DAFNE

A **D**ecision-**A**nalytic **F**ramework to explore the water-energy-food **NE**xus in complex and transboundary water resources systems of fast growing developing countries

FUTURE DRIVERS AND SCENARIOS

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List of major abbreviations

AWE-GEN-2d: Stochastic gridded weather generator

CO2 eq.: Carbon Dioxide equivalent

CS: Case Study (catchment)

D2.1: Deliverable 2.1

D3.3: Deliverable 3.3

DAF: Decision Analytic Framework

DoA: Description of Action (Annex I of the Grant Agreement)

EC: European Commission

ETo: Reference evapotranspiration

FC: Factors of Change

GA: Grant Agreement

GCM: General Circulation Model

GHG: Greenhouse Gas

ITCZ: Intertropical Convergence Zone

LU: Land unit

MMM: Multi-Model Mean (climate model ensemble)

OTB: Omo-Turkana Basins

PIP: Participatory and Integrated Planning

RCM: Regional Climate Model

RCP: Representative Concentration Pathway

SDG: Sustainable Development Goal

SSP: Shared Socio-economic Pathway

WP: Work package

ZRB: Zambezi River Basin

1. INTRODUCTION

The stated aim of this deliverable is to produce a report synthesising geo- and temporally-referenced scenarios of future climate and water availability, demand for water, energy, and food, and economic and policy development in the Omo-Turkana (OTB) and Zambezi (ZRB) river basins.

The future scenarios we consider are conceptually driven by the selected combination of Shared Socio-economic Pathways (SSP), Representative Concentration Pathways (RCP), and further refined by implementation in the modelling chain of the most likely set of future actions identified during the Participatory and Integrated Planning process (PIP) with basin stakeholders (refer to deliverable D5.1). The SSPs define the most likely directions of population and the economy, which in turn places demands on the agricultural sector and environmental services, generating a water requirement to sustain the needs of the various sectors. The RCPs, in conjunction with hydrological models, essentially describe the availability of water in the context of climate change to meet the requirements of the sectors within the WEF nexus.

In order to elaborate and test our methodology (in particular to learn how we should set up the modelling tool-chain in the case study basins), we focus first on a most likely “middle of the road” future (SSP 2 with RCP 4.5). This will be expanded to include additional SSP/RCP combinations (as outlined in chapter 8) if this is motivated by our first results.

The chapters in the remainder of this report elaborate the different sectors of the WEF nexus, and their interdependencies. Chapter 2 describes and quantifies the demographic and economic developments in the study basins as a consequence of selected SSP2 trajectory. In chapter 3 we introduce the climate and hydrologic scenarios produced based on the RCP4.5 emission scenario. Subsequently, in chapters 4, 5 and 6, the expected impacts on agriculture, environmental services and hydropower generation of the SSP2 and RCP4.5 combination are assessed, both in respect of changing production (food, services, power) and possible structural actions within the basins to cope with shortfalls in water availability (or take advantage of excess). Chapter 0 describes the envisioned policy frameworks that are in place, or could be used to ensure continued fair and equitable water use amongst the riparian states (and their trading partners). The last chapter will summarize the set of future drivers and scenarios to be considered in the subsequent work.

2. DEMOGRAPHIC AND ECONOMIC DEVELOPMENT

2.1 METHODOLOGY

The research describes socio-economic scenarios comprised of two core elements; a storyline and the table of descriptors. In other words, the scenarios refer to a qualitative narrative describing a potential future in combination with quantitative socio-economic elements and trends. The research adopts the shared socio-economic pathways (SSPs) developed by Kriegler et al. (2012). All of them consider mitigation and adaptation policies regarding climate change in the context of different scenarios and each scenario is depicted by a storyline of a different future, as explained further below. In order to capture the climate change impacts in the SSPs, RCP 4.5. is selected and integrated in the scenarios of interest (Table 1). RCP 4.5 assumes that the carbon dioxide concentration will reach 650 CO2 eq. and that radiative forcing is stabilized at approximately 4.5 W/m^2, which both will be stabilized after 2100 (Wayne, 2013).

As presented by O’Neil et al. (2013) all pathways are followed by a number of assumptions enhancing their storyline. In brief, the SSP1 represents the sustainability scenario, where the technological change is rapid with the development goals being achieved while a path of sustainability that moves towards a less intensive use of resources is followed including lower carbon energy sources and high productivity of land. On the other side, SSP5 illustrates a fossil-fuelled economy, where in the absence of climate policies, energy demand is high and most of this demand is met with carbon-based fuels. Investments in alternative energy technologies are low, and there are few readily available options for mitigation. However, economic development is relatively rapid and itself is driven by high investments in human capital. Improved human capital also produces a more equitable distribution of resources, stronger institutions, and slower population growth, leading to a less vulnerable world better able to adapt to climate impacts.

The SSP2 or the Business-as-usual pathway follows a pattern of action that is consistent with the experience of the last century. In particular, the world follows a path in which social, economic, and technological trends do not shift remarkably from historical patterns. Socio-economic progress and per capita income growth proceeds unevenly, with some countries developing rapidly while others fall short of expectations. Although sustainable development goals are a priority for global and national institutions, they make slow progress in achieving. Environmental systems degrade, although there are some advancements and overall the intensity of resource and energy use declines. Global population growth is increasing steadily across the 21st century. Income inequality persists or improves only slowly and challenges to diminishing vulnerability to societal and environmental changes remain.

In this section we will explicitly present the SSP2 through a number of socio-economic indexes projected and analysed, while SSP1 and SSP5 will be discussed qualitatively at the end of each chapter in comparison with the baseline, i.e. SSP2. To stay as close as possible to the storyline of the SSPs, the main trends and assumptions have been downscaled for each scenario in Table 1. For example, population growth in SSP2 is assumed to be moderated, while the other two scenarios assume that the growth rate will be lower indicating a gentler slope. More details regarding the downscaling of the SSPs are provided within the following sections.

Table 1 – Summary of the main trends in important factors in the SSPs

Factor	**SSP1**	**SSP2**	**SSP5**
Population growth	Low	Medium	Low
Urbanisation	High	Medium	High
Education level	High	Medium	High
Equity	High	Medium	High
Economic growth	High	Medium, uneven	High
Globalisation	Connected	Semi-open globalised	Strongly globalised
Policy focus	Sustainable development	Weak focus on sustainability	Free markets, human capital
Institutions	Effective	Modest effective	Effective
Technology development	Rapid	Medium, uneven	Rapid
Energy sources	Renewables	Fossil fuels	Fossil fuels
Energy intensity	Low	Uneven	High
Environmental impacts (Policy Focus)	Low	Continued degradation	Highly engineered
Challenge to mitigation (Policy Focus)	Low	Medium	High
Challenge to adaptation (Policy Focus)	Low	Medium	Low
Natural Capital (Policy Focus)	Very High	Medium/Low	Medium
Manufactured Capital (Industry)	High	Medium	High
Financial Capital (Industry/GDP)	Medium/High	Medium	Very High
Social Capital	High	Medium	Very High
Human Capital	Medium/High	Medium	Very High

The two DAFNE case studies will be explored: the Zambezi River Basin (ZRB) and the Omo-Turkana Basin (OTB). The time horizons for both case studies are the periods from 2018 to 2060 for ZRB and from 2018 to 2100 for OTB. Firstly, demographic projections will be exploited at different scales (sub-basin, city and country level). Except for the population projections, water, food and electricity use, forecasting will be computed as well for each scenario, while in the following section economic indicators, such as GDP growth, trade to GDP ratio, GDP composition, employment per sector and energy needs, will be predicted aiming to create a clear image of the long-term future of these riparian countries.

2.2 ZAMBEZI RIVER BASIN

2.2.1 Demography

Population projection by country

The Zambezi River Basin is shared by eight riparian countries, each with a different area within ZRB. Zambia has the biggest share followed by Angola, Zimbabwe and Mozambique (see Figure 1). In this section we aim to estimate the population within ZRB by considering social factors such mortality, fertility and international and internal migration for the period from 2018 to 2050. Firstly, we consider the SSP2 as a reference scenario, which represents the middle of the road assuming that population fertility is medium and that the urbanization level is medium. At the end, we also examine the other two socioeconomic pathways, SSP1 and SSP5 as a comparison to SSP2.

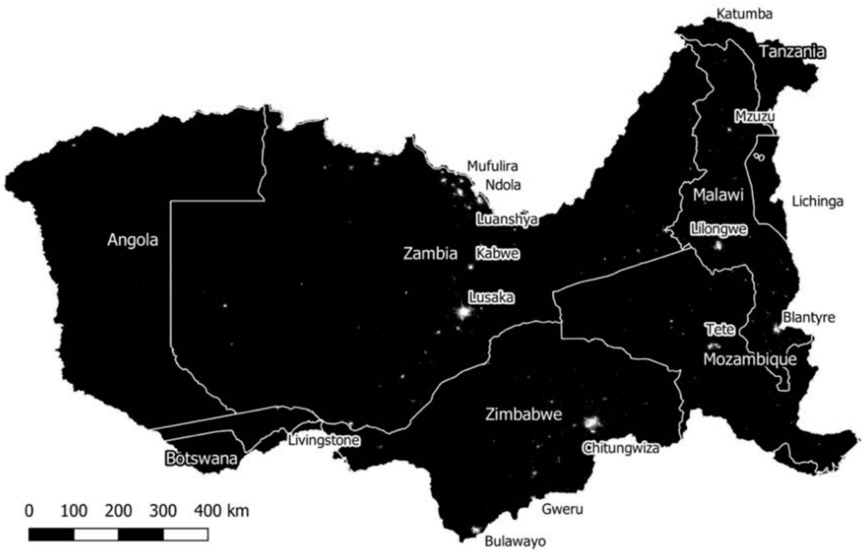

Figure 1 – Night Light Intensity across the ZRB (Source: Linard et al., 2012; Worldpop, 2015)

Population growth by country is estimated and presented in Figure 2. In order to calculate those trends, a simple model with one lag considering the values of the previous year and the annual population growth rates per country was run. Hence, a comprehensive and transparent selection of the growth rates was an important stage of this exercise, due to its impact on the future trends. After comparing a number of resources such as CIA (2019), the World Bank (2018), World by map (2017) and World atlas (2018), growth rates provided by United Nations (2017) seem to have the most transparent and analytical approach. A crucial benefit of this report is not only the 100-year forward looking, but the time slice of the predictions to 5-year periods, which enables projections to be comparatively more accurate. United Nations (2018a) revision considers various parameters in estimating the population prospects of each country such as mortality and fertility rates and international migration. As a result, ten variants are presented under different assumptions with the one with constant mortality being the most adequate for our analysis under the SSP2 scenario, as it is the most moderate one assuming normal international migration and medium fertility rates. Moreover, the estimations of this variant are in alignment with the rough estimations of the institutions listed above.

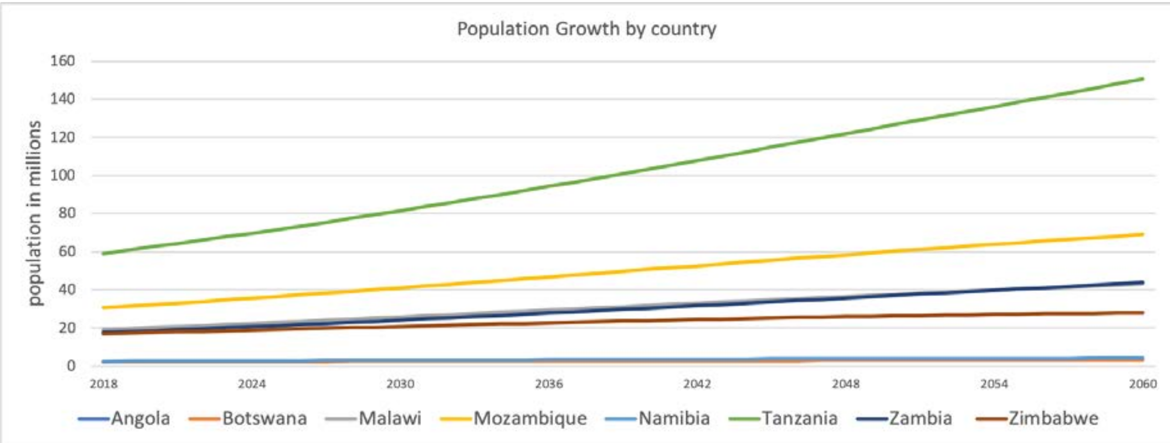

Figure 2 – Population Growth in ZRB by country

In Tanzania, population is proceeding apace in the next 40 years and it is expected to more than double, reaching almost 150 million people, which is of exceptional importance. However, such an enormous population increase will be accompanied by high concentration in major urban cities. Although only one urban city of Tanzania[1], Katumba, located at the borders of Malawi, is identified with ZRB area, intra-urban agglomeration effects may be noticed increasing claims over the water use of the river. Moreover, Malawi and Zambia, which together have as many inhabitants within ZRB as the rest of the countries jointly, seem to follow similar growth trends starting from 20 million and 18,6 million respectively and exceeding 43 million people each by 2060. Hence, the increased demand for water from half of the ZRB population is not increasing rapidly in the following 30 years leaving space for innovation and precautions.

Population projection by urban centres

Major urban centres are outlined by large populations, intensive economic activity and infrastructural development, which inevitably impose a significant strain on natural resources and especially water. In alignment with Deliverable 2.1, Table 2 presents the major urban centres with population greater than 100,000 of each country. Of the 56 urban centres identified, nineteen are geographically located within the boundaries of the ZRB.

Table 2 – List of major urban centres in ZRB countries and their 2018 populations: ZRB Urban centres in italic (Source: World Population Review, 2018)

Country	City Name	Population (2018)	Location link	Coordinates	
Angola	Luanda	2,776,168	Link	-8.83682	13.23432
	N'dalatando	383,100	Link	-9.29782	14.91162
	Huambo	226,145	Link	-12.77611	15.73917
	Lobito	207,932	Link	-12.36440	13.53601
	Benguela	151,226	Link	-12.57626	13.40547

[1] Urban centres are considered cities with a population greater than 100,000 inhabitants.

(Table 2 continued)

	Cuito	113,624	Link	-12.38333	16.93333
	Lubango	102,541	Link	-14.91717	13.49250
Botswana	*Gaborone*	*208,411*	Link	*-24.65451*	*25.90859*
Malawi	*Lilongwe*	*646,750*	Link	*-13.96692*	*33.78725*
	Blantyre	*584,877*	Link	*-15.78499*	*35.00854*
	Mzuzu	*175,345*	Link	*-11.46556*	*34.02071*
Mozambique	Maputo	1,191,613	Link	-25.9655	32.5832
	Matola	675,422	Link	-25.9622	32.4589
	Beira	530,604	Link	-19.8436	34.8389
	Nampula	388,526	Link	-15.1165	39.2666
	Chimoio	256,936	Link	-19.1164	33.4833
	Nacala	224,795	Link	-14.5626	40.6854
	Quelimane	188,964	Link	-17.8786	36.8883
	Tete	*129,316*	Link	*-16.1564*	*33.5867*
	Xai-Xai	127,366	Link	-25.0519	33.6442
	Maxixe	119,868	Link	-23.8597	35.3472
	Ressano Garcia	110,000	Link	-25.4428	31.9953
	Lichinga	*109,839*	Link	*-13.3128*	*35.2406*
	Pemba	108,737	Link	-12.9740	40.5178
Namibia	Windhoek	268,132	Link	-22.55941	17.08323
Tanzania	Dar es Salaam	2,698,652	Link	-6.82349	39.26951
	Mwanza	436,801	Link	-2.51667	32.90000
	Zanzibar	403,658	Link	-6.16394	39.19793
	Arusha	341,136	Link	-3.36667	36.68333
	Mbeya	291,649	Link	-8.90000	33.45000
	Morogoro	250,902	Link	-6.82102	37.66122
	Tanga	224,876	Link	-5.06893	39.09875
	Dodoma	180,541	Link	-6.17221	35.73947
	Kigoma	164,268	Link	-4.87694	29.62667
	Moshi	156,959	Link	-3.35000	37.33333
	Tabora	145,292	Link	-5.01622	32.82663
	Songea	126,449	Link	-10.68333	35.65000
	Musoma	121,119	Link	-1.50000	33.80000
	Iringa	111,820	Link	-7.76667	35.70000
	Katumba	*108,558*	Link	*-9.23333*	*33.61667*
	Shinyanga	107,362	Link	-3.66393	33.42118
Zambia	*Lusaka*	*1,267,440*	Link	*-15.40669*	*28.28713*
	Kitwe	*400,914*	Link	*-12.80243*	*28.21323*
	Ndola	*394,518*	Link	*-12.95867*	*28.63659*
	Kabwe	*188,979*	Link	*-14.44690*	*28.44644*
	Chingola	*148,564*	Link	*-12.52897*	*27.88382*
	Mufulira	*120,500*	Link	*-12.54982*	*28.24071*
	Luanshya	*113,365*	Link	*-13.13667*	*28.41661*
	Livingstone	*109,203*	Link	*-17.84194*	*25.85425*

(Table 2 continued)

Zimbabwe	*Harare*	*1,542,813*	Link	*-17.82772*	*31.05337*
	Bulawayo	*699,385*	Link	*-20.15000*	*28.58333*
	Chitungwiza	*340,360*	Link	*-18.01274*	*31.07555*
	Mutare	*184,205*	Link	*-18.97070*	*32.67086*
	Gweru	*146,073*	Link	*-19.45000*	*29.81667*
	Epworth	*123,250*	Link	*-17.89000*	*31.14750*

Figure 3 illustrates the population projections by major cities within ZRB, with Lusaka (Zambia) and Harare (Zimbabwe) reaching 3,1 million and 2,5 million people by 2060. Those trends are calculated following the same methodology described above. Moreover, the most populated cities belong to Zambia, Zimbabwe and Malawi, with cities located in Mozambique and Tanzania following less vigorous growth. Angola, Botswana and Namibia are not represented in the graph, since none of their major cities is placed within ZRB area. However, the graph does not include urbanization rates, which would make those trends steeper and so the demand for water more intense.

Moreover, we should consider non-major cities lying within ZRB, which are expected to increase in size. Following the same methodology described above, projections on the population of non-major cities for the period from 2018 to 2060 is derived. As presented in Figure 4, there is a number of centres, which are meeting the requirement of having more than 100,000 inhabitants sooner or later. In particular, some cities such as Kwekwe (Zimbabwe), Chipata (Zambia) and Sambawanga (Tanzania) will exceed 100,000 people in less than 6 years, with Chipata and Sambawanga exceeding 200,000 people by 2060. In alignment with the findings above, Angola, Botswana and Namibia tend not to have any major or non-major cities within the basin and the majority of cities are part of Zambia.

