formulated in the project application. The work plan was successfully processed; no additional resources were required from the BMBF. Solely "Application for the main phase of SusTral" could only be discussed, but not finalized, due to the delay in the call for proposals. The objectives of the project were achieved with the requested funds.

4 Expected benefit, in particular usability of the result in terms of the updated exploitation plan

The country reports (Annex A to Annex C) are included in this report in addition to the review report (Annex D). All this material provides valuable up to date information for other work in the region. This includes, among others, an overview of the current situation of the three countries in relation to the most urgent water availability and water quality issues as well as reviews of hydro-economic modelling with respect to water quality issues and ecosystem services.

5 Progress in the field of the project that has come to the attention of the beneficiary during the implementation of the project at other bodies

During the initial phase, no new data relevant to the SusTral project have been published.

6 Successful or planned publications of the result according to No. 5 NABF

Three country reports and two review articles were produced and published as part of the final report. See Annex A to Annex D.

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Annex A

SusTraL: Country Report - Botswana

by

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February 2023

This report was prepared as part of the third party funded project SusTraL (Sustainable resource management to ensure water security in the Limpopo River Basin: an initiative for a transboundary hydro-economic model) funded by the Federal Ministry of Education and Research (BMBF), Germany, grant number 01DG21054.

Annex A: Country report Botswana

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Annex A: Country report Botswana

1. Introduction

The Botswana side of the Limpopo River Basin (LRB) comprise of the Bonwapitse, Lotsane, Mahalapswe, Motloutse, Notwane and Shashe sub basins (Table 1).

Table 1: LRB Botswana sub-basins

Sub-basin	Total land area in ha (% of entire Limpopo basin	Number of dams	Number of mines	Number of cities/town/major village
Bonwapitse	1202985 (2.9)	0	1	0
Lotsane	1 281 010 (3.1)	1	1	2 (Serowe &Palapye)
Mahalapswe	869 968 (2.1)	0	0	1 (Mahalapye)
Motloutse	1 970 624 (4.8)	1	3	1 (Selibe Phikwe)
Notwane	1 826 381 (4.4)	4	1	5 (Gaborone, Kanye, Lobatse, Mochudi & Molepolole)
Shashe	2 946 414 (7.2)	9	30	1 (Francistown)

Source: Adapted from SADC GIZ Transboundary Water Management (n.d)

This study will however focus on the Notwane, Shashe and Motloutse sub-basins as they comprise the major activities pertinent to the study and have the largest land coverage. (Figure 1)

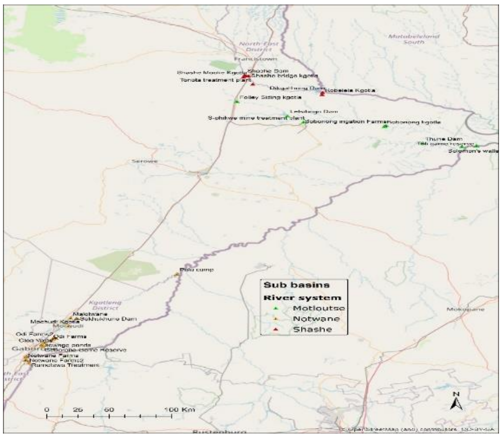


Figure 1. Limpopo River basin in Botswana showing Notwane, Motloutse and Shashe Sub-basins.

The Notwane sub-catchment (Figure 2) is located in Southeast Botswana where the country's capital city of Gaborone is located. The catchment comprises the Ngotwane River and its tributaries comprising Taung, Metsimaswaane and Molotswe. The sub-catchment is characterised by dams, farming activities, water treatment plants, sewage ponds and manufacturing industries.

Annex A: Country report Botswana

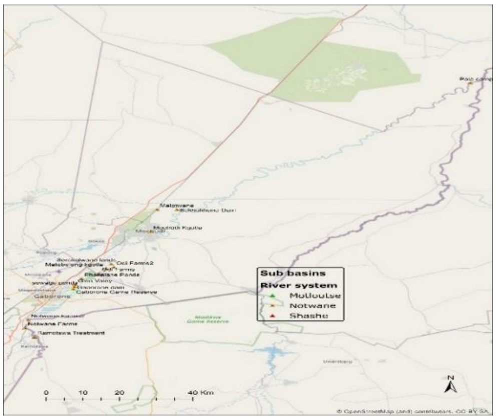


Figure 2. Notwane Sub-basin

The Motloutse sub-basin is located in the Central part of Botswana (Figure 3). It comprises the Letsibogo Dam, mining activities, irrigation farms and tourist attractions.

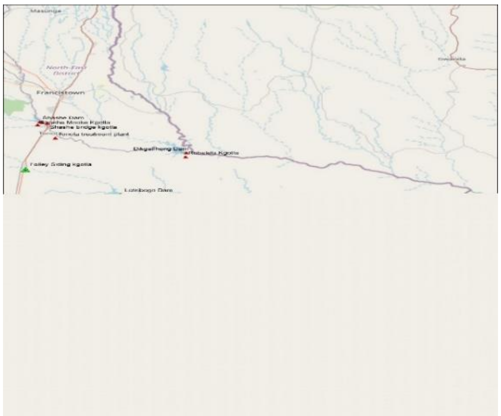


Figure 3. Motloutse sub-basin

The Shashe sub-basin is in the North East district and has a number of dams (Figure 4).

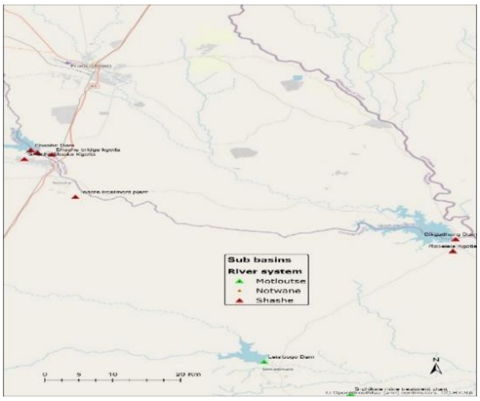


Figure 4. Shashe sub-basin

2. Characteristics of the catchment

The Limpopo River Basin (LRB) is one of the largest catchment areas in Southern Africa, at approximately 412,000 km^2 (Mosase et al., 2019). The river basin is shared by four countries namely Botswana (20%), South Africa (45%), Zimbabwe (15%) and Mozambique (20%) (Figure 5). The total area of the Limpopo River sub-basin in Botswana is estimated at 80,118 km^2. The Botswana sub-basin is drained by at least six main tributaries (Table 2). The LRB is the second most populated basin, at 14.5 million people, in the SADC region after the Orange River Basin. The Limpopo River sub-basin in Botswana is inhabited by 69% of the country's population.

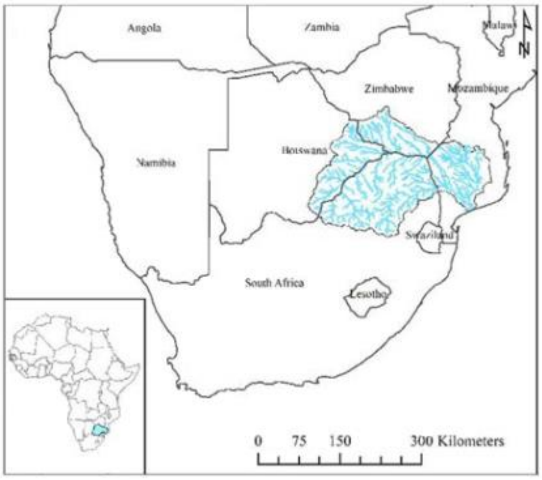


Figure 5. Map of Africa and Southern Africa showing the location of the Limpopo River Basin shared by Botswana, Mozambique, South Africa and Zimbabwe. From Mosase et al., 2019.

Table 2. Characteristics of the Botswana sub-basins of the Limpopo River – sub-catchment area, annual rainfall, naturalized mean annual runoff (MAR), and mean annual evapotranspiration (MAE).

Tributary	Catchment Area (km^2)	% of the LRB area	Rainfall* (mm/yr)	MAR# (x10^6 m^3)	MAE # (mm)
Shashe	12070	3	366	250 (270)	2100
Notwane	18264	4	271	55 (85)	1950
Bonwapitse	12030	3	249	15 (55)	2000
Motloutse	19706	5	319	111	2100
Lotsane	12810	3	306	62 (195)	2100
Mahalapswe	8700	2	281	13	2000
Total/Average	80118		299	506 (605)	2042

* Mosase et al., 2019
$^{\#}$ FAO, 2004

Annex A: Country report Botswana

2.1 Length and Discharge of the River

The Limpopo River rises at the confluence of Marico and Crocodile Rivers, both of which originate in South Africa but join to form the eastern border between Botswana and South Africa. The middle section of the river forms the border between Zimbabwe and South Africa before flowing across Mozambique into the Indian Ocean. Most of the rivers in eastern Botswana drain into the Limpopo River. Since rainfall in this sub-basin is generally much higher than in the rest of the country, the basin is very important for water resources in the country and consequently most of the dams in Botswana have been constructed in this sub-basin. In fact, this area has the highest density of surface drainage in the country. Consequently, over 70% of Botswana's total population resides in this basin. The population density in the sub-basin is much higher at 20 per km^2, compared to 4 persons per km^2 for the whole country. The total annual discharge into the Limpopo River from the Botswana sub-basin has been estimated at 506 Mm^3 (Table 2), most of which occurs for 10-70 days only during the rainy season (Dube and Sekhwela, 2007).

2.2 Climate Information

The climate of the whole LRB is influenced by four prevailing air masses namely the dry continental tropical, equatorial convergence zone, moist maritime subtropical eastern, and marine western Mediterranean air masses. The Botswana sub-basin is however predominantly semi-arid, dry, and hot, influenced by the subsiding limb of the tropical Hadley circulation. The south-western part of the country is generally hyper-arid and receives the lowest rainfall. The aridity decreases to the north and east of the country where rainfall can reach 500-600 mm per year (Figure 6). Air temperatures across the basin show a marked seasonal cycle, with the highest temperatures recorded during the austral summer months (October-March) and lowest temperatures during the cool, dry austral winter months (April-August). In austral summer, which is also the rainy season in Botswana, mean maximum temperatures have been reported between 31-33 ^{o}C across the country (Moses 2017). Air temperatures exceeding 42 ^{o}C have occasionally been reported in recent years in the country (Moses 2017), resulting in high evapotranspiration estimated around 2000 mm per year. In contrast, winter temperatures may fall to below 0 °C over some parts of the country.

Rainfall across the LRB is generally highly seasonal and unreliable, falling predominantly between October and April with high frequency of droughts (Trambauer et al., 2014). Across the country, rainfall varies from around 200 mm per year in the southwest near the border with

Namibia to over 600 mm per year in the northeast region (i.e., Kasane area) (Figure 6). Rainfall across the country peaks in February. In the Botswana sub-basin of the Limpopo River, rainfall is generally characterised as low (350-550 mm/yr; Table 2; Figure 6) and erratic with high interannual variability and a low rainfall-to-potential-evaporation ratio. Potential evapotranspiration (at 2000 mm/yr) across the sub-basin is therefore approximately 4 times higher than the annual mean rainfall at approximately 450 mm/yr. The low and erratic precipitation and high evapotranspiration significantly affect the duration and amount of surface runoff in all the tributaries in the sub-basin. Even though the sub-basin has the highest density of surface drainage in the country, its tributaries have an average flow period of only 10-70 days in a year resulting in frequent droughts (Dube and Sekhwela, 2007). Some of the worst droughts recorded resulted in significant losses of livestock in 1935, 1965, 1984 and 1991 (Bhalotra 1989 *in* Dube and Sekhwela 2007). Some moderate droughts seem to occur more frequently in the area causing significant losses of livestock as well as from dryland farming almost annually. Botswana, including the Limpopo sub-basin, is said to be highly exposed and vulnerable to climate change. Changes in precipitation due to climate change indicate a progressive drying across the country, accompanied by an increase in heavy precipitation events, reduced wet spell events and increased dry spell (Nkemelang et al., 2018).

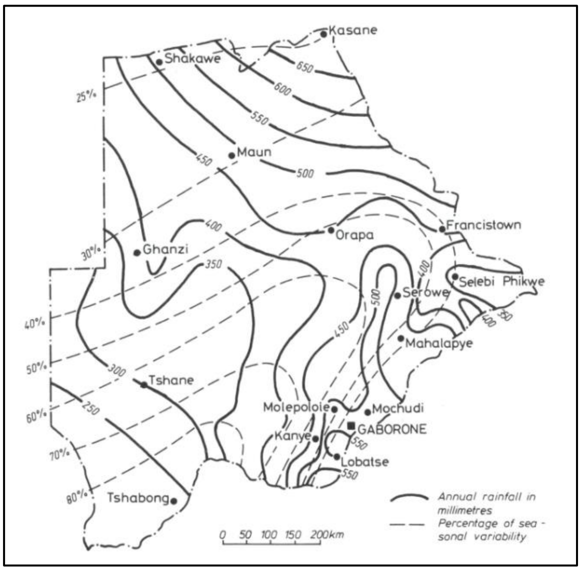


Figure 6. Average rainfall isohytes and rainfall variability across Botswana. From Ringrose et al. (1999)

Annex A: Country report Botswana

2.3 Land use

The figure below shows land use by type in Botswana. It was obtained from the GIS lab at the Okavango Research Institute (ORI). Table 3 gives a summary, based on the ORI GIS map, of the fraction of Botswana land allocated for a variety of uses.

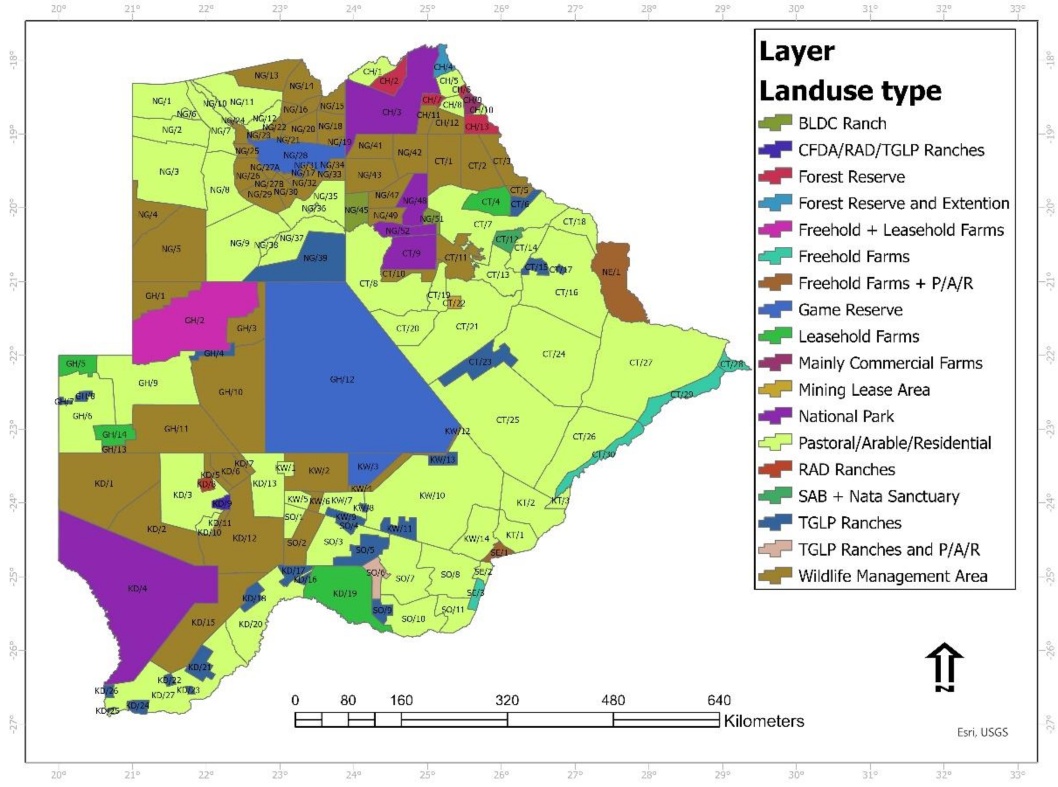


Figure 7. Map of Botswana showing land use type for each concession area. Map produced by Anastacia Makati at the ORI GIS lab.

Table 3. Fraction of land dedicated to each land use type in Botswana.

Land use type	**%**
Game Reserve	1.8
Forest reserve	0.7
National Park	7.7
Wildlife Management Area	34.3
Pastoral/arable/residential	46.2
Ranch and farm	9.2
SAB Nata Sanctuary	0.2
Mining Lease area	0.1

Forest: Botswana may be divided into three main ecological zones: the eastern hardveld, the Kalahari sandveld and the waterveld characterised by surface waters of the Okavango wetlands to the northwest (Figure 8). About 80-85% of the country is covered by Kalahari sandveld with nutrient poor sandy soils (Winterbach et al., 2014). In contrast, the hardveld, which forms part of LRB covers the remaining 15-20% of the country's total surface area and consists of the rocky hill ranges and shallow sand areas. The sandveld region, which forms part of the Kalahari Desert covers the rest of the country and is characterised by deep Kalahari sand. The waterveld which consists of only a small area (~2%) is superimposed on the northern sandveld in the lowest part of the Kalahari basin covered by the Okavango wetlands. Although both the sandveld and hardveld areas are characterised by a semi-arid climate, the two areas support relatively different vegetation communities. The vegetation of the Kalahari sandveld ranges from Miombo and mopane (*Colophospermum mopane*) dominated woodland and close-tree Acacia savannah in the north of the country, to more arid and open low tree and shrub savannah with perennial and annual grasses in the south and west (Winterbach et al., 2014). De Wit and Nachtergaele (1990) and Thomas and Shaw (1991) have described the vegetation in the sandveld as simply scattered trees and shrubs. In contrast, the hardveld region which is dominated by fertile tropical ferruginous soils is characterised by a rocky tree savanna with higher species diversity and vegetation density due to a greater range of parent material, soils and climate. According to Macala et al. (1989), the hardveld can be further divided into the northern decidous forests, the north and central Mophane veld, and the southern Acacia/Combretum complex. The vegetation communities commonly observed in the hardveld region include *Peltophorum africanum*, *Acacia tortilis*, *Acacia nigrescens* and *Combretum apiculatum*. Further to the north, Colophospermum mopane features strongly to the extent that pure stands are not uncommon (GOB, 1998)

Temperatures across the country are lowest during the dry and sunny austral winter period (May-August) and highest during austral summer period (November-March). While winter temperatures can fall below 0 ^{o}C over some parts of the country, summer mean maximum temperatures have been reported between 31-33 ^{o}C across the country (Moses 2017). Air temperatures over 42 ^{o}C have occasionally been reported in recent years in the country (Moses 2017). The LR sub-basin in Botswana supports a significant portion of the SADC population, including some of the region’s poorest and richest communities alike. The basin has numerous urban areas and commercial and subsistence farming communities, as well as important forestry resources and mines. One must highlight that there is also a large variety within the riparian countries when it comes to forest resources endowment. For instance, forest cover in Botswana, Mozambique, South Africa, and Zimbabwe ranges from less than 10% (South

Africa) to approximately 50% (Zimbabwe). Botswana has just over 20% of its land area within the Limpopo River basin allocated to forest plantations, while Mozambique has approximately 40%. According to the 2009 World Development Indicators, deforestation in the four riparian countries was quite low from 2000 to 2005 ranging from 0 % to 1.7 % (World Bank, 2010). Forest resources in the Limpopo River basin consist of natural forests and woodlands and commercial/plantation forestry. Although South Africa is the main riparian country practising plantation forestry, the plantation area as a percentage of the total provincial land area within the Limpopo River basin is only 0.5%. The commercial forest plantation sector is primarily under private ownership and based on exotic species of pine, eucalyptus, and Australian wattles (Clarke, 2008). As these species require high rainfall, plantations are therefore found in the higher rainfall belt in South Africa.

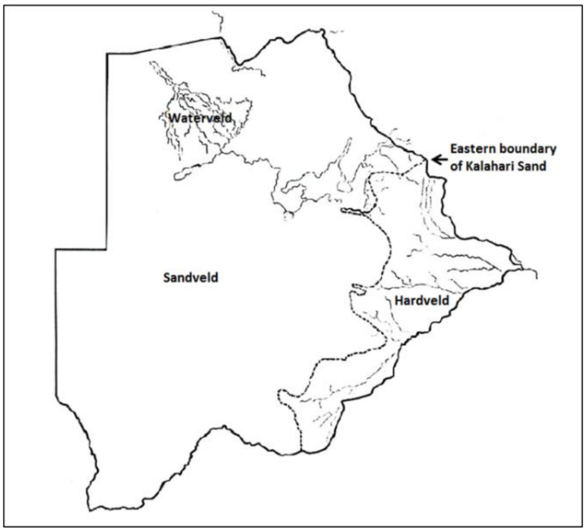


Figure 8. Map of Botswana showing the three main environmental regions: the hardveld, sandveld and waterveld.

Agriculture: About 80-85% of Botswana is covered by the Kalahari sandveld characterised by poor soil nutrients and low arable crop production due to poor soil fertility, endemic droughts. In contrast, the rocky hills and intervening valleys of the relatively wetter hardveld have a higher agricultural potential for arable crop (e.g., sorghum and maize) and livestock production on the region's predominantly fertile loamy soils (Vanderpost et al., 2007). Consequently, mixed agriculture is one of the most important economic activities in the Botswana's LR sub-basin. The landscape is therefore a mixture of arable fields, commercial farms, open pastoral/grazing areas, ranches as well as residential plots (Winterbach et al., 2014; See Figure 9). Nellis et al. (1997) described most of the arable fields as small with low capital investments using simple implements for cultivation of a variety of crops. The top three crops grown in the country include maize, sorghum and millet. The hardveld forms the prime area for livestock production in the country due to several environmental and economic factors. For instance, studies (e.g., Tacheba and Moyo 1988; Nsinamwa et al., 2005) have shown that because of fertile loamy soils the hardveld grasses contain higher dietary nutrients for livestock than those in the Kalahari sandveld. Livestock rearing in the hardveld is also influenced by the region's proximity to key markets, better access to inputs and extension services. It is important to note that population and economic activities in Botswana are concentrated in this hardveld ecoregion of the country. Consequently approximately 55% of the total cattle population (~1.6 million) in 2015 in Botswana was in the hardveld region (Statistics Botswana, 2018a). A similar distribution of cattle population across the country (Figure 10) was also displayed by Alexander et al. (2012). While agriculture comprises only 2% of GDP, the contribution of livestock, especially cattle, to the agricultural GDP is estimated at 80%.

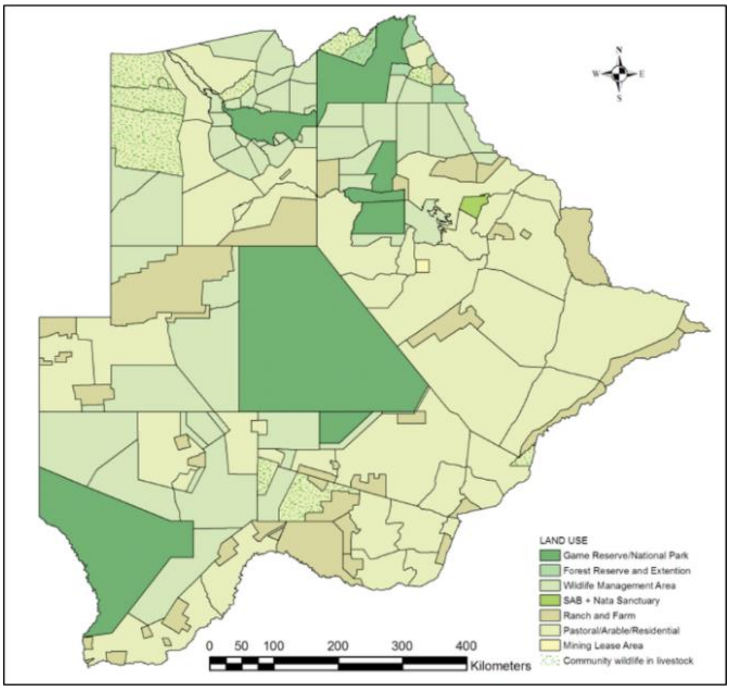


Figure 9. Land use zones in Botswana, including the eastern hardveld area. From Winterbach et al. (2014)

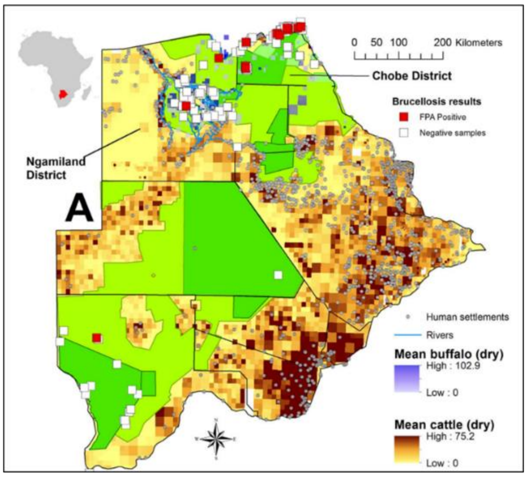


Figure 10. Dry season distribution of cattle population across Botswana. Green shaded areas are gazetted as conservation land use such as national parks, reserves, and wildlife management areas. From Alexander et al. (2012).

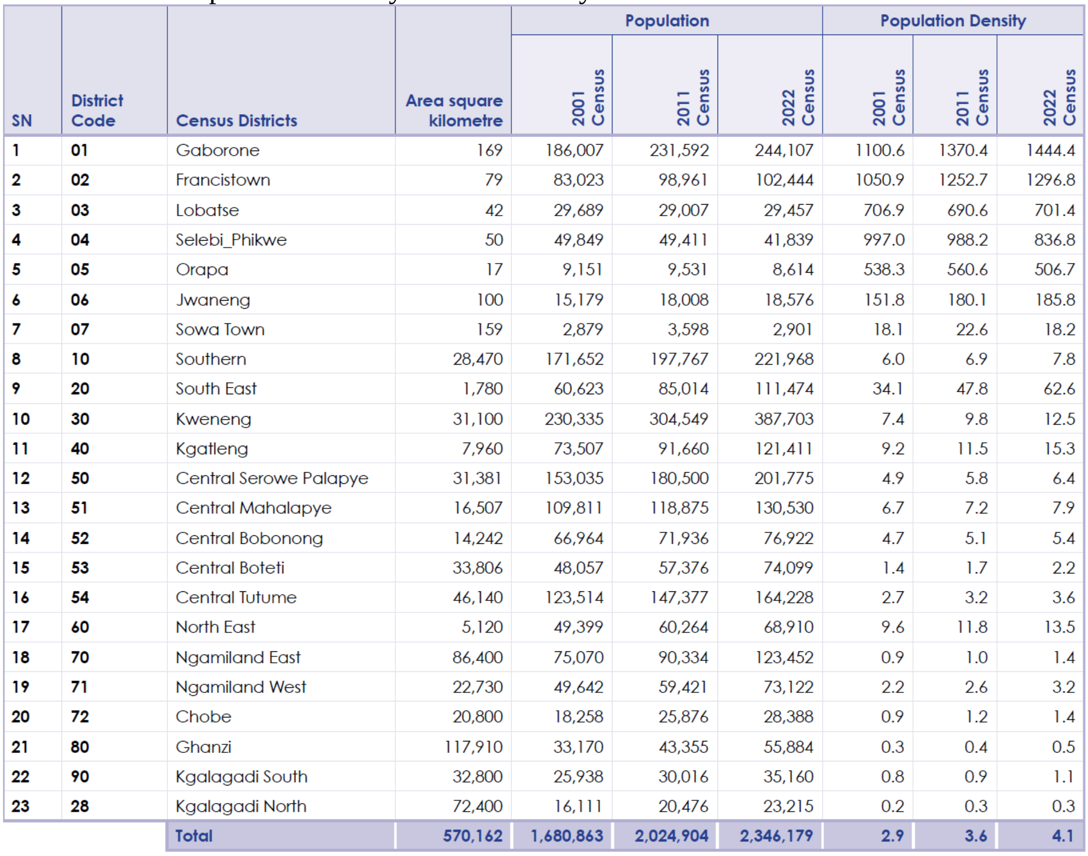
Savannah*:* The rangeland ecosystem of much of the hardveld is endowed with grasses combined with forest trees, woodland trees, shrubs, and open savanna grassland areas. The spatial and temporal distribution of vegetation across the area depends on a number of factors including annual rainfall, the soil type, and anthropogenic activities such veld burning and livestock grazing. These rangelands play important roles for livestock production and wildlife management in the hardveld area. As noted earlier, wildlife supports the ecotourism trade in the area. Some of the tree species (e.g., *Combretum apiculatum* and *Peltrophorum africanum*) found in the hardveld area have been shown to improve soil fertility and other physical soil characteristics (Aweto and Dikinya, 2003).

Protected Areas*:* Much of the land in the hardveld area has been owned by white farmers since pre-independence years. As indicated above, the hardveld ecoregion is also the most densely populated region in Botswana. The remaining land has consequently been demarcated to support the inhabitants' basic needs especially human settlement and food security through arable and pastoral/livestock farming in form of communal grazing and ranching (Figure 9). Due to land shortage, there are only a few small private game reserves such as Stevensford and Northern Tuli Game Reserves in the hardveld region. The game reserves have an abundance of wildlife and biodiversity which support the ecotourism industry in the area.

2.4 Population Density and Cities:

The total human population in Botswana was estimated at 2,024,904 in 2011. In 2022 the population was estimated to be 2,346,179 (Statistics Botswana, 2022). There are 14 major urban centres in the hardveld region, each with between 19400-231000 inhabitants and a total population of 804,000, ~40% of the country's population. The total population across the country is skewed towards the hardveld region which is home to approximately 80% of the country's population. This region contributes about 12% of the total population in the Limpopo River basin. Population density in the hardveld region is therefore estimated at 20 persons per km^2, much higher than the national density of 4.1 persons per km^2. Population density in Botswana increased from 2.9 persons per km^2 in 2001 to 3.6 persons per km^2 in 2011 and 4.1 persons per km^2 in 2022 (Statistics Botswana, 2022). The highest density, at 1444.4 persons per km^2, is in the capital city Gaborone followed by Francistown with 1,296.8 people per km^2 (Table 4, Statistics Botswana, 2022). Figure 11 shows how the population is distributed in Botswana.

Table 4. 2022 Population Density in Botswana by Census Districts.