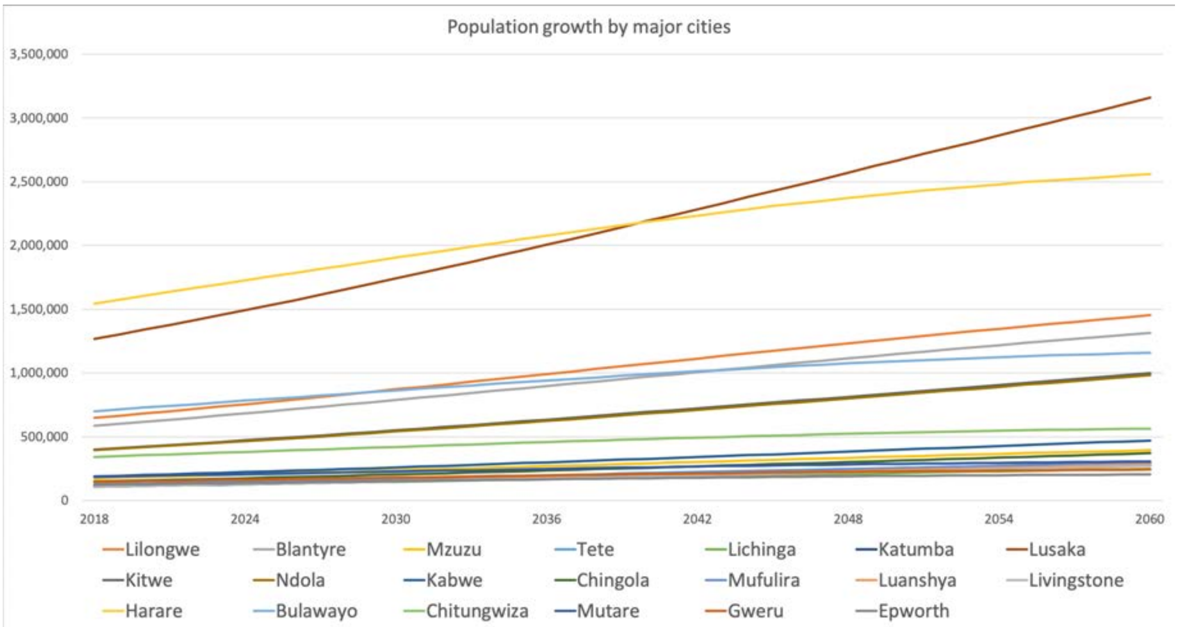

Figure 3 – Population growth in ZRB by major cities

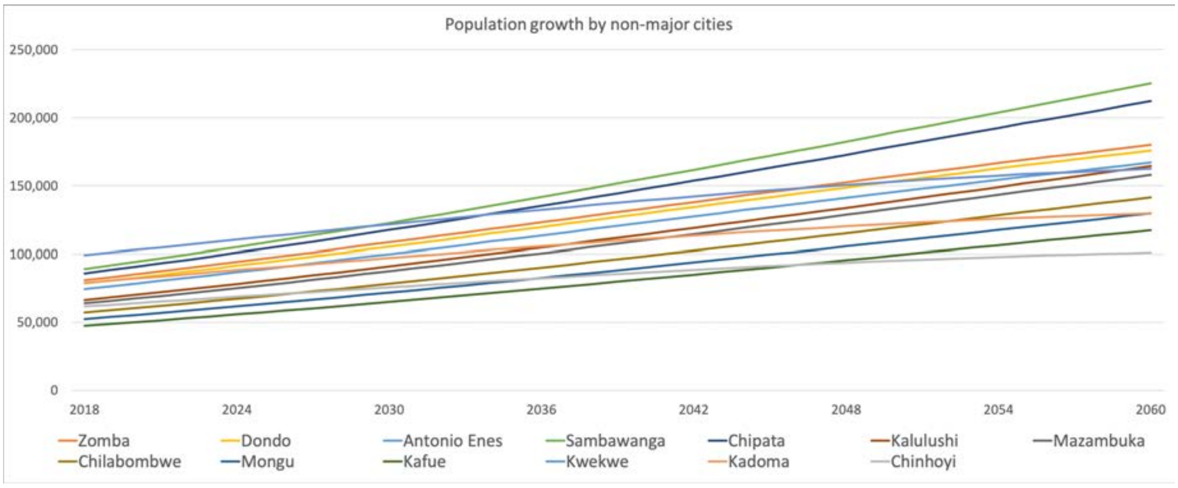

Figure 4 – Population growth by non-major cities

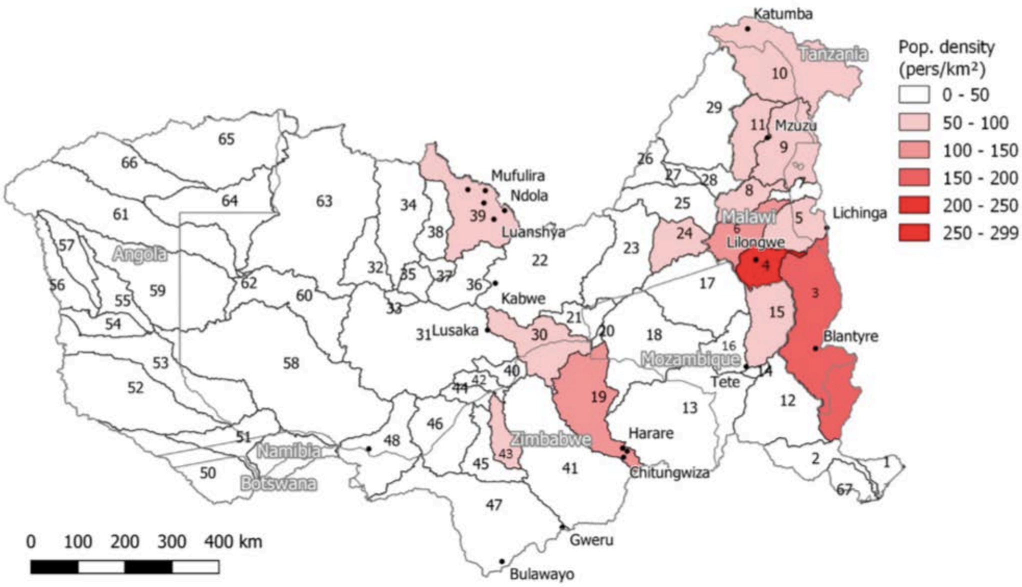

Figure 5 – Current population density per sub-basin within the ZRB (Source: Linard et al., 2012; Worldpop, 2015).

Population projection by sub-basin

Population distribution within the ZRB was computed by first disaggregating the river basin into the 67 Pfaffstetter level 5 river sub-basins within the ZRB (see Figure 5). The population growth per sub-basin was estimated without considering internal migration, but only the United Nations (2018a) assumptions (constant mortality, normal international migration and median fertility). However, in order those rates to correspond to each sub-basin, they were primarily ranked by the country they are placed into. A significant challenge at this point was to determine which growth rate should be used in case of a sub-basin lying into two or even three different countries as illustrated in Figure 5, which is being derived from Deliverable 2.1. The approach followed in this example was to use the rate of the country, which had the greatest share in the sub-basin shared by multiple countries. A possible harm of this approach is to weight unequally the influence of one country over the other. However, the benefits outweigh the costs of this approach, since in total unequal weights occur for the advantage of all the countries due to the large amount of sub-basins located in more than one country. Moreover, the fact that the growth rates are changing every 5 years means that any other approach would be even more complicated without a significant impact. The results of this prediction are illustrated in Figure 6.

A remarkable outcome of Figure 6 is that the total population within the sub-basin is expected to reach 96 million people by 2060, twice as much as its current status. Looking deeper at Figure 6, it is clear that the sub-basin 3 located in both Malawi and Mozambique, is increasing more than any other sub-basin reaching 15,8 million people by 2060, which is as high as the one third of the current population living within ZRB. Only three sub-basins (4,10 and 31) are slightly exceeding 6 million people by 2060, while the rest of the sub-basins do not exceed 6 million people with the majority lying under 1 million people each.

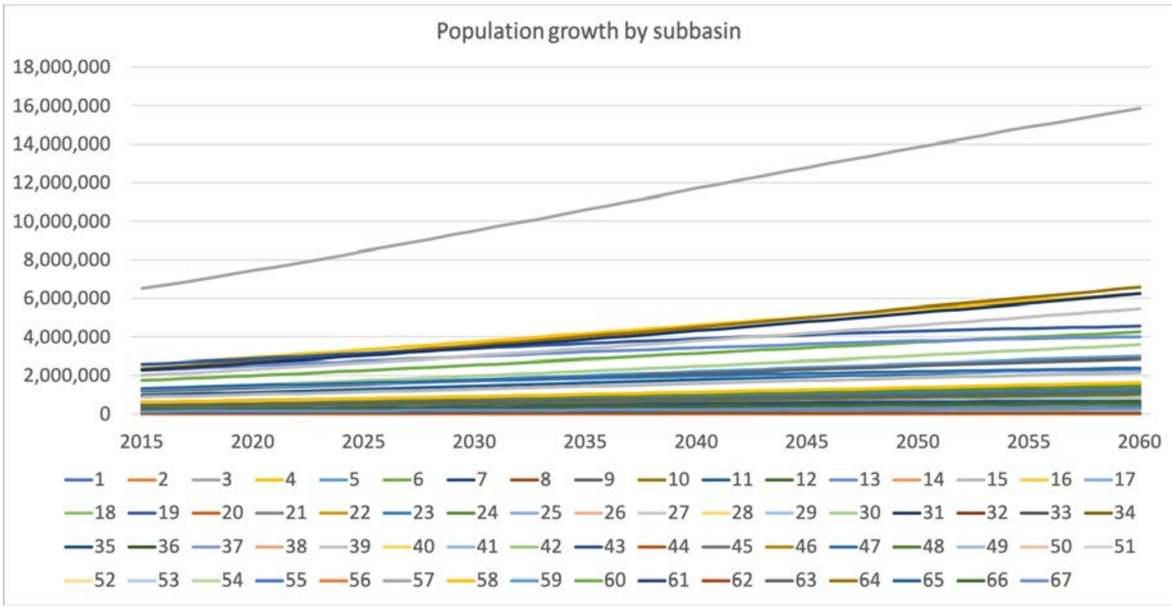

Figure 6 – Population projection in ZRB per sub-basin (internal migration is not considered)

However, the estimated rates described above do not capture internal migration. Urbanization, which is proceeding apace in African countries, is an accurate index to capture internal migration, since it captures the flow from rural to urban areas during a given period of time (The World Bank, 2018). The impact of urbanization can be controversial, as it is accompanied by both benefits and costs. On the one hand, the benefits should combine more diverse and improved employment opportunities, better accommodation and basic services, an ample choice of goods and services and generally a better living standard. On the other hand, the costs include congestion, overcrowding, resources scarcity to provide basic services, health hazards and more crime (Wenban-Smith, 2015). All these parameters have an impact on the distribution of the people within the country, since when the congestion costs outmatch the benefits, the development of secondary towns becomes an interesting alternative.

After comparing the urbanization rates of the World Bank (2018) and United Nations (2018b), the former view of UN was preferred, since the World Bank provided estimations on the percentage of inhabitants living in the cities, which incorporated population growth projections according to their assumptions, while UN declared the annual change of the urban population in each country. In order to incorporate the urbanization rate and the population growth in our projections per sub-basin, we need to divide the 67 sub-basins into rural and urban areas using urban mapping projections by SEDAC (2018). However, one challenge of this stage was the fact that some sub-basins were located in two to three countries with one rural and one urban side. In this case, no change is attributed, since the change in population, which migrated from the rural area equalizes the change in population in the urban area, as the urbanization rates of most of the African countries of interest are lying in a range between 3% and 4%. Lastly, since the urbanization rates estimated by the

United Nations (2018b) are projected until 2050, it is assumed that the urbanisation rates in the period 2050 to 2060 are as high as their corresponding values in the period 2045 to 2050.

By 2060, the total population living within ZRB is expected to reach 102 million people, which is approximately 3 percent greater than the expected population if no urbanisation would occur. Figure 7 presents the final population expectations per sub-basin incorporating assumptions over mortality, fertility, international and internal migration variants for the period 2015 to 2060. Sub-basin 3, which is identified as an urban area, is expected to grow even more reaching 16.5 million people by 2050, which is more than double than its current population. The rest of the sub-basins get normalized after considering rural- and urbanization growth rates following so, similar paths. Sub-basins 4, 10 and 31 located in Malawi, between Tanzania and Malawi and in Zambia correspondingly will reach 6.5, 6.8 and 6.4 million people each by 2060, due to the high urbanization rates in these countries which are responsible for a 200,000 to 300,000 increase in each area.

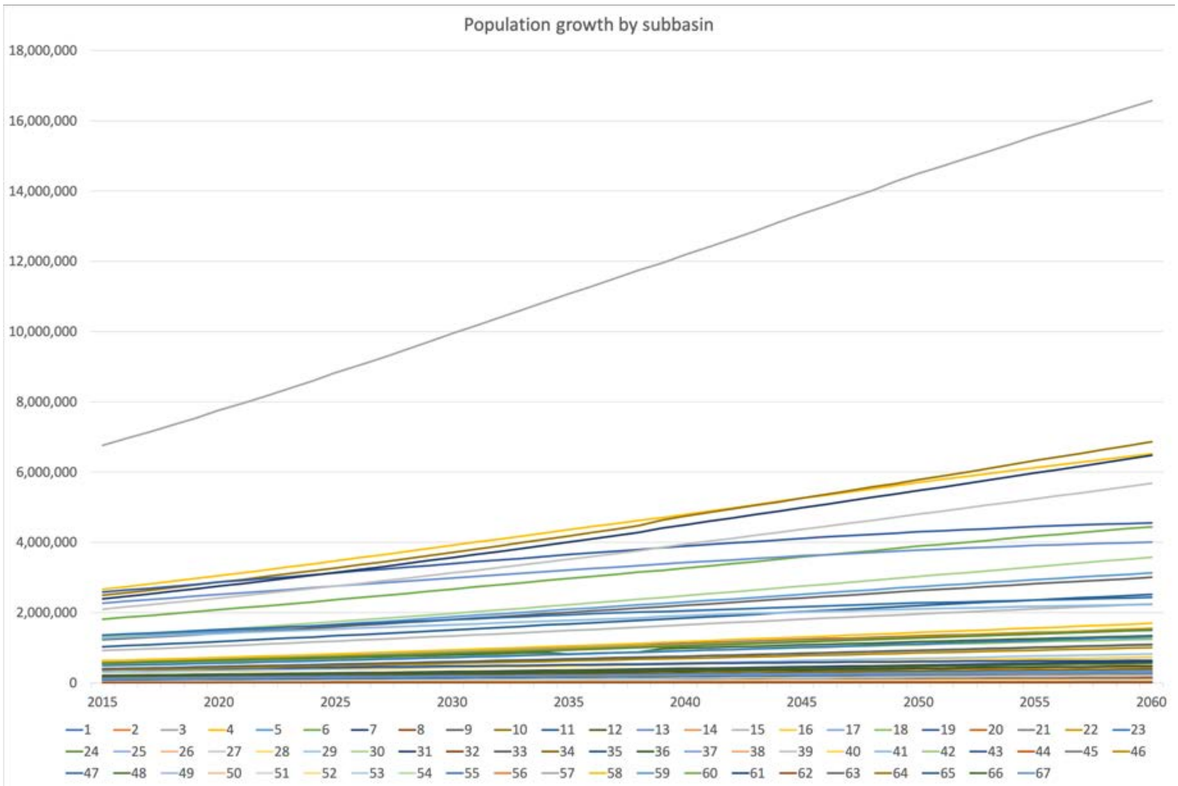

Figure 7 – Expected population in ZRB with urbanization by sub-basin

2.2.2 Water consumption by private households

Withdrawals for domestic uses include drinking water, municipal use or supply, and use for public services, commercial establishments and homes. In this section we estimate the water consumption in the domestic sector for each country and sub-basin within the ZRB for the period from 2016 to 2060. Data from Deliverable 2.1 for the annual water use per capita for each country within the ZRB and the demographic projections per country's share in ZRB and per sub-basin with urbanization assumptions have been used to compute the projected water consumption by private households, where average water use per capita is multiplied with the population of each subbasin. In the event of a sub-basin being shared by two or three countries with different water consumption rate, we computed the average consumption of those countries, and then, we multiplied it with the population of the sub-basin.

As presented in Figure 8 and Figure 9 water use is expected to increase dramatically if we only consider the demographic growth of the riparian countries. Specifically, the total water use within

ZRB is expected to reach 1,8 billion m^3 by 2060, while now it is about 0,8 billion m^3. What should be pointed out is that households in Zambia and Zimbabwe consume more water than Malawi and Mozambique, although they are not dominating demographically within the basin, constituting 25% and 17% of the total population of the basin with the latter two occupying 29% and 24% respectively.

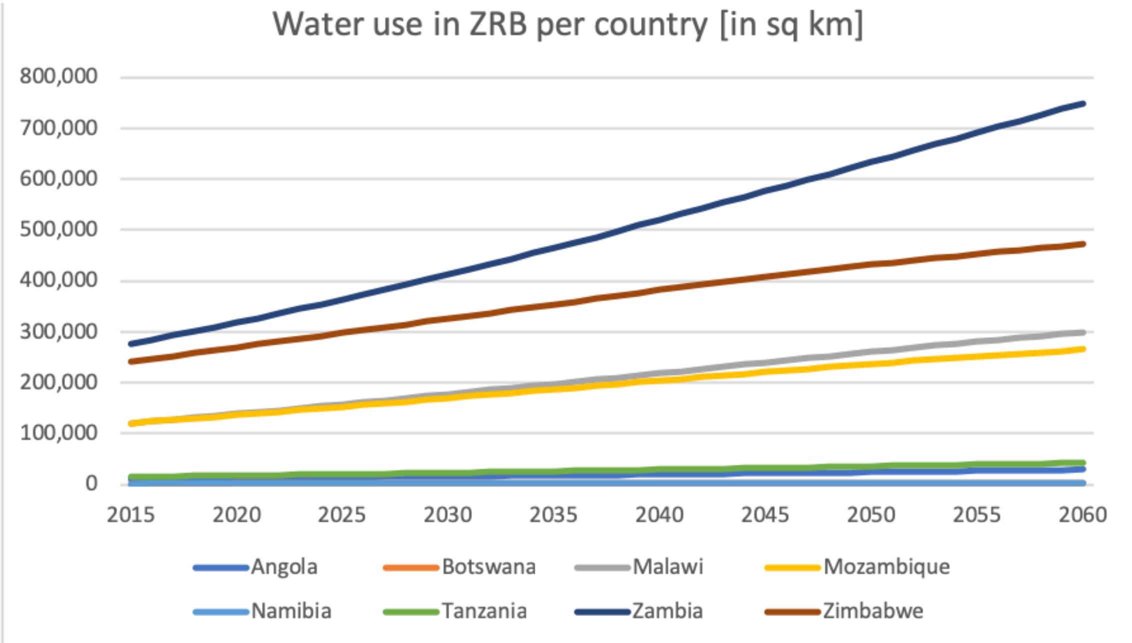

Figure 8 – Water use per country in ZRB in m^3 per year and km^2.