SN	District Code	Census Districts	Area square kilometre	Population			Population Density		
				2001 Census	2011 Census	2022 Census	2001 Census	2011 Census	2022 Census
1	01	Gaborone	169	186,007	231,592	244,107	1100.6	1370.4	1444.4
2	02	Francistown	79	83,023	98,961	102,444	1050.9	1252.7	1296.8
3	03	Lobatse	42	29,689	29,007	29,457	706.9	690.6	701.4
4	04	Selebi_Phikwe	50	49,849	49,411	41,839	997.0	988.2	836.8
5	05	Orapa	17	9,151	9,531	8,614	538.3	560.6	506.7
6	06	Jwaneng	100	15,179	18,008	18,576	151.8	180.1	185.8
7	07	Sowa Town	159	2,879	3,598	2,901	18.1	22.6	18.2
8	10	Southern	28,470	171,652	197,767	221,968	6.0	6.9	7.8
9	20	South East	1,780	60,623	85,014	111,474	34.1	47.8	62.6
10	30	Kweneng	31,100	230,335	304,549	387,703	7.4	9.8	12.5
11	40	Kgatleng	7,960	73,507	91,660	121,411	9.2	11.5	15.3
12	50	Central Serowe Palapye	31,381	153,035	180,500	201,775	4.9	5.8	6.4
13	51	Central Mahalapye	16,507	109,811	118,875	130,530	6.7	7.2	7.9
14	52	Central Bobonong	14,242	66,964	71,936	76,922	4.7	5.1	5.4
15	53	Central Boteti	33,806	48,057	57,376	74,099	1.4	1.7	2.2
16	54	Central Tutume	46,140	123,514	147,377	164,228	2.7	3.2	3.6
17	60	North East	5,120	49,399	60,264	68,910	9.6	11.8	13.5
18	70	Ngamiland East	86,400	75,070	90,334	123,452	0.9	1.0	1.4
19	71	Ngamiland West	22,730	49,642	59,421	73,122	2.2	2.6	3.2
20	72	Chobe	20,800	18,258	25,876	28,388	0.9	1.2	1.4
21	80	Ghanzi	117,910	33,170	43,355	55,884	0.3	0.4	0.5
22	90	Kgalagadi South	32,800	25,938	30,016	35,160	0.8	0.9	1.1
23	28	Kgalagadi North	72,400	16,111	20,476	23,215	0.2	0.3	0.3
		Total	**570,162**	**1,680,863**	**2,024,904**	**2,346,179**	**2.9**	**3.6**	**4.1**

Table copied from Statistics Botswana, 2022

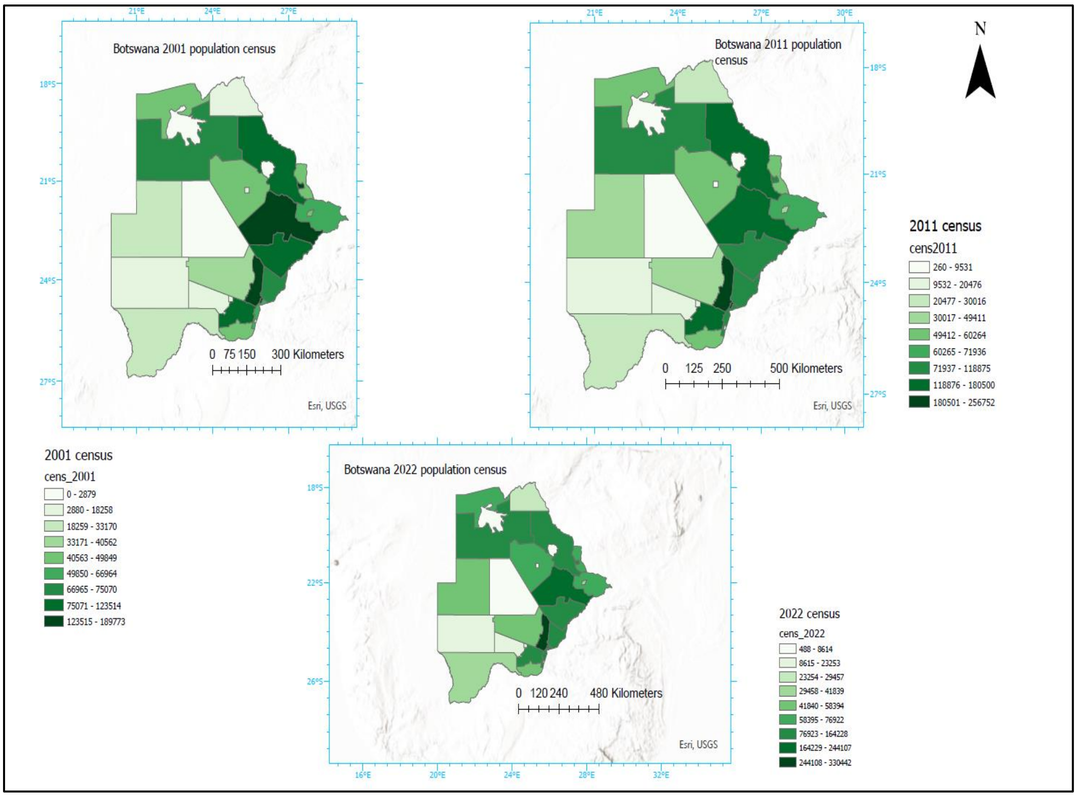


Figure 11. Population Distribution in Botswana for the years 2001, 2011 and 2022. Map generated by the ORI GIS laboratory.

3. Supply and water management options

3.1 Severe Floods and Droughts

Several significant floods resulting from tropical cyclones have occurred in the Limpopo River Basin (LRB) in the recent past. Most floods in this region are experienced in the low-lying coastal floodplains of Mozambique. Severe floods in the LRB have been recorded in the years 1955,1967,1972,1975,1977,1981, 2000 and 2003 (CRIDF, 2018). The LRB in Botswana is less prone to flooding compared to the sub basins in the other countries. Flood incidence and impacts from 2010-2017 in Botswana are published in the report by Botswana Environmental Statistics, Natural Disasters Digest 2017 (Statistics Botswana, 2018b). According to the report, floods in 2014 affected Selebi Phikwe and Francistown in the Motloutse sub catchment. In 2017, the villages of Leshibitse, Mochudi, Bakaa and Pilane in the Notwane sub catchment were affected by floods (Statistics Botswana, 2018b). It has also been reported that in 2013, the central part of Botswana experienced heavy rains affecting 842 families and displacing 400 people in the Tutume and Tonota sub-districts within the Shashe sub catchment (LIMCOM et al., 2017).

Annex A: Country report Botswana

Contrary to flood events, the frequency and duration of drought events are worse in Botswana when compared to the rest of Southern Africa (Plessis and Rowntree, 2003). Droughts in Botswana are declared in a year when the country receives below average rainfall (Statistics Botswana, 2018b). Drought declarations from 1961 to 2017 are published in the report by Botswana Environmental Statistics, Natural Disasters Digest 2018. Droughts covering the whole country of Botswana were experienced in the following years:1981-1987, 1991-1999, 2001-2005, 2007-2008, 2009-2010, 2010-2011, 2011-2012, 2012-2013, 2014-2015 and 2015-2016. The drought in 2015/2016 caused the Gaborone dam in the Notwane sub catchment to dry up and was declared the worst drought in three decades. Drought covering part of the country including in the LRB sub catchments in Botswana were recorded during the following times: 1961-1965 and 1979-1980 (Statistics Botswana, 2018b). According to the Department of Meteorological Services in Botswana, severe droughts in the country are recorded in 5,10 and 15, year cycles (Setume et al., 2016).

3.2 Water Shortage

Most of the LRB is water stressed and projected to get worse by 2050 under climate change (McMullen and Jabbour, 2009; Zhu and Ringler, 2012). The situation is dire in Botswana due to rapidly increasing population, low and variable rainfall, high rates of evapotranspiration of up to 2000mm per year and the high cost of exploiting existing water resources (Plessis and Rowntree 2003; Setume et al., 2016). As such Botswana depends heavily on groundwater with 58% of water abstracted from the environment coming from groundwater while 42% is from surface water (Setlhogile et al., 2017). Combined, the two sources of water in Botswana are estimated to have a safe yield of 250 Mm^3/ year (Setlhogile et al., 2017). Currently water is abstracted at an average rate of 187.9Mm^3 /year (Setlhogile et al., 2017). There is thus immense pressure on the water resources in Botswana.

Additionally, surface water resources are more prevalent in the northern region of the country while demand is highest in the south-east region (Setume et al., 2016). A lot of money is lost by the Government through water transfer schemes, forcing the government to consider groundwater as an alternative (Setume et al., 2016). Currently, groundwater is over extracted especially for industrial use and agriculture (BWSPB, 2012).

Botswana also imports water (about 7 Mm^3 per year) from South Africa from the Molatedi Dam on the Marico tributary of the Limpopo River (Setlhogile et al., 2017). The imported water serves mostly households in Gaborone suggesting water shortage for domestic use in the capital city.

3.3 Development of water supply over the last 15 years

When Botswana reformed the water management sector in 2009 the main priorities were to increase the security of water supply, improve water quality and service delivery, and re-use treated effluent (Setume et al., 2016). These were to be achieved, among other developments, through constructing dams, drilling more boreholes, treatment of saline water and improving recycling and treatment of effluent to 96% by 2030, from the current 20% (Setume et al., 2016). Since then, three additional dams have been constructed adding to the 6 functioning dams already present. The additional dams are located on the Lotsane, Shashe and Thune rivers in the Limpopo sub catchment in Botswana. The dams constructed mostly serve households but also industries, and the agricultural sector.

Dams in Botswana, their location and capacity are shown in the Table 5 below. As the table shows all the Dams abstract water from tributaries of the Limpopo River.

Table 5. List of dams in Botswana

Name of Dam	Year constructed	Capacity (MCM)	% capacity	River	River Basin
Gaborone	1965	141.4	15.6	Notwane	Limpopo
Shashe	1970	85	9.4	Shahe	Limpopo
Nnywane	1970s	2.3	0.3	Nnywane	Limpopo
Letsibogo	1997	100	11.0	Motloutse	Limpopo
Bokaa	1993	18.5	2.0	Metsemotlhabe	Limpopo
Ntimbale	2006	26.5	2.9	Tati	Limpopo
Lotsane	2011	42.35	4.7	Lotsane	Limpopo
Dikgatlhong	2012	400	44.1	Shashe	Limpopo
Thune	2013	90	9.9	Thune	Limpopo

Apart from the dams, Water Utilities Corporation (WUC) of Botswana operates 840 boreholes countrywide (BWUR, 2012). More boreholes have been constructed in the recent past including Masama East and West wellfields developed and commissioned in 2015 and 2019 (BWUR, 2012). The two were constructed to increase water supply to the Greater Gaborone area (BWUR, 2021). In addition, several boreholes have been recently upgraded to improve water supply to villages with severe water shortages (BWUR, 2021).

There have been developments on the re-use of treated wastewater effluent for agriculture. Recycled water from Gaborone city sewage treatment plant is currently being utilized for agriculture. Plans are underway to replicate the same throughout the country (BWSPB, 2021).

3.4 Quality of Water

The quality of water in the LRB is affected by the release of partially or improperly treated effluent from wastewater treatment facilities, agricultural and mining activities. Several wastewater treatment facilities exist in the Botswana side of the LRB and include Glen Valley, Tonota, Selibe Phikwe, Mambo and Mahalpye. Many of the wastewater treatments plants are said to be operating beyond capacity thereby discharging partially treated wastewater into the environment. Discharge of partially treated wastewater has been suggested to be responsible for elevated levels of nitrates in groundwater in central Botswana within the Limpopo River basin (Vogel et al., 2004). It has also been shown that groundwater in the Ramotswa area which lies within the Notwane sub catchment contained nitrate, chloride, and iron levels several times higher than recommended by WHO and Botswana Bureau of Standards (LIMCOM et al., 2017).

Among the tributaries of the Limpopo River in Botswana, Ngotwane River was found to have high content of nitrates (8 mg/L), iron (2.99 mg/L), manganese and low Dissolved Oxygen (DWA BW and SA, 2013). This is suggested to be from wastewater discharge from a treatment plant in Gaborone (DWA:BW and DWA:SA, 2013). The Ngotwane River is also contaminated with enteric viruses which could be from a sewage leak in the Ngotwane River (Tubatsi 2022). Notwane and Motloutse tributaries in Botswana also had electrical conductivity above South African water quality guidelines. This was also true for various points along the Limpopo River between Botswana and South Africa (DWA:BW and DWA:SA, 2013). The high conductivity in Notwane and Motloutse is suggested to be due to discharges from wastewater facilities and agricultural activities along the rivers, respectively (DWA:BW and DWA:SA, 2013). The joined water quality monitoring study conducted by the Departments of Water Affairs in Botswana and South Africa shows that the water quality in the Limpopo River is mostly affected by excess nutrients and detectable levels of heavy metals including lead (DWA:BW and DWA:SA, 2013).

3.5 Existing base of water quality data

Table 6. Water quality data (range) from the Joint Water Quality Baseline Report for Limpopo Basin between Botswana and South Africa 2011/12.

Sites	EC (µS/ms)	DO (mg/L)	pH	Turbidity (NTU)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	Cu (mg/L)	Pb (mg/L)	Cl (mg/L)	SO4 (mg/L)	NO3 (mg/L)	PO4 (mg/L)	Feacal Coliform	Intestinal enterococci
Marico-Sikwane	224-387	2.18-7.43	7.46-8.09	32.4-50.8	154-2.6	31.23-53.25	22.97-39.50	8.78-96	5.19-45.32	0.48-0.83	0.02-0.09	ND	ND-0.002	5.5-14.7	9.63-20.58	1.75-2.44	0-0.12	113-12800	30-6400
Marico-Olifants Drift	450-672	2.47-7.43	7.53-8.29	28.2-62.9	187-472	21.50-48.35	11.30-28.15	15.1-77.63	6.23-21.45	0.29-0.38	0-0.21	ND	ND-0.003	10.7-78.31	8.59-49.08	2.25-4.93	0-0.8	20-800	40-800
Limpopo-Olifants Drift	570-820	2.38-6.74	7.64-8.81	35.2-69.1	166-365	19.24-44.07	9.73-29.74	48.44-76.1	5.9-24.56	0.34-0.59	0-0.03	ND	ND-0.003	5.08-101.7	1.1-66.18	1.27-9.56	0-ND	0-180	16-60
Notwane River- Limpopo	299-789	1.2-5.91	7.89-8.73	14.5-79.0	194-392	26.08-39.45	9.64-34.05	27.16-81.75	6.5-18.4	0.56-2.99	0-0.11	ND	ND	43.2-104	17.62-86.82	0.69-8.2	0-ND	0-170	0-160
Limpopo- Buffle's Drift	648-809	6.2-7.56	7.73-8.04	16.2-33.4	220-512	19.5-88.9	23.25-33.3	46.94-77.2	7.55-22.03	ND-0.64	ND-0	ND-0.02	ND	23.4-100.3	17.9-65.18	1.17-9.3	0-ND	28-240	20-200
Lotsane River	131	7.09	8.23	2.92	85	14.34	4.95	8.01	6.73	0.65	0	ND	ND	3.25	3.07	4.6	0	200	78
Limpopo-Martin's Drift	631-674	7.09-7.92	7.84-8.36	9.9-13.8	411-516	10.65-31.56	9.05-28.9	18.73-73.95	7.4-9.34	0.3-1.12	0-0.06	ND	ND	9.56-65.56	8.21-36.65	0.79-7.9	0-ND	40.8-140	20-140
Motloutse River	524	7.1	7.8	7.27	335	53.1	18.1	26.6	3.11	0.28	0.08	ND	ND	36.21	21.14	4.8	0	70	35
Limpopo River-Lentswe le Mc	528	7.81	7.8	12.5	301	5.85	2.74	19.5	10.24	0.93	0	ND	ND	26.6	15.7	3.97	0	1600	220
Shalimpo	287-601	5.52-6.96	7.69-8.34	5.97-10.2	198-399	6-48.36	2.13-18.26	15.63-22.7	3.85-10.19	0-0.84	0-0.04	ND	ND	22.12-74.0	17.19-45.4	0.87-5.89	0-ND	28-230	16-79
Shashe River Mbalambi	42	6.92	7.48	14.5	27	7.79	2.87	2.87	0.94	1.46	0.14	ND	ND	2.49	2.74	10.98	0	1520	888
Tati River - Masunga	174	6.84	7.84	8.17	113	25.3	4.43	4.43	4.32	0.14	0	ND	ND	10.17	4.07	10.17	0	160	72

Sampling was conducted in the summer season (Nov/Dec 2011), Rain season (Feb 2012) and Winter season (July 2012).

Table 7. Water quality data (average) from Mladenov et al. 2005.

Sites along Notwane River	%DO (sat)	BOD (mg/L)	COD (mg/L)	Ammopnia N (mg/L)	Nitrate (mg/L)	Dissolved P (mg/L)	TDS (mg/L)	TSS (mg/L)	Fecal coliform (no. per 100 mL)	Fecal streptococci (no. per 100 mL)
Ruretse	62	14	129	0.07	3.53	3.65	314	38	886	824
Oodi	37	15	72	0.06	2.38	2.44	320	18	1296	872
Matebele	71	20	112	0.23	1.47	2.39	304	34	450	526
Morwa	77	18	118	0.04	1.03	1.98	372	41	374	712
Mochudi	56	18	115	0.06	1.43	0.99	306	30	516	690
Malotwane	78	30	98	0	2.59	0	211	52	845	875

Sampling was conducted bi-weekly during rainy season from November to January 1998-1999.

3.6 Water Tariffs

As from June 1st 2021, the following revised tariffs were implemented by the government of Botswana. Tariff changes over the last few years are presented in the section on Changes and Projections.

Table 8. Botswana Water Utilities Corporation Tariffs (VAT inclusive) Effected 1st June 2021.

Domestic Tarrifs	
Tariff Block Category	Traiff (Pula per KL) 1st June 2021
Minimum Charge	0
0-5 KL	3.50
> 5-15 KL	13.43
> 15-25 KL	23.51
> 25-40 KL	36.16
> 40 KL	45.21
Commercial, Business and Industrial Tariffs	
Tariff Block Category	Traiff (Pula per KL) 1st June 2021
Minimum charge	0
0-5 KL	4.92
> 5-15 KL	14.61
> 15-25 KL	25.58
> 25-40 KL	39.35
> 40 KL	49.20
Government Tariffs	
Tariff Block Category	Traiff (Pula per KL) 1st June 2021
Minimum Charge	87.85
>0-5 KL	12.65
> 5-15 KL	33.73
> 15-25 KL	43.92
> 25-40 KL	70.28
> 40 KL	87.85

4. Water demand information

4.1 Main Water Users (m^3 or % of total consumption?)

The Botswana National Water Policy of 2012 posits that in order for future policies and strategies to meet national water demands in the future, they will "…need to be directed towards improving allocative efficiency and enhancing technological developments to improve water resources stewardship and water demand management."(Government of Botswana, 2012: p.4).

According to the Ministry of Land Management, Water Resources and Sanitation Services (MLMWRSS, 2017) Botswana Water Accounting Report, Water extracted from the environment to support the Botswana economy in 2015-16 was 201.3 MCM of which 96.3 MCM was extracted by WUC while the remaining 105 MCM was extracted directly by self-providers (agriculture and mining sector) (MLMWRSS, 2017). Three years later in 2018-19, total abstraction remained relatively the same at 202 MCM with self-providers extracting 102.8 MCM and Water Utilities Corporation (WUC) responsible for 99.2 MCM (DWS 2021). As the statistics show, over half of the water consumed in Botswana is through self-providers such as the minerals, livestock and wildlife sectors which accounts for more than 50 percent of all consumption, with the remainder being accounted for by WUC, Department of Water Affairs (DWA) and the District Councils (Government of Botswana and The World Bank, 2016; Hambira & Kolawole, 2021).

Table 9, 10 and 11 and Figure 12 show physical use and supply of water in Botswana for the reporting period 2015-2016, 2017-2018 and 2018-2019. The total water consumption in 2015-16 in Botswana was 170 MCM of which 135 MCM and 39.1 MCM accrued to industry and households respectively. By the year 2018-2019, total water consumption reduced to 133.8 MCM of which households accounted for 20.2 MCM and industries consumed 120.1 MCM (Table 9, 10 and 11) (DWS 2021). During both reporting periods, the agriculture sector was the largest consumer of water at 83 MCM in 2015-16 (48% of Botswana's total water consumption) and 76.5 MCM in 2018-2019 (57% of total consumption in that period). More than 50% of water consumed by the agricultural industry (48.3 MCM in 2015-2016, and 40.1MCM in 208-2019) was for livestock water consumption while 34.7 MCM and 36.4 MCM in 2015-2016 and 2018-2019, respectively, accrued to total irrigation water consumption (MLMWRSS, 2017; DWS, 2021). In the tables, other industries comprise manufacturing, construction, trade, hotels and restaurants, transport, finance, and business as well as social and personal services such as health, education, dry cleaners, car washes and saloons (Government of Botswana and World Bank, 2016). The Government sector is made up of Central and Local government. It includes all public administration segments but excludes education, health, and social work activities.

Even though the statistics provided above are national, there are significant differences between regions in water consumption with highly populated cities and towns, such as Gaborone, Francistown and Selibe Phikwe among the highest consumers. It should be noted that these cities and towns fall under the Notwane, Shashe and Motloutse sub-basins of the Limpopo River basin.

Annex A: Country report Botswana

Table 9. Physical supply and use of water in million cubic meters (MCM) in Botswana for the year 2015-2016.

		Agriculture	Mining and quarrying	Electricity	WUC	Sewage	Government	Other industries	Total agr & ind	Households	Rest of the world	Total
I. Physical use table												
From the environment	**1. Total abstraction**	**81.0**	**23.2**	**0.8**	**96.3**	**0.0**	**0.0**	**0.0**	**201.3**	**0.0**	**0.0**	**201.3**
	1i. Surface water	32.4	0.7		55.9	0.0	0.0		89.0	0.0	0.0	89.0
	1ii. Ground water	48.6	22.4	0.8	40.4	0.0	0.0		112.3	0.0	0.0	112.3
Within the economy	2. Use of water from other economic sectors	2.0	4.9	0.3	2.4	8.5	10.5	12.2	40.5	39.1	0.0	79.9
	3. Total use of water (1+2)	**83.0**	**28.1**	**1.1**	**98.7**	**8.5**	**10.5**	**12.2**	**242.1**	**39.1**	**0.0**	**281.3**
II. Physical supply table												
Within the economy	4. Supply of water to other economic units	0.0	2.7	0.1	72.1	1.8	0.0	0.0	76.7	0.0	3.8	80.5
Into the environment	5. Total returns	0.0	0.0	0.0	30.8	0.0	0.0	0.0	30.8	0.0	0.0	30.8
	6. Total supply of water (4+5)	**0.0**	**2.7**	**2.7**	**102.9**	**1.8**	**0.0**	**0.0**	**107.4**	**0.0**	**3.8**	**111.2**
	7. Consumption (3-6)	**83.0**	**25.4**	**25.4**	**-4.2**	**6.7**	**10.5**	**12.2**	**134.7**	**39.1**	**-3.8**	**170.0**

Adapted from MLMWRSS, 2017

Table 10. Physical supply and use of water in million cubic meters (MCM) in Botswana for the year 2017-2018.

		Agriculture	Mining and Quarrying	Electricity	WUC	Sewage	Government	Other Industries	Total Industries	Households	Imports	Total
I. Physical use table												
From the environment	**1. Total abstraction**	**79.6**	**26.9**	**0.4**	**97.1**	**0.0**	**0.0**	**0.0**	**203.9**	**0.0**		**203.9**
	1i. Surface water	23.7	2.7	0.0	56.3	0.0	0.0	0.0	82.8	0.0		82.8
	1ii. Ground water	55.9	24.2	0.4	40.8	0.0	0.0	0.0	121.2	0.0		121.2
Within the economy	2. Use of water from other economic sectors	2.0	8.6	0.8	7.1	40.1	9.0	10.5	78.1	33.7	0.0	111.8
	3. Total use of water (1+2)	**81.5**	**35.5**	**1.1**	**104.3**	**40.1**	**9.0**	**10.5**	**282.0**	**33.7**	**0.0**	**315.7**
II. Physical supply table												
Within the economy	4. Supply of water to other economic units	0.1	8.2	0.1	62.1	1.8	5.8	6.8	85.0	21.7	5.0	111.8
Into the environment	5. Total returns	0.0	0.0	0.0	41.7	38.3	0.0	0.0	80.0	0.0		80.0
	6. Total supply of water (4+5)	**0.1**	**8.2**	**0.1**	**103.8**	**40.1**	**5.8**	**6.8**	**165.0**	**21.7**	**5.0**	**191.8**
	7. Consumption (3-6)	**81.4**	**27.3**	**1.0**	**0.4**	**0.0**	**3.2**	**3.7**	**117.0**	**12.0**	**-5.0**	**123.9**

Adapted from DWS 2021.

Table 11. Physical supply and use of water in million cubic meters (MCM) in Botswana for the year 2018-2019.

		Agriculture	Mining and Quarrying	Electricity	WUC	Sewage	Government	Other Industries	Total Industries	Households	Imports	Total
I. Physical use table												
From the environment	**1. Total abstraction**	**74.6**	**27.8**	**0.4**	**99.2**	**0.0**	**0.0**	**0.0**	**202.0**	**0.0**		**202.0**
	1i. Surface water	22.1	2.2	0.0	71.3	0.0	0.0	0.0	95.6	0.0		95.6
	1ii. Ground water	52.5	25.6	0.4	27.9	0.0	0.0	0.0	106.4	0.0		106.4
Within the economy	2. Use of water from other economic sectors	2.0	10.8	0.1	8.5	40.1	11.2	13.1	85.8	41.9	0.0	127.7
	3. Total use of water (1+2)	**76.6**	**38.6**	**0.5**	**107.7**	**40.1**	**11.2**	**13.1**	**287.8**	**41.9**	**0.0**	**329.7**
II. Physical supply table												
Within the economy	4. Supply of water to other economic units	0.1	7.6	0.2	77.3	1.8	5.8	6.8	99.5	21.7	6.5	127.7
Into the environment	5. Total returns	0.0	0.0	0.0	29.8	38.3	0.0	0.0	68.1	0.0		68.1
	6. Total supply of water (4+5)	**0.1**	**7.6**	**0.2**	**107.1**	**40.1**	**5.8**	**6.8**	**167.6**	**21.7**	**6.5**	**195.8**
	7. Consumption (3-6)	**76.5**	**31.0**	**0.4**	**0.6**	**0.0**	**5.4**	**6.3**	**120.1**	**20.2**	**-6.5**	**133.8**

Adapted from DWS 2021.

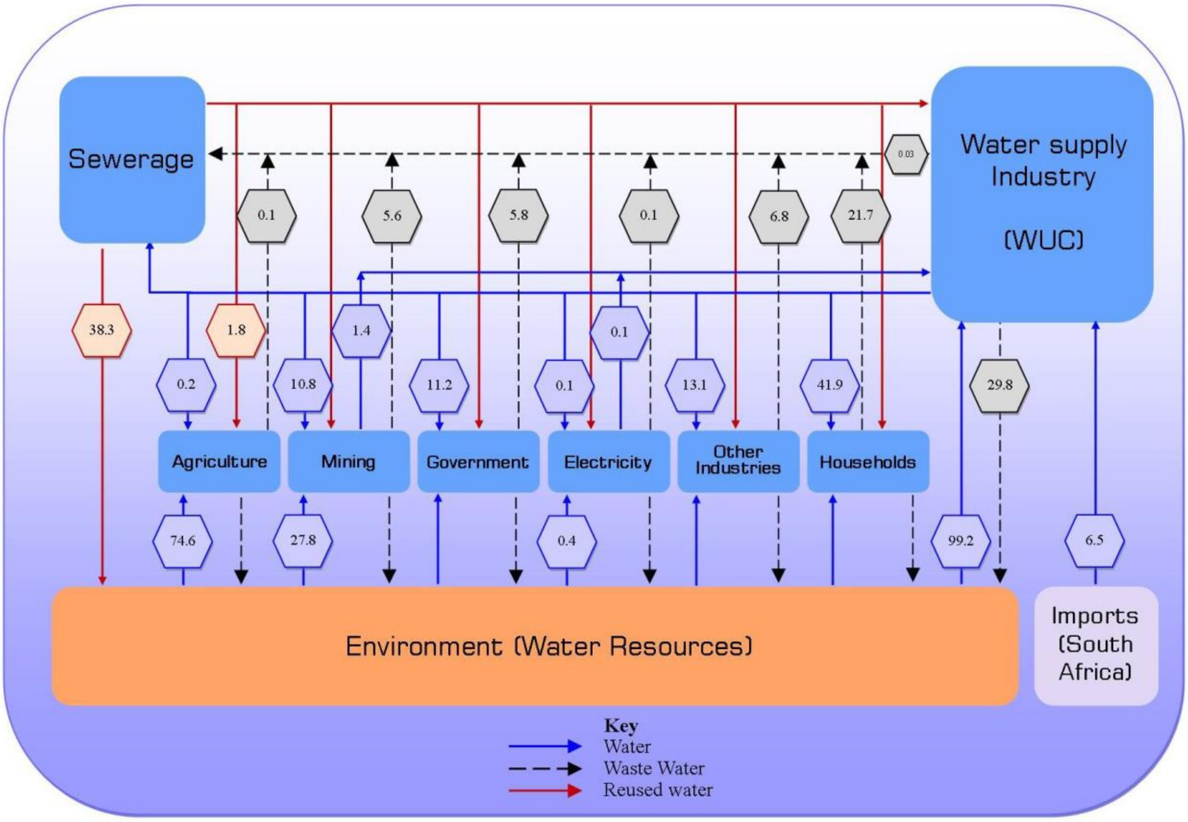


Figure 12. Schematic diagram of physical supply and use of water in million cubic meters (MCM) in Botswana for the year 2018-2019. (Copied from DWS 2021)

Generally, there is a fluctuating trend for total water consumption in Botswana. Figure 13 shows the long-term trend in water consumption in Botswana, from 1991 to 2019. The highest consumption of 178 MCM was recorded in 2014 and the lowest (123.9 MCM) in 2018. Between 2016 and 2017, total consumption reduced significantly by 44 MCM due to a significant decline in consumption by households and the agriculture industry (DWS 2021).

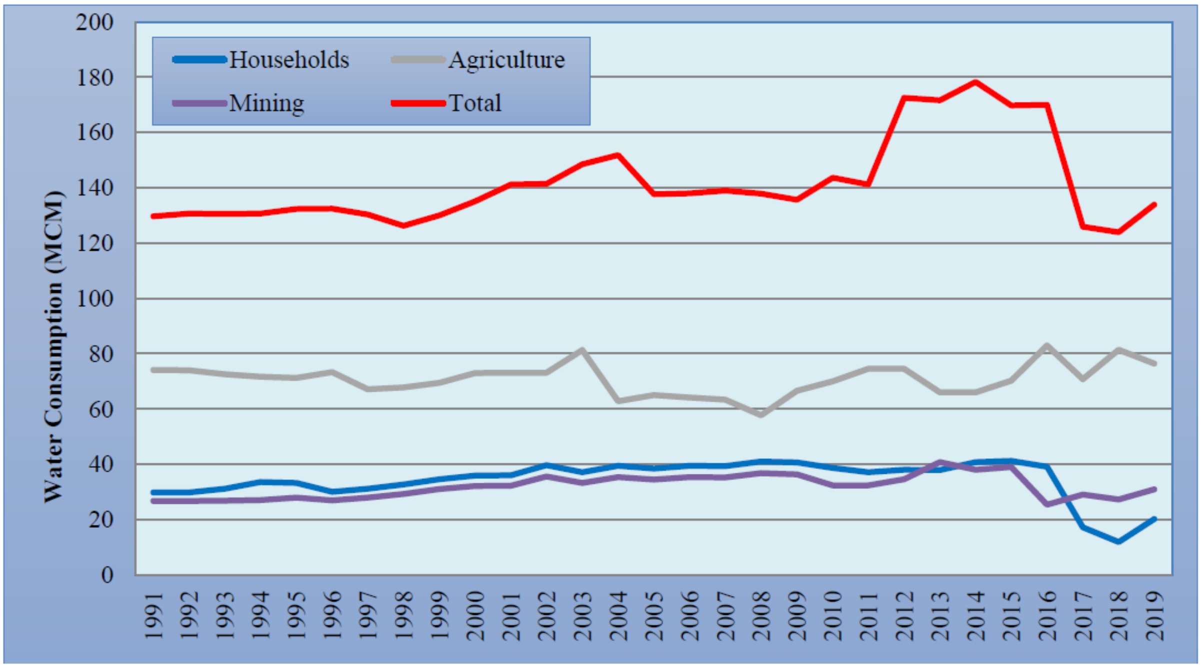


Figure 13. Long-term trend in water consumption in Botswana, from 1991 to 2019. Copied from DWS 2021.

4.3 The efficiency of water usage:

Water loss for 2015-16 stood at a national average of 30% 2014-15. The WUC Mahalapye Management centre had the highest loss of 52% (MLMWRSS, 2017). The management centre falls within the Mahalapswe Sub-basin of the LRB. According to MLMWRSS (2017), the losses may be attributed to dilapidated infrastructure and billing inefficiency. The water losses are high despite some improvements in some Management Centres (Table 12).

Figure 14 shows non-revenue water by WUC Management Centres for 2017-2018 and 2018-2019. Non-revenue water (NRW) is the water that was not billed, either due to authorised unbilled consumption of water or due to water losses. It is calculated as the difference between water produced and water billed due to consumption.

Table 12. Water losses by Management Centre

Management Centre (& catchment area within which it is located)	**PRODUCTION (MCM)**	**Use (MCM)**	**LOSSES (MCM)**	**LOSSES %**
Serowe (Lotsane)	4.3	2.3	2.0	46%
Selebi Phikwe (Motloutse)	11.1	8.6	2.5	23%
Francistown (Shashe)	15.9	10.8	5.1	32%
Gaborone (Notswane)	24.4	21.1	3.3	14%
Lobatse (Notwane)	6.9	3.8	3.1	45%
Molepolole (Notwane)	6.0	3.7	2.3	39%
Letlhakane	1.9	1.2	0.7	36%
Mochudi (Notwane)	3.6	2.4	1.2	34%
Mahalapye (Mahalapswe)	5.1	2.4	2.7	52%
Masunga	4.6	2.9	1.7	38%
Palapye (Lotsane)	3.5	3.0	0.6	16%

Adopted from MLMWRSS, 2017.

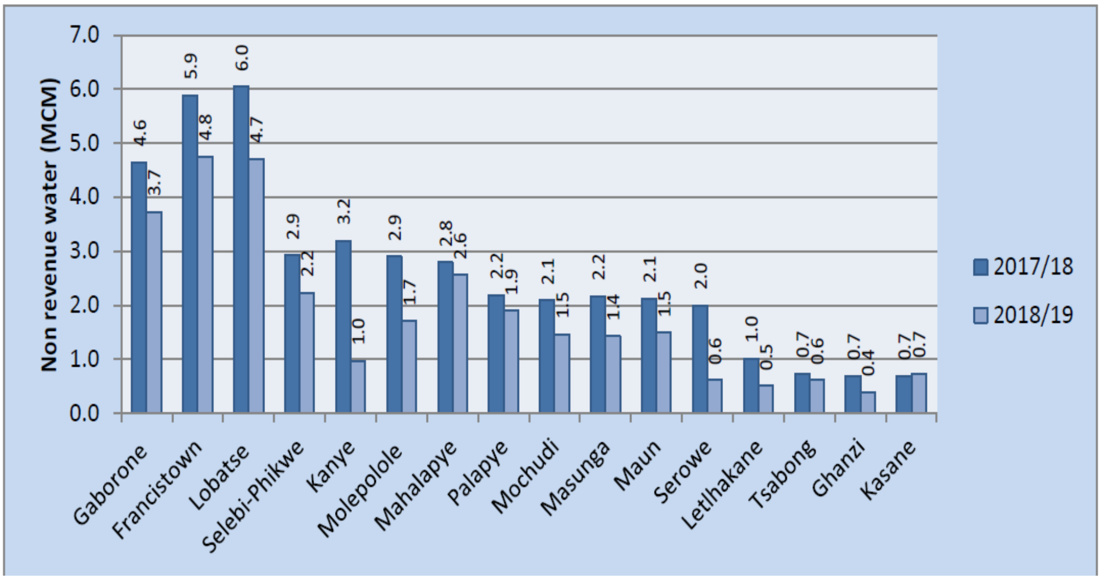


Figure 14. Non-revenue water from WUC MCs. (Copied from DWS 2021).

5. Technologies

5.1 Technologies to reduce water demand and waste

Water management in Botswana has in the past focused more on increasing water supply rather than on reducing demand and promoting water conservation (Toteng, 2008). Following countrywide water reforms in 2009, several water conservation measures were proposed and implemented. Some of these measures aimed at increasing water efficiency and include constructing better reservoirs with lower water losses from seepage and evaporation for agricultural use, maximizing reuse of treated wastewater and mine water, and using water saving irrigation technologies (DWA, 2013). As far as implementation is concerned, use of drip irrigation in the agricultural sector has been adopted in Botswana to reduce water demands and in the diamond mining industry, technologies for improving water efficiency have been adopted (BWSPB, 2012).

6. Changes over the last 10-20 years

The table below shows summary of changes related to water supply (2003-2019), water pricing (2003/4 to 2021) and population density and distribution (2001 to 2022). The time periods indicated were chosen due to data availability. Water supply and use data were obtained from Water Accounting Reports. Reports are available for the years 1993-2003, 2010/11, 2011/12, 2015/16, 2017/18 and 2018/19.

Water tariffs were obtained from WUC annual reports which began in 2012. Prior to 2012, water was supplied by three different agencies. WUC supplied urban areas, DWA supplied large villages and District Councils supplied small villages. Each of these suppliers had their own tariffs. Tariffs were normalized nationwide by WUC in 2015 after they completed the takeover of water services from the other agencies.

Information on population density and distribution was obtained from Botswana population census reports. Population and Housing Census in Botswana is done after every 10 years.

Land use land cover changes (LULCC) changes have been evaluated for two places within the Limpopo region in Botswana. One of these places is Bobirwa and the other is the Gaborone dam catchment area. In Bobirwa, LULCC were evaluated in 1995, 2006 and 2016 for five classes of land use type identified based on Landsat images: Built-up areas (village settlements, rock surfaces, paved roads, etc); Croplands (Cultivated areas under rain-fed and irrigation, plantations), Water bodies (Dams, ponds, rivers, streams etc), Vegetation (Predominantly trees, shrubs or grasslands) and Bare land (bare land with exposed soil surfaces, with no vegetation all year round, or with very sparse vegetation) (Mugari and Masundire, 2022). Figure 15 shows how the different LULC types changed in Bobirwa between 1995 and 2016. LULCC evaluated for the Gaborone dam catchment from 1984-2015 revealed six major LULC categories: cropland (Cropland, forage, orchards, nurseries, horticultural land, fallow land, intensively, moderately and sparsely cultivated lands), bare land (Exposed soils, sand, bare rocks, with less than 10% vegetation cover, floodplain, quarries, sparse vegetation), shrub land (Woody plant, less than 5 m in height, no defined crown, a mixture of trees with grasses), built-up area (Residential, commercial, industrial, transportation, communication and urban areas), tree savanna (Woody plant more than 5 m in height with a somehow definite crown), and water bodies (Streams, canals, lakes, dams or reservoirs, ponds) (Matlhodi et al., 2019). To determine LULCC for the whole country between 2005/6 to 2022 (last 15 years), we first averaged area under each land use type in the two studies, then determined average change/year between 1995-2015/16 before estimating what land use looked like in 2022. Table 13 below shows our calculations.

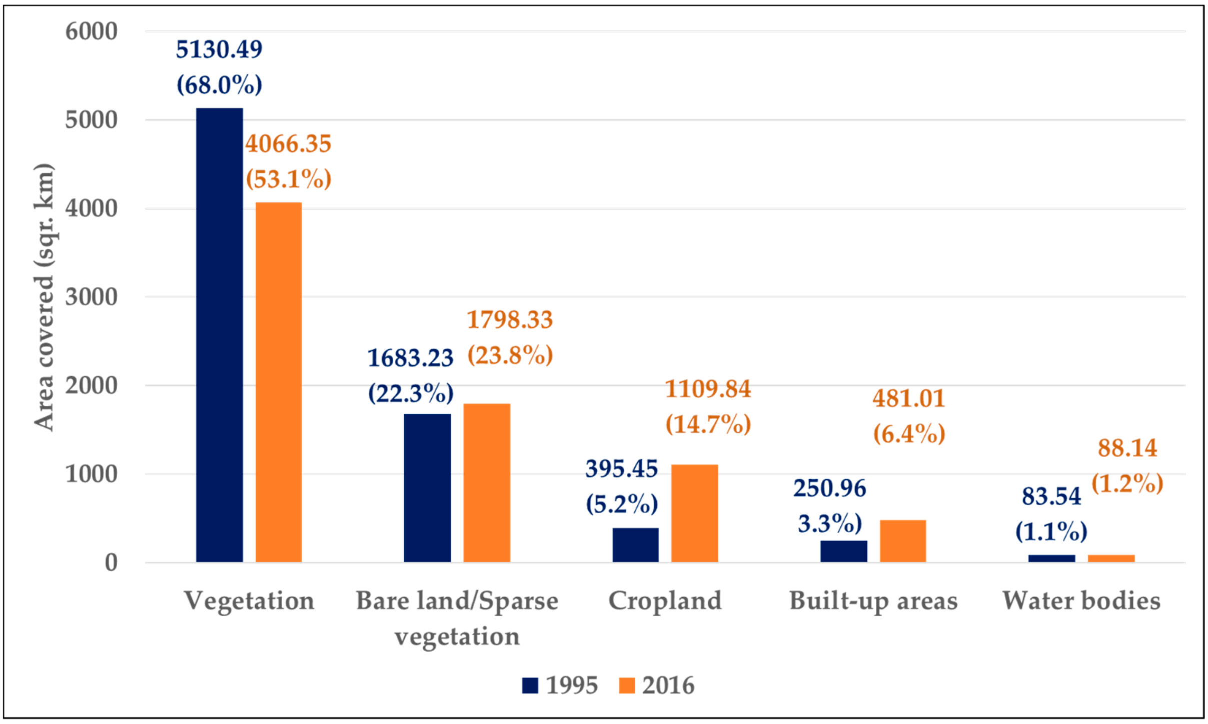


Figure 15: Comparison of LULC classes in Bobirwa sub-district between 1995 and 2016. Copied from Mugari and Masundire (2022).

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Table 13. Average area covered in km^2 for different land use types.

Land use	Averaged km^2 in 1995	Averaged km^2 in 2005/06	Averaged km^2 in 2015/16	km^2 change (1995-2015/16)	km^2 change/year	Estimated km^2 change (2015/16-2022)	Estimated km^2 in 2022
vegetation	4315	3739	3495	-819.8	-41.0	-286.9	3208.0
cropland	570	656	1061	490.1	24.5	171.6	1232.2
bare land	857	1246	989	132.3	6.6	46.3	1035.8
built-up area	153	266	355	201.5	10.1	70.5	425.1
waterbodies	52	41	48	-4.1	-0.2	-1.4	46.1

NB: Average values calculated from Mugari and Masundire (2022) and Matlhodi et al. (2019).

Table 14. Summary changes over the last 10-20 years

Indicator	**Changes over last -15 years**
1. Land use (%)	
Vegetation	Was 3739 km^2 in 2005/6 and decreased to 3208 km^2 in 2022 (-15% change)
Bare land	Was 1246 km^2 in 2005/6 and decreased to 1035.8 km^2 in 2022 (-21% change)
Crop land	Was 656 km^2 in 2005/6 and increased to 1232.2 km^2 in 2022 (54% change)
Built- up areas	Was 266 km^2 in 2005/6 and increased to 425.1 km^2 in 2022 (45% change)
Water bodies	Was 41 km^2 in 2005/6 and increased to 46.1 km^2 in 2022 (11% change)
2. Population	
Density (P/km^2)	Population density increased from 2.9 persons per square kilometer in 2001 to 3.6 in 2011 and 4.1 in 2022 (Statistics Botswana, 2022).
Distribution	In the year 2001 and 2011 about 22 % of the population lived in cities and towns (district code 1-7 in Table 15 below) and the rest in villages. In 2022, 19% of the population lived in towns and 81% of the population in the villages (Statistics Botswana, 2022).
Number of cities >500.000 inhabitants.	Gaborone is the most populated city in Botswana. Its population increased from 186007 in 2001 to 244107 in 2022. There were slight changes in the population of the other 6 cities/towns but none went above 500000. The number of villages, however, with a population of more than 5000 increased from 27 in 2001 to 46 in 2011 to 61 in 2022 (Statistics Botswana, 2022).
3. Water supply (given as total use of water in million cubic meters) from 2003 to 2019. Total water use increased from 170.3 MCM in 2003 to 181.9 MCM in 2019.	

Households	Decreased from 56.9 MCM to 41.9 MCM
Mining and quarrying	Increased from 26.8 MCM to 38.6 MCM
Agriculture	Increased from 63.4 MCM to 76.6 MCM
Electricity	Decreased from 0.7 MCM to 0.5 MCM
Government	Decreased from 11.5 MCM to 11.2 MCM
Other Industries	Increased from 11.0 MCM to 13.1 MCM
4. **Water price in BWP per kiloliter.** Changes from 2003/4 to 2021.	In 2003, domestic, industrial, business, and commercial tariffs averaged BWP 6.44 per KL (The average value of BWP 6.44 is calculated from WUC and DWA tariffs). This changed to BWP 25.55 in 2021. Table 16 below shows how the water tariffs have changed from 2015 to 2021 after normalization by WUC.

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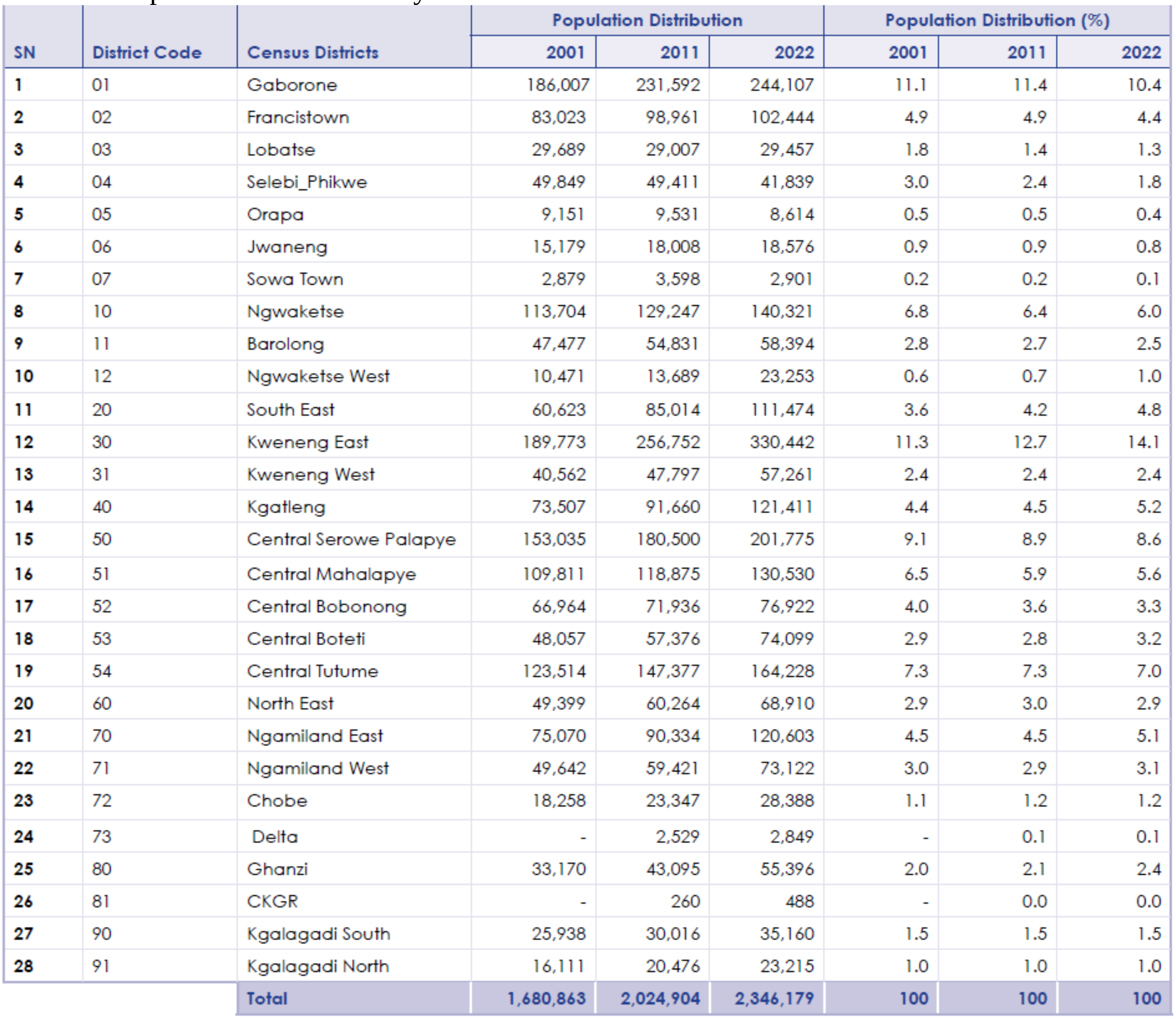
Table 15. Population Distribution by Census Districts



			Population Distribution			Population Distribution (%)		
SN	**District Code**	**Census Districts**	**2001**	**2011**	**2022**	**2001**	**2011**	**2022**
1	01	Gaborone	186,007	231,592	244,107	11.1	11.4	10.4
2	02	Francistown	83,023	98,961	102,444	4.9	4.9	4.4
3	03	Lobatse	29,689	29,007	29,457	1.8	1.4	1.3
4	04	Selebi_Phikwe	49,849	49,411	41,839	3.0	2.4	1.8
5	05	Orapa	9,151	9,531	8,614	0.5	0.5	0.4
6	06	Jwaneng	15,179	18,008	18,576	0.9	0.9	0.8
7	07	Sowa Town	2,879	3,598	2,901	0.2	0.2	0.1
8	10	Ngwaketse	113,704	129,247	140,321	6.8	6.4	6.0
9	11	Barolong	47,477	54,831	58,394	2.8	2.7	2.5
10	12	Ngwaketse West	10,471	13,689	23,253	0.6	0.7	1.0
11	20	South East	60,623	85,014	111,474	3.6	4.2	4.8
12	30	Kweneng East	189,773	256,752	330,442	11.3	12.7	14.1
13	31	Kweneng West	40,562	47,797	57,261	2.4	2.4	2.4
14	40	Kgatleng	73,507	91,660	121,411	4.4	4.5	5.2
15	50	Central Serowe Palapye	153,035	180,500	201,775	9.1	8.9	8.6
16	51	Central Mahalapye	109,811	118,875	130,530	6.5	5.9	5.6
17	52	Central Bobonong	66,964	71,936	76,922	4.0	3.6	3.3
18	53	Central Boteti	48,057	57,376	74,099	2.9	2.8	3.2
19	54	Central Tutume	123,514	147,377	164,228	7.3	7.3	7.0
20	60	North East	49,399	60,264	68,910	2.9	3.0	2.9
21	70	Ngamiland East	75,070	90,334	120,603	4.5	4.5	5.1
22	71	Ngamiland West	49,642	59,421	73,122	3.0	2.9	3.1
23	72	Chobe	18,258	23,347	28,388	1.1	1.2	1.2
24	73	Delta	-	2,529	2,849	-	0.1	0.1
25	80	Ghanzi	33,170	43,095	55,396	2.0	2.1	2.4
26	81	CKGR	-	260	488	-	0.0	0.0
27	90	Kgalagadi South	25,938	30,016	35,160	1.5	1.5	1.5
28	91	Kgalagadi North	16,111	20,476	23,215	1.0	1.0	1.0
		Total	**1,680,863**	**2,024,904**	**2,346,179**	**100**	**100**	**100**

Copied from Statistics Botswana, 2022.

Table 16. Botswana Water Utilities Corporation Tariffs (VAT inclusive)

Domestic Tarrifs			
Tariff Block Category	Tariff (Pula per KL) 1st April 2015	Tariff (Pula per KL) 1st April 2017	Traiff (Pula per KL) 1st June 2021
Minimum Charge	20	0	0
0-5 KL	2.00	3.50	3.50
> 5-15 KL	7.33	11.65	13.43
> 15-25 KL	12.50	20.38	23.51
> 25-40 KL	18.50	31.36	36.16
> 40 KL	23.00	39.20	45.21
Commercial, Business and Industrial Tariffs			
Tariff Block Category	Tariff (Pula per KL) 1st April 2015	Tariff (Pula per KL) 1st April 2017	Traiff (Pula per KL) 1st June 2021
Minimu charge	20	0	0
0-5 KL	2.00	3.92	4.92
> 5-15 KL	7.33	11.65	14.61
> 15-25 KL	12.50	20.38	25.58
> 25-40 KL	18.50	31.36	39.35
> 40 KL	23.00	39.20	49.20
Government Tariffs			
Tariff Block Category	Tariff (Pula per KL) 1st April 2015	Tariff (Pula per KL) 1st April 2017	Traiff (Pula per KL) 1st June 2021
Minimum Charge	50.00	70.00	87.85
>0-5 KL	7.20	10.08	12.65
> 5-15 KL	19.20	26.88	33.73
> 15-25 KL	25.00	35.00	43.92
> 25-40 KL	40.00	56.00	70.28
> 40 KL	50.00	70.00	87.85

Table obtained from WUC annual reports for 2015/16, 2017/18 and 2021/22.
In 2015, domestic, commercial, business, and industrial tariffs were set for three types of users. The values reported above for domestic, commercial, business, and industrial tariffs are the averages of the three types of users.

7. Regulations for water supply and water pollution

7.1 Water supply regulation:

Botswana Water Utilities Corporation (WUC) is a parastatal established by an Act of parliament. Initially, the organization was responsible for supplying and distributing water in the Shashe Development Area and to cities, towns, and mines (Setume et al., 2016). Water supply to villages was left to the District Councils (for small villages) and to the Department of Water Affairs for major villages (Setume et al., 2016). In 2009, during the water sector refoms in Botswana, the roles and responsibilities of the different institutions changed. The new regulations tasked WUC with water supply, wastewater management and providing sanitation services across the country (Setume et al., 2016).

7.2 Water pricing:

The water pricing policy in Botswana is based on three main principles: equity, efficiency, and affordability (Toteng, 2008). Safe water to cover basic needs is considered a necessity which everyone should have access to, hence the equity principle. Efficiency recognizes that providing water comes at a price thus provision of water should be cost-effective, and affordability relates to provision of water for basic needs at an affordable cost to the consumer (Toteng, 2008). The Water Regulator is responsible for setting and regulating the water price. The Regulator's role as stipulated in the National Water Policy is to ensure financial sustainability across the water sector, reduce wastage through streamlining of operations, oversee compliance of service standards to policies and legislation, and determine revenue requirements to inform regular tariff adjustments (Setume et al., 2016). An incremental tariff system is used by the WUC to bill consumers with private water connections. Water supplied through communal standpipes is free of charge.

7.3 Water Allocation:

The Water Resource Board has the authority to oversee and allocate independently and equitably Botswana's water resources (DWA, 2013). Water is allocated to Botswana Water Utilities Corporation, and the mining, agriculture, and electricity sectors. The WUC is a service provider as they abstract water and distribute to other users (mainly households) through 16 management centres (MCs) with each centre serving several settlements in the country (BWUR, 2021). Water can also be abstracted for own use by self-providers which are mostly mines and farmers (Setlhogile et al., 2017). As per the TSWASA bilateral agreement, Botswana is also allocated 13.85Ml/day of raw water from the Molatedi Dam in South Africa provided the dam level is above 33.8%. When the Dam level is below 33.8%, Botswana gets only half of the 3.85Ml/day (BWUR, 2021).

7.4 Policies that affect water supply/demand

Water and Wastewater Policy (2012). The policy aims to increase accessibility of good quality water to users and to promote sustainable development of water resources to support economic growth, diversification, and poverty eradication (Setlhogile et al., 2017). The policy establishes a Water Resource Board and Water Regulator. The former has the responsibility of overseeing and allocating water resources and development of water related policies, while the Regulator ensures financial sustainability in the water sector by guiding and monitoring water tariff structures (Setlhogile et al., 2017).

The 2006 Botswana National Water Master Plan Review (NWMPR) advocates for water demand management as opposed to expanding supply of water. Expanding supply is unsustainable and would lead to high water costs (Setlhogile et al., 2017). The plan further emphasizes the re-use of treated effluent for activities such as construction and landscaping as a way or reducing water demand (Setlhogile et al., 2017).

7.5 Is water pollution monitored?

The Water Utilities Corporation (WUC) has a water quality programme which monitors compliance of water and wastewater with Botswana standards. A variety of paraments are tested in their accredited laboratories and sent for further testing where necessary. Dams, rivers, and boreholes are sampled and tested by the WUC. Testing happens at various points along the supply network at varied frequency depending on the size and nature of the network, parameter variability as well as incidence pattern of consumer complaints (BWUR, 2021). The WUC also monitors the ground water at various areas. Reports for groundwater monitoring are submitted to the Water Apportionment Board.

8. Data availability (for SWAT model)

8.1 Digital elevation maps.

The Digital elevation maps of the Limpopo catchment in Botswana is given below.

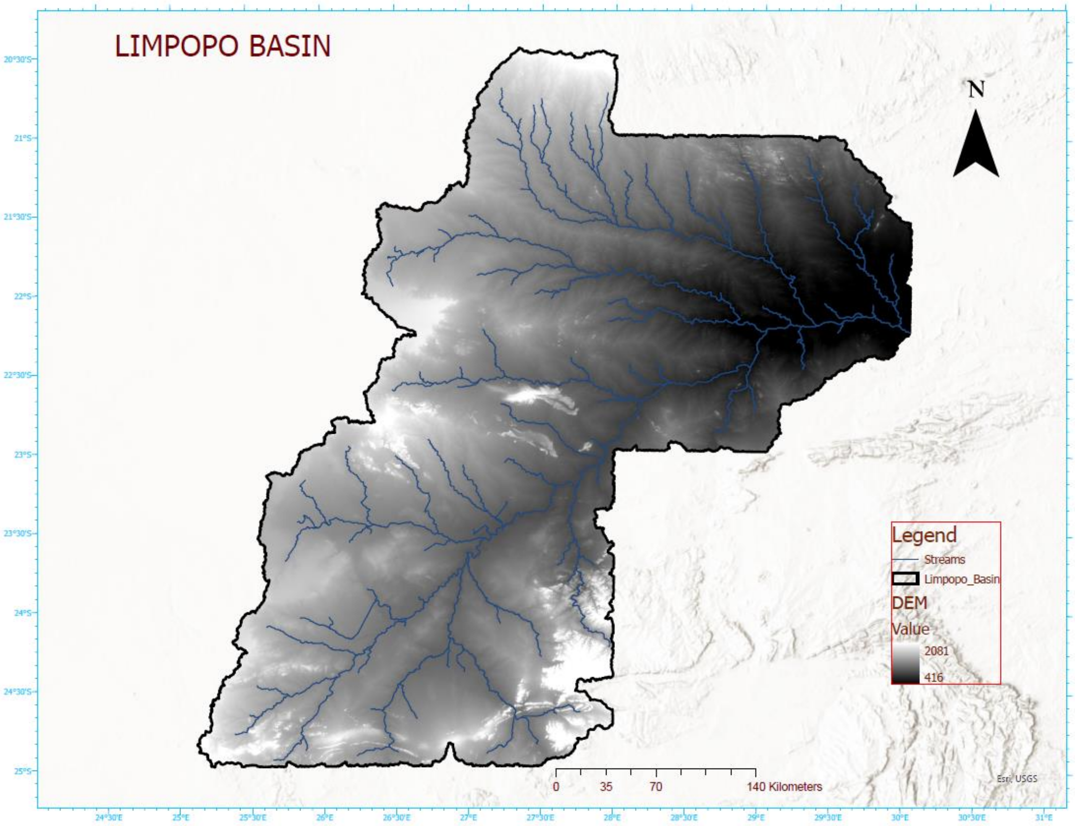


Figure 16. Digital elevation map for the Limpopo catchment in Botswana.