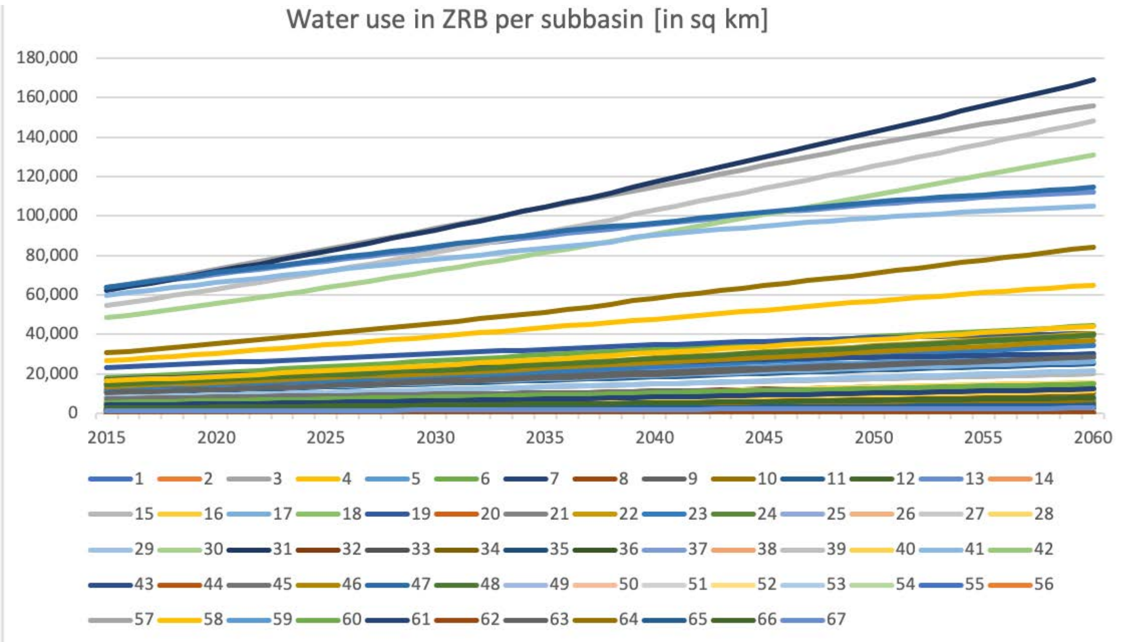

Figure 9 – Water use per sub-basin in ZRB in m^3 per year and km^2.

2.2.3 Electricity consumption and access to electricity by private households

The electricity consumption per capita in the domestic sector of each country of the ZRB computed in Deliverable 2.1. is used to estimate the annual electricity consumption per country's share within the ZRB and per sub-basin for the domestic sector under urbanization assumptions. In case of a sub-basin being shared by more countries with different water consumption rate, we computed the average consumption of those countries, and then, we multiplied it with the population of the sub-basin.

Figure 10 and Figure 11 show the projected electricity use for the period from 2015 to 2060. By 2060 the total electricity consumption within ZRB is expected to reach 207 TWh, which is more than twice as much as it is today. As before, Zambians living within the ZRB are expected to consume in total more electricity requirements than inhabitants of Zimbabwe and Mozambique, not because of their demographic advantage, but because of their high electricity use per capita. However, Namibia and Botswana seem to use very low quantities of water for domestic purposes, due to their minor demographic share within ZRB and not due to their actual water needs.

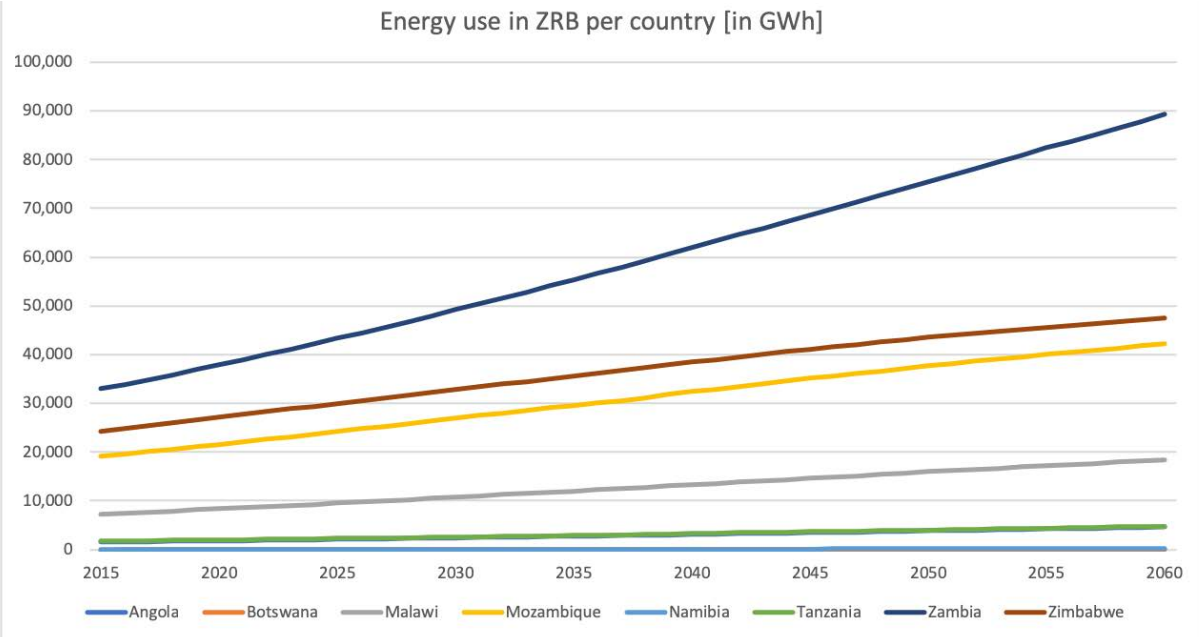

Figure 10 – Electricity use per country in ZRB in GWh per year.

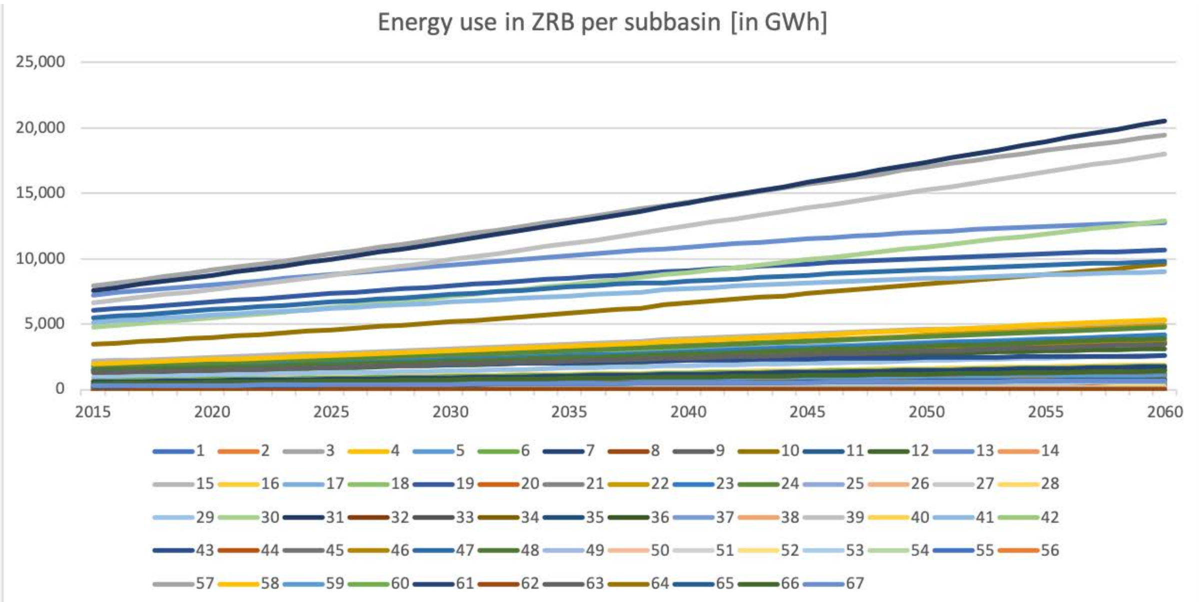

Figure 11 – Electricity use per sub-basin in ZRB in GWh per year.

2.2.4 Food consumption at sub-basin scale

In alignment with the previous two sections, data for the daily calorie, protein and fat intake needs of an individual for each country from FAO (2018) are used to estimate the long-term food demand. Based on these data, we computed the annual food consumption per person, which we multiplied with the population projections per sub-basin and per country estimated in the previous chapter including urbanization to obtain the estimates corresponding to basin scale. The outputs of these projections per national consumption of people living within the basin can be seen in Figure 12, Figure 13 and Figure 14. The growth pattern does not change significantly among the graphs. In all graphs Malawi, Zambia and Mozambique have the greatest requirements, with Malawi being the leader. In terms of total calorie intakes, the total expected requirements in ZRB in 2060 will reach 74,670 Tcal, with Malawi consuming 31% of them. In terms of protein and fat intakes, the total requirements will reach 1,7 Megatonnes and 1,3 Megatonnes respectively, with Malawi consuming 32% and 26% in each case.

Figure 15, Figure 16, and Figure 17 present the graphs for future food requirements measured in calories, proteins and fats, respectively. As expected, the sub-basin with the majority of food requirements are located in Malawi and Mozambique (sub-basin 3) and its food requirements are expected to be 20%, 16% and 15% of the total requirements of the basin in each case. In general, the intakes of the rest of the sub-basins seems to increase slower than sub-basin 3.

Considering all diagrams on food projections per sub-basin and per country, someone can clearly see that in the next 40 years food intakes are expected to increase dramatically reaching twice as much the current needs. Hence, this will put an extra burden in the economies of these riparian countries, which if they wish to meet their increased demand without imports, they will be required to produce twice as much food as they already do. Consequently, more water will be required by the agriculture sector.

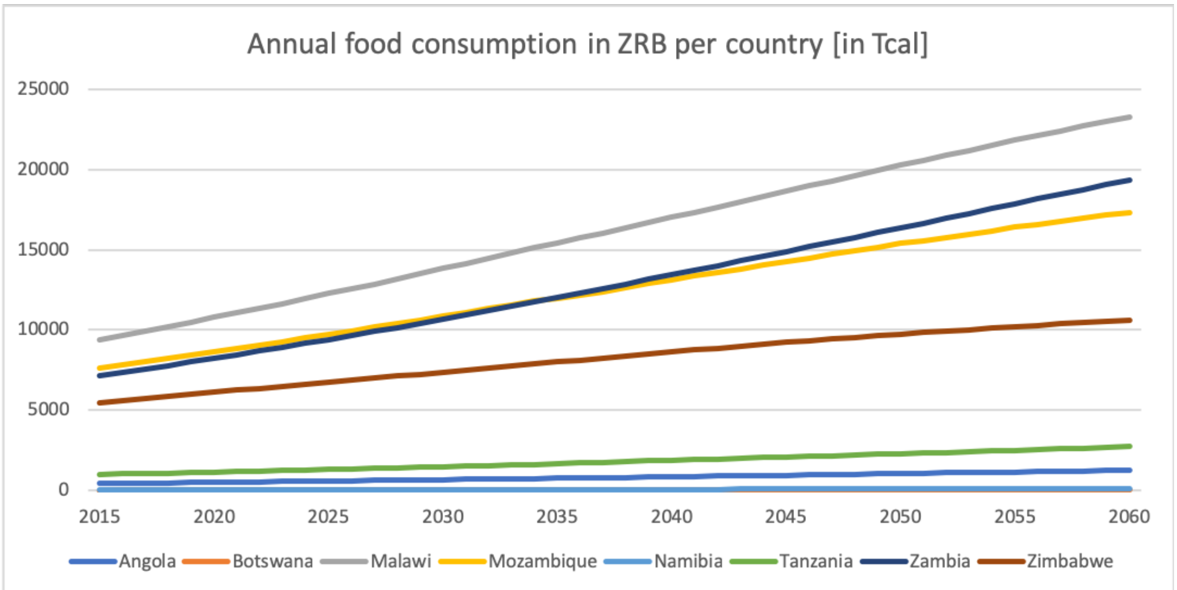

Figure 12 – Food requirements in ZRB per country in Tcal per year.

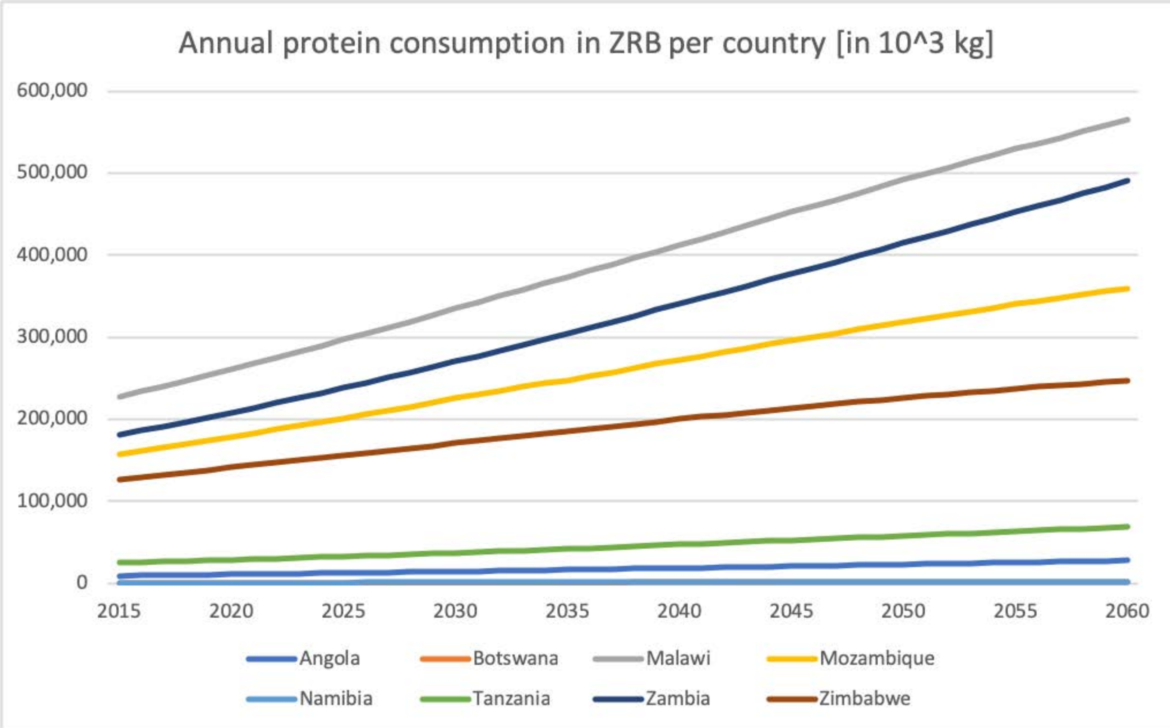

Figure 13 – Protein requirements in ZRB per country in 10^3 kg per year.

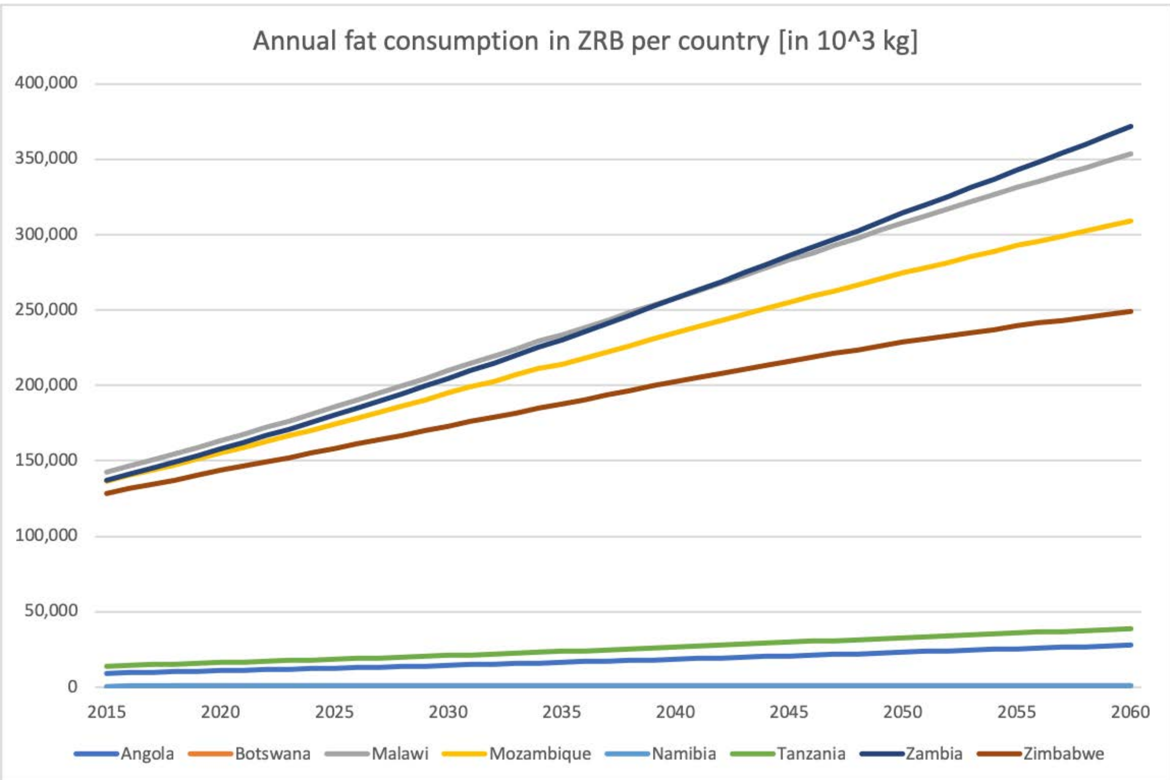

Figure 14 – Fat requirements in ZRB per country in 10^3 kg per year.

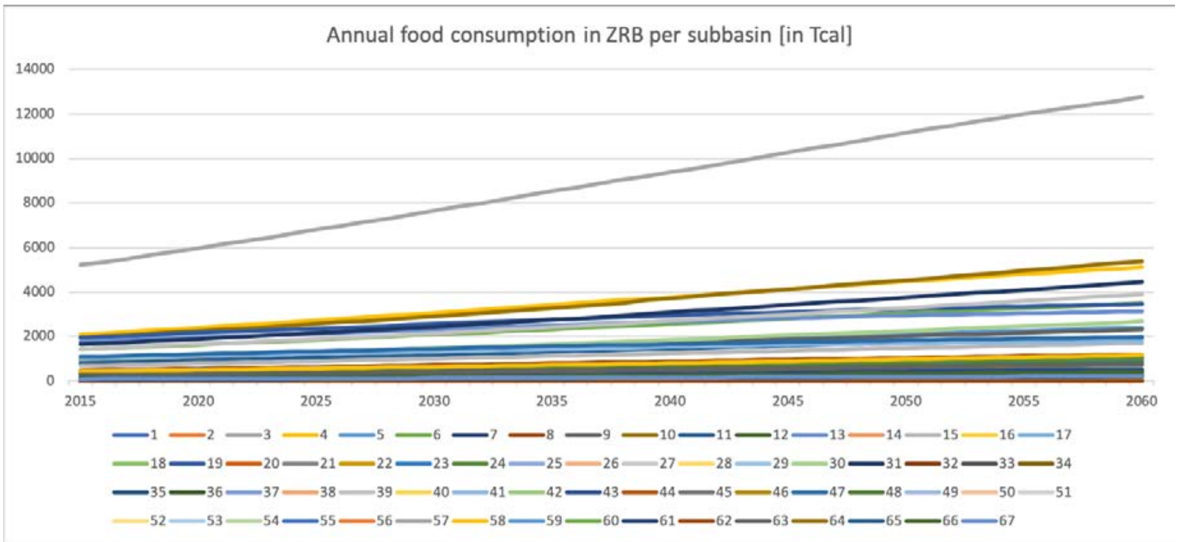

Figure 15 – Food requirements in ZRB per sub-basin in Tcal per year.

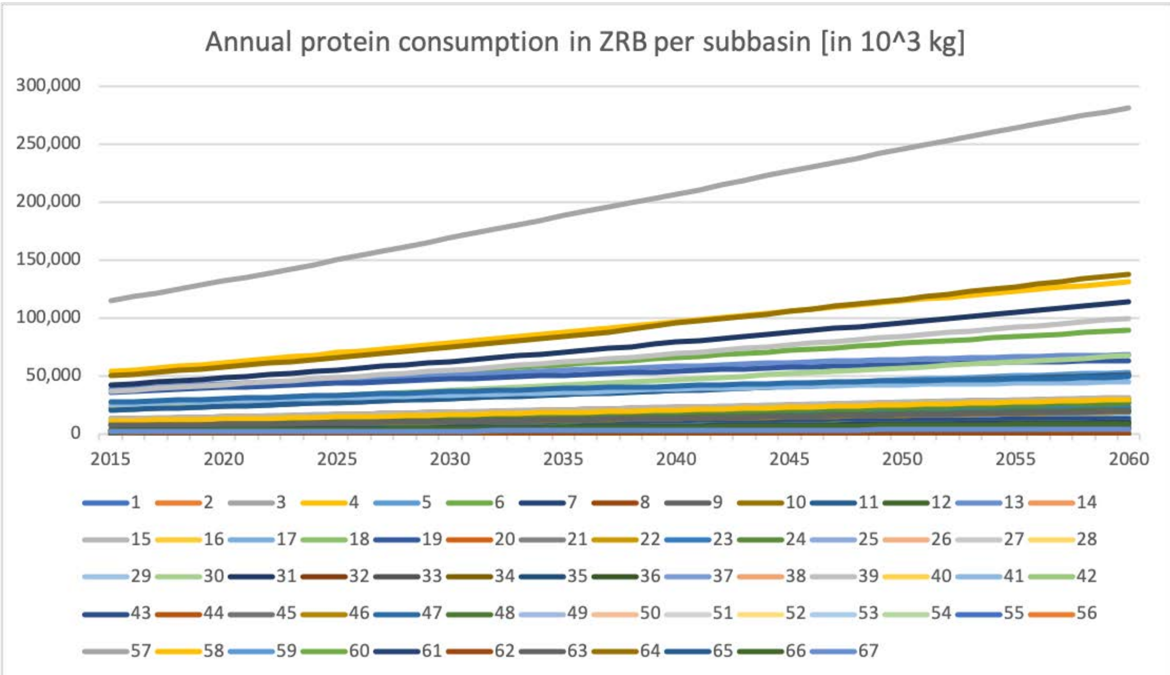

Figure 16 – Protein requirements in ZRB per sub-basin in 10^3 kg per year.

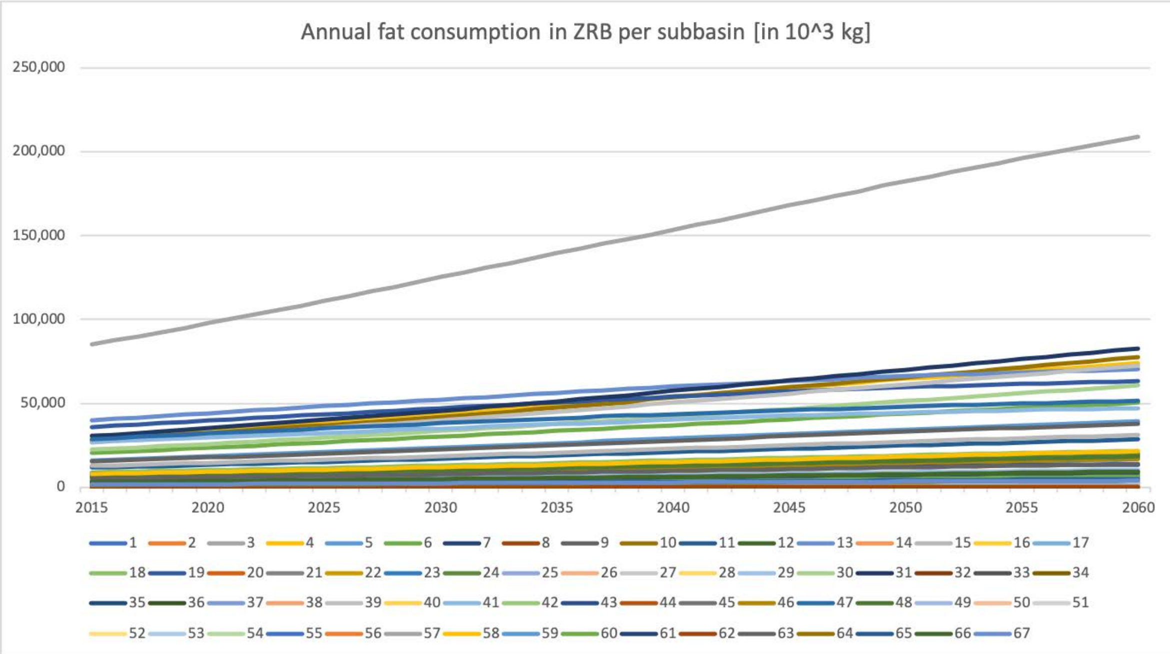

Figure 17 – Fat requirements in ZRB per sub-basin in 10^3 kg per year

2.2.5 Economic Development

GDP Growth

As presented in Figure 18, Angola's Gross Domestic Value (GDP) is almost as high as the GDP of all the other riparian countries combined, reaching $125 billion in 2017. However, its GDP growth (18%) over the 7-year period from 2017 to 2023 is not as high as the one in the other countries. The estimations of IMF (2018b) show that by the end of 2023 the GDP in Tanzania, Malawi and Mozambique will be increased by 45%, 35% and 35% correspondingly, probably due to expected improvements in the political system of those countries, which have been associated with mismanagement, pressure on the media and corruption. Malawi's elections will take place with three competing parties in May 21st 2019, Mozambique's elections in October 2019, while in 2020 Tanzania's elections are scheduled (EISA, 2019).

In terms of WEF nexus, GDP growth can be constrained or accelerated by water, energy and food risks. Increasing GDP could increase further the demand for water, energy and food, as more and more people could afford to consume higher quantities of these goods. Consequently, an increased burden could be placed on the management of the resources, which except of smoothing people's lives, are also initial inputs for the economic growth. Hence, if they are not managed efficiently, they could even slow down the growth of the economy.

Moreover, in order to make comparisons with the other trends, GDP growth projections need to be run until 2060. However, due to lack of data after 2023, GDP projections have been made using an AR(1) with one lag model (random walk) with constant slope using data from the post-war period from 1980 to 2017. However, the uncertainty coming from the long-term projections in alignment with the intense growth of the riparian countries in the recent future influences significantly the projections making them unreliable after year 2040. The reason why 2040 is selected as a turning point, is that no specific plans are available for the period following and hence, a remarkably rapid growth could not be justified neither by development plans nor by past data. Hence, for the period 2040 to 2060 proxies from other similar countries (in terms of development) will be used through splitting the period in decades and using different growth rates.

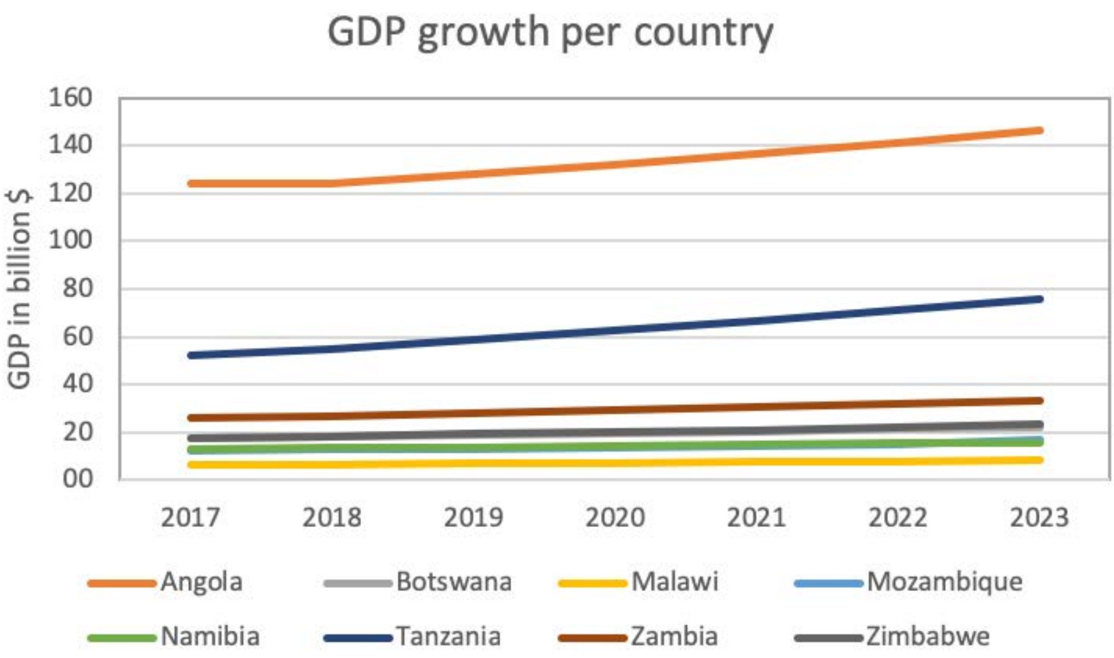

Figure 18 – GDP growth in ZRB per country 2017-2023 (sources: World Bank (2018); IMF (2018b))

The growth in the period 2018 – 2040 will be significantly high, since in this period the development is enhanced by the 2030 development goals of those countries and the international movements for better life standards in African countries. For example, Universal, affordable and sustainable access to Water, Sanitation and Hygiene (WASH) is a key public health issue within international development and is the focus of Sustainable Development Goal 6 and according to the performance statistics for 2015, Tanzania and Zimbabwe are placed among the high-performing countries, while Namibia among the low-performing countries (WASHfunders, 2019). Hence, the GDP growth rates must be in alignment with these ratings until 2030, with high-performing countries growing faster (e.g. Tanzania's GDP is growing with 8,3% rate) than low-performing countries (e.g. Namibia's GDP is growing with 4,7%).

For Angola, projections become unreliable from 2030 onward, when the GDP is expected to reach $317 billion, which is higher than any other riparian country. Comparing this value with the GDP of other countries in the past, someone can see that the growth rate is restricted between 2,3% and 7%. In this case, it is used the proxy of Turkey, which in 2000 had almost $300 billion GDP, 10% of which was deriving by agricultural products, and increased with an average of 5,5% for the next decade. Similarly, in 2030 the real GDP of Angola is expected to reach $300 billion, 10% of which will come from agriculture. So, for the period from 2030 to 2040, the average growth rate of Turkey is used to indicate the GDP growth of Angola. Likewise, proxies for each country and decade are selected.

According to UN (2018) growth in Angola will accelerate, as a result of increased industrial activity and improving energy supplies, while the new administration of President João Lourenço is committed to restoring macroeconomic stability and implementing reforms. Since the election last year, the administration has started to implement relevant policies including dismissing officials linked to the previous administration, launching investigations into possible misappropriation of funds at several public entities, and creating a specialized anti-corruption unit. Additionally, the impact of a dramatic drop in oil prices that started in mid-2014 in the economy led the officials to address vulnerabilities more forcefully and diversify the economy away from oil, including a significant—17.5% of GDP—improvement in the non-oil primary fiscal balance over 2015–16 (IMF, 2018a).

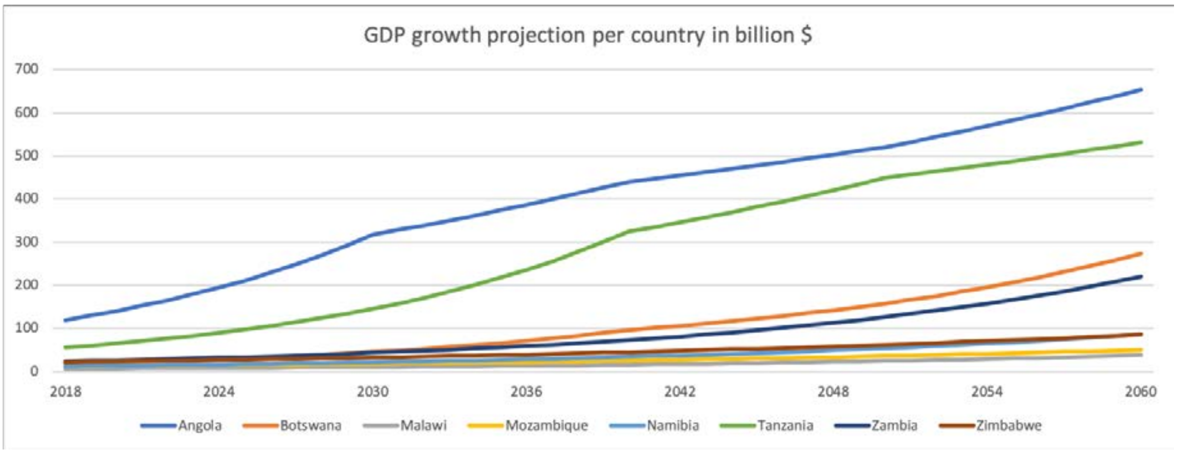

Figure 19 – GDP growth projections in ZRB per country

Growth in Botswana will be a result of advancements in all main sectors of the economy, but mainly by mineral prices. The outlook for the mining sector of Botswana is positive due to an anticipated increase in demand for Botswana's rough diamonds, with diamonds comprising 75 percent of the country's total exports. The non-mining sectors are also expected to pick up further, driven by structural reforms, including an amended immigration law that ensures rattling processing of work and residence permits and a move that provides utilities at reasonable prices to encourage domestic manufacturers. Construction is anticipated to continue being benefited by the ongoing fiscal stimulus (AfDB, 2019).

Prospects have been enhanced in Malawi after the reestablishment of its relations with foreign donors. Malawi's growth ensues from agricultural improvements, stable macroeconomic fundamentals, the recovery in global commodity prices, and continued foreign direct investment inflows (AfDB, 2019). However, weather-related shocks are key risks to export commodities such as tea, tobacco, and other products, as experienced in 2017, due to high dependence on rain-fed agriculture. The long dry spell in the first half of 2018 and fall 2018's armyworm infestation reduced the maize output, contributing substantially to GDP deceleration in 2018.

Additionally, Magufuli's presidency in Tanzania is expected to create the necessary circumstances for a boost in economic performance of the country, such as road building or fighting corruption. As reported by IMF (2018a), economic growth in Tanzania has been relatively strong in the past decade resulting from wise macroeconomic policies and consecutive Fund programs, which contributed to low inflation and contained public sector debt.

In Zimbabwe, policy-related macroeconomic instability remains a key challenge for private sector development. In particular, the macroeconomic instability is related to lack of funding, land tenure, and investment regulations, high input costs and outdated machinery, inefficient government bureaucracy and inadequate infrastructure (particularly energy). However, the country has one of the most youthful populations consisting of 36% of the total population, with the population ages 15–34 (AfDB, 2019). The agricultural sector and mining are expected to be the main drivers of growth, backed by increased public and private investment. Lastly, the government has adopted and is implementing prudent fiscal policy underpinned by adherence to fiscal rules reprioritizing capital expenditure through commitment to increase the budget on capital expenditures from 16% of total budget expenditures in 2018 to over 25% in 2019 and 2020.

The medium-term outlook of Namibia is mixed. Aggregate demand is expected to recover steadily, as private activity picks up and new infrastructure projects are implemented as part of the stimulus package. Growth will also be driven by increased capacity utilization in a new uranium mine as well as by improved business confidence, since reforms are accelerated. However, growth could remain weak if growth in key trading partners, such as South Africa, continues to be slow or if international prices of Namibia's commodity exports fall. Uncertainty over land reform and the economic empowerment agenda could also constrain the growth outlook. The government's assurance that land will not be expropriated without compensation should help ease such concerns.

Investment in Mozambique is being delayed by the government's default in January 2017 and the increased debt, while growth in Mozambique will additionally be restrained due to political tensions. Recently, a massive popular protest against fuel price increases has taken place. On top of that, downside risks to Mozambique's economic growth include rising prices for key imports such as fuel and food and economic difficulties in South Africa, Mozambique's second largest export destination. Lastly, according to AfDB (2019), Mozambique's public debt is in distress and failure to agree on restructuring debt and restoring investor confidence could deepen economic hardship and slow growth.

The persisting dependence of Zambia's growth on the price of copper, which fell by more than 18% in 2018, will be restrained by deficiencies in the electricity supply, 97 per cent of which is generated by hydropower, and by lower demand from China associated with escalating trade tensions (UN, 2018; AfDB, 2019). To improve investor confidence in Zambia and hence, debt sustainability, which is another key challenge of Zambia's economy, the government announced measures aimed at improving debt sustainability and returning to a rating of moderate risk of debt distress. The measures include an indefinite postponement of new infrastructure projects and the cancellation of some contracted loans that are yet to disburse.

However, considering the historical data of all riparian countries – except of Botswana, which is one of Africa's most stable countries with continuous multi-party democracy - political instability is increased driving so, the levels of uncertainty attached to the projections of these countries higher.

International trade

Angola has significantly liberalized its trade scheme over the last few years. Trade represented, on average, 52,2% of the country's GDP in 2017 (World Bank, 2018). The country is a member of SADC (Southern African Development Community) and ECCAS (Economic Community of Central African States). Custom duties are relatively low lying between 5% and 10%, while authorizations requirements remain from the concerned official ministries on the imports of certain products, such as pharmaceuticals and agricultural products. Angola has also adopted the SADC guidelines on biotechnology, which ban the import of biotechnological particles. Angola's exports consist mainly of oil, diamonds and coffee, while its imports involve machinery, vehicles, spare parts, medicines, food, textiles, and military goods. Angola's main trade partners are China (more than 40% of exports), the United States, India, France, Taiwan, South Africa, and Canada while its main suppliers are Portugal (18% of total imports), China, the United States, Brazil, and South Africa.

Botswana has made significant efforts to open up to international trade and enhance its integration in the region, despite its geographical position. The country is a member of several regional and trade organisations, such as the WTO, the SACU (South African Customs Union) and the SADC, while it has signed trade agreements with the European Union and the United States. Botswana is among the freest economies in Sub-Saharan Africa with international commerce accounting for 73% of the country's GDP in 2017 (World Bank, 2018). The country's trade balance has returned to positive level and it is expected to maintain a trade surplus in the coming years. Botswana primarily exports diamonds, copper, nickel, machinery and electrical equipment, meat, salt, vehicles and transport equipment, gold and textiles, while it imports mainly foodstuffs, machinery, electrical products, fuel, chemical products, vehicles, metal, textiles, wood and paper. The country is heavily dependent on electricity imports, as it only produces domestically 60% of its needs. Botswana's leading commercial partners are the South African Customs Union, the European Union, the United Arab Emirates, India and Canada (Société Générale, 2019).