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8.2 conflicts among water users or relevant actors

Table 17. List of Relevant Publications in the Limpopo River sub-Basin in Botswana

Authors	Title	Year
E. Mugari and H. Masundire	Consistent Changes in Land-Use/Land-Cover in Semi-Arid Areas: Implications on Ecosystem Service Delivery and Adaptation in the Limpopo Basin, Botswana	2022
G. Tubatsi, L. P. Kebaabetswe	Detection of Enteric Viruses from Wastewater and River Water in Botswana	2022
B. Matlhodi, P. K. Kenabatho, B. P. Parida and J. G. Maphanyane	Analysis of the Future Land Use Land Cover Changes in the Gaborone Dam Catchment Using CA-Markov Model: Implications on Water Resources	2021
E. Mugari, H. Masundire and M. Bolaane	Adapting to Climate Change in Semi-Arid Rural Areas: A Case of the Limpopo Basin Part of Botswana	2020
E. Mugari, H. Masundire and M. Bolaane	Effects of Droughts on Vegetation Condition and Ecosystem Service Delivery in Data-Poor Areas: A Case of Bobirwa Sub-District, Limpopo Basin and Botswana	2020
B. Matlhodi, P. K. Kenabatho, B. P. Parida and J. G. Maphanyane	Evaluating Land Use and Land Cover Change in the Gaborone Dam Catchment, Botswana, from 1984–2015 Using GIS and Remote Sensing	2019
E. Mosasea, L. Ahiablameb, R. Srinivasan	Spatial and temporal distribution of blue water in the Limpopo River Basin, Southern Africa: A case study	2019
E. Mosase and L. Ahiablame	Rainfall and Temperature in the Limpopo River Basin, Southern Africa: Means, Variations, and Trends from 1979 to 2013	2018
Climate Resilient Infrastructure Development Facility (CRIDF)	Case study on flood forecasting systems in the Limpopo River Basin.	2018
K. Tshepo, N.T. Tafesse, R.T. Chaoka, B.F. Alemaw, K. Laletsang	Impacts of Treated Wastewater on the Surface Water and Groundwater Quality: A Case Study in North East Gaborone, Botswana	2017
LIMCOM, USAID RESILIM, GWP SA, GRID-Arendal and SARDC	Limpopo River Basin: changes, challenges and opportunities	2017
P. Trambauer, M. Werner, H. C. Winsemius, S. Maskey, E. Dutra, and S. Uhlenbrook	Hydrological drought forecasting and skill assessment for the Limpopo River basin, southern Africa	2015

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P. Trambauer, S. Maskey, M. Werner, F. Pappenberger, L. P. H. van Beek, and S. Uhlenbrook	Identification and simulation of space–time variability of past hydrological drought events in the Limpopo River basin, southern Africa	2014
Department of Water Affairs Botswana and Department of Water Affairs South Africa (DWA:BW and DWA:SA).	Joint Water Quality Baseline Report for Limpopo Basin between Botswana and South Africa 2011/12	2013
T. Zhu and C. Ringler	Climate Change Impacts on Water Availability and Use in the Limpopo River Basin	2012
P. K. Kenabatho, N. R. McIntyre, R. E. Chandler, H. S. Wheater	Stochastic simulation of rainfall in the semi-arid Limpopo basin, Botswana	2011
P. K. Kenabatho, N. R. McIntyre, R. E. Chandler, H. S. Wheater	Application of generalized linear models for rainfall simulation in semi arid areas: A case study from the upper Limpopo basin in north east Botswana	2008
O. P. Dube, M. B. M. Sekhwela	Indigenous knowledge, institutions and practices for coping with variable climate in the Limpopo basin of Botswana	2007
O. P. Dube, M. B. M. Sekhwela	Community coping strategies in Semiarid Limpopo basin part of Botswana: Enhancing adaptation capacity to climate change	2007
V. Vanderpost, S. Ringrose, D. Kgathi and W. Matheson	The nature and possible causes of land cover change (1984-1996) along a rainfall gradient in southeastern Botswana	2007
N. Mladenov, K. Strzepek and O. M. Serumola	Water Quality Assessment and Modeling of an Effluent- Dominated Stream, The Notwane River, Botswana	2005
H. Vogel, K. Mokokwe and T. Setloboko.	Nitrate hotspots and salinity levels in groundwater in the Central District of Botswana	2004
D. P. Turnipseed	Development of a Program for Improved Flood Preparedness, Warning, and Response in the Limpopo River Basin of Botswana	unknown

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Annex B

SusTraL: Country Report - Mozambique

by
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Content

1. THE LIMPOPO RIVER BASIN IN MOZAMBIQUE

1.1. Overview of the Limpopo River Basin

The Limpopo River, 1 750 km long originates from Limpopo province in South Africa. The catchment area of River Basin falls under South Africa, Zimbabwe, Botswana and Mozambique. It covers a basin area of about 415,000 km2, with the percentage share as presented in Table 1.

Table 1: Countries *S*haring the Limpopo River Basin and respective Total Area within the Basin

Country	Area within Limpopo Basin (Km^2)	% share
South Africa	193,500	47,0
Mozambique	79,600	19.3
Botswana	73,000	17.7
Zimbabwe	66,000	16,0
Total	**415,000**	**100**

The entire Limpopo basin comprises of 11 sub-basins, but in Mozambique there are 4 basins (Figure 1 and Table 2). Limpopo basin in Mozambique is a home of 1,712,037 inhabitants (2020), and is expected to be around 2,045,000 inhabitants by the year 2030 (according to INE, 2020), contributing to about 6% of the total basin population.

1.2. Subcatchments in Mozambique

The Limpopo river basin in Mozambique falls almost entirely within Gaza Province and it covers portion of three districts in Inhambane Province. The urban centers such as Xai-Xai and Chókwè are also located within the basin and are the most important towns regarding current and future water demand.

Table 2: Sub-basin of the Limpopo River Basin in Mozambique (DNA, 1996)

River	Area (Km^2)		Length (Km)	
	Mozambique	Total	Mozambique	Total
Changane	43.000	43.000	436	436
Elephants	6.900	68.000	-	657
Others (include: the main course of Limpopo river in Mozambique, Mwenezi river and Lumane river catchments)*	29.700	-	561	1.461
Total	79.600	-	-	-

* Indicated length refers to the Limpopo River length

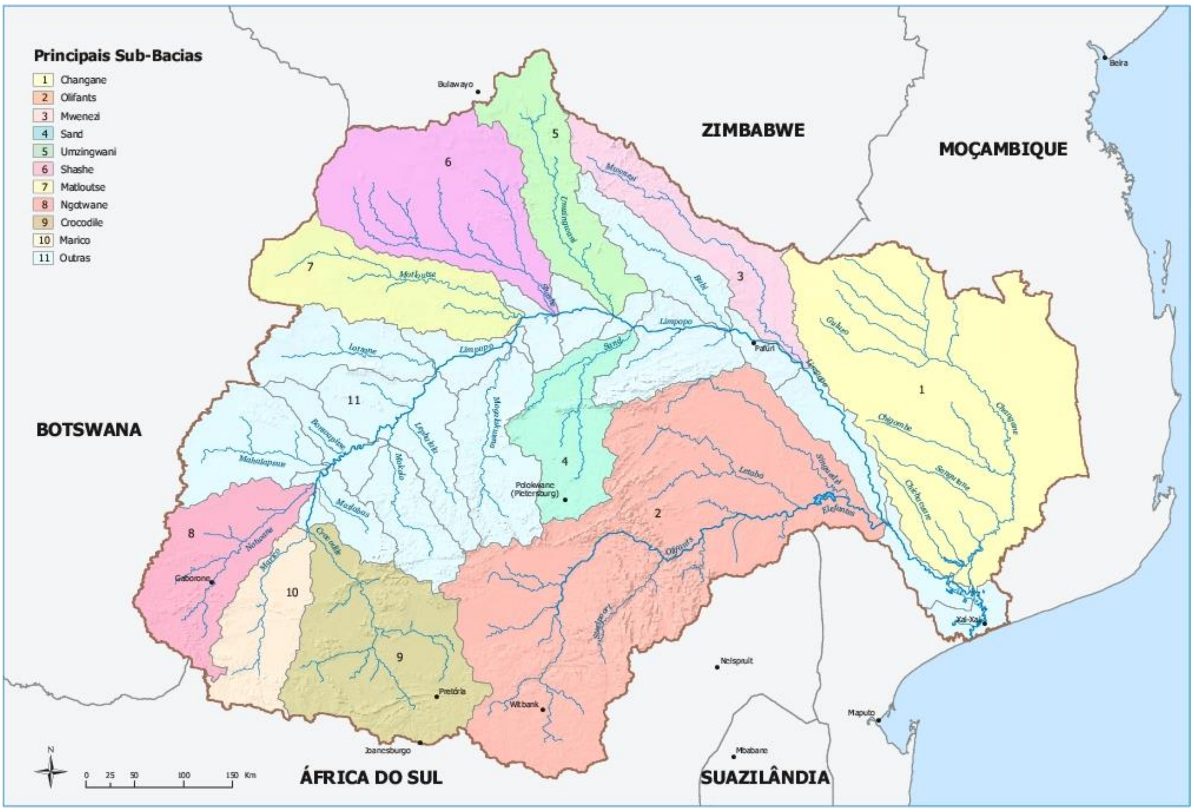

Figure 1: Main sub-basins of the Limpopo River Basin (INGC, 2003). In Mozambique the main sub-basins are (1) Changana, (2) Olifants, (3) Mwenezi, and (4) the limpopo river valley.

1.3. Climate

The climate in the Limpopo River Basin is influenced by air masses of the equatorial convergence zone, by subtropical eastern continental and moist maritime air masses (cyclones). The Limpopo River Basin lies in the area of influence of tropical cyclones deriving from the Southwest Indian Ocean, which make landfall over Madagascar and/or Mozambique about three times per year. Apart from the devastation caused by the storm surges over coastal regions, rainfall associated with tropical cyclones can also cause widespread flooding over the eastern parts of the southern African interior including Limpopo River Basin. During January-March the Inter Tropical Convergence Zone, which influences the seasonal variances of rainy and hot season, becomes more active. The tropical cyclone season is generally between November to April with the peak in January and February. These systems are associated with south-eastern flow of air masses that cause periods of intense rain (INGC, 2009).

A major factor affecting tropical cyclone frequency is the El Niño Southern Oscillation phenomenon a global oceanic temperature anomaly (Ho et al., 2006). The El Niño Southern

Oscillation is associated with year-to-year rainfall variability: periods of heavy, extended rainfall are characteristic of the La Niña phase of El Niño.

Based on the classification of Köppen, the climate in the Limpopo river basin in Mozambique changes from tropical rainy savanna (AW) along a narrow strip parallel to the coast, to tropical dry savanna (BS) in most of the area going towards the interior, and to tropical dry desert (BW) in a confined smaller place near the border with South Africa and Zimbabwe (see fig. 1).

The average annual rainfall in this area varies from 1 000 mm along the coast to 350 mm in Pafuri, the driest place in Mozambique located in the border with Zimbabwe and South Africa at the entrance of the Limpopo river in Mozambique (see fig. 2). The rains shows two distinct periods, the rainy season with 76 to 84% of the rain going from October to March, and the dry season with 24 to 16% of the rain going from April to September. The rainy season coincides with the hottest period of the year and the dry season with the coldest (Reddy, 1986).

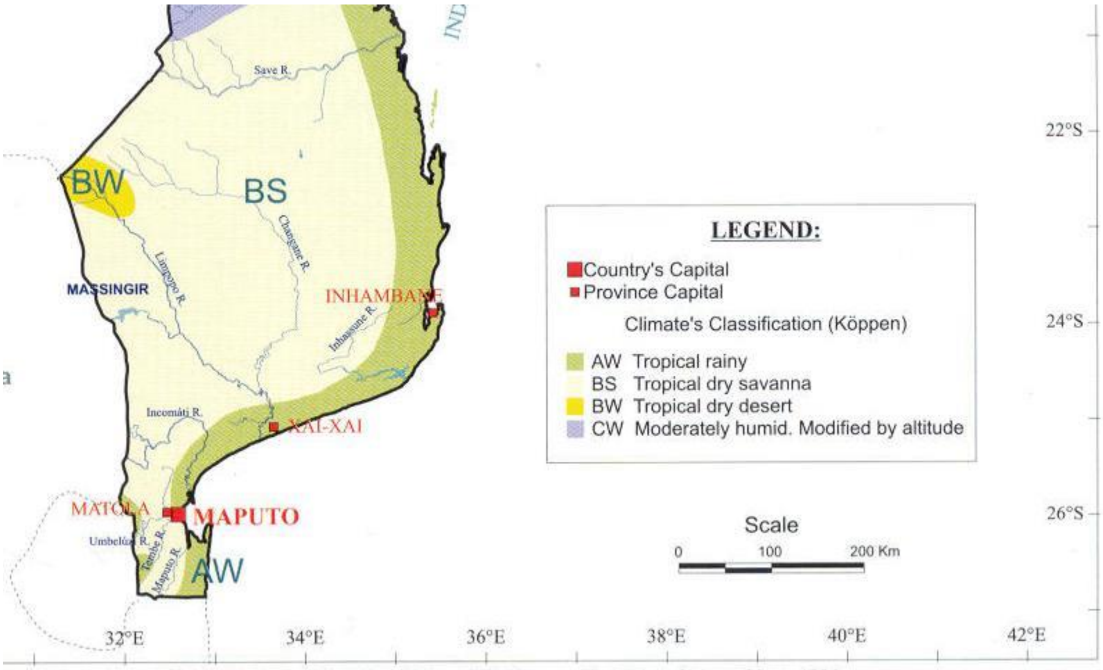

Figure 1: Climate in Southern Mozambique according to Köppen classification (INGC, et.al, 2003).

Taking into account the high variation of rainfall from upper most point Pafuri to lower parts of the basin in Xai-Xai, the Limpopo basin in Mozambique has been actually divided in three regions namely Upper, Middle, Lower regions. The lower Limpopo receives much more rainfall compared to upper Limpopo districts like Pafuri area as shown in Figure-2 and Figure-3, with a rapid decrease on average annual rainfall and increase in temperature from the coastal area in Xai-Xai, throhg Chokwe up to Pafuri.

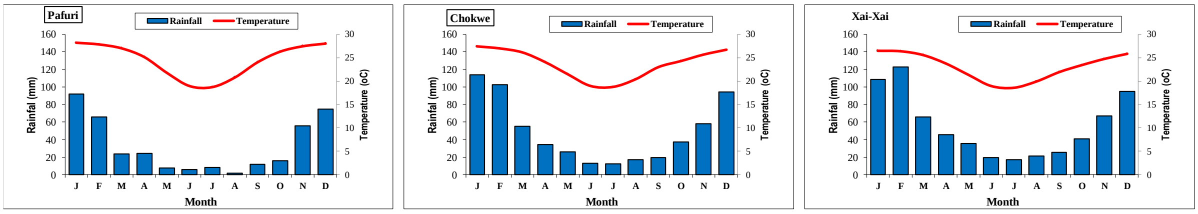

Figure 2: Average monthly rainfall and temperature from the costal area in Xai-Xai to Chokwe (intermideate) and Pafuri (the hoter and driest area).

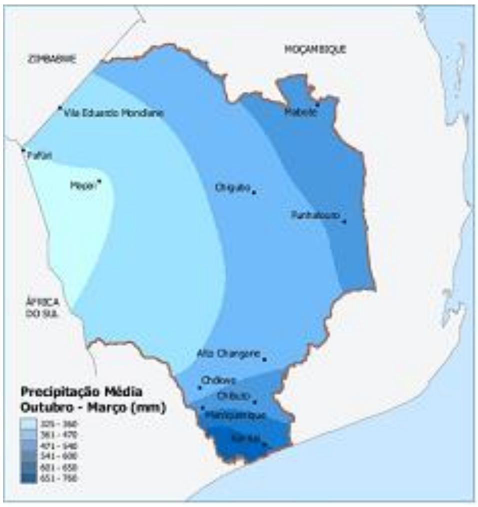

Figure 3: Spatial variation of the seasonal rains during the wet season (October to March) along the Limpopo river basin in Mozambique (INGC, et.al, 2003).

1.4. Demographic and Socio-Economic profile of Limpopo River Basin

Population:

The Limpopo River Basin in Mozambique falls almost entirely within Gaza Province. It also covers portions of three districts in Inhambane Province. According to INE (2020), the population in the basin in Mozambique is estimated to be more than 1.7 Million people (year 2020) which accounts for about 5.7% of the total country population. Much of Population is concentrated along the cost where the main road passes and with more favourable agro-ecological conditions. Besides this populations settlements follow closely the main branch of the Limpopo River towards Pafuri on the South-Africa-Zimbabwe border and other concentrate around Massingir dam and the Olifants, Singuedzi and Changane Rivers. The following are highlights about the population in the basin:

- 80% of the population is leaving in rural areas and most of it practicing agriculture, in fact, 90%;
- Population growth is estimated to about 0.7% (Gaza Province) against 2,5% national population growth.
- The population density within the Limpopo River Basin ranges from 1 person/km^2 in Chigubo District to more than 100 persons/km^2 in Xai-Xai District.
- The basin wide average density in Mozambique is 19 persons/km^2 substantially lower than the National average of 37,6 persons/km2.
- From the population pyramid (Figure 4) total female population is more than 54%. Therefore, until the age of 24 years there are more men and after this age the number of women is higher. The Limpopo basin has historically been an area from which migrant labor is drown largely, especially to South-Africa but also to Maputo.

In the basin, almost all members of households are engaged in agriculture activities or any other self-earning methods during dry seasons. Among poor and very poor income categories, it has been noticed that women headed families are normal. Children in Middle and better-off categories give importance to education while the remaining are forced to make an earning by contributing to the labor force. Very poor and poor income household members are involved in various agriculture activities like land preparation, planting, weeding, bird scaring, harvesting etc. irrespective of their gender and age.

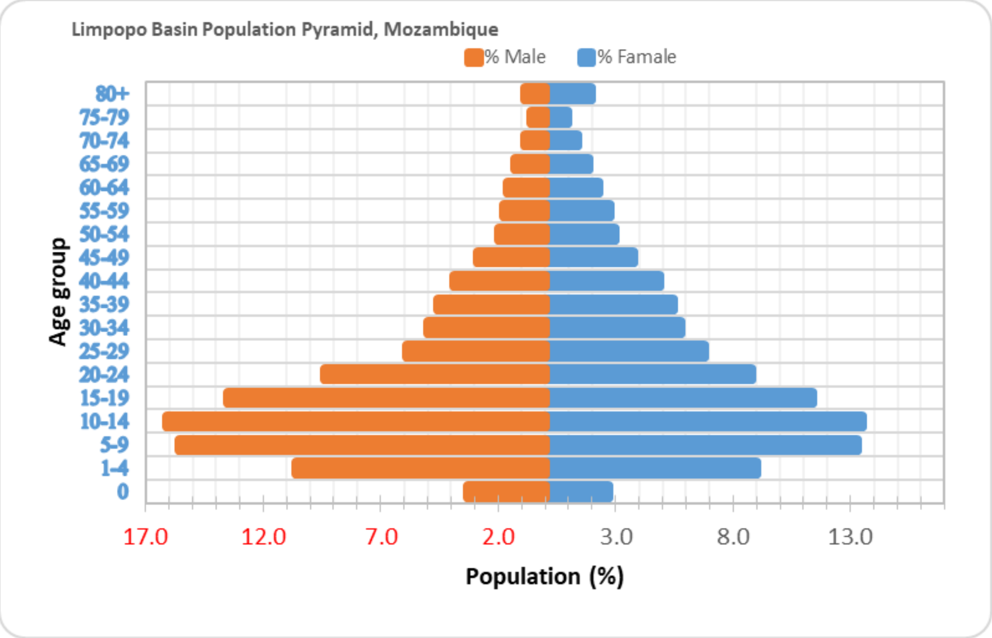

Figure 4: Population Pyramid of the Limpopo Basin in Mozambique, Gaza Province (INE, 2020)

2. LANDUSE AND ECONOMIC ACTIVITIES

Agriculture plays an important role in the Mozambican economy. It contributes about 23% of the Gross Domestic Product (GDP) and employs approximately 80% of the country's economically active population. The agrarian structure in Mozambique is dominated by small farms, representing 99% of the total area and more than 90% of food production.

In general, agricultural production in the Limpopo basin in Mozambique is characterized by low input use, a small amount of cattle for ploughing, and low use of improved agricultural practices. Agricultural production in rain fed regime is insecure and variable due to low and unpredictable fall of precipitation. Given the poor climatic conditions, the risk of crop loss in the study area varies from moderate to very high. The risk is moderate in the Lower Limpopo region whose annual average of rainfall ranges from 800 to 1 000 mm and very high in the Upper Limpopo region where the annual rainfall is averaging below 600 mm.

The total area cultivated by small and medium-scale farms in Gaza Province, which makes up the bulk of the Limpopo basin in Mozambique, is 422 389 ha. Maize is the most important crop in the Limpopo Basin, either as staple food or cash crop, which is why this crop tends to occupy most of the land for family subsistence. Maize crop is produced by 96% of households with small and medium farms. Other high-yield crops, especially vegetables crops, mostly grown in the Xai-

Xai and Chokwe districts under irrigation and motivated in part by the proximity to the urban market.

Rice, an extremely water demanding crop, is grown only in the wettest regions of the Limpopo basin in Mozambique, notably in Lower Limpopo (Xai-Xai district) and the Middle Limpopo (mostly in the Chókwè and Guijá districts). In Gaza province, only about 4% of medium and small farms grow rice.

Drought-resistant crops such as millet and sorghum are practiced in some districts of the north, particularly in Massangena. In fact, around 3% of households with small and medium-sized farms, throughout the province of Gaza, grow millet and sorghum. Cassava, another drought tolerant crop is common in many districts of Gaza and Inhambane.

Legumes, such as beans and peanuts, are grown in the Middle and Upper Limpopo regions. About 54% of households with small and medium-sized farms throughout the Gaza province grow peanuts.

2.1.1. Drought in the Limpopo Basin

The Food and Agriculture Organization of the United Nations (FAO) summaries that a lack of water is the main cause of drought but many other socioeconomic factors compound and intensify the drought effects. Thus, FAO sets drought in four categories and all of them can occur in the basin:

- Meteorological drought
- Agricultural drought
- Hydrological drought
- Socioeconomic drought

Table 3 Extreme climate Events from 1980-2013

Country	Drought	Extreme Temperature	Floods	Storms
Botswana	3		8	1
Mozambique	12		24	19
South Africa	7	2	27	25
Zimbabwe	6		9	2

Source: LIMCOM, 2016

2.1.2. Floods in the Limpopo basin

In the last 40 years Mozambique faced different flood hazards along the Limpopo river.In Mozambique since independence in 1975, the Limpopo river basin has been the region most devastated by floods (Carmo Vaz, 2000). This is caused by the natural characteristics of the basin itself and the climate in the region, on one hand; on the other hand, the Limpopo is the Mozambican basin with more development encroached in the flood plain. Floods in the Limpopo basin in the last 25 years occurred in 1975, 1977, 1981, 1996 and 2000. The floods in 1975, 1981 and 1996 were of smaller magnitude and caused inundation at a limited scale, besides some concern about the roads, bridges and protection dykes. In 1996, the major concern was with the Massingir dam, which has serious leakage problems (putting its stability at risk) and is due to start a rehabilitation program. The incoming flood to the reservoir was big and for the first time since its construction in 1977 floodwater was passing through its non-gated spillway. The flood that occurred in February 1977 was the worst that occurred in Mozambique until that date.

The whole Lower Limpopo was flooded. The Massingir dam, which was under construction, provided for an important attenuation, storing a large volume of floodwater. The main impacts and consequences of this flood were:

- many people died
- damages of some protection dykes
- inundation of some areas in the (protected) irrigation perimeters of Chokwé and Lower Limpopo
- enormous damages to many small rural villages in the flood plain
- Destruction of bridges in the EN1 road to Xai Xai Immediately after the flood, the Government launched a program of re-settlement of people of the rural villages, creating new villages in more secure areas and with better infrastructures and social services (“aldeias comunais”).

The recent floods of February 2000 largely surpassed the flood of 1977 in its magnitude and effects Carmo Vaz 2000 nad Dgege, 2022). The major impacts and consequences of this flood were:

- More than 500 hundred people died (the estimate of the total number of deaths for all the flooded basins is around 700) and more than 200,000 forced into refugee camps
- The inundation by more than 2 m of water of the city of Chokwé, forcing its evacuation. The city of chokwe suffered large damages, the water supply and electricity systems were broken and it was more than a month later that its inhabitants could return and the social and economic activities could re-start

- The inundation by about 3 m of the downtown part of the city of Xai Xai, capital of the Gaza Province. The damages were extremely severe, for both infrastructures like streets, urban and sewerage water supply, electricity and protection dykes as for private and public buildings.
- Serious damages to the Macarretane dam that serves the Chokwé irrigation scheme, affecting also the road and railway line to Zimbabwe
- Serious damages to the Chokwé irrigation scheme – protection dykes, main and secondary irrigation canals, field infrastructure · serious damages to the roads and bridges in the approach to Xai Xai, preventing for more than 6 months normal traffic along the EN1 road · serious damages to the railway line to Zimbabwe
- Complete disruption of the social and economic life in vast areas of the Gaza Province and, indirectly, also in Inhambane Province.

3. WATER QUALITY

The most known aspects of water quality in the LRB the ones related to ground water salinity and sea salt intrusion in the coastal areas. These two aspects affect negatively the water development options since they have direct and immediate impact in water management for different economic purposes. Still there is no detailed information on the extent and dynamic of the problem.

Many reports conclude that large-scale groundwater abstractions in the Limpopo River Basin are very limited as a consequence of low productivity and poor water quality. There exists a deep aquifer between 250-350 m, which may be continuing to the south, but exploitation of this source is not economically feasible. Water quality becomes progressively worse downstream of Chókwè and the confluence with the Changane River. Only the dune unit can be used for small- and medium-scale abstractions without restrictions posed by water quality.

It is reported that approximately 10% of HICEP area in the Chokwe irrigation scheme is affected by salinity and that RBL faces challenges for pumping water during low river flow periods to avoid intake of salt water because of sea water intrusion. In this case, some pumping station are no longer in operation due to salt intrusion from the sea.

Water quality in the Limpopo River basin changes according to the flow regime, rainfall pattern and sampling period. Chilundo *et al* (2008) found that the water quality parameters in January lower than those in November that could be explained by dilution effect after the rainfall starts.

Table 4 Some physical and Chemical variables on water quality in the Limpopo River Basin

Variable	**Average November 2006**	**Average December 2007**	**Paired t-test (p value)**
pH	7.9	8	0.61
Electrical conductivity (EC)	5571	3132	0.003**
Total dissolved solids (TDS)	4300	2390	0.002**
Sodium adsorption ratio (SAR)	136	82	0.006**
Total hardness (TH)	1430	790	0.000**
Dissolved Oxygen (DO)	7.2	7.2	0.84
Temperature (T)	27.8	29	0.023*
Chloride (Cl^-)	2227	1248	0.073
Ammonium (NH_4^+-N)	0.27	0.23	0.592

Source: Chilundo *et al*, 2008

Besides the change over the season, the water quality in that period was not adequate for human consumptions. Therefore, a reconnaissance study by Chilundo et al., 2017 in the LRB, about water quality, show the need for the establishment of a monitoring network for the monitoring of water quality in order to determine the actual risk and sources of the chemical, physical and biological pollution. The Contamination of surface water by heavy metals, especially in the proximity of the borders was captured. The research showed that the Elephants sub-catchment had relatively better water quality compared to the Changane sub catchment. Thought, there is a need for further research to find the major source of pollution, affected areas and potential impacts on ecosystems as well as on people livelihoods.

2.4 Water price

Raw water use pricing varies from different River Basin and different users. Each Management unity has a specific price for different uses. The water uses stated in the Decree, are Agriculture, Industry, Water Supply and others (e.g. commercial aquiculture, basic food, tourism and others).Tables 6 to 7 show the taxes applied for the Limpopo river basin for use of raw water in MZN/m3.

Table 5. Regularized raw water tax in the Limpopo Basin MZN/m3 (1 MZN =0.016 USD)

Activity	**Use Type**	**Fixed Tax**		**Regularized usage fee (MZN/m3)**
		TFI (Concession)	**Tf2 (MZN/m^3)**	
Income Agriculture	Family Sector ≤ 1 ha	0	0	0
	Commercial Sector ≤ 50 ha	1500.00	300.00	0.09
	Commercial Sector50 < ha ≤ 1000	5000.00	1000.00	0.19
	Commercial Sector > 1000 ha	7500.00	2500.00	0.39
Industry	Processing /Manufacturing	7500.00	2500.00	0.26
	Extractive	25000.00	5000.00	0.47
Water Supply	Small systems(≤ 5000 connections)	1000.00	750.00	0.09
	Large systems (> 5000 connections)	5000.00	2000.00	0.18
Thermoelectric	Power Station ≤ 2MW	5000.00	1500.00	0.10
	Power Station > 10 MW	25000.00	6000.00	0.26
Others	Other Uses	1500.00	300.00	0.09

Table 6. Tax Applied in the Agriculture (Basic Food Production) for regularized water (1 MZN = 0.016 USD)

Type of Use	**Sub Category**	**Fee for regularized water (MT/m3)**	**Fee for Not regularized water (MT/m3)**
Family Sector ≤ 1 ha		0	0
Associates 1< ha ≤ 25	Subsistence Associates	0.04	0.04
Associates 25< ha ≤ 350	emerging associates	0.06	0.05
Associates > 350 ha	Commercial Associates	0.07	0.06
Private 1< ha ≤ 25	Private	0.07	0.06
Private 25< ha ≤ 350		0.09	0.06
Private > 350 ha		0.12	0.08

Table 7. Not Regularized raw water tax in MZN/m3 (1 MZN =0.016 USD)

Activity	**Use Type**	**Fixed Tax**		**Water fee (MT/m3)**
		Tf1 (Concession)	**Tf2 (MT/m^3)**	
Income Agriculture	Family Sector ≤ 1 ha	0	0	0
	Commercial Sector ≤ 50 ha	1200.00	240.00	0.05
	Commercial Sector50 < ha ≤ 1000	4000.00	800.00	0.12
	Commercial Sector > 1000 ha	6000.00	2000.00	0.23
Industry	Processing /Manufacturing	6000.00	2000.00	0.16
	Extractive	20000.00	4000.00	0.47
Water Supply	Small systems(≤ 5000 connections)	800.00	60.00	0.08
	Large systems (> 5000 connections)	4000.00	1600.00	0.16
Thermoelectric	Power Station ≤ 2MW	4000.00	1200.00	0.10
	2< Power Station ≤ 10MW	6800.00	2400.00	0.18
	Power Station > 10 MW	20000.00	4800.00	0.26
Others	Other Uses			

4. MAIN HYDRAULIC AND WATER MANAGEMENT INFRASTRUCTURES:

The relevant water management infrastructures in the Limpopo the Limpopo River Basin are major dams and major irrigation schemes. There are two major dams, the Massingir dam in the Elephants River and the Macarretane Weir in the Limpopo River. The main purpose of the two dams is the irrigation of the Limpopo Valley. Additionally, Massingir dam is to support controlling floods, saline intrusion into the estuary, producing electricity and ensuring water supply to urban and rural areas in the basin (DNA, 1996). There is still ongoing a feasibility study for the implementation of the hydropower plant in the Massingir dam.