Malawi is relatively open to international trade, which represents 65,3% of the country's GDP. The country is a member of the WTO and has bilateral trade agreements with two of its main trade partners, South Africa and Zimbabwe. Malawi is also a beneficiary of the AGOA (African Growth and Opportunity Act), a U.S. trade preference program. As part of its trade policy, the country has been gradually reducing protections granted to domestic trade by shifting its sources of revenue from customs duties to consumption and direct taxes. The average applied tariff rate is 4.8%. Malawi's trade balance is structurally in deficit, which is greater than the previous year by 16.5%. The most recent exports are led by raw tobacco, sugar and machinery, while the main imports are led by refined petroleum which represent 9.4% of the total imports. The main export destinations in 2017 were the EU, Zimbabwe and Mozambique and the import origins were South Africa, the EU and China.

Mozambique is open to foreign trade, which represents nearly 113,3% of the country's GDP (World Bank, 2018). The current government's trade policy aims to implement structural reforms to customs duties, customs and VAT procedures to encourage exports. Currently, customs duties remain high, while there are non-tariff barriers in the country. Additionally, the Government seeks to reform its trade regulations to improve its business climate. Mozambique's trade balance is negative and should remain so until coal and gas exports to Asia begin. The negative current account balance is due to the country's need to import goods and services to develop its infrastructure (gas, transport). Natural resources (aluminium, hydrocarbons, coking coal, coal, titanium, gemstones), tobacco and sugar led the exports of the country, while hydrocarbons, metal products, vehicles, machinery and equipment, chemical products, foodstuffs (rice, wheat) and medications led its imports. In 2017, its main customers were India, South Africa, the Netherlands, Italy and China and its main suppliers were South Africa, the United Arab Emirates Singapore, China, the Netherlands, India and France (Société Générale, 2019).

Namibia is very open to foreign trade, which represents 84,1% of the country's GDP in 2017. The Government's policies have been proactive in encouraging trade, some of which include the Private Sector Development Programme, the Foreign Investment Act and the Export Processing Zone Act. Customs duties are low (at an average of 0.8%) and there are no major trade barriers. The country's economy is closely linked to that of South Africa, with the Namibian dollar pegged to the South African rand. The country is a member of the SACU SADC, whose FTZ (free-trade zone) was inaugurated in 2008. Namibia's trade balance is structurally in deficit, which in the last years tends to decrease thanks to dynamic exports and lower imports. Diamonds, copper ores, fish, gold, aluminium and vessels continued to lead the market for export commodities, while mineral fuels and oils, vehicles, diamonds and cupper were the major imports to Namibia. Namibia's exports reached primarily Switzerland (18.8%), South Africa, Botswana, Zambia and Spain, while South Africa (57,2% of imports), Botswana, Zambia, China and Norway were the main suppliers.

Tanzania is open to foreign trade, which represents 32% of its GDP in 2017. The aim of the country's trade policy is to create local industries that are more competitive and to diversify its export sector in order to stimulate economic growth. Tanzania is a member of the EAC (East African Community), along with Burundi, Uganda, Kenya and Rwanda, which has signed a protocol outlining its plans for launching a monetary union by 2024, using the shilling as the common currency. Low customs duties (the average applied tariff rate is 7%) and few trade restrictions make the country easily accessible for international trade. Trade barriers are mainly of a logistic and non-tariff nature. For example, increased traffic in and out of the Dar es Salaam port, the main port of entry and exit of merchandise for both Tanzania and its landlocked neighbouring countries (Uganda, Rwanda, Burundi and Zambia), has not been followed up with the necessary infrastructural investments. This constitutes one of the main barriers to trade with these countries. Poorly maintained roads and railroads also make trade difficult. However, the government has launched a large number of projects to improve infrastructure. Obtaining construction permits, registering land, and tax payments remain difficult nonetheless.

Tanzania suffers from a chronic and growing trade deficit as it imports twice as much as it exports. However, due to the increase the country's hydrocarbon and coal reserves, the deficit is expected to decline sharply in the coming years. The most recent exports were led by gold which represent 34.9% of the total exports of Tanzania, followed by raw tobacco (7.6%) and coconuts (7.3%). The top export destinations of Tanzania are Switzerland (16.2%), India (14.8%), South Africa (13.3%) and China (7.5%) and Kenya (6.6%). The main imports were petroleum oils (17%), palm oil (3.4%)

and medicaments (3.4%). The top import origins are China (20.8%), India (18.1%), United Arab Emirates (7.5%), South Africa (6%) and Japan (4.7%) (Société Générale, 2019).

Zambia is open to foreign trade, which represents 71,4% of the country's GDP (World Bank, 2018). The trade policy of Zambia aims to diversify its economy through privatisation programmes and the expansion of its export base. The country is a member of COMESA and has signed IEPA (Interim Economic Partnership Agreements) with the European Commission. The country became part of the WTO in 1995. Custom duties are high, but the country has few non-tariff trade barriers. Certain products such as crude oil, medical supplies and fertilisers are exempt from import duties. Irregularities in the taxation system and high transportation costs are real barriers to trade.

Zambia's trade balance is expected to move out of deficit and return to surplus in 2018 to 2022 due to high productivity in the mining sector. In July 2017 the country recorded a trade surplus after a two-year deficit. Zambia's lack of economic diversification and dependency on copper as its sole major export (75% of Zambia's exports) makes it vulnerable to fluctuations in the world commodities market. Zambia exports mainly copper and other minerals. Switzerland remains Zambia's major export destination with 50.2% of the total export earnings, followed by China (11.8%), South Africa (10.1%), Congo DR (5.8%) and Hong Kong (4.1%). Zambia sources almost half of its imports from South Africa, Congo DR, China and Kuwait, the main import products being machinery, transportation equipment and petroleum products.

The Zimbabwean Government is generally open to foreign trade, which amounts for more than 50% of its GDP in the latest estimates. In the context of economic and regional integration, the country has strengthened its ties with the SADC member countries and levies lower duties on imports from these countries. However, the strict control on trade exercised by the Government and the relatively high customs duties, make the country difficult to access. There are other barriers that continue to impact trade such as the lack of long-term economic and political reforms, state control over companies, insecurity and a lack of skilled labour forces. The average tariff in the country is 13.6%.

The country's trade balance is in deficit, due to the economic shift from being an agricultural exporter to an importer. This trend should continue in the coming years, despite the recovery of gemstone exports and the decline in the global oil prices. The Government has reduced certain tariffs to facilitate imports. Exports are dominated by minerals (gold, nickel, platinum, diamonds) and tobacco. The major export markets are South Africa, Mozambique, UAE, Botswana, Zambia, Belgium and Botswana. Imports include diesel, unleaded petrol, agrarian products (corn, crude soy bean, rice), electrical energy, medicines, vehicles and electrical devices. These goods come from South Africa, Singapore, China, Zambia, India and Mozambique.

According to World Bank (2018), the trade to GDP of the Least Developed Countries (LDC) varies between 51% and 62% for the period from 2000 to 2017 with an average equal to 56%. Among them are placed four riparian countries: Angola, Malawi, Mozambique and Zambia. In alignment with the Business as Usual, or at the SSP2 scenario, we assume that in the long term, i.e. until 2060, the trade to GDP of those countries will lie between those boundaries. In detail, as presented in Figure 20, Angola's trade to GDP trend is expected to grow until 2030, due to increased economic activity in the country and foreign investments, as explained above, while after that point it will start decreasing with an average rate deriving from the period 2000-2017. It will stop falling only when it will reach an acceptable value according to LDC trend. Similar path will be followed by Malawi, the trade of which is expected to increase in the coming years as a result of has gradually reducing trade protections. It will keep on increasing until 2030 (reaching 75,7%), in alignment with the SDGs, and then it will start decreasing reaching so, the LDC trends.

On the other side, Mozambique will not follow a similar path with Angola and Malawi, thanks to the discovery of new reserves, which are estimated to be the third largest reserve in Africa. According to Société Générale (2019), Mozambique could become one of the largest exporters of natural gas in the world by 2020. Hence, until 2020 the trade to GDP growth will be moderate, while on 2020 it will accelerate with a pace coming from the average growth rate of the last few years, which is 5,5%. However, given the high trade records of the country and since the increase is enormous, it will not keep on increasing limitless. Specifically, if we consider that some of the most developed countries, such as Germany and Sweden, do not exceed the burden of 90% trade to GDP ratio, 151% of Mozambique by 2025 is significantly high. Consequently, we assume that it will not increase further and remain stable at least for a decade. After that point, even if RES (renewable energy sources) do not develop to their maximum potential, as assumed by SSP2, they will still be competitive enough to the current forms of energy, having so an impact to Natural Gas exports, leading to a progressive decrease in the trade to GDP ratio until the end of the period.

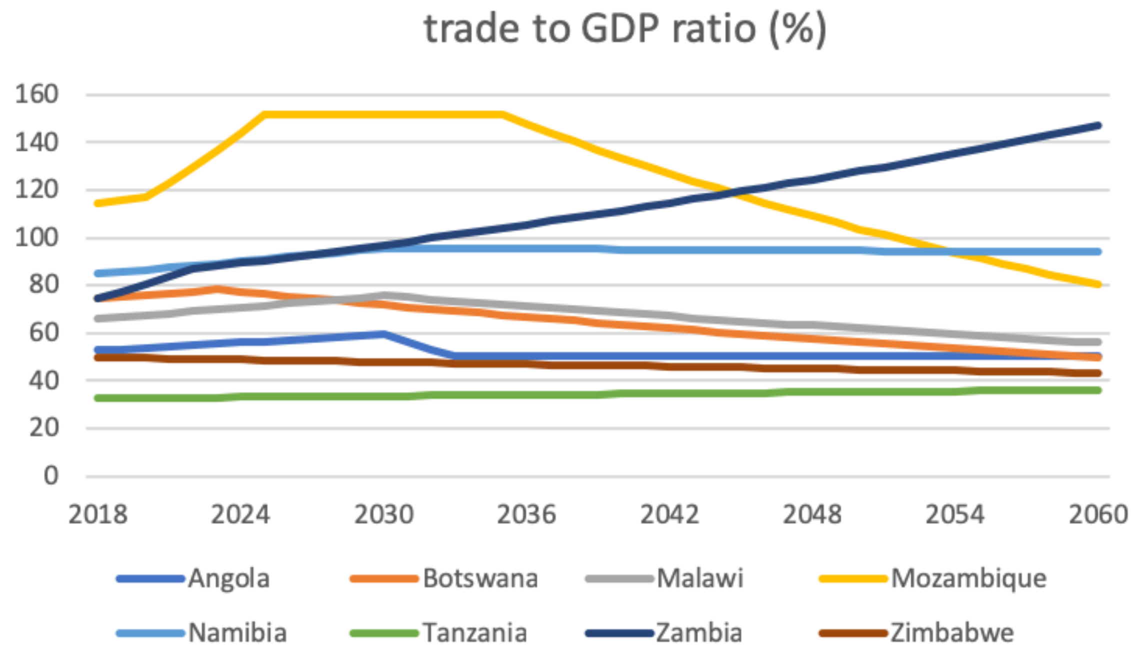

Figure 20 – Trade to GDP in ZRB per country projections

Simultaneously, Zambia's expectations for high productivity in the mining sector for the period from 2018 to 2022 will be accompanied by increased trade. However, its great dependence on copper makes Zambia vulnerable to fluctuations which will constraint the growth of the trade of the country. Considering the available data on previous fluctuations someone can notice that on average the trade if growing with a rate 1,4%, which we will use to project the trade in the long term. Botswana's opening to the markets will play a significant role in adverting its decreasing slope in the short-term. However, the high dependence on diamond exports in alignment with the increased competition from new diamond producers such as Angola will put Botswana on track of declining trade to GDP according its previous records.

Although Namibia is considerably open to foreign trade following relevant policies, which facilitate the free trade between the countries, trade growth is highly linked to the growth South Africa. In the short-term, economic growth resulting from increased capacity utilization in a new uranium mine and from improved business confidence, will enhance the foreign trade, but in the long-term it will follow its average trends deriving from the previous years, where it tends to remain stable. Tanzania's aperture to foreign trade in alignment with expected increase in hydrocarbon and coal reserves of the country will lead Tanzania to a greater ratio of trade to GDP. Lastly, Zimbabwe is relatively open to international trade, but if nothing changes as SSP2 assumes, it will keep on declining slowly, due to existing barriers on the trade explained above.

Lastly, increased trade could also affect the WEF nexus of a country. As described minutely below, water and energy are significant inputs of all sectors. Hence, increased demand for exports of a good or service would increase further its production and so, the use of its inputs. For example, Zambia is expected to increase significantly its trade to GDP rate, probably due to increased mining exports, which will be followed by further exploitation of water and energy necessary to extract copper.

GDP composition projection

As presented in Figure 21, services are the driving sector of the economy of each riparian country individually. In particular, it skyrockets in Zimbabwe reaching 61%, while it takes its lowest value in Tanzania with only 38% GDP share. In terms of agriculture, only Tanzania, Malawi and Mozambique have a considerable presence in the economy, while the comparatively more industrial countries are Angola (the second largest oil producers in Africa), Zambia (the second largest copper producer in Africa after Congo) and Botswana (one of world's major diamond producers). The data presented in Figure 21 are taken from World Bank (2018) and they show the share of each sector to GDP in terms of added value, with agriculture sector including forestry and fishing and industry sector including construction.

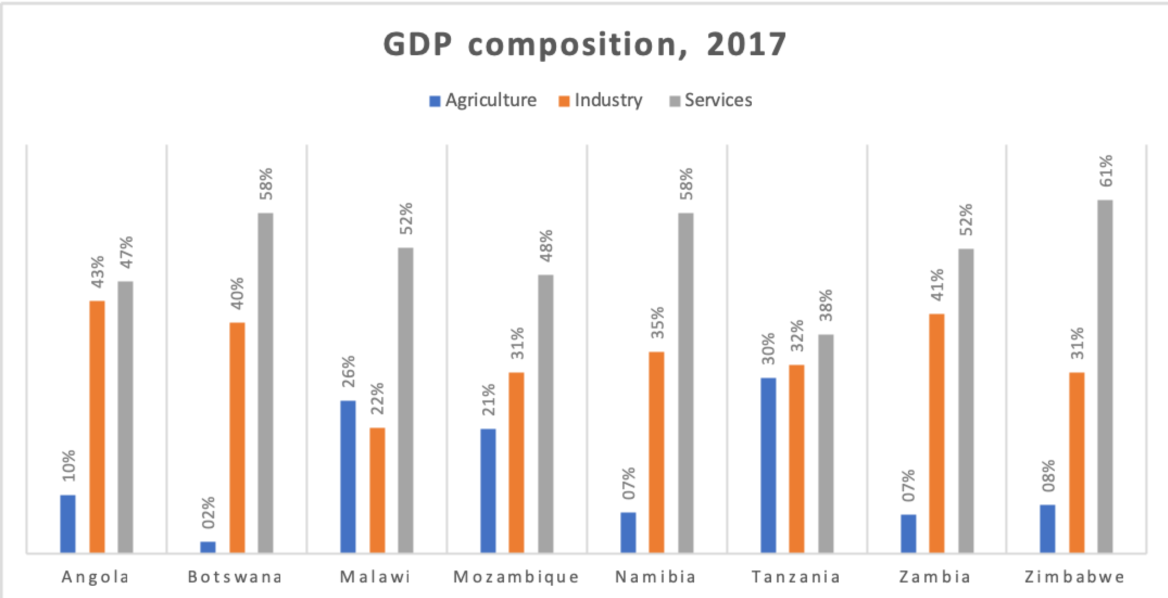

Figure 21 – GDP composition in ZRB per country, 2017 (source: World Bank, 2018)

According to SSP2 assumptions, where the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns, GDP composition projections will also follow the historical trends. Hence, a linear regression model (time series) is used as the appropriate tool for this example tracing data from the period 2000 until 2017, which is a politically - comparatively to the previous years- stable period for all riparian countries. For instance, for the period from 1975 to 2002, Angola suffered from a 27-year civil, which led to devastating the country's infrastructure and severely damaging public administration and the economy in general, while Zimbabwe until 2008 was characterized by unstable political situations (so, in this case the average rate is computed for the period from 2008 to 2023). The reason, for considering the progress made in this period only is the SSP2 assumption, that no significant change, like a war, will occur in the upcoming years. The projection of the GDP composition for all riparian countries until 2060 can be seen in Figure 23.

Mining and Industry Sector

For the least developed countries as given by the UN classification, i.e. Angola, Malawi, Mozambique and Zambia, the industry GDP share fluctuates around 25,8% across the years. That classification considers the countries with the lowest HDI (Human Development Index), which is composed of indexes such as life expectancy, education and per capita income. However, in the business-as-usual scenario, the industry sector of Angola and Zambia is expected to maintain its high share in the economy with 49,6% and 40,8% each by 2060. In SSP2, although the global and national institutions work toward, they make slow progress in achieving sustainable development goals. Hence, it is justifiable to expect that the intense oil and diamond production in Angola and copper extraction in Zambia will drive the industry and mining sectors in their countries.

The impressive economic growth of Angola is accelerated by its oil sector. Angola is the second largest oil producer in Africa and is also a full member of OPEC since 2007 producing 1,6 million barrels per day, which accounts for 50 percent of the country's GDP and for 92 percent of total exports (OPEC, 2019). Since 2004 the oil production of the country has more than doubled with 9.5 billion barrels reserves. However, the oil fields are offshore located in the northern-west side of the country, while the refineries at the capital, Luanda. Hence, none of these is placed within the ZRB area. In particular, 90% of total exports of the country come from oil exports.

Moreover, another promising industry is the diamond industry, which makes Angola one of the most prospective countries for new diamond discoveries. According to Société Générale (2019) Angola is the world's fourth largest exporter of diamonds. As presented in Figure 22, only some secondary diamond fields are located within the ZRB area with the majority of the primary diamond fields being located in the centre of the country. Lucapa Diamond Company is operating in Angola with the Lulo Diamond Project, which is located out of the ZRB area. The new Angolan President João Lourenço has made his major priority since being elected in 2017 to create a new legislative framework to attract more foreign investment in Angola's diamond sector and Lulo diamonds are expected to be the first to be priced under the new marketing policy in a competitive bid process closing on 31 January 2019 (Lucapa Diamond Company, 2019).

Correspondingly to Angola, the economic growth of Zambia is driven by its copper production, which is expected to increase even more. Copper output increased by 10% in 2017 and according to the Ministry of Mines Permanent Secretary, Paul Chanda, it is expected to reach more than one million tonnes in 2018 (Reuters, 2018). The reason of the increased prices and so, of the increased demand is hidden in the growing production of electric cars, the main component of which is copper. Moreover, another reason the mining output of Zambia is expected to increase by 4%–5% in 2019, are the improvements in electricity generation associated with the replenishment of the Kariba Dam due to good weather conditions (AfDB, 2019).