Two major irrigation schemes are operational in the basin, which operates independently under the ministry of Agriculture namely Chokwe Irrigation Scheme managed by the public company HICEP and the Lower Limpopo Irrigation Scheme managed by the public company RBL-EP.

The Chókwè irrigation scheme is the largest in Mozambique, covering about 35,000 ha. It was planned in 1920’s to irrigate the Limpopo river valley and constructed in the early 1950’s to support intensive irrigated agriculture but it suffers badly from deficient maintenance due to lack of funds and technology. The RBL-EP irrigation in the Lower Limpopo is actually about 20,920 ha. Table 9 and Figure 5 and 6 present the summary of actual and planned irrigation areas within the LRB in Mozambique. Table 10 presents the main hydraulic infrastructures

Table 8: Actual and planned Irrigation Area, LRB in Mozambique (WAPCOS LDA., 2018)

Area	Actual (ha)	Planned (ha)	TOTAL (ha)
Upper Limpopo	360	11,909	12,269
Middle Limpopo	27,651	35,996	63,647
Lower Limpopo	22,737	18,040	40,777
TOTAL			116,693

Table 9: Main Characteristics of the Existing Dams in the LRB (DNA, 1996)

Description	Massingir Dam	Macarretane Weir
Type	Earth dam	Concrete weir
Lengh (m)	4,600	640
Height (m)	46	3.2
Maximum storage (Mm^3)	2,840	15
Dead storage (Mm^3)	140	-
Catchment Area (km^2)	67,540	-
Maximum discharge (m^3/s)	11,200	17,940
Average incoming flow (m^3/s)	58,4	-
Average Annual incoming flow (Mm^3)	1,846	-

The feasibility study of Mapai Dam construction in the district of Chicualacuala ha been conducted recently. The Mapai Dam will be earthen dam, mainly protecting the lower and middle regions of Limpopo basin from the floods. The basic features of the Mapai Dam are as follows:

- Type of dam: Earth Dam (zoned profile)
- Effective storage capacity for water supply: 2,250 Mm^3
- Effective storage capacity for flood control: 3,903 Mm^3
- Total storage capacity (at the MFWL5000): 7,288 Mm^3
- Minimum operational volume: 750 hm^3
- Powerhouse – installed capacity: 3 x 6,12 kW= 18,36 MW

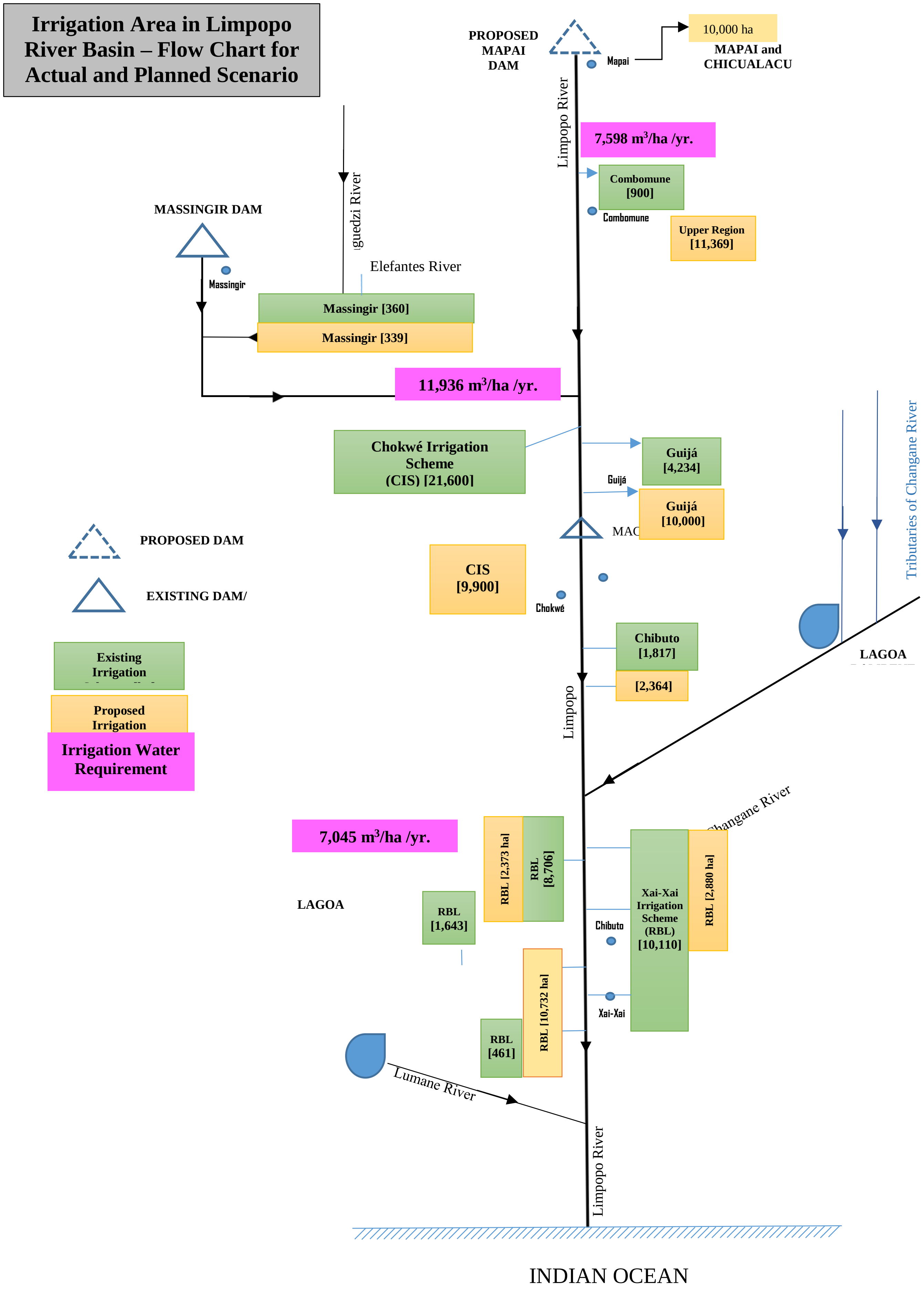

Figure 5: Flow Chart of Existing and proposed dams and irrigation

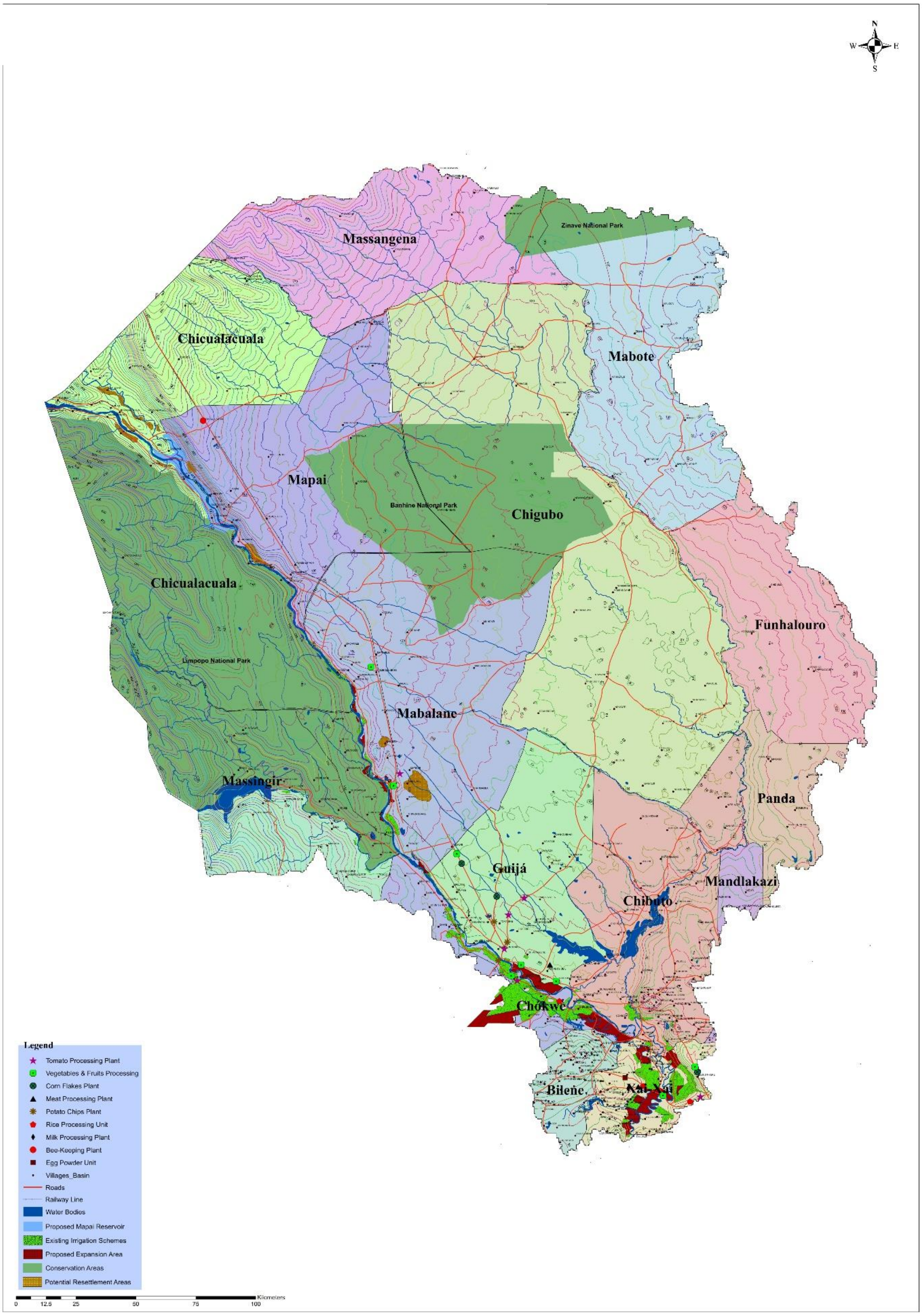

Figure 6: Existing and proposed irrigation schemes in the LRB

Annex B: Country Report Mozambique

5. WATER RESOURCES

5.1 Surface Water:

There are three major Rivers namely Limpopo, Elephants and Chanagane. The Changane River runs dry almost 8 months of a year, Elephants is the only perennial Rivers. The Limpopo River runs dry as well few months a year, ie, two months a year in 17% of the time. The Mozambican part of the Limpopo basin contributes to around 10% of the total annual runoff of the Limpopo River. The average total runoff of the Limpopo River is estimated to be around 5,200 Mm3. The largest sub-basin within the national territory is the Changane River sub-basin. This sub-basin is characterized by very low runoff and long dry periods (DNA, 1996).

Extreme droughts and cyclic floods affect the Limpopo basin area in Mozambique. The most arid zones (Gaza inland, northern and hinterland of Inhambane) are also more prone and more vulnerable to extreme droughts, since the normal rainfall of these zones is below 600 mm within the minimum limits of production possibilities under rain fed conditions.

Floods are most frequent along the shores of the Limpopo basin, mainly because of rainfall in neighbouring countries. Cyclones are also common due to the geographical location of Mozambique, in general. The effects of these calamities are compounded by the weakness of the economic and hydraulic infrastructures.

Within the period between 1955 and 2000, nine major floods were recorded, of which 6 were considered extreme and 3 exceptionally extreme (Table 5). The year 2000 came with devastating floods that destroyed all the efforts put by farmer's groups and associations towards developing agriculture in the area. Most of the farmer's products were lost and the already deficient drainage system was deteriorated.

Table 10: Main Recorded Floods events in the period 1955 – 2000 in the LRB in Mozambique

Year	**River Flow (m^3/s)**	
	Chókwe	**Xai-Xai**
1955	5,050	3,310
1958	4,870	2,270
1966	3,890	2,020
1967	4,190	2,670
1972	5,210	3,150
1975	5,190	3,520
1977	5,810	4,350
1981	4,490	3,090
2000	19,967	-

5.2 Groundwater Resources

Groundwater potential is limited in the Limpopo basin, especially due to the high degree of mineralization of the aquifers in the lower parts of the extensive floodplains. In these cases, most groundwater have high levels of salinity making it unsuitable for human consumption and agriculture (DNA, 1996).

The upper reaches of Limpopo basin consist of sandstones and conglomerates with clayey cements, both practically impermeable.

Alluvial formations of significant extent also occur primarily along the lower reaches of the Limpopo River. In contrast, the Changane alluvial system is very limited in depth and extension and very clayey, with generally poor quality. The Changane valley system drains the adjacent brackish aquifer system, especially along the area situated below the confluence of the Limpopo and Elefantes Rivers. Fresh water being recharged from the River is found occasionally in these areas. In the area between Changane and Limpopo Rivers the sandstone has higher clay content which impacts negatively on borehole yields. In addition, borehole quality is poor with TDS values generally more than 3 000 mg/l reaching in places 30 000 mg/l. (*CSIR, 2003*).

Six different zones are considered in characterizing the groundwater potential in the Limpopo River Basin in Mozambique:

- Dune area: a 40-60-km wide strip along the coast. Productivity is considered low to medium. Quality is good because of to the high recharge rate of 50-200 mm/year. Studies estimate the exploitable amount of groundwater to be about 5-10 m^3/h per km^2.
- Alluvial valleys: formed by the incised main valleys of the Limpopo and Elefantes Rivers. Productivity is high, but water quality is a major problem because the rivers drain the adjacent plains that have highly mineralized groundwater. Fresh groundwater occurs where the surface waters of the rivers replenish the aquifers directly, but care is needed to prevent overexploitation and avoid the risk of salinization of the aquifers.
- Old alluvial plains: bordering the dune area. This region does not provide any potential for groundwater exploitation as it is highly mineralized.
- Erosion plains and erosion valleys: a shallow alluvial cover of sandy clays over the entire inland area. Productivity is low in general but calcareous sandstones have higher specific yields. Water quality is usually poor, with exceptions found along water lines and local depressions that are recharged from the temporary rivulets.

- Deeper aquifer: found in the medium and lower Limpopo River Valley at depths ranging from 80 m at Mabalane to 200 m at Xai-Xai. The total exploitable groundwater in this aquifer, which seems to be enclosed by a saline cover and a brackish base, has been estimated at 300-600 m^3/h.
- Lebombo Range: the rhyolites of the Lebombo Range have very low productivity. Very few wells have been drilled in this region and the failure rate is high.

The safe upper limit for drinking water is 500 mg/l and optimum value is 85-115 mg/l. However, for different crops the TDS value varies accordingly, because of high concentration of salt content most of the crops does not survive.

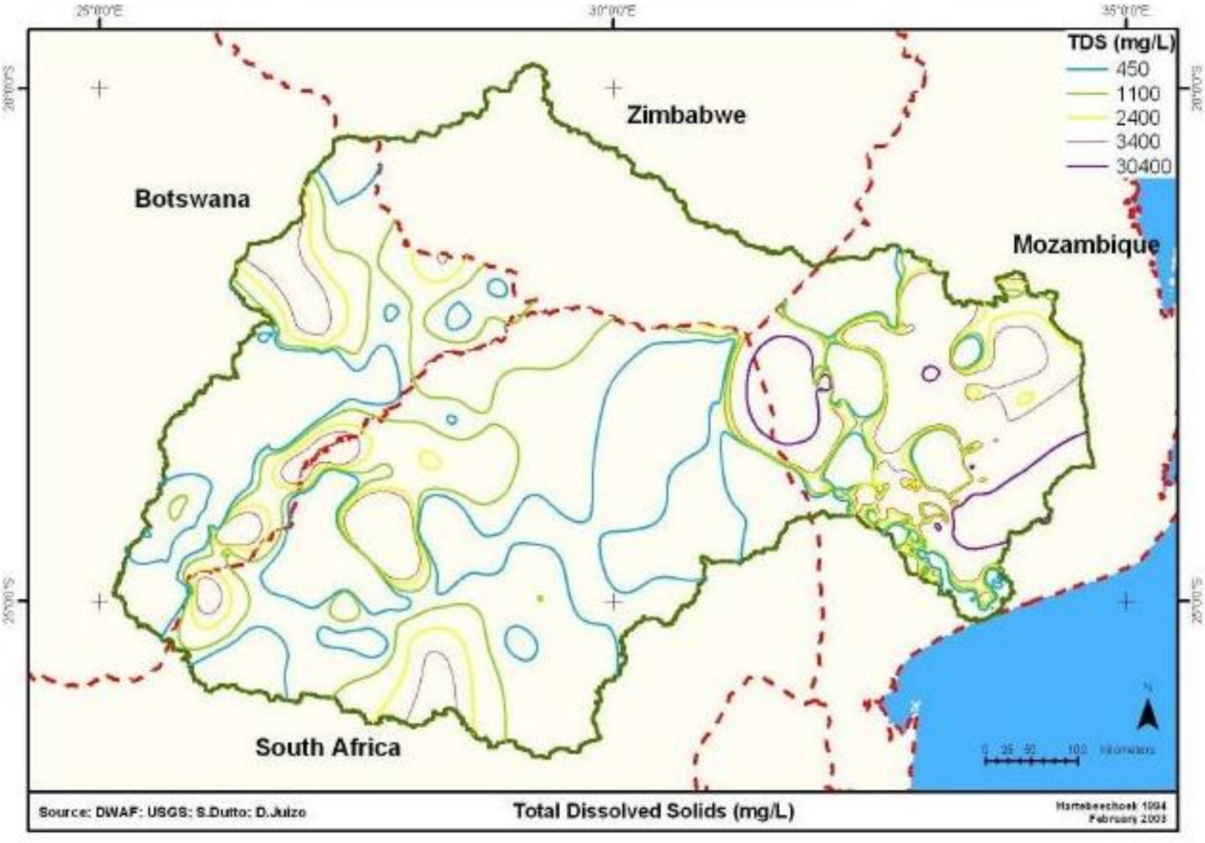

Figure 7: Groundwater quality expressed as TDS (mg/l) across the Limpopo basin (WAPCOS LDA., 2018)

Another source of water in the lower Limpopo that is partially used for irrigation is the water from the peat soils in the wetlands (locally called Machongos). Machongos are mainly found in the coastal zone in river valleys or associated with small streams where the flow of water is periodically obstructed.

6. WATER DEMAND MANAGEMENT INFORMATION

Irrigated agriculture is the most water demanding sector. The Irrigation water requirement is determined taking into consideration the specific climatic conditions of the areas, the actual and planned irrigation area and cropping patterns. Average irrigation water requirements the for upper region is 11,451 m^3/ha/year, for middle region is 14,615 m^3/ha/year and for lower region is 8,626 m^3/ha/year.

Table 7 presents the estimates of water demand in the LRB based on the local studies widely comparative studies from elsewhere. In general, there is not much local information or studies to support a reasonable estimates of water demand.

Domestic water demand: for the Limpopo basin has been taken for urban area as 40 litres at house and 55 litres at the source of water. For rural area, as 31 litres at house and 42 litres at the source of water.

Livestock Water Demand: The norms for water consumption for different livestock has been estimated as 35 l/day for cows and 5 l/day for pigs, goats and sheep with the growth rate of cattle's of 8% and ruminants and pigs is 6%.

Ministry of Industry: no detail of investments is available, so a constant global value of 1 hm^3/year is considered also for the future exploration of heavy sand and other minerals.

Power Production: no data is available so as per norms the demand is considered as 10% of the total domestic requirement. This intends to include average consumptive water requirement of a conventional thermal power station and for liquid fuel/gas based power station.

Environmental flow requirement: using the minimum release concept decided to use 5% of mean natural flows.

Table 11: Estimated Average Water Demand in the LRB in Mozambique (adapted from WAPCOS Lda., 2018)

Sector	**Water Demand (Mm^3)**	
	Actual	**Future (2040 - 2045)**
Agriculture (irrigation)	848	1,456
Domestic Water Supply	20	36
Livestock	10	94
Industry and Mining	1	1
Power	2	4
Environmental Flow*	731	731
Total	**1,612**	**2,322**

* Environmental flow estimated as 5% of the average flow in Chokwe

7. REGULATIONS FOR WATER SUPPLY AND WATER POLLUTION

There are many regulating documents related to water supply in the river basin. Those documents are general rules for the basin or specific for the country. The Existing agreements such as the Revised Protocol on Shared Watercourses of the SADC region from 2000, and the Limpopo River Watercourse Commission created from 2003, play an important role in the management of transboundary water resources between SADC Member States, but offer theoretical rather than practical solutions that can optimize the benefits of sharing results (ÁLVARO 2019).

In Mozambique, the 1991 National Water Law established the property right regime of the water resources in Mozambique by stating that superficial and underground water are owned by the State. In addition, the 1991 Water Law created the National Water Council (CNA) through the Decree no. 25/91. The CNA is an inter-ministerial organ composed by members from various government ministries. It is an advisory board to the Council of Ministers and it is responsible for advising the government on issues related to water management and policy including the implementation of the 1991 Water Law (NEPAD 2013). The water policy (Resolução 42/2016 de 30 de Dezembro) in Mozambique regulates the water use under the global vision of integrated water resource management. Since the approval of the National Water Policy, many reforms were implemented in the Urban Water Supply sub-sector, where a new delegated management framework was created, allowing the management of the main cities' systems to be in charge of a private operator, while assets and investments were entrusted to the new parastatal institutions, the Water Supply Investment and Heritage Fund and the Water Supply and Sanitation Infrastructure Administration, with the role of managing the contracts concluded in the Delegated Management Framework and an independent regulator, the Council of Water Regulation, which has the role of promoting and guaranteeing the sustainability of water supply and wastewater drainage services, including the balanced defense of the interests of the parties involved.

At regional level, the management of water resources is performed by the five regional water agencies (ÁLVARO 2019; LIMCOM 2013) (ARA-Sul IP, ARA-Centro IP, ARA-Zambezi IP, ARA Centro-Norte and ARA-Norte). At the basin level, each regional water agency is represented by the river basin management unity (UGB) and each UGB has its basin committee. In the Limpopo UGB was created in 1997. At provincial level, the water management is performed by Provincial Directorates of Public Works. At local level, the municipal councils are responsible for issues related to water supply and sanitation. The existing water companies such as the Investment Fund and Assets for Water Supply (FIPAG) are responsible for water supply in the main cities.

Therefore, following the creation of ARAs, in 1992 through the Ministerial Diploma no. 172/92, the government approved the internal regulation of the National Directorate for Water, and in 1993 through the Ministerial Diploma no. 134/93, the government approved the statutes of ARA-Sul. The ARAs mandate was changed and approved in 2021 under the resolution nr. 18/2021 of 17th May. This change on the ARAs mandate was to accommodate full juridical and Administrative and Financial Autonomy in order to keep the pace for locals to manage water in their territory.

In order to facilitate the implementation of the 1991 Water Law, in 1995 the government approved through decree no. 7/95 the first National Water Policy. The first National Water Policy put the basis for restructuring the water sector through the creation of different water organizations and policies and the development of public water supply systems. As a result of the 1995 National Water Policy, the government approved the resolution no. 60/98 on Policy for Water Tariffs. Therefore, due to ongoing changes in water management scenarios, the government through the Degree n. 20/2016 of 6th June approved a regulation for taxation of raw water on each of Regional Administration of Water (ARAs).

The National Water Policy defines water as a Good. The tariff system ad establishment mechanisms of economics and therefore, rates should reflect the need and helps to promote and stimulate decentralization in order to recover the costs.

Raw water, drinking water in urban areas, drinking water in rural areas, conventional sanitation, low cost sanitation, water for irrigation and other uses were included in the definition of polluter and user pays principle.

The tariff system applicable to raw water covers the private use of surface and groundwater for human consumption, irrigation, electricity production and others, as well as the rejection of effluents in rivers or aquifers (Ministros 1998). Actual water taxes are stated in the Decree nr. 20/2016 of 6th June. The taxes in this Decree are actualized by Ministry of Public Works Housing and Water Resources and Ministry of Finances. Revenue from taxation is used to finance States Budget (60%) and the Water Resources Management Entity (40%). A fine is applied for those that not comply with the obligation. The revenue from fine payment is divided in opposition to the taxation revenues, that is 60% for Water Resource Management Unity and 40% for State´s Budget.

8. DATA

- Available data:

The National Directorate of Water Resources Management, abbreviated as DNGRH, is the body of the Ministry of Public Works, Housing and Water Resources (MOPHRH,) responsible for the Management of Hydrographic Basins, Hydraulic Works and International Rivers. Besides many other activities DNGRH is responsible for Periodically assess the water resources of the river basins and the water needs at national and regional level. At local level Regional Administration of Water (ARA) is responsible for water management at regional level. The existing data in the Limpopo basin in Mozambique side is scattered in different sectors and documents. The data is in document format (Soft and hard copies), GIS Format and Website format. These data is collected through a network of monitoring stations that includes weather stations, river flow monitoring stations, and Dam and weir protocols. The collected data is manipulated and them translated in to hydrological bulletins for public use or translated into thematic maps.

9. SCIENTIFIC LITERATURE AND RESEARCH PROJECTS

Selected Studies on Water Availability and Quality:

There are many studies that tackle water and environment related issues in the basin. This summary is a taken from the last 20 years’ literature from Mozambique side of the Limpopo Basin. The list presented does not follow a cronological order, thus it represents the status of the research and documentation in the last few years. The following are the title of documents with a brief summary.

- **Design of a water quality monitoring network for the Limpopo River Basin in Mozambique** by Mário N. G. Chilundo, Peter Kelderman J.H. O´keeffe (2008). This paper data indicated that sites located at proximities to the border with upstream countries were contaminated with heavy metals. The Elephants subcatchment was found with a relatively better WQ, whereas the Changane subcatchment together with the effluent point discharges in the basin were found polluted as indicated by the low dissolved oxygen and high total dissolved solids, electric conductivity, total hardness, sodium adsorption ratio and low benthic macroinvertebrates taxa
- **Profile of the Limpopo Basin in Mozambique** by (Brito et al. 2009). This is part of the compilation of Limpopo basin profile in Mozambique.
- **Land and Water Governance and Propoor Mechanisms in the Mozambican part of the Limpopo Basin: Baseline Study** written by Ducrot (2011). This paper has the aim to delineate the main ecological, social, political characteristics of water management in the Limpopo basin in Mozambique at the different scales (from plot to basin level); and to assess the information gaps and need for further information concerning the social and political dimension of water management and governance.
- **Modelo de Alocação de Recursos Hídricos Transfronteiriços na Bacia do Rio Limpopo – África Austral** by ÁLVARO (2019). The study tries to bring the best water allocation. This also discuss the rights of the use of the waters of the Limpopo

water basin which is allocated to the four riparian countries according to the contribution and participation that each country presents in the use of that resource.

- **Assessing Groundwater Dynamics and Hydrological Processes in the Sand River Deposits of the Limpopo River, Mozambique** by Sérgio et al. (2022). This paper aoutlines the use of ground water in the sand river beds and come up with recommendations for the management and use of the Limpopo sand river system as a water source for crop production and/or drinking supply for small farmers and communities.
- **Smallholder Irrigators , Water Rights and Investments in Agriculture : Three Cases from Rural Mozambique** by Veldwisch and Bolding (2013). This paper strengthens the position of smallholders in response to increasing threats of land and water grabbing in different irrigations systems including one in Limpopo, the Chókwe irrigation Scheme.
- **Water rights in informal economies in the Limpopo and Volta basins** by Koppen (2010). The research project found that introduction and enforcement of permit systems brings major administrative burdens for the state and for small-scale users, whose administrative obligations are disproportionate to the volume of water used. Regulatory measures, such as taxation or registration, can also be implemented without changing entitlements to water.

<u>Research Projects in the LRB:</u>

- **Groundwater Dynamics and Hydrological Processes in the Sand River Deposits of the Limpopo River** by Politecnic institute of Gaza (ISPG) with IHE from DELFT and Free State University from SouthAfrica
- **Farmer-led Smallholder Irrigation in Mozambique (FASIMO)** by Faculty of Agronomy and Forestry Engineering - University Eduardo Mondlane
- **Transboundary Water Resources for People and Nature: Challenges and Opportunities in the Olifants River Basin** by IWEGA and Bonn University

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Annex C

SusTraL: Country Report - South Africa

By

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Annex C: Country Report South Africa

Background information of the Limpopo River Basin

This report aims to provide insights that can be used to develop the full proposal. The report is not exhaustive. We will keep upgrading and improving it as new information arise. The report is made of nine sections that range from the physical and socio-economic characteristics of the Limpopo River Basin (LRB) to the existing regulatory frameworks and institutional settings that support the implementation of water and environmental policy reforms in South Africa. Other sections of the report include data needed, the technologies available, the existing scientific literature. An updated version of the report will be produced once we finalize our meetings with key stakeholders in the country and the Limpopo River Basin. These meetings should take place within 2022.

1. THE LIMPOPO RIVER BASIN (LRB); STYLIZED FACTS AND INSIGHTS

Characteristics of the catchment: The Limpopo River Basin (LRB) is situated in the east of southern Africa linking South Africa, Botswana, Mozambique, and Zimbabwe. The basin lies between latitudes 22°S - 26°S and longitudes 26°E -35°E and is the fourth largest transboundary river basin in Southern Africa spanning over 416,296 km^2. Right before entering Mozambique, 1770 km of the LRB forms the border between Botswana and South Africa and the entire border between Zimbabwe and South Africa. It starts at the confluence of the Marico and Crocodile rivers in South Africa and flows northwest of Pretoria. It is joined by the Notwane river flowing from Botswana, and then forms the border between Botswana and South Africa and flows in a north-easterly direction.

At the confluence of the Shashe river, which flows from Zimbabwe and Botswana, the LRB turns almost due east and forms the border between Zimbabwe and South Africa before entering Mozambique at Pafuri. For the next 561 km, the river flows entirely within Mozambique and enters the Indian Ocean about 60 km downstream of the town of Xai-Xai. The Limpopo basin covers almost 14 percent of the total area of its four riparian states (Botswana, South Africa, Zimbabwe, and Mozambique). And of the basin's total area, 45% is occupied by South Africa, 21% by Mozambique, almost 20% by Botswana, and 16% by Zimbabwe (LBPTC, 2010).

Length and Discharge of the River: The River basin has 24 main tributaries with a length of 1750 km^2 and an estimated total natural runoff of about 8000 million m^3 in South Africa. These

24 tributaries have very diverse catchment areas ranging from the small Shabili River in Zimbabwe to the large Olifants River shared by South Africa and Mozambique (Zhu and Ringler, 2010). Most of the existing tributaries have either seasonal or episodic flows. In historical times, the Limpopo river was a strong-flowing perennial river but is now regarded as a weak perennial river where flows frequently cease (SARDC, 2002). During drought periods, no surface water is present over large stretches of the middle and lower reaches of the river. The Crocodile River is the largest of the Limpopo tributaries in terms of both catchment area and volume of flow, draining an area of 29,600 km^2 (Nhassengo et al., 2021). The Crocodile joins the Marico River some 250 km from its source to form the main stem of the Limpopo River. The Notwane river is another major and important tributary of the Limpopo River. It rises on the edge of the Kalahari in Botswana, flowing in a north-easterly direction until it reaches the Limpopo River about 50 km downstream of the confluence of the Crocodile and Marico rivers. The Notwane river has a catchment area of 18,053 km^2.

Some other tributaries of the Limpopo River are the Bonwapitse and Mahalapswe rivers, which rise in Botswana and flow in a mainly easterly direction to the Limpopo River, draining a combined catchment area of 42,090 sq km. The contribution to flow in the Limpopo River from these two rivers is appreciably lower than the tributaries draining from South Africa. There is normally no surface runoff during the winter months in these rivers. The Matlabas, Mokolo, and Lephalala rivers are three of the main right-bank tributaries in a downstream sequence, joining the Limpopo River upstream of the Sterkloop/Seleka Farm flow gauge. These rivers flow in a mainly northerly direction, draining a combined area of about 36,180 km^2. The flow pattern in these tributaries is very irregular because of low rainfall and appreciable transmission losses. Normally there are long periods of no flow during the winter months. Other major sub-catchments of the Limpopo include the Shashe river, which rises in Botswana and has the Ramokgwebana, Simukwe, Shashani, and Tuli rivers as tributaries. The Umzingwani river is another major tributary of the Limpopo, draining a catchment area of about 12,600 km^2. Some additional sub-catchments of the Limpopo River include the Lotsane, Motloutse, Bubi, Nzhelele, Sand, Mwenezi, Olifants, Luvuvhu, Shingwedzi, Letaba, Changane and Mogalakwena river catchments. Table 1 below presents the major watersheds that form the LRB.

Table 1: Major watersheds of the Limpopo River Basin and associated drainage areas in riparian countries

Notation	Watershed Name	Area (km^2)	% of the Basin	Country
ws1	Crocodile	29696	7	South Africa
ws2	Marico	13291	3	South Africa, Botswana
ws3	Notwane	18137	4	Botswana, South Africa
ws4	Bonwapitse	11975	3	Botswana
ws5	Matlabas	5666	1	South Africa
ws6	Mokolo	8333	2	South Africa
ws7	Mahalapswe	8693	2	Botswana
ws8	Lephalala	6774	2	South Africa
ws9	Lotsane	12599	3	Botswana
ws10	Motloutse	19596	5	Botswana
ws11	Mogalakwena	19196	5	South Africa
ws12	Shashe	29612	7	Botswana, Zimbabwe
ws13	Sand	15729	4	South Africa
ws14	Mzingwani	20747	5	Zimbabwe
ws15	Nzhelele	4246	1	South Africa
ws16	Bubi	8640	2	Zimbabwe
ws17	Luvuvhu	5603	1	South Africa
ws18	Mwenezi	14995	4	Zimbabwe
ws19	Upper Olifants	11629	3	South Africa
ws20	Middle Olifants	23149	6	South Africa
ws21	Steelpoort	6896	2	South Africa
ws22	Letaba	13861	3	South Africa
ws23	Lower Olifants	15773	4	South Africa, Mozambique
ws24	Shingwedzi	9309	2	South Africa, Mozambique
ws25	Lower Middle Limpopo	7980	2	Mozambique
ws26	Changane	64039	16	Mozambique
ws27	Lower Limpopo	5757	1	Mozambique

Climate Information: The climate of the basin varies spatially. Three wind systems have been identified as having a strong influence on the basin's climate: tropical cyclones from the Indian Ocean, south-easterly wind systems that bring rainfalls from the Indian Ocean, and Inter-Tropical Convergence Zone (ITCZ) which in some years moves sufficiently far southwards to influence rainfalls in the northern parts of the basin. The basin is predominantly semi-arid, dry, and hot. Air temperatures across the basin show a marked seasonal cycle, with the highest temperatures recorded during the early summer months and lowest temperatures during the cool, dry winter months. In summer, daily temperatures may exceed 40 °C, while in winter temperatures may fall to below 0 °C. The general figures for air temperature are related closely to altitude and proximity to the ocean. The mean maximum daily temperature in most of the Limpopo River Basin, notably South Africa, Botswana, and Zimbabwe, varies from about 30–34 °C in the summer to 22–26 °C in winter. The mean minimum daily temperature in most areas lies between 18–22 °C in summer and 5–10 °C in winter (FAO, 2004; Khanya, 2007).

Rainfall is also highly seasonal, falling predominantly as intense convective thunderstorms during the warmer summer months. There is considerable spatial and temporal variation in the rainfall regime in the Limpopo River Basin, as in most dryland areas, as much of the rainfall occurs in a limited number of rain events. Rainfall varies from a low of 200 millimeters (mm) in the hot dry areas to 1500 mm in the high rainfall areas. Most of the catchment receives less than 500 mm of rainfall per year. Annual rainfall varies between 250 mm in the hot, dry western and central areas to 1,050 mm in the high-rainfall eastern escarpment areas. About 95% occurs between October and April, typically concentrated in several isolated rain days and isolated locations. These rainfall characteristics limit crop production because annual rainfall mainly occurs during a short summer rain season with high interannual variations (Zhu and Ringler, 2010).

The relative humidity is generally higher than 70% and may reach even higher values between May and August, except within the drier Pafúri region (Brito et al., 2009). Evaporation within the LRB varies from 1600 mm/year to more than 2600 mm/year. The highest evaporation occurs in the hot Limpopo River Valley. High levels of evaporation mean that the soil dries up quickly and this reduces the effective rainfall, runoff, soil infiltration, and groundwater recharge.

Forest: The LRB supports a significant portion of the SADC population, including some of the region's poorest and richest communities alike. The basin has numerous urban areas and commercial and subsistence farming communities, as well as important forestry resources and mines. One must highlight that there is also a large variety within the riparian countries when it comes to forest resources endowment. For instance, forest cover in Botswana, Mozambique, South Africa, and Zimbabwe ranges from less than 10% (South Africa) to approximately 50% (Zimbabwe). Botswana has just over 20% of its land area within the Limpopo River basin allocated to forest plantations, while Mozambique has approximately 40%. According to the 2009 World Development Indicators, deforestation in the four riparian countries was quite low from 2000 to 2005 ranging from 0 % to 1.7 % (World Bank, 2010). Forest resources in the Limpopo River basin consist of natural forests and woodlands and commercial/plantation forestry. Although South Africa is the main riparian country practising plantation forestry, the plantation area as a percentage of the total provincial land area within the Limpopo River basin is only 0.5%. The commercial forest plantation sector is primarily under private ownership and based on exotic species of pine, eucalyptus, and Australian wattles (Clarke, 2008). As these species require high rainfall, plantations are therefore found in the higher rainfall belt in South Africa.

Agriculture: Agriculture is perhaps one of the most important economic activities in the LRB, with a large portion of the population depending on it for livelihoods. The dominant soil types of the basin are moderately deep sandy to sandy-clay loams in the south, grading to shallower sandy soils in the north, and deeper sandy soils in the west and east. The deeper loam soils are extremely important for agricultural activities and support extensive irrigation developments along many of the tributary rivers in South Africa, such as the Crocodile River catchment. A few extensive areas of black vertisols in the southern parts of the basin also support important agricultural developments. Water usage in the LRB system is dominated by irrigation—the agricultural sector accounts for half of total water usage, urban usage accounts for 30%, and the remaining demand is divided evenly across the rural, mining, and power sectors (LBPTC, 2010). The total harvested crop area is 2.9 million hectares, and 91 percent of the area is cropped under rainfed conditions (Mwenge et al., 2016). The number of hectares under irrigation in South Africa is about 198000 ha; 40000 in Mozambique, 3992 ha in Zimbabwe, and 1 381 ha in Botswana. A significant proportion of the rural population is involved in rainfed agriculture to sustain their livelihoods (LBPTC, 2010). The basin has a wide range of wildlife and biodiversity which sustains tourism in the region. Currently, almost all the water in the upper LRB is allocated to different water users in the social and economic sectors such as agriculture, industry, power stations, and municipalities (Mwenge et al., 2016; Botai et al., 2020).

Savannah*:* The Limpopo River basin is dominated by the Savannah Grassland Biome, which is known in the region as Bushveld. Other classes include Montane Grasslands, coinciding with the higher elevation regions and mountain ranges in the central and southwestern basins. Flooded Grasslands and Savannas follow the flood plain of the southern portion of the Changane River in Mozambique, which meets Tropical and Subtropical Moist Broadleaf Forests at the river mouth at Xai Xai. The basin consists largely of undulating terrain between ranges of hills and mountains. The northward flowing (South African) tributaries of the Limpopo river have incised deep gorges through the hills and mountain ranges that are visible as erosional remnants (SARDC, 2002). Elsewhere, the river valleys are broad and flat-bottomed with river channels that are slightly or moderately incised into the surrounding parent material. The upstream portion of the Limpopo is characteristically flat with kopjes and small hills rising not more than 200m above the general level and occasional elongated ridges of more resistant strata forming the only local relief. The relief is more pronounced in the south-eastern corner where the quartzites of the Transvaal Sequence, which form the ridges of the Magaliesberg and the Witwatersrand, have been deeply incised by the river to depths of up to 600m. The Waterberg Plateau forms another area of more pronounced relief on the eastern side of the central portion of the basin.

Protected Areas*:* Protected environmental areas comprise a very large part of the Limpopo River basin. The large national parks contain unique biota with several threatened species and provide a significant part of economic activities in the river basin through tourism (Bangira and Manyevere, 2009). In Zimbabwe and some parts of Botswana and South Africa, the introduction of community-based programmes such as the Communal Areas Management Programme for Indigenous Resources (CAMPFIRE) have worked positively to meet the challenges for sustainable use of wildlife resources (Scheiter et al., 2018; Tchakatumba et al., 2019).

Activities in the Limpopo River: Largely because of poverty and pressures for economic development, the environment remains the traditional source of livelihood for millions of people who depend on it for their basic needs such as food, shelter, and medicine. Even though there are concerns about unsustainable and uncontrolled offtakes in most parts of the basin, game meat, traditionally obtained through hunting, is a major source of protein for the people of the basin. Another important source of food and income for the inhabitants is the mopane worm. In parts of South Africa, Gwanda in Zimbabwe and south-east Botswana, a household can raise about US$450 per year from the sale of the worms (SARDC, 2002). However, there is a need to improve the harvesting, processing, and marketing of forestry resources such as mopane worms to increase the income derived from them. The environment is also a major source of other commercial projects such as the development of marula, which are undertaken by communities for both local consumption and commercial trade. The marula tree is in fair abundance in the basin. Each tree can produce as much as 810 kg of fruit per year depending on the season. Besides producing wine, the fruit can also be used in the production of jam (from the fleshy part) and butter/oil from the seed. Woodcarving is another fast-growing industry in the basin whose economic contribution and environmental effects are often ignored or underrated. There are also roadside production and trade of carved products, which are carried out by residents of the basin. Woodcarving has always been a traditional speciality by local communities in the basin and has been carried out mainly for the production of utilitarian items such as spoons, plates, hoe handles, walking sticks, and several other practical and spiritual objects. Mines are key economic performers in the LRB and several large mines and industries have significant water requirements. Mining operations have expanded over the years due to the vast untapped mineral resources in the area. The exact water requirements associated with these sectors, however, are difficult to determine for confidentiality reasons in some cases, and limited information.

Population Density and Cities: Even though South Africa contains about 45% of the catchment area, the country uses 60% of the total water of the basin. However, Botswana has the highest percentage (69%) of its population living in the Limpopo River basin followed by South Africa with 22%, Zimbabwe with 10%, and lastly Mozambique with 7% (Mosase and Ahiablame, 2018; Nhassengo et al., 2021). The Basin is of critical socio-economic importance to about 18 million people distributed across the four riparian states of Botswana, Mozambique, South Africa, and Zimbabwe. Zhu and Ringler (2010) estimate that the River Basin will be supporting as many as 23 million people By 2040. The basin is home to over ten ethnic groups, eight of which are communities transcending national boundaries and which share many cultural values and languages. South Africa has the largest number of people living in the basin area and Botswana has nearly 70 percent of its total population residing within the catchment of the basin. Both countries have a high dependency on the basin due to widespread scarcity of water resources, which makes the Limpopo river basin a large attraction for human settlements and key economic activities.

Almost four percent of the Limpopo River basin consists of built-up hard surfaces. There are substantial urban areas including 10 large cities in the basin. In South Africa, human settlements are concentrated in cities and around service centres. The provinces of Gauteng, Mpumulanga, North-West, and Limpopo (Northern) are all in the basin. Pretoria, Polokwane (formerly Pietersburg), and parts of Johannesburg are some of the basin's largest urban settlements. Crocodile (West) and Marico Water Management Area (WMA) where Johannesburg and Pretoria are situated have an urban population of about 4.5 million residents and a rural population of 1.5 million dwellers. The annual urban water requirements in the WMA are 546.4 Mm^3 and the rural water requirement of 37.7 Mm^3. In the Olifants WMA, the largest centres are Witbank and Middelburg, with a population of 912,151 urban dwellers. In the basin, there are also smaller towns such as Musina, Mokopane, Witbank, and Thohoyandu. In Botswana, the Limpopo catchment supports the capital city, Gaborone, and other urban centres such as Francistown and Selebi-Phikwe. In the rest of the country, settlements tend to be scattered and are determined largely by the availability of water and opportunities for extensive livestock farming. The Mozambican and Zimbabwean portions of the basin are predominantly rural, and settlements tend to be scattered. In Zimbabwe, the major urban centres in the basin are Beitbridge and Gwanda. However, Bulawayo, Zimbabwe's second-largest city is located at the divide with the Zambezi basin.

2. SUPPLY AND WATER MANAGEMENT OPTIONS

Supply Information: For most of the sub-catchments in the basin, the water availability is less than the water demands, and the catchments are stressed. Effective storage and bulk distribution of water are located mainly in the upper part of the Crocodile River and the upper and middle parts of the Elephants River. Only a few additional development options exist within the Limpopo River, which are the Pont Drift, Martin's Drift, and Cumberland dam sites. Some 100 large dams exist of which about 40 are categorized as major dams with a capacity of more than 2 million m^3. The total capacity is almost 2,500 million m^3.

Flood and Drought: floods are a regular occurrence for the inhabitants of the Limpopo Basin (CRIDF, 2017). Severe floods have been recorded in the past 60 years. A flood event is usually triggered by heavy rainfall on all or a portion of a sub-catchment. During a flood event, rain falls at a rate faster than the soil and vegetation can absorb, and surface run-off enters streams and rivers where it increases streamflow and sends a pulse of water down the river. If rainfall persists, the amount of water flowing downstream continues to grow, eventually exceeding the capacity of the river channel. Typically, the highest rainfall amounts occur over the regions with steep topographical gradients between the mountainous regions of north-eastern South Africa and the Mozambican floodplains. This low-lying region is particularly susceptible as it receives a large portion of the waters from the upper basin during periods of high flow. The river basin has been subject to several significant flooding events over the recent years, which were responsible for considerable socioeconomic and environmental damages.

Many of these heavy rainfall events are associated with major negative impacts, including sometimes loss of life. For instance, about 1000 people were killed when tropical cyclone Eline caused severe flooding over the basin. It tracked across Zimbabwe in February 2000 after making landfall near Beira on the central Mozambican coast (Rapolaki et al., 2020; Reason and Keibel, 2004). The floods of 2000 also had significant impacts in Botswana, South Africa, and Zimbabwe, with the Limpopo River rising to its highest levels in over 15 years, causing widespread damage to property and loss of life (human and wildlife). Another notable flood event occurred in January 2013, leaving approximately 200,000 people homeless and leading to more than 100 deaths in central and southern Mozambique (Manhique et al., 2015). More recently, tropical storm Chedza caused severe flooding along the Mozambique side of the LRB in 2015, with many people displaced and 75 deaths reported (Rapolaki et al., 2019; Rapolaki and Reason, 2018). The negative impacts of the recent flooding, and many of the previous events, are not solely limited to the tragic loss of life and the immediate economic impacts of a loss of property and crops. The events have also had a significant long-term effect on affected regions' economies (Rapolaki et al., 2020). Furthermore, the severity of the floods devastated the topsoil of large portions of agricultural land in the lower LRB. The soil was removed entirely in some cases, exposing the bedrock below.

Extreme drought in the LRB is a regular phenomenon and has been recorded for more than a century at intervals of 10-20 years (FAO, 2004). It is a major challenge affecting the availability and distribution of water for agriculture, industry, and other significant water uses. The impact of low rainfall has adverse effects on the agricultural sector. It results in decreases in agricultural activities, loss of livestock, shortage of drinking water, low yields, and shortage of seeds for subsequent cultivation. Other impacts of drought in the LRB area include reduced increased food insecurity, increased forest and range fires, water scarcity, and loss of income by basin users (Maponya and Mpandeli, 2012).

Differences in a different part of the LRB: South Africa contains most of the total catchment area (about 45%) and is responsible for 60% of the total water usage. Over the years, the distribution of water usage has become increasingly harder to sustain as Botswana, Zimbabwe, and Mozambique experienced rapid urban growth and increased large-scale national development projects. Annual water withdrawals for domestic use in Botswana was 41 % of the total withdrawal in 2007, according to World Development Indicators (World Bank, 2010). Botswana is characterized by significant rural-urban migration and increasing water for irrigation and industrial development. The total water demand of Botswana was estimated at 193.4 Mm^3 for 2000. Of this total, 24 percent goes to urban centres, 23 percent to livestock, 18 percent to mining and energy, 15 percent to irrigation and forestry, 11 percent to major villages, 5 percent to rural villages, 3 percent to wildlife, and 1 percent to settlement (FAO, 2004). In recent years owing to high water demands, many of the sub-catchments in Botswana have a water deficit and rely on water importation and water-saving techniques to meet demand (Petrie et al., 2014). Increasing domestic and industrial demand places additional stress on the water supply. Most of the farms along the LRB are game and cattle ranches, and land ownership is not widespread. Private farms dominate land use, and private landowners drive governance and influence most critical decisions. This is enabled by the centralized institutional structure of Botswana’s water policy. Most water reforms in southern Africa have taken water policy toward decentralized management approaches. However, Botswana remains the most centralized of the four riparian countries.

The highest water use in the Limpopo River basin in Mozambique is primarily for irrigation at about 95% of the total water demand. Urban and industrial demand is less than 4 %, while rural demand largely relies upon groundwater (LBPTC, 2010). Continued, accelerated development in Mozambique depends on the supply of water resources for growing industrial, agricultural, and domestic use. Mozambique serves as the downstream riparian for eight international river basins systems, making the country highly invested in water security. Over half the country’s area is positioned in an international water basin, with more than 50% of the country's surface water emanating from river inflows from upstream countries (Petrie et al., 2014).

Zimbabwe's water demand is concentrated in the upper part of the catchment in the Upper Mzingwane River and the Mwenezi River sub-catchments. Bulawayo, the second-largest city in Zimbabwe, partially sits in the Upper Mzingwane River catchment. The agriculture and urban (including industry and mining) sectors account for approximately 50% of Zimbabwe's total supply from the LRB. They are the largest water uses in the catchment, with water demand figures of roughly 640 and 690 Mm^3/a. While rural water supply only accounts for less than 1% of the total water requirements. It is expected that water allocation to these three sectors will grow to about 1,000, 810, and 6 $Mm^3/year$, respectively, by 2025 (LBPTC, 2010).

Each of the four-member countries within the LRB also has ambitious national development plans that rely heavily on the exploitation of mineral resources from the LRB to provide energy security, job creation, and economic growth (Petrie et al., 2014). Each member state's water allocation system reserves a set amount of water usage for environmental flows and household users. It requires large-scale commercial users in agriculture, mining, energy, or industry to apply for a water usage permit from the national Department of Water and Sanitation. This provides a binding legal agreement to limit commercial water usage and ensures enough resource is left for domestic use.

Projections for the Future: the LRB trajectory conveys a picture of increasing difficulty in obtaining sufficient water to satisfy the industrial, agricultural, mining, energy, and household needs of all the riparian countries, exacerbated by increasing environmental degradation and climate change concerns (Petrie et al., 2014). In addition, millions of people are trying to escape poverty, and socioeconomic development remains a prerogative in the region. In 2008, Ashton et al. projected an increase in water demands in the LRB by about 46%, due to enormous pressure from rapid growth in urban populations, mining, energy projects, and irrigation. Furthermore, even though South Africa uses 60% of the total water usage, the distribution of water usage will grow increasingly more difficult to sustain as Botswana, Zimbabwe, and Mozambique experience rapid urban growth and increase large-scale national development projects.

Mwenge Kahinda et al. (2016) report projected change in maximum temperatures over the LRB for the near-future (2011–2040) and far-future (2071–2100) vs a baseline climatological period (1961–1990). Temperatures during the period 2011–2040 are projected to be 1°C – 2°C warmer than the baseline period over the entire Limpopo River basin. The rate of warming is projected to accelerate during the 21st century, with the upper reach of the Limpopo River basin projected to be more than 4°C warmer for the period 2071–2100 compared to the baseline period 1961–1990. The projections represent a dramatic increase in temperature, which would be expected to exert significant adverse impacts on general biodiversity, agriculture, water supplies stored in reservoirs, and the overall hydrological cycle within the region. The projected change in the average annual rainfall over the LRB (expressed as a percentage change) for the same periods is also reported. The pattern of change is projected to amplify as a function of time, with rainfall decreasing by greater than 15% projected for large parts of the upper Limpopo for the far-future period 2071–2100 vs 1961–1990. The projected strengthening of the subtropical high-pressure belt over southern Africa in the future climate provides a plausible explanation for the projected changes in extreme weather events over the Limpopo River basin (Engelbrecht et al., 2009). The more frequent occurrence of mid-level anti-cyclones over southern Africa is likely to induce the occurrence of heatwaves over the Limpopo River Basin and a displacement in the tracks of tropical lows and cyclones that make landfall over the southern African subcontinent (Mwenge Kahinda et al., 2016).

Is there enough water for everyone? One of the most significant challenges of the Limpopo River basin is to distribute the water resources in an equal and sustainable way. The Limpopo River basin is quite developed in terms of storage dams, without which it would not have been possible to make intensive use of its water resources. In areas with semi-arid to arid conditions, water resources are scarce, and prolonged periods of droughts occur. Many people living in the semi-arid regions are thus vulnerable to secure water supply for domestic use and livestock and reliability of subsistence agriculture (Botai et al., 2020). Water demand exceeds availability in the LRB. Shortfalls are being met by importing water via inter-basin transfers and balancing the deficits from the ecosystem allocations. As of 2000, the LRB had a Water crowding index (WCI) of 4,219, well beyond that of 2,000 which is recognized as a marker of water stress and a barrier to further human development (Falkenmark, 1989). Despite building new dams, the Limpopo WCI could reach about 5,000 by 2030 (Petrie et al., 2014), further exacerbating the situation. Ashton et al. (2008) forecast an increase in water demand in the basin of 46% by 2025, with urban demands rising the fastest.

What is the Quality of the water? Poor water quality in the basin is one of several causes of the reduced availability of water for people and aquatic ecosystems. Effluents from industrial and urban uses in the olifants' headwaters around Gauteng and decant of acid mine drainage from defunct coal mines on the Mpumalanga highveld result in severe contamination of waters further downstream (McCarthy, 2011). Return flows and run-off from agricultural areas contribute pesticides, herbicides, and nutrients to the waters. The awful state of wastewater treatment plants in the region is causing the large-scale influx of highly nutrient-enriched waters into tributaries of the Limpopo River (principal run-off from Gauteng province into the crocodile River). This water is heavily contaminated by bacteria and blue-green algae, causing significant losses to farm communities and important product markets. The contamination also contributes to excessive loading of sulphates, ammonia, chlorides, ph extremes, and unacceptable trophic conditions (related to nutrient loading). This pollution makes the main tributaries (such as the crocodile and the Olifants River) toxic to the healthy functioning of aquatic ecosystems. Water pollution is a driving concern in the basin – stemming from industrial effluent, acid mine drainage, and badly maintained sewage infrastructure, especially in the Olifants River.

Aquatic biodiversity is particularly sensitive to changes in water quality which, coupled with the temperature and water availability effects of climate change, leave marine biodiversity increasingly vulnerable. In general, impacts on aquatic biodiversity occur throughout the basin through water abstraction, bed and channel modifications, inundation of riparian zones through barrier construction, and the invasion of exotic aquatic fauna along with the river courses. In South Africa and Botswana, sand mining from river water for construction purposes also degrades local environments. Over time, this has led to riparian degradation, including wetland destruction, lowering of water tables, bank erosion, loss of riparian function, and increases in water turbidity (Kori and Mathada, 2013). The various land use activities in this very large basin have also influenced the water quality. Bangira and Manyevere (2009) show that the water quality in Botswana and South Africa is dominated by sodium and chloride. In general, the high abstraction rate of water for irrigation, industrial and urban use compromises water quality in the system by reducing flows and increasing the ambient concentrations of harmful substances. The addition of extra water through the inter-basin transfers at the headwaters of the crocodile and olifants rivers works to benefit the system because, without these inflows, the quality of waters in the rivers could be much worse.

Biodiversity and Ecosystem Service: Even though, biodiversity patterns have been relatively poorly studied in the LRB (Petrie et al., 2014; Reyers et al., 2002), the LRB is endowed with various biological resources, ranging from crawling insects to large mammals such as the elephants and from non-vascular to vascular plants. Some of the biological resources found in the basin are endemic, and others are migratory. Biodiversity provides important ecosystem services such as food, livestock production, medical plants, or fuelwood to people. However, during recent decades, vegetation in the basin experienced substantial changes and loss of biodiversity due to habitat loss, land-use intensification, and climate change (Scheiter et al., 2018). The basin has also been of critical importance to the people because of its variety of wild fauna and flora used by communities for traditional and medicinal purposes (SARDC, 2002). Many species of birds, lizards, insects, trees, and mammals are preserved because they are sacred, while others are conserved because of their medicinal value. The region has a wide variety of genes, species, and ecosystems. It contains several globally important centres of endemism; however, this heritage is threatened through resource degradation caused primarily by human activity.

The region is mostly covered by a savanna biome, a tree-grass interaction controlled in part by the seasonal climate in which a long dry season and a shorter wet season affect vegetation-fire dynamics. However, the key biodiversity aspects are the upland catchment areas, which also correlate to centres of endemism and high biodiversity and are of significant conservation importance. For example, the Soutpansberg- Blouberg complex, including nearby Wolkberg, is a centre of plant endemism and is highly diverse (Mostert et al., 2008). Between 2,500 and 3,000 vascular plant taxa comprising 1,066 genera and 240 families occur on the mountains – 68% of all plant families of the entire flora of the southern African region (Petrie et al., 2014).

3. WATER DEMAND INFORMATION

Main Water Users: In 2010, the total estimated demand was about 4,700 Mm^3/a (African Water Facility, 2014). Almost two-thirds of the demand is in South Africa, 30% in Zimbabwe, 6% in Mozambique, and 2% in Botswana. The total natural run-off generated from rainfall is approximately 7,200 Mm^3/a, this implies that a significant portion of the run-off generated in the basin is currently being used. Livestock is very important in socioeconomic terms, with a total of about 2.2 million animals in the Limpopo area, of which 70% is cattle. The corresponding water demand is quite significant, in the order of 25-30 Mm^3/a. Total annual water demand for South Africa is about 3,000 Mm^3/a, of which 1,485 Mm^3/a are for irrigation, which is the largest consumer, 665 Mm^3/a for urban supply, 140 Mm^3/a for rural supply, 445 Mm^3/a for mining and power production, 45 Mm^3/a for afforestation and 250 Mm^3/a for water transfers to neighbouring river basins (Botai et al., 2020). The Crocodile River, with 40% of the total water demand, and the Olifants River, with 30% of the total water demand, are the sub-catchments with the largest water use. Although there is no information available on water usage related to forestry in the riparian countries, it can be assumed that the water demand from the forestry sector in Botswana, Mozambique, and Zimbabwe in the Limpopo River basin is minimal.

The efficiency of water usage: The SADC Protocol on Shared Watercourses requires all basin states to adopt Integrated Water Resource Management Plans (IWRMP) to address water resource usage and conservation. The requirement has led to a drive to develop wastewater reuse as a water conservation method in the basin. Treated municipal wastewater is used to enhance water supply to users once the quality is adequate. Since agriculture is the major water user in the basin, various water conservation strategies are being practised to meet present and future water supply. Existing options include protecting the environment at the catchment level, switching from flooding to drip irrigation, retrofitting water pumps and showerheads to conserve water, and reducing water wastage through curbing non-revenue water (NRW). Water losses in the urban and domestic sectors are being minimized with the implementation of the best practices for reducing NRW at the municipal level including metering of all supply systems. Water losses in the irrigation sector can be attributed to three main components: conveyance losses; inefficient irrigation system types, and inefficient operation and management of the system (Lombaard et al., 2016). Most mining companies have the expertise to implement advanced processes to ensure recycling and reuse of all water streams, which improves the operation's profitability. In addition, mining houses have to comply with strict license conditions for effluent (and the cost thereof). It, therefore, pays a mine to recycle its water rather than discharge large volumes of it into the river after use. There are high levels of efficiency at most mines with, on average, 5% water losses (Lombaard et al., 2016).