On the other side, Botswana's industry (and mining) sector is expected to slightly drop its share from 39,6% to 32,7% in the economy. Diamond exports (88% of the total in 2016) in Botswana experienced only a slight increase in 2015 and 2016, due to weak international demand and a drop in global prices (Société Générale, 2019). A possible root of the fall in prices is the growing competition in the diamond market in alignment with the more and more conflict-free diamonds consumer requests. Exports of copper and nickel have also taken a hit in recent years. To compensate those trends, Botswana seeks to increase its coal exports (second largest reserve in Africa). As such, the country plans to expand its railway infrastructure.

Service Sector

The service sector for all countries across the world seems to be the dominant one (as GDP share) with the global average for the last 20 years being more than 50%. However, among the eight riparian countries, Zimbabwe is expected to have the greatest share in the service sector reaching more than 65%. Given the vast natural resources, relatively good stock of public infrastructure, and comparatively skilled labour force, Zimbabwe aims to join existing supply chains in Africa through the Continental Free Trade Area. Towards taking advantage of such opportunities, the government has adopted a three-pronged strategy based on agriculture, ecotourism as the green job generator, and special economic zones.

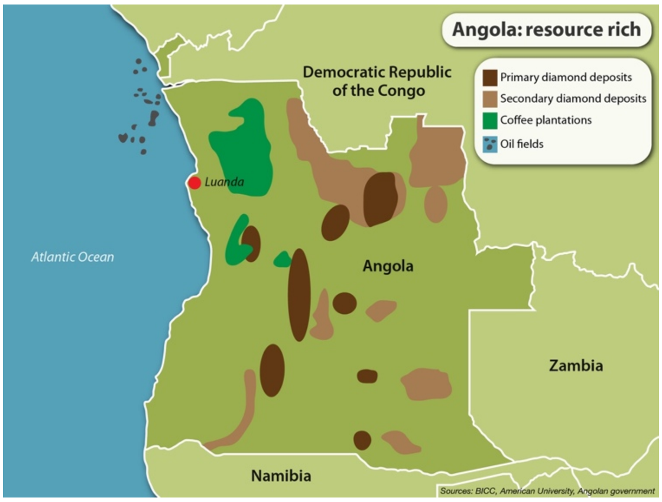

Figure 22 – Angola's resources (source: GIS, 2019)

Agricultural Sector

On the other side, agricultural sector is mainly associated with poor countries generating less than $25 bil. GDP per year (World Bank, 2018a). Hence, Malawi and Mozambique, which can be considered as the poorest riparian countries, are expected to have a significant share of the agricultural sector in their economy reaching almost 25%. Angola is the world's fourth largest coffee exporter, while other exports include sisal and fish $750 million have been invested in the sugarcane and ethanol industries (Société Générale, 2019). However, although the Government of Angola is trying to develop the agricultural sector in order to diversify exports, it seems to make small to no difference to the market share of the sector, probably due to the low added value in comparison with the other sectors.

Zambia is dominated by its copper extraction as analysed above. So, towards diversifying the economy, investment in food progression is increasing without though a significant outcome. Zimbabwe, which was once a major agricultural exporter, today imports foodstuffs and manufactured goods in large quantities. This is mainly due to land expropriation and state-owned enterprises distorting the economy, as well as government's intervention, inadequate supervision, and political instability that undermine the financial system (Société Générale, 2019). However, the Country Programming Framework (CPF) for Zimbabwe 2016-2020, which is mapping the priority areas of the country, aims to enhance agricultural productivity and competitiveness, while strengthening Policy and Institutional Frameworks (FAO, 2019).

Employment

As presented in Figure 24, in most cases, agriculture occupies the majority of people, although it is the least valuable sector in comparison with the others. In particular, in Malawi, Mozambique, Zimbabwe and Tanzania almost 70% of the total employment is occupied by the agricultural sector, driving so, the welfare of the total economy. However, we should not forget that the agricultural sector of Malawi, Mozambique and Tanzania has a significant presence in their economy with a share lying between 21% and 30%. Regarding the comparatively more industrial countries, such as Angola (the second largest oil producers in Africa), Zambia (the second largest copper producer in Africa after Congo) and Botswana (one of world’s major diamond producers), the economy of which is driven by the industrial sector, do not seem to occupy the corresponding share of people. Enabling less people to participate in the industrial process may have a significant impact in the welfare of the society as well, maintaining or even increasing the existing inequalities, given that the generated wealth is distributed only to a small share of the population.

In a global scale, the share of employment in service sector in total employment is steadily increasing during the last 30 years expanding from 33% to 51%. On the far side, the share of employment in agriculture in total employment is constantly decreasing reaching 26% in 2018, while the employment in industry sector seems to fluctuate around an average of 22,5% (World Bank, 2018a). According to SSP2 assumptions, where the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns, employment composition projections will also follow the historical trends. Hence, a linear regression model with one lag (time series) is used as the appropriate tool for this example tracing data from the period 2000 until 2017 for reasons explained above. The projection of the employment composition for all riparian countries until 2060 can be seen in Figure 25.

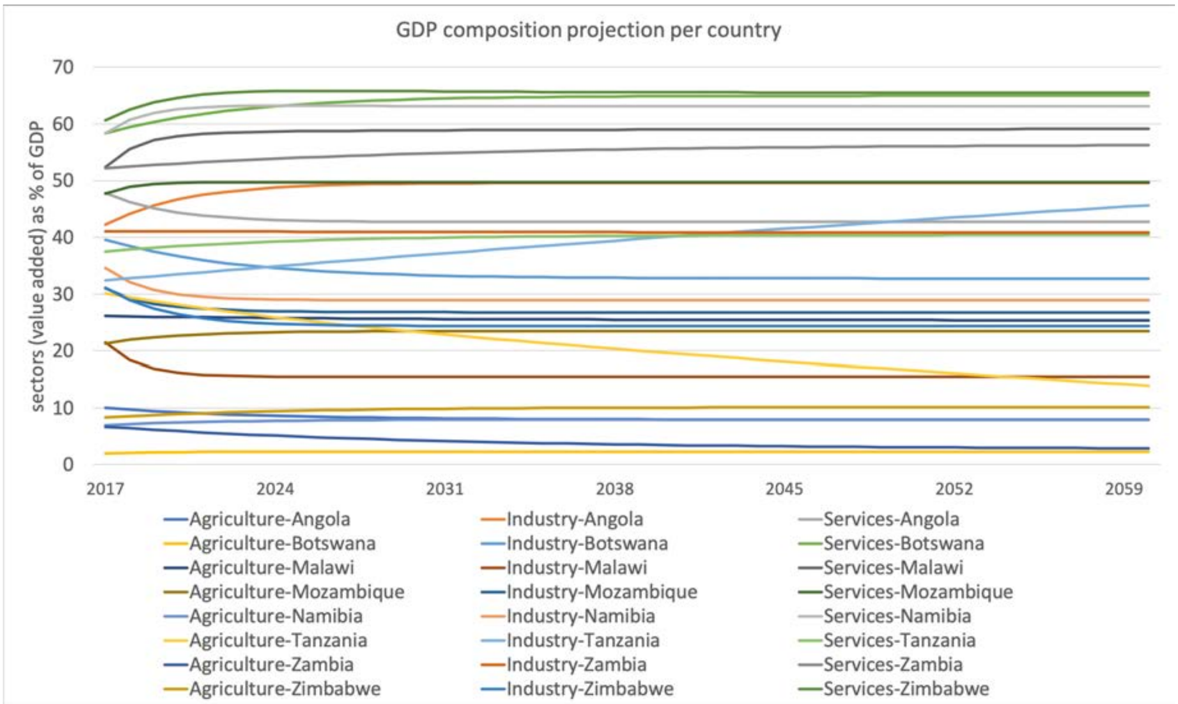

Figure 23 – GDP composition in ZRB per country

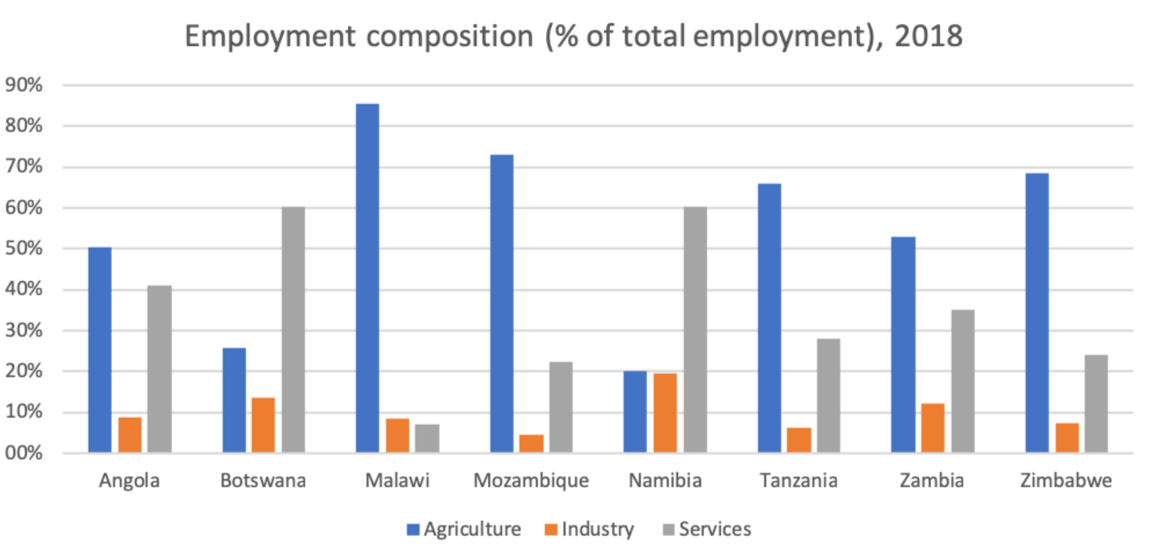

Figure 24 – Employment composition in ZRB (% of total employment), 2018

Agriculture is the backbone of Zimbabwe's economy as Zimbabweans remain largely a rural people who derive their livelihood from agriculture and other related rural economic activities. Historically, 60-70 percent of the population is employed by the agricultural activities, while the sector supplies 60 percent of the raw materials required by the industrial sector and contributes 40 percent of total export earnings (FAO, 2019). According to the regression taken place in this example, Zimbabwe's as well as Malawi's, Angola's and Mozambique's inhabitants will keep on being based on the agricultural sector as a source of generating income with this number skyrocketing in Malawi reaching 81,5% by 2060.

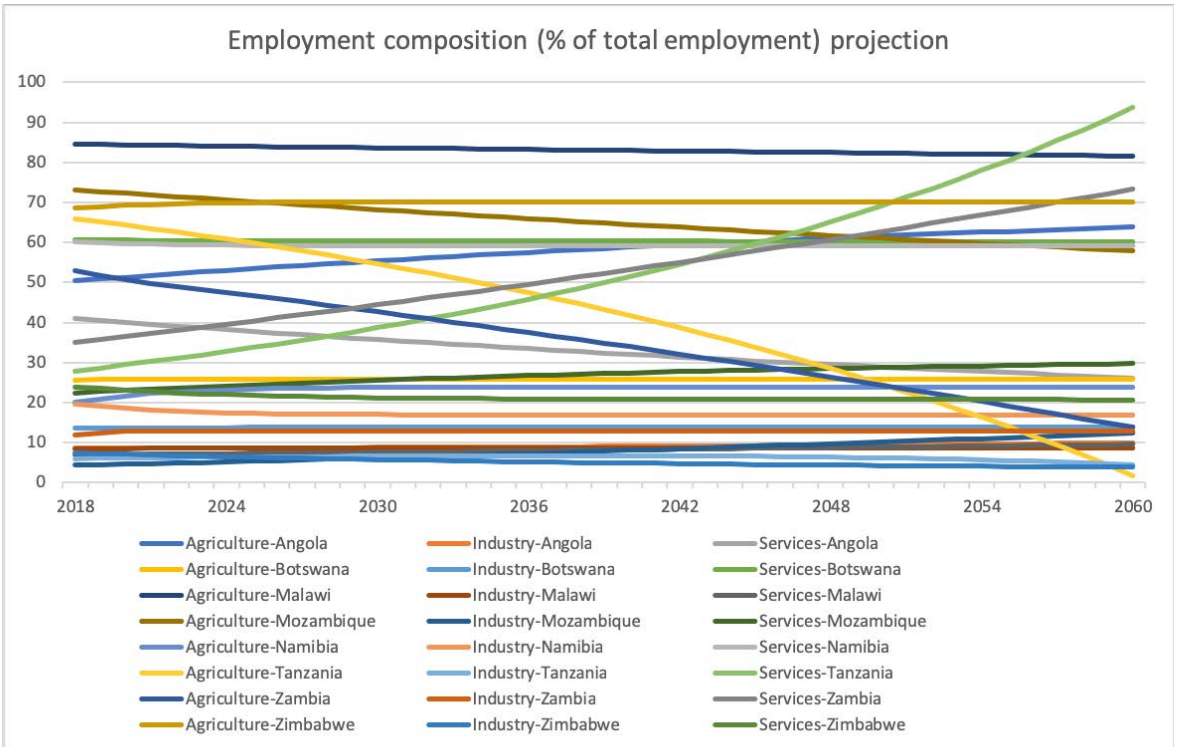

Figure 25 – Employment composition in ZRB (% of total employment) projection

Water

The water use associated with the industrial, agricultural and service sectors differs significantly not only across the sectors, but across countries as well. It is clear that the majority of freshwater withdrawals occur within industry sector, the annual consumption of which in 2017 varied from 13 billion cubic meters in Namibia to 611 billion cubic meters in Angola. Such a difference is not attributed to the difference in their industry sector's share of added value to their GDP, which is only 8 percent, but to their vast GDP difference, which implies a significant disparity in the size of the industry sector in each country. Indeed, according to World Bank (2018) the value of the industry sector in Angola is $52,3 billion, which is four times higher than the annual GDP of Namibia.

In order to compare the annual water consumption of the three sectors, we can consider the average water use in 2017 of the eight riparian countries in each sector. Apparently, almost all freshwater withdrawals are consumed by the Industry sector, which on average needs 134,5 billion cubic meters per year, while the agriculture needs only 1,1 billion cubic meters and the service sector less than 0,3 billion cubic meters. In order to come up with these numbers data from World Bank (2018) are used for annual freshwater withdrawals per sector to calculate the water use in billion cubic meters per 1 percent of added value in the GDP. Due to lack of data, this step was necessary in order to get an average water use per country and compute the current values. Then, this value was multiplied with the current share of the sector to the GDP giving the total water use per sector and per country.

Another interesting aspect of the water use per sector is its projection in the future. Considering the trends on GDP composition projection derived in the previous section and the average water use per sector and country, annual projections have been computed and illustrated in Figure 26. As SSP2 scenario commands, without any dramatic changes in the distribution of the economy of the riparian countries, water use will keep on being extremely high for the industry sector of Angola, Zambia and Zimbabwe varying between 126 and 719 billion cubic meters in 2060.

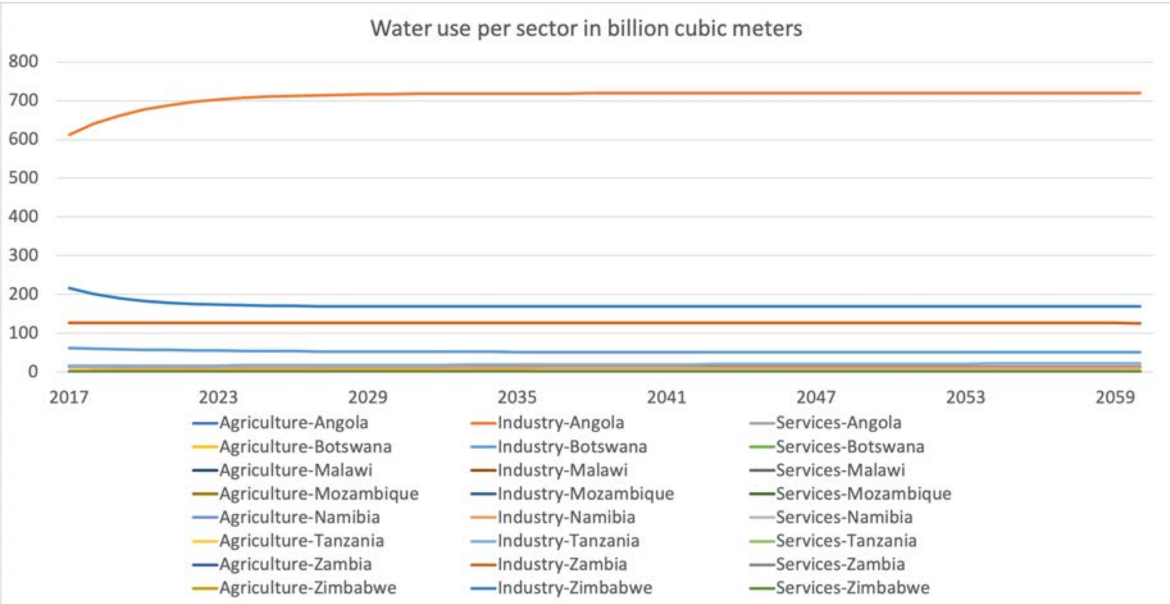

Figure 26 – Water use projections in ZRB per sector per country

Energy

In order to replace the mainstream sources of energy with more efficient and better targeted social safety nets for the most vulnerable energy sources, some countries make significant use of subsidies. In particular, as presented in AfDB (2019), Zimbabwe, Zambia and Mozambique received the highest subsidies among the other African countries. In Zambia, mining output is expected to increase by 4%–5% in 2019, benefiting from improvements in electricity generation associated with the replenishment of the Kariba Dam due to good weather conditions (AfDB, 2019).

Aiming to boost domestic supply of local products, some of the riparian countries chose more conservative policies, such as banning imports or implementing tariffs. For instance, Botswana, Zambia, and Zimbabwe ban imports of poultry, maize meal, and cooking oil, while Zimbabwe's competition and tariff by-laws require supermarkets to buy domestically at least 20 percent of the goods they are selling. As far as these policies are being performed, domestic agriculture, fishing and animal husbandry will be boosted by facing a comparatively more protected demand and fair prices.

Mozambique could become one of the largest exporters of natural gas in the world by 2020 (the country hosts the third largest reserve in Africa) thanks to the discovery of new reserves. Lastly, the planned construction of natural gas plants as well as a new dam should allow the country to increase its electricity exports to neighbouring countries. Export infrastructure (railroads, deep water ports, liquefied natural gas plants) is also under construction. The country is expected to export natural gas and coal to Asia by 2020.

2.2.6 Summary of Middle of the road Scenario (SSP2)

Society. This path follows a pattern of actions that is consistent with the experience of the last century. Under this scenario the ZRB can expect to see the total population living within the basin after considering urbanization trends to reach 99 million people by 2060 with 3 million of them being due to urbanisation assumptions. Education levels are moderate limiting so, the social and human capital of the riparian countries, but explaining the significant increase in the population.

Economy. In SSP2 although all countries are developing, some of them are making greater progress than the others. Given the historical patterns, the forecasting shows that Angola, Tanzania and Botswana, which are relatively richer in absolute values than Malawi and Namibia are expected to increase with a higher pace (around 8%) than the other countries, which can accelerate with rate between 3,3% and 5,3%. Hence, existing inequalities are increasing more and more creating a greater gap between developing and developed world. Economic growth is followed by increased employment as well, with agriculture sector playing a significant role in that trend.

Climate Change. Limited pro-active initiatives are considered from both Government and institutions in SSP2. The world is semi-open globalised, while the policies do not prioritise sustainability and the institutions are modestly effective. On top of that, extensive use of fossil fuels leads to continued degradation of the environmental assets, while the challenge to mitigate or adapt to these effects is moderate.

Impact on WEF nexus. As a consequence of the socio-economic developments, water, energy and food consumptions within ZRB are expected to increase significantly by 2060, mainly driven by high population growth. The total water use within ZRB is expected to increase up to 1,8 billion m^3 from 0,8 billion m^3, which is current value, while the total electricity consumption within ZRB is expected to reach 207 TWh by 2060, which is more than twice as much as it is today. In terms of total calorie intakes, the total expected consumption in ZRB in 2060 will reach 74,670 Tcal, with Malawi consuming 31% of them. In terms of protein and fat intakes, the total requirements will reach 1,7 Megatonnes and 1,3 Megatonnes.

2.2.7 Alternative SSPs: SSP1 and SSP5

While the previous sections depict in detail the SSP2 scenario, where global development follows a middle of the road path, this section summarises two alternative futures under SSP1 and SSP5. SSP1 is perceived as the sustainable pathway focusing on the role of the environmental services in the economy, while SSP5 is the economically driven scenario, which, although it recognizes the economic impacts of the environmental degradation on the economy, does not undertake pro-active steps, but focuses on technology improvements able to mitigate the skyrocketed emissions of the human activity.

Sustainability Conscious Scenario (SSP1)

Society. SSP1 envisions a development path with increased investment in education and health. Hence, greater access to education is leading to a relatively rapid demographic transition, due to birth controls and lower child mortality rates, which tones down the moderate population growth noted in SSP2, and also increases the human and social capital of the economy (Jones and O’Neil, 2016). By contrast, urbanization is assumed to be rapid in SSP1, which drives high income growth. Under this scenario urbanization is desired given the high efficiency that compact urban areas may achieve.

Economy. The main feature of the economy narrative under SSP1 is the achievement of development goals while following a path of sustainability that moves towards a less intensive use of resources. As presented in Table 1 the economic development in SSP1 is expected to be high, with GDP growing more rapidly than that corresponding to SSP2 and illustrated in Figure 42. The drive of economic growth in this scenario is the fact that the human-wellbeing is redefined in SSP1 considering the ecosystem services, which are included in the economic development initiatives and in the overall shift of the economy to environmentally friendly actions with the help of rapid technology improvements. Employment in SSP1 will also be rapid following the great economic development of the countries, overpassing the levels of SSP2.

Climate Change. In SSP1, sustainable development is the central focus of all policies across the world, which is connected in decision making with strong and effective institutions. Renewable sources of energy lead to an optimal treatment of the natural capital, while the need for mitigation or adaptation remains low.

WEF nexus. Water-Energy-Food (WEF) nexus projections in SSP1 result in a different pattern as a result of different population inputs, the increased value of ecosystem services and a more sustainable energy policy than in SSP2. In particular, since the overall population will decrease and the urbanization levels will remain as high as in SSP2, the final population within the basin will be significantly lower and hence the needs for water, energy and food will not increase dramatically.

Fossil Fuel-Driven Scenario (SSP5)

Society. Similar to SSP1, SSP5 envisions a development path with increased investment in education and health. Hence, greater access to education is leading to a relatively rapid demographic transition, due to birth controls and lower child mortality rates, which tones down the moderate population growth noted in SSP2, and also increases the human and social capital of the economy (Jones and O'Neil, 2016). By contrast, urbanization is assumed to be extremely rapid in SSP5, driving high income growth. Cities attract migration due to other reasons from SSP1, such as rapid technological change allowing for large-scale engineering projects to develop desirable housing.

Economy. The main characteristic of the SSP5 economy narrative is the rapid development of the economy and the intensive use of fossil fuels. As presented in Table 1 the economic development in SSP5 is expected to be high, with GDP growing more rapidly than that corresponding to SSP2 and illustrated in Figure 42. However, the economic strategy of this scenario differs considerably than the SSP1 and SSP2, letting so GDP growth rates take their highest possible values. Innovation and investments are the most preferable options in SSP5, where technological progress and competitive markets drive growth. Employment in this scenario will also be rapid following the great economic development of the countries.

Climate Change. In SSP5 free markets and emphasis on human capital drive the economy under a strongly globalised status quo administrated by effective institutions. High fossil-fuel reliance in alignment with the high economic growth leads to higher GHG emissions and so, higher mitigation challenge. However, although the dominance of fossil fuels impacts significantly the environment, it doesn't degrade it more than SSP1, due to high mitigation policies, which control environmental processes through highly engineered systems, nevertheless with no focus on adaptation.

WEF nexus. Water-Energy-Food (WEF) projections in this scenario would also diversify as compared to SSP2 ones, as a result of different population inputs, industrial water demand and climate change adaptation measures. Likewise the SSP1 case, the population per country will decrease, thus inducing a decrease of water, energy and food needs per person. However, in this case the urbanization levels are more rapid than the other two paths, which means that the final population within the basin can be as much as in SSP2, ultimately leading to similar needs for water, energy and food.

2.3 OMO-TURKANA BASIN

2.3.1 Demography

Population projection by country

The OTB comprises of four countries, which occupy different areas within OTB. The biggest part is occupied by Ethiopia and Kenya (see Figure 27). In this section the study aims to estimate the population within ZRB by considering social factors such mortality, fertility and international and internal migration for the period from 2018 to 2100. As previously stated, SSP2 was considered as a guideline for analysis, before a comparison with SSP1 and SSP5 is subsequently made in section 2.3.7.

Figure 27 – Night Light Intensity across the OTB (Source: Linard et al., 2012; Worldpop, 2015)

As explained further in ZRB case (section 2.2.1), in order to calculate population growth projections, a simple model with one lag considering the values of the previous year and the annual population growth rates per country is run. Hence, a comprehensive and transparent selection of the growth rates was an important stage of this exercise, due to its impact on the future trends. After comparing a number of resources such as CIA (2019), the World Bank (2018), World by map (2017) and World atlas (2018), growth rates provided by United Nations (2017) seem to have the most transparent and analytical approach. A crucial benefit of this report is not only the 100-year forward looking, but the time slice of the predictions to 5-year periods, which enables projections to be comparatively more accurate. United Nations (2018a) revision considers various parameters in estimating the population prospects of each country such as mortality and fertility rates and international migration. As a result, ten variants are presented under different assumptions with constant mortality one being the most adequate for our analysis under the SSP2 scenario, as it is the most moderate one assuming normal international migration and medium fertility rates. Moreover, the estimations of this variant are in alignment with the rough estimations of the institutions listed above.

Figure 28 illustrates the population growth projections of the four countries sharing the OTB. Ethiopia is portrayed by a dramatic population increase reaching 210 million people by the end of the century, while the other three countries demonstrate an increase ranging from 89 to 147 million people. However, all countries except of Uganda tend to reach a peak before falling, attributed to improved healthcare and education systems, leading to lower child mortality and higher employment, which both drive lower birth rates. In particular, the peak period for Kenya's population is from 2069 to 2080 reaching almost 100 million people, while the peak year for Ethiopia is 2085 with 215 million people.

Population projection by urban centres

In Ethiopia and Kenya, there are currently seventeen urban centres at present with more than 100,000 inhabitants. As illustrated in Deliverable 2.1., in comparison to the ZRB, the major urban centres in OTB are significantly fewer, with only one city having more than 100,000 inhabitants, Jimma (Ethiopia), located within the geographical area of the OTB (see Table 3). In Figure 29

Jimma's population growth is illustrated, which from 128 thousand is expected to reach 250 thousand people by 2100, following the same pattern with Ethiopia, reaching its peak in 2085 and then slightly decline. Those trends are calculated following the same methodology described above.

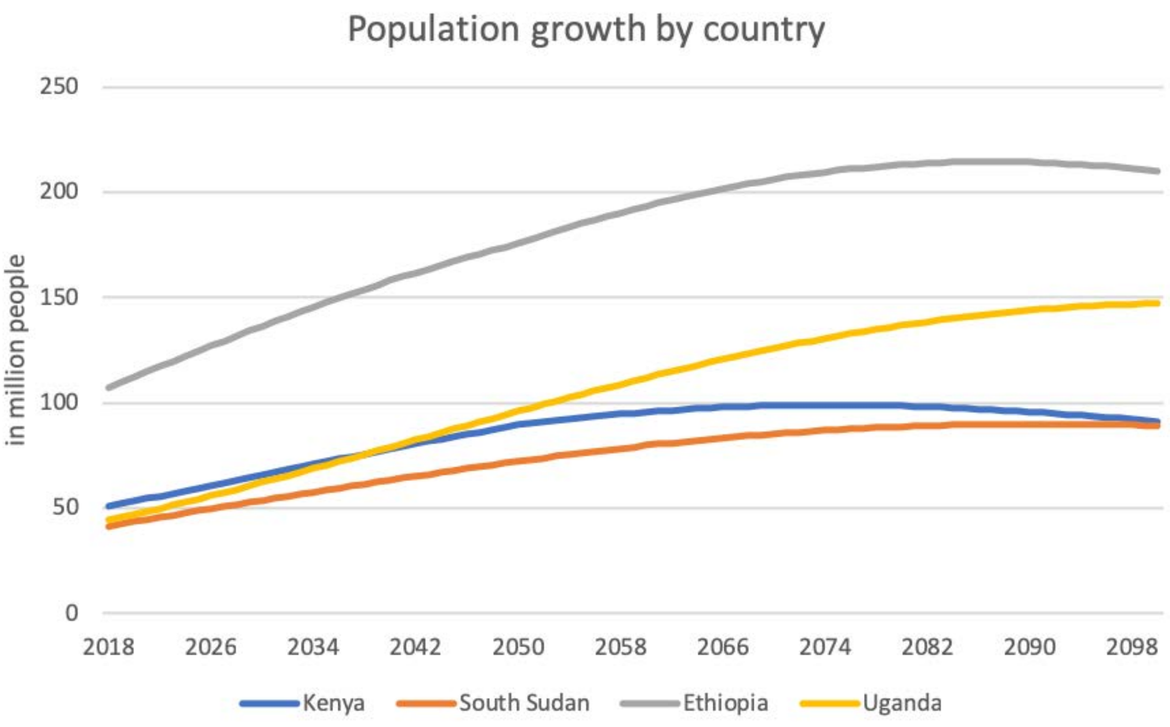

Figure 28 – Population growth in OTB by country

Table 3 – List of major urban centres in OTB countries: OTB urban centres in italic (Source: World Population Review, 2018).

Country	City Name	Population (2018)	Location link	Coordinates	
Ethiopia	Addis Ababa	2,757,729	Map	9.02497	38.74689
	Dire Dawa	252,279	Map	9.59306	41.86611
	Mek'ele	215,546	Map	13.49667	39.47528
	Nazret	213,995	Map	8.55000	39.26667
	Bahir Dar	168,899	Map	11.59364	37.39077
	Gondar	153,914	Map	12.60000	37.46667
	Dese	136,056	Map	11.13333	39.63333
	Hawassa	133,097	Map	7.06205	38.47635
	Jimma	*128,306*	*Map*	*7.67344*	*36.83441*
	Bishoftu	104,215	Map	8.75225	38.97846
Kenya	Nairobi	2,750,547	Map	-1.28333	36.81667
	Mombasa	799,668	Map	-4.05466	39.66359
	Nakuru	259,903	Map	-0.28333	36.06667
	Eldoret	218,446	Map	0.52036	35.26993
	Kisumu	216,479	Map	-0.10221	34.76171
	Thika	200,000	Map	-1.03326	37.06933
	Malindi	118,265	Map	-3.21799	40.11692

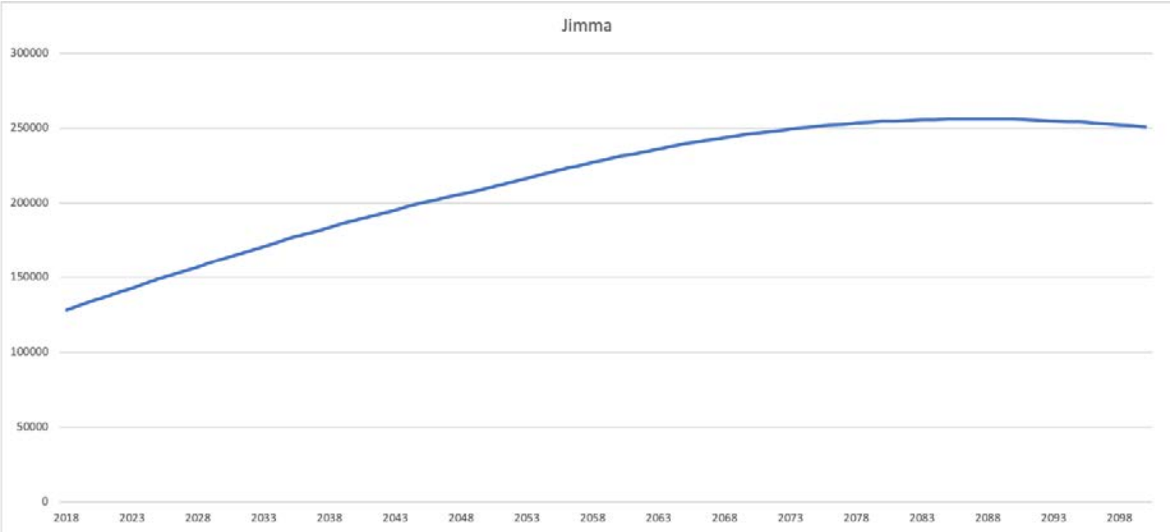

Figure 29 – Population growth of the major city in OTB.

Moreover, there is one city within OTB, which although in 2018 does not meet the requirements to be counted as a major city, in 2026, it is expected to exceed 100,000 people. The city of interest is Sodo, a town in south-central Ethiopia and its population growth can be identified in Figure 30, which is projected following the same methodology described above. Sodo meets the requirement to be accounted as a major city in only 8 years. Consequently, the need for water, energy and food will accelerate due to increased population and hence the increased concentrated economic activity in the area.

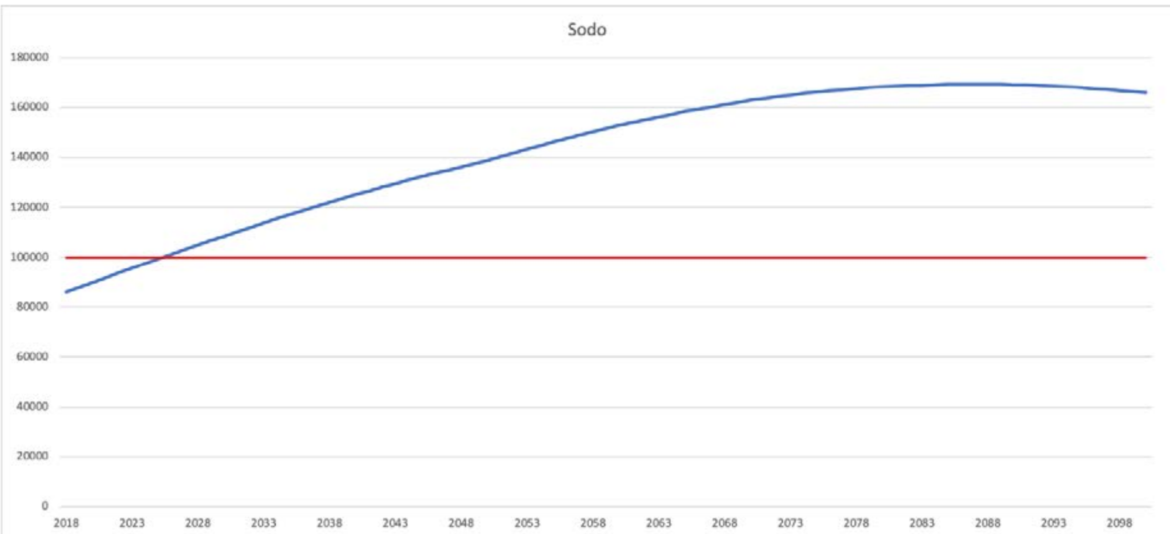

Figure 30 – Population growth in OTB for one exemplary non-major city

Population projections by sub-basin

According to Deliverable 2.1, the population density of OTB in 2018 was 103.12 people/km^2 with a total of 10,081,880 inhabitants. For the purposes of the analysis the area within OTB is divided into 9 sub-basins, as illustrated in Figure 31 which presents the current view of the area and they are further analyzed in Deliverable 2.1.

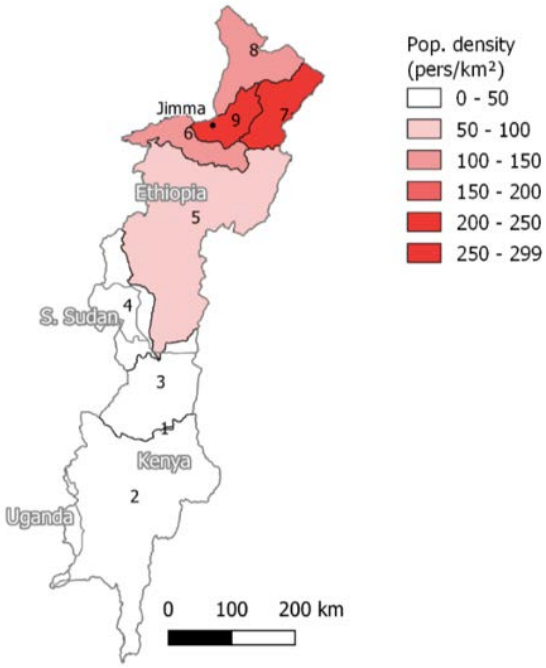

Figure 31 – Population density in 2018 per sub-basin within the OTB (Source: Linard et al., 2012; Worldpop, 2015)

The population growth within the OTB presented in Figure 32 was calculated using the same methodology as for the ZRB (see section 2.2.1). The population within OTB is expected to reach 21.4 million people by the end of the century, which is two times greater than its current population. As demonstrated in Figure 32 sub-basins 5, 7 and 8 seem to increase more than any other sub-basin within OTB and they are all located in Ethiopia. This disproportionate population increase will add an additional pressure (crucially in a transboundary context) on the natural resources, i.e. the water use, as more people need more water consumption which demand is being met by more exploitation of permanent and exhaustible resources.

Nonetheless, the estimated population trends described above do not capture internal migration. Urbanization, which is increasing rapidly on the African continent, is a useful index to capture internal migration, since it captures the flow from rural to urban areas during a period of time (The World Bank, 2018). As explained above (see section 2.2.1.) the impact of urbanization can be controversial, as it is accompanied by both benefits and costs, from improved employment opportunities, better accommodation and basic services and generally a better living standard to congestion, overcrowding, resources scarcity and health hazards (Wenban-Smith, 2015).