4. TECHNOLOGIES

Technologies to reduce demand and waste: The SADC Protocol on Shared Watercourses requires all basin states to adopt IWRMP to address water resource usage and conservation. In South Africa, the principle of striving to achieve the overall best utilisation of water forms one of the cornerstones of the National Water Resource Strategy. Various innovations that provide an alternative water source and reduce pollution are encouraged in the LRB. Significant alternative technologies that enable water reuse serve to substitute or augment the water supply in the basin. For instance, water reuse in the largest sectors (agricultural and industrial) allows for a greater allocation to other sectors. At the household level, greywater (un-treated household wastewater discharged from bathtubs, showers, and washing machines) is also reused without pre-treatment for some agricultural or landscape irrigation.

Wastewater treatment facilities are also important technological infrastructures in the LRB. Municipal wastewater, including domestic and industrial wastewater, is treated at designated Wastewater Treatment Works (WwTW) before the effluent is discharged into existing water resources. The treated effluent released back into water resources is called return flows. Reuse of treated effluent is already being applied in the mining and industrial sectors within the LRB. Various water reclamation processes or technologies are applied in WwTW located in different catchments. For example, the Polokwane local municipality already recycles effluent water through an innovative artificial recharge scheme in which treated effluent is transferred from the Mokopane WwTW to the Anglo Platinum Mogalakwena Mine near Mokopane in the Mogalakwena catchment. The Louis Trichardt WwTW was upgraded and is projected that 1.6 million m^3/a (4.3 Ml/d) of treated effluent can be reused by 2025 and 1.7million m^3/a (4.7 Ml/d) by 2030 (Lombaard et al., 2016).

5. REGULATIONS FOR WATER SUPPLY AND WATER POLLUTION

Water supply regulation: Since the LRB is located in the southern African region, it falls under the Southern African Development community’s (SADC’s) regional-cooperation-for-development mandate. Overall, legal, and institutional mechanisms are in place for the riparian countries of the Limpopo River basin to achieve substantive progress in the joint integrated management of the basin's water resources. All have signed the SADC Revised Protocol on Shared Watercourses, whose principles are essential for collaborative governance. All have the laws, regulations, and institutions required for this cooperative effort (Bangira and Manyevere, 2009). Major regulators in the Limpopo Basin States include the Limpopo Water Commission (LIMCOM), and the Limpopo Basin Permanent Technical Committee (LBPTC). LIMCOM was officially launched in July 2014 and the agreement for Mozambique to act as its host country was signed during this launch. In South Africa, they include the Department of Water and Sanitation (DWS), the custodian of South Africa's water resources, and Catchment

Management Agencies (CMA). The SADC Water Division (SADC/WD) was established in 2003 and is an important institutional actor in the governance of the LRB. SADC/WD's mandate is to promote regional cooperation between 14 international river basins within the region. The division's main objectives are developing, implementing, and monitoring a regional water policy and strategy that reflects the international water management norms advanced by the UN Watercourse Convention, the Helsinki Rules, and the Dublin principles. The recently launched LIMCOM is the basin's River Basin Organization (RBO) that evolved out of the SADC structures and mandate. However despite these efforts voices are raised to claim that the current transboundary governance arrangements are not strong enough to promote the extent of resilience-building needed in the basin, now or in the future (Mhizha et al., 2011; Petrie et al., 2014). There is, notwithstanding, dialogue on the concept of managing the basin's resources more effectively through shared benefits, but this is unlikely to happen in the absence of a shared vision and appropriate institutional arrangements for coordinating this process (Petrie et al., 2014).

The South African Department of Water and Sanitation (DWS) is responsible for the nation's water management system and regulates the water price. The department oversees the provision of water by provincial and municipal authorities. The National Water Policy White Paper (1997), Water Services Policy (1997), and National Water Act (1998) provide the framework for South Africa's current institutional structure. Established in light of the Helsinki Rules and Integrated Water Resource Management (IWRM) principles, the documents highlight the importance of equitable benefit sharing, decentralization of management structures, and consideration of transboundary effects of national water use. While South African policy does involve the devolution of power to the regional level, the current framework maintains that the national government has central control and responsibility for water resources. The policy reforms of 1997 and 1998 transformed water management structures, dividing the country into 19 Water Management Areas (WMAs). The LRB in South Africa comprises four WMAs: the Limpopo, Luvuvhua & Letaba, Olifants, and Crocodile WMA. Within each WMA is a Catchment Management Agency (CMA), headed by a board that reflects the demographics of the surrounding commercial and domestic community. Below the CMA is Water User Associations (WUAs) put in place to provide a platform for stakeholder participation. Progress has been made toward establishing the structures necessary for a decentralized water management system; however, both CMAs and WUAs lack the capacity to fulfil their mandates adequately. As a result, power over the system remains concentrated in the DWS (Petrie et al., 2014).

Water pricing: The South African Department of Water and Sanitation (DWS) regulates the allocation of water by controlling the licensing process. The National Water Act 1998 recognises water as a basic human right and water needed to meet basic human needs is therefore free in South Africa. The Free Basic Water (FBW) subsidy programme was implemented in 2001 to provide 6,000 L/month of water to every household (Metcalf-Wallach, 2008). Water tariffs are determined on an Increasing Block Rate (IBR) regime, implying that the more water consumed, the higher the rate. On average, the share of water in total intermediate costs in 2001 was slightly more than 1% of the national economy (Lange and Hassan, 2006; Limpopo River Awareness Kit, 2010). Trade and services sectors paid the highest amount per unit of water at R12/m^3, mining paid R3.76/m^3, manufacturing paid R1.58/m^3, domestic use paid R1.19/m^3 and agriculture paid only 2.3 cents/m^3. Agriculture pays very little for water, and yet it used 80 percent of the total water consumed in 2000 and contributed only 3 % to the national income (Lange and Hassan 2006). Based on Statistics South Africa data and DWS Drop data and annual reports, the tariff rates for the different sectors have exponentially increased in recent years. For instance, the weighted average water tariff for domestic use increased from R4.63/m^3 in 2012 to R6.67/m^3 in 2016. Agriculture, forestry, and fishing still paid very little for water at R0.11/m^3 in 2012 and R0.13/m^3 in 2016. Mining paid an average of R9.06/m^3 in 2012 and the tariff increased to R14.06/m^3 in 2016 (Maila et al., 2018).

Water Allocation: Much of the surface water exploitation in the four basin states rely on supplies provided from water storage reservoirs that have been constructed on perennial and seasonally flowing tributary rivers. South Africa's portion of the Limpopo River basin is fed by more than 14 rivers that flow from south to north through the country's Northwest and Limpopo provinces. Surface water use is directed primarily to irrigation, afforestation, and domestic water supply to towns and communities, with some allocations to industry, power generation, and mining activities. Abstraction permits, compulsory licensing and water-use authorisations are methods used to determine and monitor water use and allocation. Licenses and permits are used to control water use, promote equity, and protect environmental flow requirements in the LRB. The DWS is responsible for implementing the National Water Resource Strategy and various functions under the National Water Act and Water Services Act, such as the administration of the new license system and the allocation of water. The provision of water services lies primarily within the responsibility of local municipalities and Catchments Area Authority unit, with the DWS exercising an oversight function. The country has a system of permits attribution for large-scale commercial users, household users, and small-scale farmers. Increasing trends of exploitation of the basin's surface water resources, especially in the upper reaches of the tributaries in South Africa, have led to sustained reductions in river flows and competition among users in downstream reaches (Mwenge Kahinda et al., 2016).

6. DATA

Available data: South Africa has the most advanced data collection and reporting system of the riparian countries and provides a bulk of reliable data for the basin. Data is collected through a network of regional monitoring stations and is compiled by the DWS into the three main systems: surface water, GIS data, water quality, and groundwater. Data on the system input volume water was obtained from the DWS No Drop database. The data is reported at a municipal level. Data on wastewater is reported on DWS’s Green Drop database. This can be analysed to determine the total volume of water treated in wastewater treatment works (WWTW). The data is available at a plant level, and each plant is categorised under a local or metropolitan municipality. The data can be restructured using a Geographic Information System (GIS) to give volumes of treated water per WMA. Risk and vulnerability mapping can also be done using GIS and Maps to form a spatial picture of climate risk and vulnerability across the basin. Data on the water demand from the LRB can be obtained from the DWS and the recent studies done in the various sub-catchments of the Limpopo River basin located in the country. Population data for the four Limpopo River basin states is available. The population data can be obtained from national censuses which are conducted every ten years in each of these states. From this census data, population projections have been made by Central Statistics Offices in the four countries.

The main climatic data needed for transboundary water management are rainfall and temperature data. Daily rainfall, and maximum and minimum temperature gridded data for 375 locations within the LRB since January 1979 can be extracted from the Climate Forecast System Reanalysis (CFSR) global weather database (https://globalweather.tamu.edu/). The CFSR weather data were generated by using conventional meteorological gauge observations and satellite irradiances coupled with advanced modelling of the atmosphere, ocean, and land surface systems at 38 km resolution (Dile and Srinivasan, 2014). The data on water quality assessment can be obtained from the DWS Water Quality database, which is available from the DWS Resource Information Services directorate[1]. This data can be used to determine the history and trends of the water quality over a period of time and assess the present or current water quality status. Socioeconomic information on different activities (ranging from agriculture, residential, industry, tourism, etc) can be obtained from national, regional, district, and municipal development plans, reports, and surveys.

Missing data: The South African region of the LRB mostly has high-quality data coverage for large-scale basin-wide water resources assessments. However, there are some compatibility problems between data in the four countries. The level of aggregation of the information sometimes differs. Some categories are aggregated in one level and disaggregated in another depending on the country (for instance, industrial use is reported as part of urban use in some surveys). Also, some available information is not referred to the same base year, which makes the comparison between them more difficult.

The second problem is that data gaps for extended periods and over large areas occurred in Zimbabwe and Mozambique during their civil war times. LBPTC (2010) reports that another problem with data in the LRB relates to (physical) water losses and demand in the system. Particularly, there is no agreement between the riparian countries on what range of losses should be considered acceptable in the water-stressed basin. Lastly, there is a need for harmonization as the basis for water demand estimates is not the same in all countries.

7. SCIENTIFIC LITERATURE

Selected Studies on Water Availability and Quality: Several studies have investigated water availability and climate change implications in the LRB (De Groen and Savenije, 2006; Kleynhans, 1996; Legesse Gebre and Getahun, 2016; Machethe, 2011). Nhassengo et al. (2021) studied environmental flow sustainability in the Lower Limpopo River Basin. The paper evaluated monthly and annual water volume scarcity in the Lower Limpopo River Basin (LLRB) to quantify sustainable balances between ecological integrity and anthropogenic activities. The study shows that currently, annual water shortages occur between August and October and are the main concern of local stakeholders. Mosase and Ahiablame (2018) used

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[1] www.dwa.gov.za/iwqs/wms/data/000key.asp.

statistical and GIS techniques to evaluate annual and seasonal rainfall and temperature variations in time and space from 1979 to 2013 in the Limpopo River Basin (LRB). Trend analysis showed upward trends for annual and seasonal rainfall in most parts of the basin, except for the winter season, which showed a decreasing trend. The analysis of minimum temperature on an annual basis and for the winter and spring seasons show upward trends during the study period over the whole basin while the minimum temperature for summer and autumn showed decreasing trends. In a similar study, Botai et al. (2020) evaluated the projected future climate and anticipated impacts on water-linked sectors on the transboundary Limpopo River Basin (LRB) with a focus on South Africa. The study used the CORDEX-Africa daily climate simulation data at a spatial resolution of 50 km to force an Agricultural Catchment Research Unit (ACRU) hydrological model. The study shows that water resources in the LRB are already stressed, as supported by observed decreasing trends in historical streamflow from 1976 and 2005. The study concluded that such trends are likely to continue considerably in the future, as a result of the projected high variability of rainfall patterns and increases in hydro-climatic extremes within the LRB region

Studies have reported pollution increase in the LRB derived from upstream and downstream activities such as mining, impoundments, water abstraction, agriculture, industrial, and discharge of untreated domestic wastewater (Louw and Gichuki, 2003). Dzurume (2021) identified major land use and land cover changes (LULC) from two protected wetlands (Makuleke and Nyslvei) and their impacts on water quality within the Limpopo Transboundary River Basin. The study shows that even though these wetlands are protected they are not free from threats and contamination. Analysis of the 2009–2015 data from four Olifants River sites along the LRB by Marr et al. (2017) showed deterioration in the river’s ecological condition between where it enters the Lowveld and where it enters the Kruger National Park. Of the tributaries evaluated in the current study, the Selati River was shown to have the largest detrimental impact on the water quality of the lower Olifants River. This is due to mining, industrial activities, and excessive water abstraction from the river.

Mwenge Kahinda et al. (2016) analyzed the socio-ecological, hydrological, climatic, and governance systems of the Limpopo River basin. They indicate that ongoing and projected land-use changes and water resources developments in the basin's upper reaches, coupled with projected rainfall reductions and temperature increases, and allocation of the flows for the ecological reserve, are likely to reduce downstream river flows further. The authors conclude that the institutional arrangement of the Limpopo River basin is neither simple nor effective. They emphasized that the basin is rapidly approaching closure because almost all of the available supplies of water have already been allocated to existing water users.

Studies on Hydro-economic Modelling HEM in the LRB: There are some available studies on hydrologic modelling in the LRB, however, those that incorporate economic theory in a hydro-economic modelling framework are very rare. Mosase (2018) used the Soil and Water Assessment Tool (SWAT), a widely used watershed hydrologic scale and process-based hydrological model to determine water risk areas in the LRB. The method successfully simulated the long-term impacts of land management practices and climate change on the basin's hydrologic and water quality conditions. Furthermore, the study also investigated water demand/use in domestic and agricultural sectors using the Simplified Hydro Economic Demand Model developed by New Mexico State University (Hurd, 2015). In another study, Asante et al. (2007) describe the application of remotely sensed precipitation to monitoring floods in the LRB. They integrate remotely sensed precipitation data into a hydrologic model that is parameterized using spatially distributed elevation, soil, and land cover data set. This study concludes that remotely sensed precipitation and derived products greatly enhance the ability of water managers in the Limpopo basin to monitor extreme flood events and provide at-risk communities with early warning information.

Trambauer et al. (2014) used a continental-scale hydrological model PCRaster Global Water Balance (PCR-GLOBWB) that includes an irrigation module to account for large irrigated areas of the Limpopo River basin. Hydrological drought was characterized using the Standardized Runoff Index (SRI) and the Groundwater Resource Index (GRI), which make use of the streamflow and groundwater storage resulting from the model. The indicators considered in the study can represent the most severe droughts in the basin and to some extent identify the spatial variability of droughts. Zhu and Ringler (2012) analyze the hydrological and irrigation water supply impacts of climate change in the LRB, using a semi-distributed hydrological model and the Water Simulation Module (WSM) of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). The study estimation is based on the 1971–2000 climate baseline and the CNRM2 and ECHAM3 GCM projections for 2050

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[2] Centre National de Recherches Météorologiques

[3] ECHAM is a general circulation model (GCM) developed by the Max Planck Institute for Meteorology.

emissions. The study reports significant annual precipitation reductions in 2050 for all countries for both climate change scenarios, compared with the climate baseline.

8. RESEARCH PROJECTS IN THE LRB

The Joint Limpopo Basin Scoping Study was conducted in 2010, with support from the SADC transboundary water resources management programme which was funded by BMZ and DFID and implemented by GIZ. The project identified key challenges and proposed steps to be taken to implement sustainable water resources management and development in the basin. The Scoping Study provided the basis for undertaking the Integrated Water Resources Management (IWRM) Planning process at the basin level, which resulted in the LIMCOM IWRM Plan for 2011- 2015. The LIMCOM IWRM Plan (2011-2015) aims to develop the capacities (individual, organizational and institutional) in the riparian states for the sustainable management and development of the Limpopo River Basin. The plan provided a framework for implementing the LIMCOM Agreement and for the effective cooperation with international cooperating partners (ICPs) which provided support to implement the LIMCOM Agreement.

In addition to the ICP support provided to LIMCOM through the SADC transboundary water management programme, another major support to LIMCOM during the 2011-2015 period was provided through the Resilience in The Limpopo Basin (RESILIM) Program, financed by USAID. The goal of RESILIM was to improve transboundary management of the Limpopo River Basin and enhance the resilience of its people and ecosystems with its three strategic objectives: (i) Reducing climate vulnerability by promoting the adoption of science-based adaptation strategies for integrated transboundary water resource management (ii) Conserving biodiversity and sustainably managing high-priority ecosystems and (iii) Building the capacity of stakeholders to sustainably manage water and key ecosystems.

By integrating water management, biodiversity conservation, and adaptation to climate change to build resilience for the long-term sustainability of the basin, RESILIM made three important contributions. First, the project made major advances on policy and governance that fully invested in Basin-based governance in its efforts to secure water, protect biodiversity, and adapt to climate change, along with plans and tools to strengthen day-to-day management. Second, the project made foundational contributions to the scientific evidence base essential to effective management of water and biodiversity in the Basin, and provision of related decision-making tools. Third, RESILIM made significant investments to help people and communities build resilience through new climate-friendly livelihoods and stronger systems for resolving conflicts and managing competition for resources (UNDP-GEF, 2019).

The Department of Water and Sanitation (DWS) of South Africa identified the need to develop the Limpopo Water Management Area Strategy north of the Limpopo basin. Various projects were undertaken to ensure effective and efficient current and future management of the water resources. For example, the Water Resources Situation Assessment in the Limpopo Water Management Area aims to determine the water resources availability, requirements, and water shortages to provide necessary information to develop future water supply strategies for the Limpopo basin. The water augmentation project in Mokolo and Crocodile rivers (west) analyzed water transfer from the Mokolo River and Crocodile River (West) to the Steembokpan and Lephalale to augment future water supply and allocation in those areas. A study to classify all significant water resources in the river catchment was undertaken to protect the country's water resources as well as to ensure a balance between the need to develop and sustain them. DWS in 2014 created a Reconciliation Strategy for the Limpopo River Basin to reconcile future water requirements with water supply for a 25-year planning horizon. The strategy also provides a framework for decision-making regarding both securing supply and managing the water requirements.

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Annex D

Integrating ecosystem services into hydro-economic models

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1 Hydro-Economic models: Motivation, definition and goals

Globally the world is experiencing a decline in water availability and quality while water demand is rising (Momblanch et al., 2016, p. 294). The reasons for this are manifold and oftentimes context-dependent, however, three overarching global developments play an important role. Firstly, climate change leads to rising average temperatures in many areas, thus exacerbating already existing and creating new water scarcity issues (Kahil et al., 2019, p. 73; Pérez-Blanco et al., 2021, p. 1; Pörtner et al., 2022). Secondly, an intensively growing and wealthier world population naturally demands more resources, water being a vital one (Kahil et al., 2019, p. 73). Thirdly, most regions develop towards "mature water econom[ies]" (Randall, 1981). A mature water economy can be characterized by rapidly increasing marginal costs of water resources due to increasingly limited and expansive options for water supply augmentation (Bekchanov et al., 2017, p. 1; Harou et al., 2009, p. 628). Frequently, a rising number of conflicts among water users and other stakeholders are the consequence (Harou et al., 2009, p. 628). Potentially conflicting parties include the agricultural and hydropower sector, urban demands, industries and mines, and environmental groups. Without coordination and policy transparency, conflicts may aggravate, and highly inefficient outcomes are the consequence, especially in transboundary river basins (Casarotto, 2018, slide 2).

The progressive depletion of water resources together with increasing demand (and pollution) motivates an economic approach to water management. The economic approach implies an efficient allocation of scarce water resources and a reduction of wasteful practices with the aim of maximizing social welfare (Harou et al., 2009, p. 629). Powerful analytical tools in this context are so-called Integrated Water-Economy models (WEMs) (Bekchanov et al., 2017, p. 1). According to Bekchanov et al. (2017, pp. 2-3), Water-Economy Models can be subdivided into two general types: Economy-wide models, such as Input-Output models and Computable General Equilibrium (CGE) models, and network-based Hydro-Economic models (HEMs).[1] In the following, the focus is on HEMs.

HEMs can be defined as models that represent a combination of (spatially distributed) water resource systems with key economic demand functions based on a coherent framework of hydrology, economics, engineering, and environmental sciences (Harou et al., 2009, p. 628; Momblanch et al., 2016, p. 294). This combination, in essence being an amalgamation of different sciences with a centrality of economics, brings HEMs to the heart of integrated water resource management (IWRM), in that they provide an interdisciplinary effective tool to guide water management and policymaking around the globe (Hossen et al., 2021, p. 1370; Salman et al., 2018, p. 2). Integrated water resource management aims at maximizing economic and social welfare, while sustaining vital ecosystems (Kragt, 2013, p. 2). The models allow for an assessment of (optimized) water allocation between different uses across time and space, under uncertainty and across different sectors (Bekchanov et al., 2017, p. 15; Salman et al., 2018, p. 2). They generate useful information on marginal values of water, water infrastructure and ecological flows (Harou et al., 2009, p. 629), which can be utilized to analyze water scarcity issues, climate change adaptation pathways, the effects of infrastructural and policy interventions, to design institutional policies and potentially help alleviate or even resolve conflicts (Hossen et al., 2021, pp. 1359, 1371). In contrast to providing a single aggregated indicator of desirability (Cost-Benefit Analysis) and analyzing effects on the whole economy (General Equilibrium models or Input-Output models), HEMs show the dynamic variation of water values and how economics affects water resource management (Harou et

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[1] The classification of WEMs/HEMs in the literature is not unambiguous. For example, Hossen et al. (2021) subdivide HEMs into CGE models and Non-CGE models, therefore diverging from the classification by Bekchanov et al. (2017) or Harou et al. (2009).

al., 2009, p. 639). Consequently, the main objective of HEMs is to assist water managers to optimally steward water resources through allocating water to maximize economic value, or put differently, to maximize total benefits in a basin (Harou et al., 2009, p. 628; Hossen et al., 2021, p. 1359; Momblanch et al., 2016, 294). HEMs allow for a "fresh" perspective on water resource systems and may open up new solutions (Harou et al., 2009, p. 640). Moreover, by including multiple stakeholder interests, they can transparently negotiate between resulting trade-offs (Casarotto 2018, slide 10).

Since first introduced, a growing number of approximately more than 300 HEMs – covering a range of resource problems and locations – have been developed worldwide (Harou et al., 2009, p. 635; Hossen et al., 2021, p. 1371). In the last years, a number of review studies have tried to capture the spectrum of HEM applications.[2] Different review criteria and labeling slightly complicate a comparison, however, it is generally fair to conclude that most applications have been used on water resource allocations, institutions and infrastructure planning as well as impact analysis and adaptation (Harou et al., 2009, p. 638; Momblanch et al., 2016, p. 297). Most frequently included water use sectors are the agricultural, hydropower, industrial, and municipal sector (Bekchanov et al., 2017, p. 10; Momblanch et al., 2016, p. 297). Figure 1 displays the frequency of main research themes according to the categorization by Bekchanov et al. Figure 2 provides an overview of the geographical distribution of HEM application. Although Bekchanov et al. (2017, p. 15) emphasize the extensive and successful application of HEMs, Hossen et al. (2021, p. 1361) state that outside the academic realm, i.e. by policymakers or water managers, they have not been accepted warmly.

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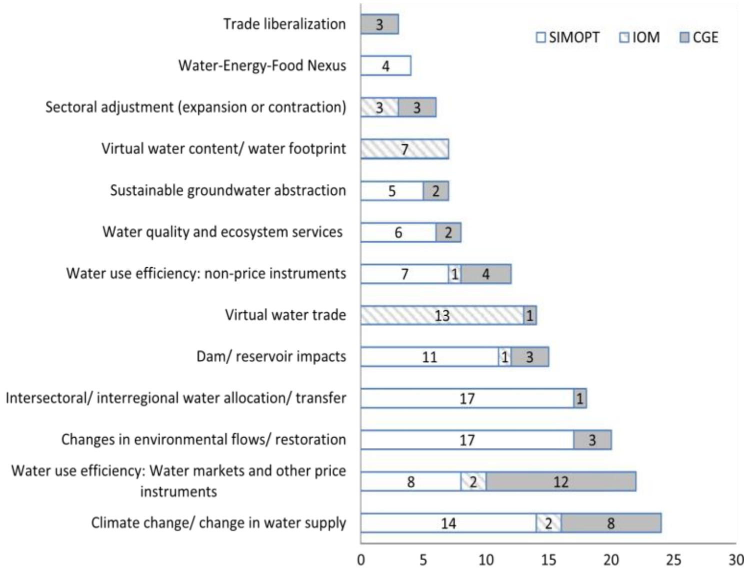
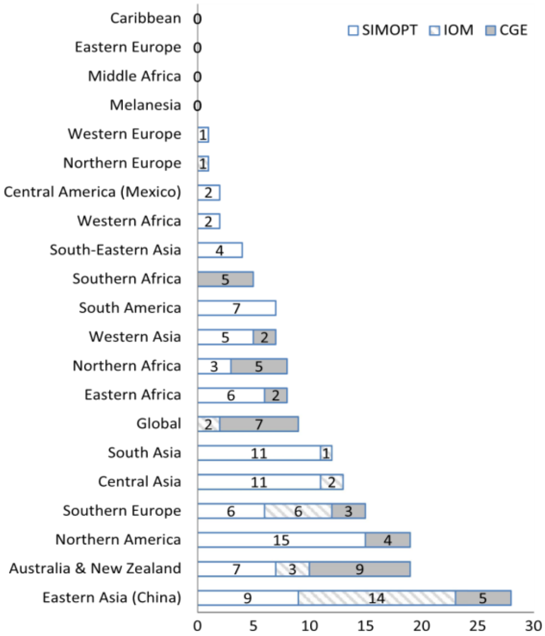
[2] For details see Harou et al. (2009), Momblanch et al. (2016), Bekchanov et al. (2017) and Hossen et al. (2021).

Figure 1: Comparison of 160 different modeling studies according to their main research theme[3]



Source: Bekchanov et al. (2017, p. 6)

Figure 2: Geographical coverage of the base study regions of HEM implementation[4]



Source: Bekchanov et al. (2017, p. 9)

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[3] Out of 160 studies: 89 papers use SIMOPT (HEMs), 29 papers use IOMs, and 42 papers use CGE models; one paper can include multiple indicators.

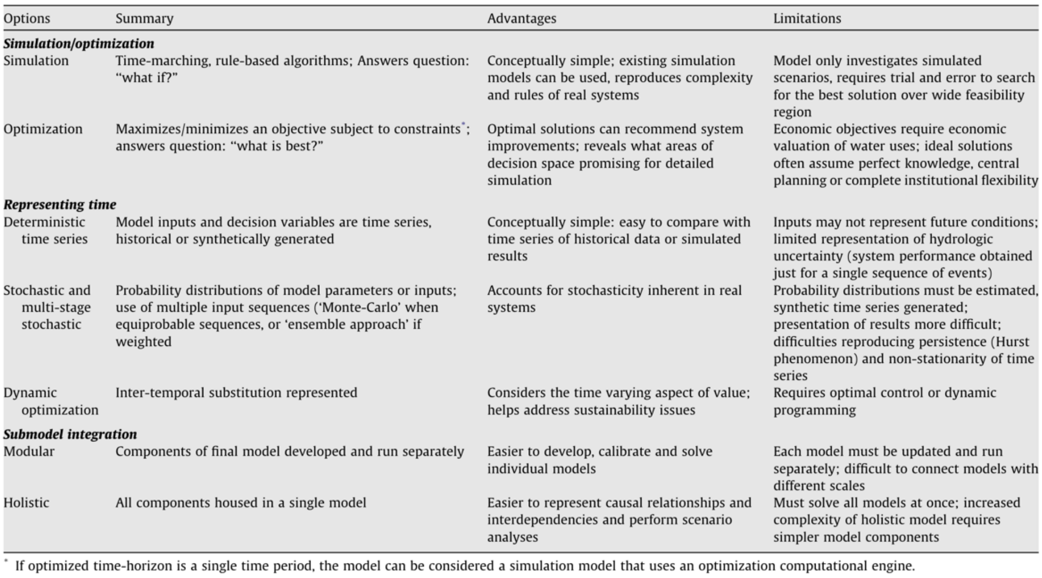
[4] A single region is assigned to each paper; global or multiregional coverage is termed global.

2 HEM structure and design choices

Typically, HEMs use a node-link network representation of a (physical) basin with nodes representing river flows, reservoirs, or diversion points based on simplified hydrologic equations, and links representing linkages between the nodes such as river reaches, canals, and pipelines (Harou et al., 2009; Hossen et al., 2021, p. 1367). The consistent accounting of hydrologic flows and storages is necessary and can, for example, be based on a combination of inflow data and parameters of water management infrastructure (Harou et al., 2009, p. 632; Casarotto, 2018, slide 3). In essence, HEMs have three core components: A hydrologic component (water balance model), an economic component and an objective function (rules, or constraints). These try to integrate all main hydrologic, economic, institutional, and environmental variables as well as stakeholders in a basin (Hossen et al., 2021, pp. 1359-1360). The hydrologic module provides information on water flows and availability, and can be calculated on a yearly, seasonally, monthly, weekly, daily or even hourly basis. The economic module calculates the economic value from different water uses under different climatic, economic, management or environmental conditions. Finally, the objective function represents constraints such as political and institutional realities as well as ecological goals that must be considered (Harou et al., 2009, p. 634).

Aside from these general design features, the modeler must make several design decisions. Table 1 provides an overview of some of the main design options. Not covered in the table but similarly important is to specify the domains of the model, i.e. the spatial and temporal boundaries including their subdivisions (Harou et al., 2009, p. 634). Fundamentally, HEMs are either simulation-based or optimization-based or a combination of simulation and optimization models. Simulation-based HEMs analyze and evaluate “what if” scenarios under specific hypothetical conditions, i.e., for different allocation policies or institutional arrangements, for example. Optimization-based HEMs, on the other hand, identify the best among many options (“what’s best”) based on maximizing or minimizing a specified mathematical objective function. In other words, they identify efficient allocation policies and their impacts and can, therefore, transparently negotiate between conflicting stakeholder interests (Salman et al., 2018, pp. 2-3). Figure 3 displays a conceptual flow diagram of an optimization-based HEM for a surface water system. Importantly, benefit maximization entails a normative decision, i.e., policymakers need to choose between multiple Pareto-optimal allocations. Figure 3 visualizes this trade-off situation between multiple Pareto-optimal solutions (along the Pareto frontier) in the case of choosing between net benefit maximation of downstream or upstream stakeholders (Casarotto, 2018, slides 6-8). Usually, a HEM study considers a base case with current management and infrastructure parameters and compares this with various development and management scenarios (Salman et al., 2018, p. 6).

Table 1: Design choices and implications for building a HEM



Options	Summary	Advantages	Limitations
Simulation/optimization			
Simulation	Time-marching, rule-based algorithms; Answers question: "what if?"	Conceptually simple; existing simulation models can be used, reproduces complexity and rules of real systems	Model only investigates simulated scenarios, requires trial and error to search for the best solution over wide feasibility region
Optimization	Maximizes/minimizes an objective subject to constraints[*]; answers question: "what is best?"	Optimal solutions can recommend system improvements; reveals what areas of decision space promising for detailed simulation	Economic objectives require economic valuation of water uses; ideal solutions often assume perfect knowledge, central planning or complete institutional flexibility
Representing time			
Deterministic time series	Model inputs and decision variables are time series, historical or synthetically generated	Conceptually simple: easy to compare with time series of historical data or simulated results	Inputs may not represent future conditions; limited representation of hydrologic uncertainty (system performance obtained just for a single sequence of events)
Stochastic and multi-stage stochastic	Probability distributions of model parameters or inputs; use of multiple input sequences ('Monte-Carlo' when equiprobable sequences, or 'ensemble approach' if weighted	Accounts for stochasticity inherent in real systems	Probability distributions must be estimated, synthetic time series generated; presentation of results more difficult; difficulties reproducing persistence (Hurst phenomenon) and non-stationarity of time series
Dynamic optimization	Inter-temporal substitution represented	Considers the time varying aspect of value; helps address sustainability issues	Requires optimal control or dynamic programming
Submodel integration			
Modular	Components of final model developed and run separately	Easier to develop, calibrate and solve individual models	Each model must be updated and run separately; difficult to connect models with different scales
Holistic	All components housed in a single model	Easier to represent causal relationships and interdependencies and perform scenario analyses	Must solve all models at once; increased complexity of holistic model requires simpler model components

[*] If optimized time-horizon is a single time period, the model can be considered a simulation model that uses an optimization computational engine.

Source: Harou et al. (2009, p. 634)

Figure 3: Conceptual flow diagram of an optimization-based HEM for a surface water system

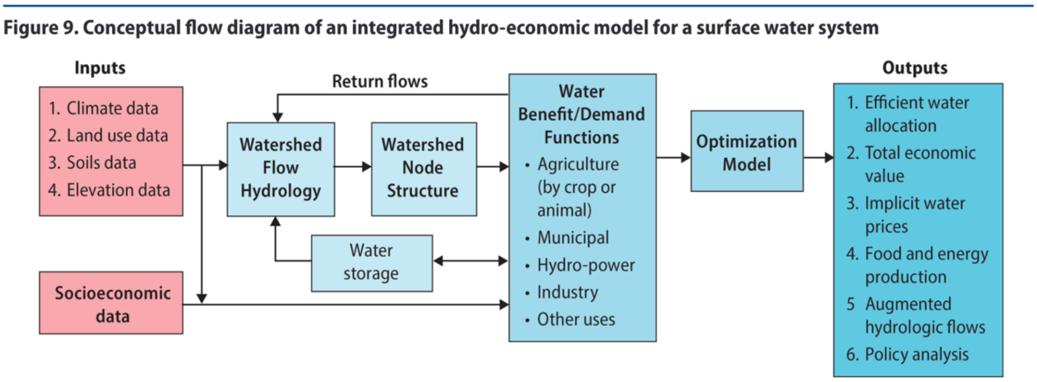
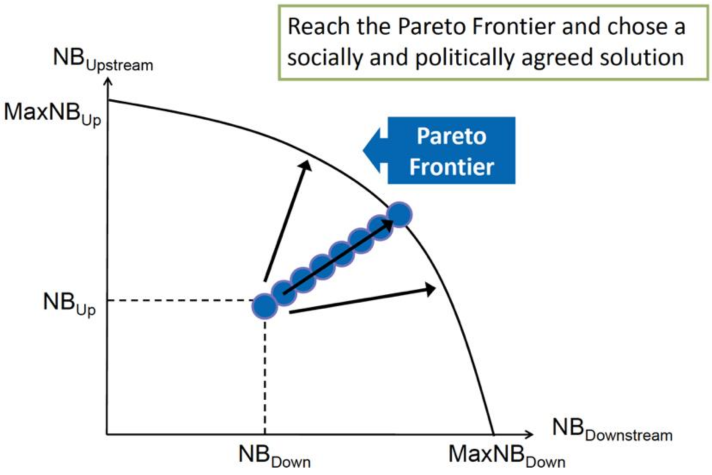


Figure 9. Conceptual flow diagram of an integrated hydro-economic model for a surface water system

Source: Baker et al. (2021, p. 11)

Figure 4: Pareto frontier for benefit maximization



Source: Casarotto (2018, slide 8)

3 Exemplary HEM application

In recent decades, several HEMs have been designed and implemented. Examples include the Nile Economic Optimization Model (NEOM) by Whittington et al. (2005), the Ganges Economic Optimization Model (GEOM) by Wu et al. (2013), the Colorado River CALVIN model by Newlin et al. (2002), among many others. For illustrative purposes, this section describes the development of a HEM in West Africa as an example.

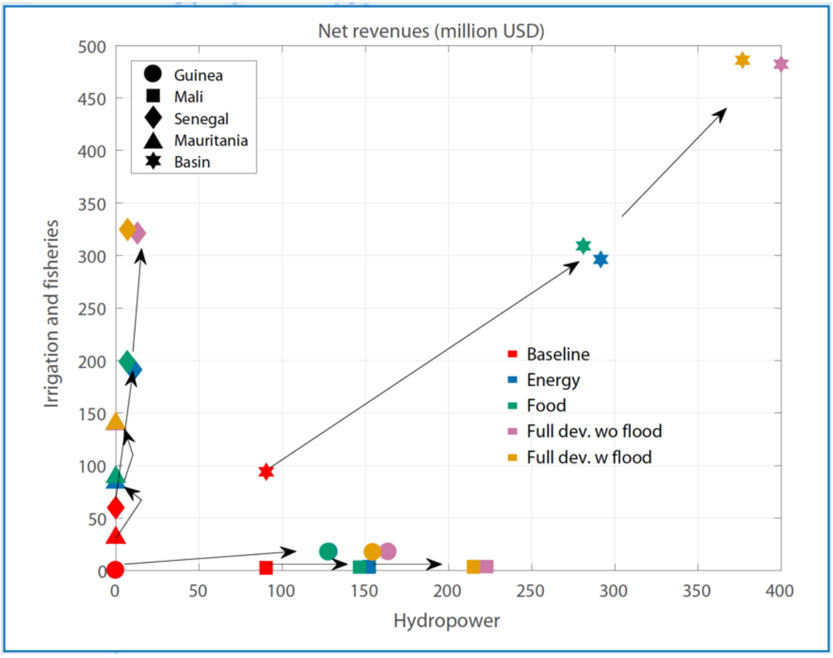
Salman et al. (2018) develop a HEM for the Senegal River basin as part of the Food and Agriculture Organization of the United Nations project “Enhanced Cross-boundary Water Resource Management in the Senegal River Basin”, which follows three main objectives, namely to improve the efficiency of transboundary water resources management, to promote agricultural development and food security. The Senegal River basin is a large transboundary watershed shared by four countries (Guinea, Mali, Mauritania and Senegal) and characterized by a high-flow (July to October) and a low-flow season (November to June). The high-flow season is prone to great year-to-year variability in river discharge, which poses a hydrological risk to water users such as subsistence farmers. The main water use sectors are (irrigation and flood recession) agriculture, fisheries, navigation (transportation) and, more recently, hydropower. As water resources are progressively stressed, the potential of HEMs to find efficient water allocation strategies and assess their impacts is becoming increasingly relevant in the basin.

According to the authors, benefit maximization in the Senegal River basin necessitates balancing between three hydro-economic principles. Firstly, in order to achieve efficiency and benefit maximization, water should be used where and when its user value is the greatest. In the Senegal River basin, this principle involves the weighting of multiple trade-offs between consumptive versus non-consumptive uses, instream versus offstream uses and immediate versus future uses. Secondly, water should be stored in reservoirs upstream during periods of excess supply. This principle allows – with lowest evaporation losses – to move water in times when water demand is greater than supply, thereby potentially generating significant basin-wide benefits. Thirdly, consumptive water uses should take place downstream after being used for non-consumptive purposes. This implies, for example, that irrigated agriculture as a consumptive water sector should be developed downstream and hydropower as a non-consumptive sector should be developed upstream. The developed HEM, now, solves the water allocation problem by balancing the discussed principles for three different development scenarios and four different management scenarios. The development scenarios (baseline scenario, development around 2030 & development around 2050) portray different levels of water resource commitment, the management scenarios (Food Security scenario focusing on agriculture-fisheries & Energy Security scenario focusing on energy and transportation) evaluate the consequences of setting different priorities for the main water use sectors, i.e., they highlight trade-offs. There are two more balanced management scenarios that are variants of the two extremes (Low Flood Extent scenario & Navigation scenario). Considering navigation, municipal and industrial uses, and the artificial flood as constraints, the model maximizes aggregate net benefits from hydropower and irrigated agriculture on a monthly time step.

The model shows that large increases in net revenues are possible through coordinated operation of the transboundary basin. As shown in Figure 5, respective to the status quo there is the potential of a threefold increase in the food sector and a fourfold increase in the energy production sector. Benefit distribution greatly dependence on the regions or countries natural endowments. In this case, Mali and Guinea, as upstream countries, have great potential for hydropower, while Senegal and Mauritania are naturally endowed increase yields in irrigated agriculture. Figure 6 and 7, which show simulated annual energy production values and recession agriculture cultivated areas for the three development levels, indicate that the absence of artificial flooding would have a significant negative impact on cultivated recession agriculture area, while hydropower production would only be reduced by maximally 7 percent. To sum up, there is room for significant improvements in the performance of the

Senegal River system through a coordinated operation. Importantly, a balancing of competing stakeholders is inevitable.

Figure 5: Potential of coordinated water resource management in the Senegal River basin



Source: Salman et al. (2018, p. 7)

Figure 6: Annual energy production for different management and development scenarios

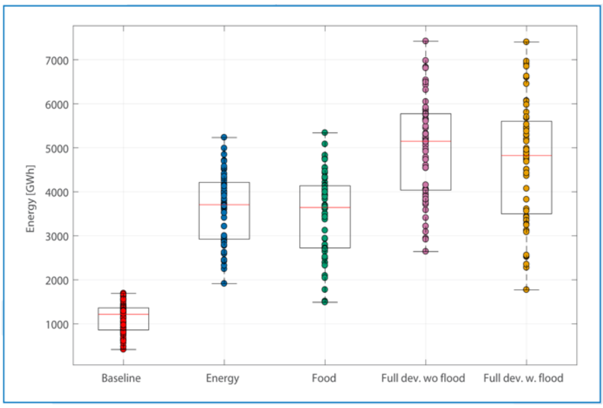
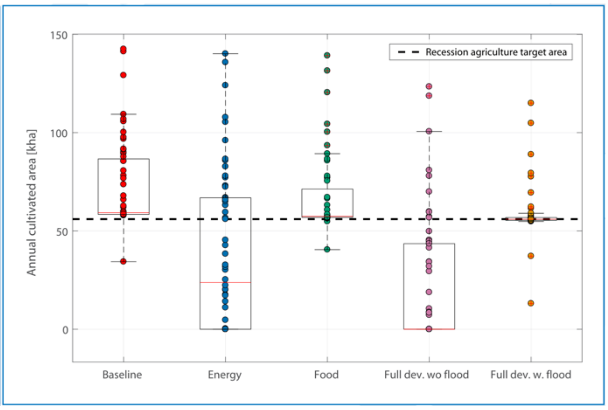


Figure 7: Annual cultivated area for different management and development scenarios



Source: Salman et al. (2018, p. 8)

4 Integrating ecosystem services in HEMs

The theoretical origins of HEMs date back to the 19th and 20th century. Although HEMs were first developed in arid regions of the USA and Israel in the 1960s, largely in context of the interdisciplinary Harvard Water Program, water engineers have already incorporated economic principles, primarily optimization, decades earlier (Bekchanov et al., 2017, p. 3; Harou et al., 2009, p. 628). Since their initial introduction, HEM have evolved from single-water use analysis at supply scale to integrate multiple-demand and multiple-source analysis over larger hydrologic regions (Momblanch et al., 2016, p.294). Researchers have continuously expanded the scope and modern models can incorporate aspects such as individual demand and supply components, governance and institutional conditions, and environmental values (Booker et al., 2012, p. 172). In sum, parallel to the advancements in associated sciences, the functions and potentials of HEMs have become more complex and sophisticated over time, now allowing for comprehensive analyses. The following section focuses on and specifically addresses the inclusion of environmental values based on the concept of ecosystem services.

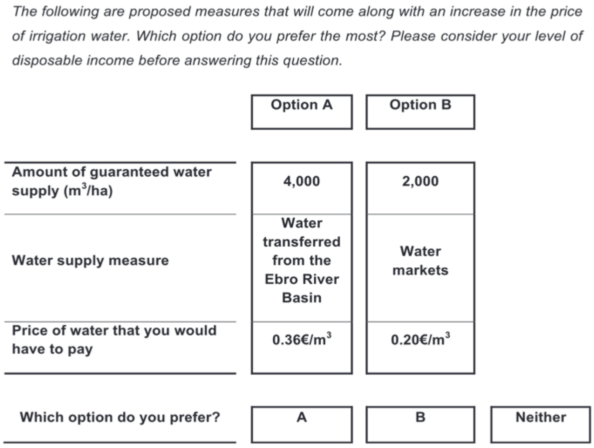
Ecosystem services (ES) can be relatively easy explained. They refer to the manifold diverse benefits that people obtain from ecosystems. Recognizing human dependance on ES for survival and quality of life can have major implications, and thus great potential for sustainability and environmental protection (Brauman et al., 2007, p. 68). For example, water systems create vital ES like water provision, disease control, recreation, fisheries, aquatic habitat provision, and other cultural services (Vollmer et al., 2022, p. 627). The indispensability of ES, as provided by hydrologic processes, to the maintenance and fulfillment of human life is evident. Although some ES are only substitutable at high economic cost or not at all, they can in principle be converted into economic, i.e. monetary, value (Momblanch et al., 2016, p. 294). Such conversions are based on valuation methods, which generate shadow prices (Alcon et al., 2014, p. 226). In the literature, economic valuation methods are commonly classified into six standard typologies: Market value, production-based, cost-based (replacement cost method, avoided cost method), revealed preferences (travel cost method, hedonic pricing), stated preferences (contingent valuation method, choice experiment method) and benefit transfer (Momblanch et al., 2016, p. 295-296). In the context of HEMs, all these can be used to produce a value function for different water uses and associated environmental benefits and costs (Momblanch et al., 2016, p. 296).

A valuation method is necessary in the first place because ES, like recreational values, are not usually traded on markets, and thus don't have a market price indicating opportunity costs. However, as Ward & Pulido-Velázquez (2008) note, pricing a good (water) at its real marginal costs, which encompasses full opportunity costs including environmental externalities, is crucial for efficiency. The assignment of a truthful monetary value to (water-)related ES, therefore, may significantly help to establish efficient (water use) practices. Moreover, recognizing full opportunity costs, i.e., including environmental externalities, is logically central for sustainability as well. Nonetheless, assigning monetary value can be a challenging task, especially when markets do not exist or are imperfect.

How reliably have ecosystem services been integrated into HEMs? Overall, it can be said that there is still much room for improvement in this respect. Momblanch et al. (2016, p. 294) summarize that review studies almost uniformly show the limited representation of environmental costs and benefits in HEMs. In agreement, Hossen et al. (2021, p. 1361) state that only few studies recognize environmental values and that environmental values of water are entirely missing in almost every reviewed application. Vollmer et al. (2022, p. 628) conclude that ES are only slowly gaining relevance in water resource management. One salient reason for the poor status quo might be the lack of sufficient data about associated environmental processes and values (Momblanch et al., 2016, p. 298). Consequently, Bekchanov et al. (2017, p. 14) emphasize that more effort should be directed towards understanding long-term linkages between water flows and the production of ecosystem services. Especially long-term impacts can be substantial or even irreversible.

Notwithstanding, there are numerous studies that implement nonmarket valuation methods. Which valuation technique should be used, depends on the ES to be valued (Souliotis & Voulvoulis, 2021, p. 41). In the field of water resource management, many valuation studies use a stated preferences approach and, more specifically, choice experiments (CE). Stated preference methods usually construct a hypothetical market scenario based on a questionnaire that, directly or indirectly, asks for respondents' willingness-to-pay (WTP) to avoid or obtain a change in environmental conditions. The WTP indicates the value to environmental assets (Kragt et al., 2011, p. 95). CEs, also known as discrete choice experiments, are a stated preference method that ask respondents to choose a preferred scenario in several choice questions. The systematic questioning enables the estimation of marginal values for different environmental attributes (Kragt, 2013, p. 7). Figure 9 and 10 present examples of a CE scenario.[5]

Figure 9: Exemplary choice set 1

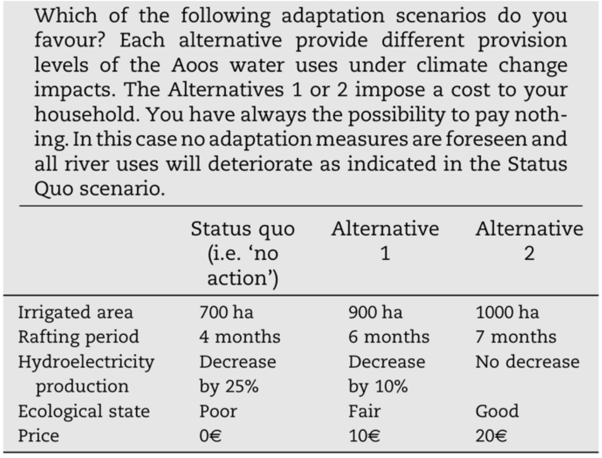


The following are proposed measures that will come along with an increase in the price of irrigation water. Which option do you prefer the most? Please consider your level of disposable income before answering this question.

	Option A	Option B	
Amount of guaranteed water supply (m^3/ha)	4,000	2,000	
Water supply measure	Water transferred from the Ebro River Basin	Water markets	
Price of water that you would have to pay	0.36€/m^3	0.20€/m^3	
Which option do you prefer?	A	B	Neither

Source: Alcon et al. (2014, p. 230)

Figure 10: Exemplary choice set 2



Which of the following adaptation scenarios do you favour? Each alternative provide different provision levels of the Aoos water uses under climate change impacts. The Alternatives 1 or 2 impose a cost to your household. You have always the possibility to pay nothing. In this case no adaptation measures are foreseen and all river uses will deteriorate as indicated in the Status Quo scenario.

	Status quo (i.e. 'no action')	Alternative 1	Alternative 2
Irrigated area	700 ha	900 ha	1000 ha
Rafting period	4 months	6 months	7 months
Hydroelectricity production	Decrease by 25%	Decrease by 10%	No decrease
Ecological state	Poor	Fair	Good
Price	0€	10€	20€

Source: Andreopoulos et al. (2015, p. 95)

Based on a CEs, Alcon et al. (2014) evaluate farmers' acceptance and adoption of supply and demand policy strategies to increase water supply reliability in Segura, Spain. Amadou and Youssoufou (2021) use CEs determine farmers' WTP and preference for climate change adaptation options. Andreopoulos et al. (2015), too, use CEs to quantify value changes of different ecological services following climate change impacts in the Greek Aoos basin. Barton and Bergland (2010) argue for CEs' potential to develop feasible pricing schemes and evaluate an irrigation water charge linked to frequency of irrigation. Chipfupa and Wale (2019) employ a CE to assess South African smallholder farmers' preference for irrigation water resource management. Conrad et al. (2017), focusing on Okanagan region of British Columbia, use CEs to investigate farmers' preference for different drought response policies. Houessionon et al. (2017), too, investigate farmers' preference and WTP for ES in Burkina Faso. Doherty et al. (2014) explore Irish residents' preference for several aquatic ES based on CEs. Khan et al. (2022) conduct CEs with 900 households in the Chinese Wei River basin to assess the WTP for improvements in ES.

In this context, water quality is an important parameter. Evidently, water quality is important for potable water supply. Beyond that, water quality is an essential factor in most other hydrologic services (Brauman et al., 2007, p. 77). Due to its importance, Momblanch et

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[5] See Kragt et al. (2011, p. 95) for some limitations of CEs.

al. (2016, p. 300) posit that water quality processes should be represented in HEMs and linked to valuation functions. Yet, numerous review studies agree that hardly any HEM application explicitly models water quality (Bekchanov et al., 2017, p. 8; Harou et al., 2009, p. 634; Momblanch et al., 2016, p. 294).[6] Although water quality can be modeled implicitly by accounting for additional costs or constraints, it is associated with an additional level of complexity, computational costs, and difficulty to quantify economic effects (Harou et al., 2009, p. 634). Again, more scientific progress is needed in understanding the linkages between water quality and economic values (Bekchanov et al., 2017, p. 14). Incorporating ES and especially water quality will be a particularly important endeavor for future research.

The following studies contain useful considerations of how HEMs and water quality issues can be addressed together. Baker et al. (2021) emphasizes that integrated water resource management and hence the use of HEMs have significant links and interactions with other key sectors of development, including agriculture and energy, among others. This interconnectedness is often referred to as the food-energy-water nexus (FEW). While HEMs explicitly account for trade-offs and synergies within the FEW nexus, water quality aspects, heavily influential in this context, are largely missing.[7] Therefore, the authors conclude that HEM frameworks need to be adjusted and expanded to incorporate the key parameter of water quality, for example, by equating aspects of water quality with those of water scarcity. Brouwer et al. (2008) develop an integrated water quality economic model that links a bio-geochemical water and substance flow model with an economic model. The authors' Applied General Equilibrium (AGE) model of the Dutch economy assesses the effects of the implementation of three different water quality policy scenarios. Gunawardena et al. (2018) take a look at the Kelani River in Sri Lanka, whose water quality has drastically deccreased as a consequence of industrialization and urbanization. They develop an integrated HEM consisting of a water quality and economic optimization model in order to determine the cost-effectiveness of a command-and-control (CAC) and market-based policies. Hao et al. (2020) present a HEM that can design cost-effective agri-environment schemes (AES) for nitrate and phosphate mitigation. Udias et al. (2016) develop an integrated HEM which is conceptualized to provide economically and environmentally optimal management options with respect to

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[6] See Bateman et al. (2006) for an example of explicit water quality modeling.

[7] Water quality may influence FEW aspects via many routes. For example, high salinity levels in irrigation water can reduce agricultural productivity. On the other hand, agriculture and energy production often negatively impact water quality (Baker et al., 2021, p. 31).

water use and water quality. Ward and Pulido-Velázquez (2008) develop a basin scale framework, integrating elements of hydrology and economics, and apply it to quantify trade-offs between efficiency, equity, and sustainability for different water pricing programs. Focusing on the Rio Grande Basin of North America, the authors assess the impact of both marginal cost pricing and two-tiered pricing under weak and strong water quality standards in an urban water supply. Kragt (2013) presents a HEM that integrates hydrology, ecology, nonmarket valuation in a Bayesian Network modeling framework, thereby accounting for system uncertainty. The integrated HEM developed for the George catchment in Tasmania allows an assessment of hydrological, ecological and economic values and specifically includes a (biophysical) modeling of water quality.

5 Combining HEMs and agent-based modeling

Agent-based models (ABMs) represent a bottom-up approach to emulate complex social systems based on the behavior of heterogeneous individuals and their interactions with one another and their environment. These autonomous agents can influence and learn from each other as well as adapt their behavior. In fact, the agent's behavior can be specifically encoded to mirror real-world conditions. Consequently, by decomposing real-world systems into autonomous social entities, ABMs can, in theory, provide authentic representations of complex social systems. A strength of ABMs is, therefore, their middle to low level of aggregation, or abstraction, which allows for realistic simulations of (system) dynamics between a large number of agents (Kahil et al., 2019, p. 77; Xie et al., 2021, p. 2).[8]

These characteristics make agent-based modeling a useful tool in the modeling of Socio-Ecological Systems (SESs). SESs combine natural and social components in an interactive manner, are dynamically very complex, and provide essential ES. While social actors and institutions have frequently been only implicitly represented in environmental models, incorporating adaptive agents, despite a few associated disadvantages, can be key to achieve a realistic model representation of a SES (Gotts et al., 2019, pp. 1-2, 11).[9] Kasargodu Anebagilu et al. (2021, p. 2), too, conclude that ABMs are a crucial tool for studying human-environment feedbacks. The incorporation of complex human interactive behavior has, within hydrology,

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[8] See Kasargodu Anebagilu et al. (2021, p. 2) for a short history of agent-based modeling.

[9] ABMs have problems with model transparency and validation. Furthermore, ABMs show limitations with capturing cross-scale interactions between different but potentially strongly interdependent levels (Gotts et al., 2019, pp. 2, 11).

led to the field of socio-hydrology. In socio-hydrological models, either groups of people (sectors, villages) or single water users (person, household) are defined as agents and can be used to better understand complex aspects of water management (Arasteh & Farjami, 2021, p. 1; de Bruijn et al., 2022, pp. 2-3). HEMs, now, can serve as linker platforms for different models. This linkage with ABMs can, beyond the optimized behavior, provide a realistic representation of complex social systems in HEMs such as water allocation among sectors or water sharing mechanisms between agents (Kahil et al., 2019, pp. 76-77).[10] In other words, since HEMs are suboptimal tools for simulating actual water markets due to their inability to incorporate individual behavior and transaction costs, combining them with an ABM can effectively fill this gap (Harou et al., 2009, p. 638).

A number of agent-based models have been developed in the field. Aghaie et al. (2020) introduce an agent-based groundwater model, consisting of a decision-making sub-model and a groundwater sub-model, to analyze economic and hydrologic impacts of different cap-and-trade scheme market mechanisms and water buyback programs. 200 farmers and one government agent are defined as agents, which interact in a (ground-)water market. Results are applied to the Rafsanjan Plain in Iran. Also focusing on an Iranian Plain, the highly water-scarce Yazd Plain, Arasteh & Farjami (2021) combine agent-based methods with system dynamics methods to test hydro-economic strategies for drinking water demand management. Figure 4 shows the complex relationship among system variables in their HEM. Kuhn (2016) applies the simulation-based HEM LANA-HEBAMO to assess the viability of water management institutions at Lake Naivasha in Kenya. They try to incorporate multiple, non-cooperative agents by using the multiple-optimization solution format MOPEC, which they classify as a simultaneously-solving ABM. Ding et al. (2021) assess the ability of three policies to sustainably provide food-energy-water services to different stakeholders in Cape Town, South Africa. The coupled human-natural system model involves an ABM simulating water policy and demand as well as a regional hydrological model. Evaluating the potential of small-irrigation development in Sub-Saharan Africa, focusing on Ethiopia, Xie et al. (2021) develop an agent-based irrigation model and combine it with a Soil and Water Assessment Tool (SWAT) model. The goal is to establish an approach to mapping national development potential for

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[10] Importantly, a market-based allocation of water resources is a complex system with heterogenous autonomous water users connected through the common resource of ground or surface water. Water mater institutions, including water markets, can therefore appropriately be analyzed and assessed on agent-based frameworks (Aghaie et al., 2020, p. 1).

small-scale and dry-season irrigation. Giordano et al. (2021) address nature-based solutions, such as wetland restoration, watershed restoration, or the creation of groundwater recharge areas, and how to overcome barriers to collaborative implementation. They apply a combination of Social Network Analysis together with a hybrid AMB/System Dynamic Model. Kasargodu Anebagilu et al. (2021) examine the interaction between farmers' attitudes and behaviors towards the natural environment to adjust environmental policies while optimizing environmental criteria. Focusing on farmers around the Larqui River basin in Chile, the authors couple an ABM with an agro-hydrological model for vegetative filter strips. de Bruijn et al. (2022) develop a coupled agent-based hydrological model, called the Geographical, Environmental and Behavioural model (GEB), to simulate large-scale hydrological processes and the interactive behavior of more than ten million individual farm households with the hydrological system. The model is used to simulate farmer's adaptive patterns to water stress.

Figure 9: Causal loop diagram of system variables in HEM

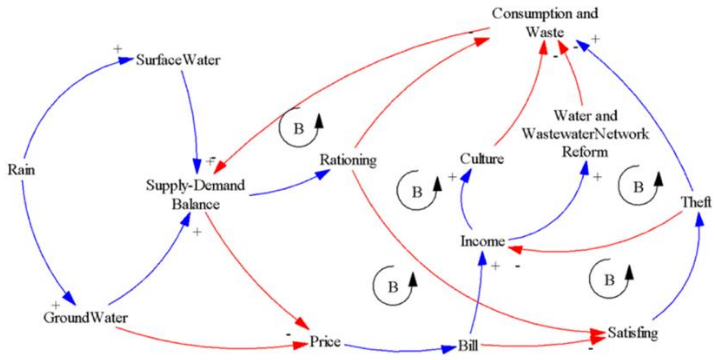

Fig. 8. The causal loop diagram of the model.

Source: Arasteh & Farjami (2021, p. 3)

6 Conclusion

As the review shows, hydro-economic models have been applied in a broad variety of cases helping to better understand water scarcity problems and to inform decision makers about management actions that could help to reduce the scarcity and improve the allocation of water to those uses that would generate the largest benefits. One research gap that still exists is the incorporation of ecosystem services and their economic value into hydro-economic models. One approach to achieve this would be to use non-market valuation techniques as developed in environmental economics. The output generated by those valuation techniques to correct water price to reflect not only the value due to market transactions but also the non-market value. Consequently, this would likely change recommendations for an efficient use of water. Empirical applications would have to show to what extent this takes place. Another interesting avenue for future research would be the combination of hydro-economic models and agent-based modelling. Agent-based models would allow to investigate to what extent cooperation among agents, be it farmers or private households, for example, influences the use of water resources. Often, cooperation among agent is essential for achieving sustainable solutions, and only relying on standard economic approaches that focus on individuals as isolated agents would fall short.

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