After comparing the urbanization rates of the World Bank (2018) and United Nations (2018b), the latter view of UN was adopted; as the World Bank provides estimations based on the percentage of inhabitants living in cities (incorporating population growth projections according to their assumptions), while UN declared the annual change of the urban population in each country. Approaching the unification of the urbanization rate and the population growth in the projections per sub-basin, the 9 sub-basins were firstly divided into rural and urban areas using urban mapping projections by SEDAC (2018).

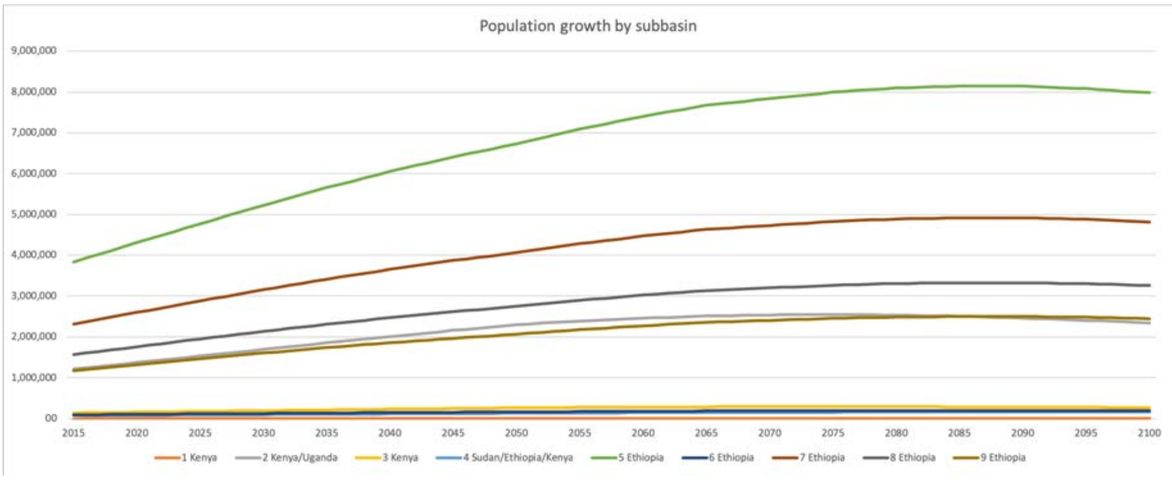

Figure 32 – Expected population in OTB by sub-basin

According to SEDAC (2018), only Ethiopia seems to have urban areas in this case with Kenya, Sudan and Uganda being mainly rural in the areas of interest. Hence, in order to get more accurate results, the expected population trends for the former countries will decrease by 3% to 4,2%, i.e. as much as the urbanization rate is in their countries, while the expected population in areas 5 to 9, which all are located in Ethiopia, will increase from 3% to 4,6% annually. Lastly, one more challenge of projecting the population until 2100 is the lack of data. The urbanization rates estimated by the United Nations (2018b) are projected until 2050, so, it is assumed that the urbanisation rates in the period 2050 to 2100 are as high as their corresponding values in the period 2045 to 2050.

Figure 33 displays the final population projections per sub-basin incorporating assumptions about mortality, fertility, international and internal migration variants for the period 2015 to 2100. Sub-basins 5, 7, 8 and 9 all increase by the same rate, since they all lie in the same country and they are all identified as urban areas, while sub-basins 1,3 and 4 show a significantly lower increase by virtue of being characterized as rural areas and so some people from this places is expected to move to bigger cities, where more opportunities can be found. However, 500 thousand more people will inhabit the OTB by the end of the century due to internal migration reaching a total of 21.9 million.

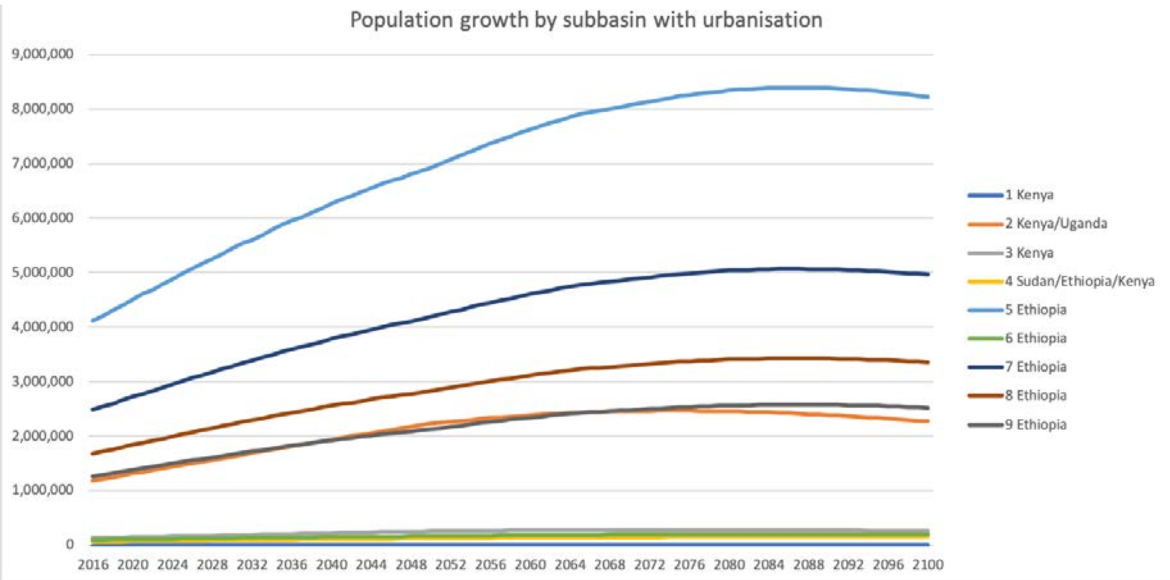

Figure 33 – Expected population in OTB with urbanization by sub-basin

2.3.2 Water consumption by private households

Withdrawals for domestic uses include drinking water, municipal use or supply, and use for public services, commercial establishments and homes. In this section estimates the water consumption in the domestic sector for each country and sub-basin within the OTB for the period from 2016 to 2100. Using the data from Deliverable 2.1. for the annual water use per capita for each country within the OTB, we use the demographic projections per country's share in OTB and per sub-basin with urbanization assumptions to compute the projected water consumption by private households. In the event of a sub-basin being shared by two or three countries with different water consumption rate, we computed the average consumption of those countries, and then, we multiplied it with the population of the sub-basin.

As presented in Figure 34 and Figure 35 the water use is expected to increase dramatically only if the demographic growth of both countries is considered. Specifically, the total water use within the OTB is expected to increase from approximately 120 million m^3 at present, to 238 million m^3 by the end of the century. As expected, Ethiopian households consume more water than Kenyan, due to their demographic dominance within the basin, constituting 88 percent of the population within the basin.

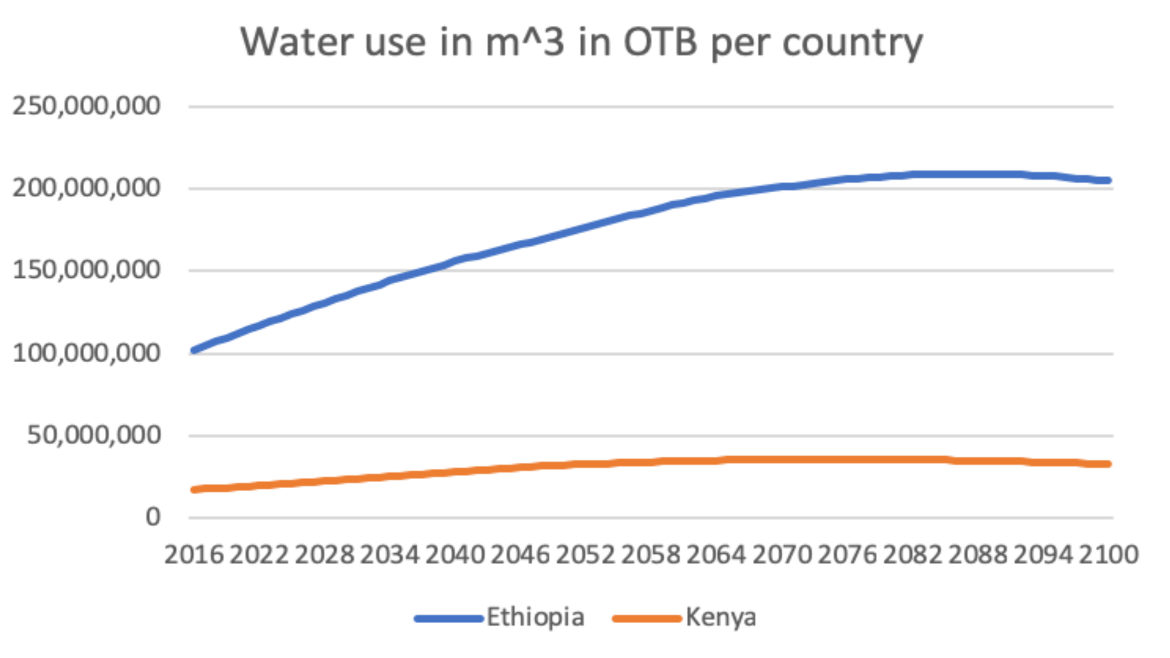

Figure 34 – Water use per country in m^3 per year

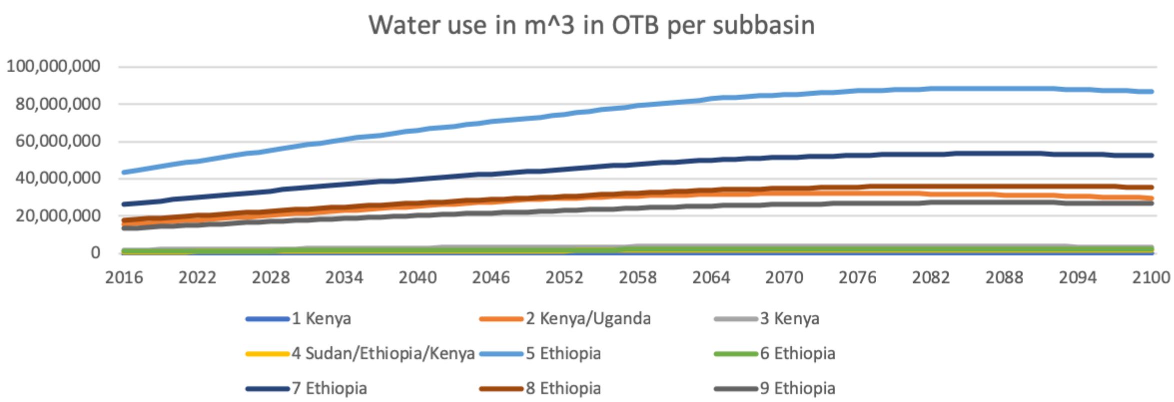

Figure 35 – Water use per sub-basin in m^3 per year

2.3.3 Energy consumption and access to electricity by private households

As in the previous section, the energy consumption per capita in the domestic sector for each country of the OTB computed in Deliverable 2.1. is used to estimate the annual energy consumption per country's share within the OTB and per sub-basin for the domestic sector under urbanization assumptions. In case of a sub-basin being shared by two or three countries with different energy consumption rate, we selected the rate of the country having the greatest share in the controversial sub-basin. Energy consumption refers to energy usage from petroleum and biomass and waste electricity (the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source).

Figure 36 and Figure 37 show the projected energy use by the end of the century. By 2100 the total energy requirements within OTB is expected to reach 73,845 GWh, which is twice as much as it is today. As expected, Ethiopians living within the OTB are expected to consume in total more energy than Kenyans, due to their demographic advantage.

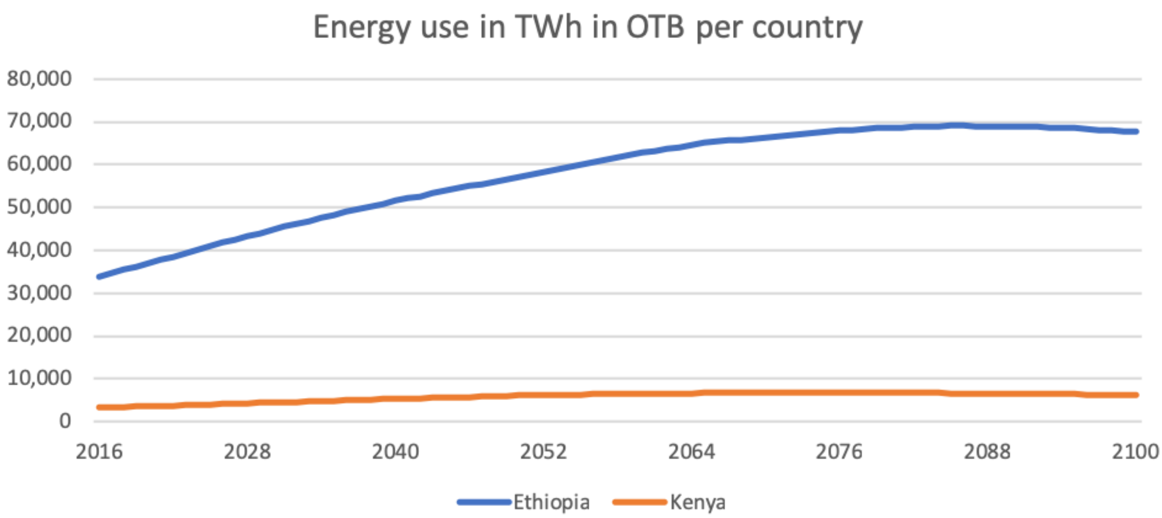

Figure 36 – Energy use in OTB per country in TWh per year.

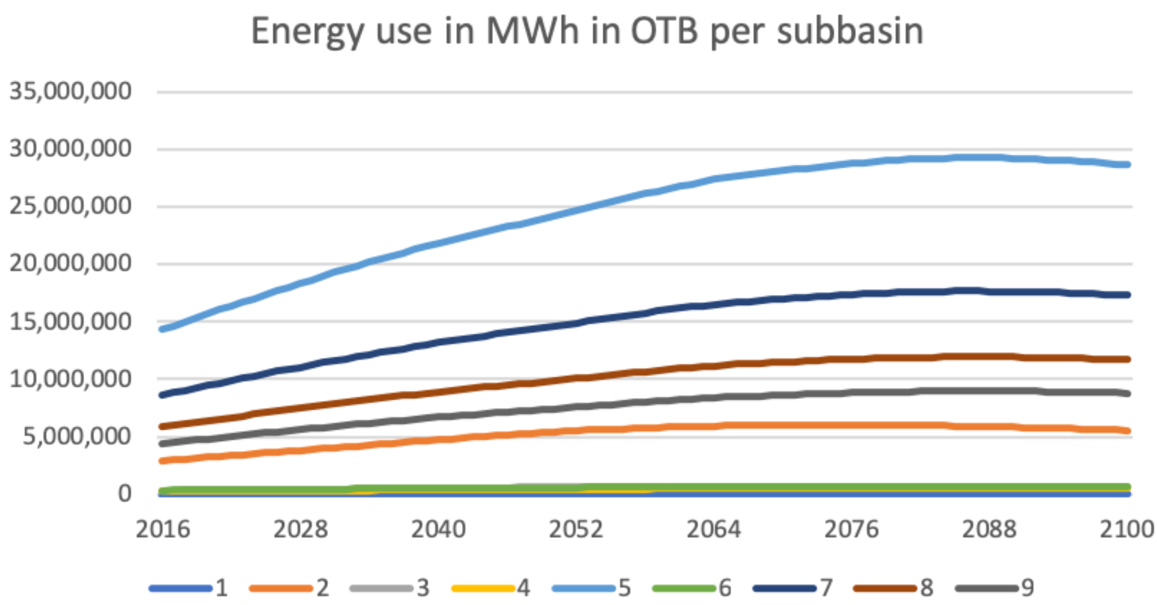

Figure 37 – Energy use in OTB per sub-basin in MWh per year

During the last 16 years great progress has been made in terms of access to electricity worldwide. In particular, since 2012, 100 million people per year have gained electricity access, while the corresponding rate for the period between 2000 and 2012 was 62 million people per year. According to IEA (2017) both Ethiopia and Kenya are on track to reach universal electricity access by 2030, nevertheless the rural areas may remain without electricity access due to the uneven progress across the region. Moreover, although until 2016 new grid connections were powered with energy generated by fossil fuels, over the last five years, renewables have been accelerated increasing more and more their share in the market, which are expected to gain even more ground in the future with off-grid and mini-grid systems providing the means for almost half of new access by 2030.

In 2016, the share of people without electricity access in Ethiopia was 60%, although half of which were above the poverty line. However, as illustrated by IEA (2017), as a country's wealth increases, its reliance on the traditional use of biomass, which is usually used in inefficient stoves for non-commercial purposes, tends to decline while electricity use and its per-capita energy use rise. In other words, the fuel mix for low-income countries, such as Ethiopia and Kenya, tends to be dominated by biomass energy resources, while the fuel mix of high-income countries, such as Germany or Japan, contains almost zero quantities of biomass.

Additionally, electricity access can be associated with increased female employment as a result of improved efficiency in achieving household tasks. For example, in South Africa, electrification raised female employment by almost 10 percent in newly electrified communities, while in Nicaragua, the ability of rural women to work outside the home has been increased by 23% due to access to reliable electricity (Dinkelman, 2011; Grogan and Sadanand, 2013). As presented by the Practical Action (2016), the rationale behind those trends is that in developing countries, the responsibility for collecting and preparing fuel for cooking is born mainly by women and children, who spend on average 2 hours and 1 hour daily in collecting fuel in Ethiopia and Kenya correspondingly (IEA, 2017).

2.3.4 Food requirements at sub-basin scale

In alignment with previous two sections in order to estimate the food demand in the long-run, data for the daily calorie, protein and fat intake needs of an individual for each country are used from FAO (2018). After, we computed the annual food consumption per person, which we multiplied with the population projections per sub-basin estimated in the previous chapter including urbanization.

The outputs of these projections can be seen in Figure 38, Figure 39 and Figure 40, where the pattern is similar between the graphs. The greatest food requirements are expected to occur within sub-basin 5, probably due to its demographic advantage, as it is the most populated sub-basin within the basin. In terms of total calorie intakes, the total expected intakes in OTB in 2100 will reach 15,6 Tcal, with Ethiopia consuming 88% of them. In terms of protein and fat intakes, the total requirements will reach 0,45 Megatonnes and 0,19 Megatonnes respectively, with Ethiopia consuming 87% and 77% in each case.

2.3.5 Economic Development

The economy of the two main countries of the OTB, Ethiopia and Kenya, is based on the industry and mining sector. Supply of consumer goods creates employment opportunities and exports bring foreign exchange in the country. The following projections are developed under the SSP2 assumptions, known as the middle of the road path, which follows a pattern of action that is consistent with the experience of the last century.

Over the past 25 years few African countries have developed as rapidly as Ethiopia with the economic growth being associated with a sizeable expansion of service delivery. However, Ethiopians' access to basic services remains between the lowest levels in the world. In 2016, after a decade of strong growth, Kenya ascended to the status of 'mid-income country'. Kenya is particularly advanced in the sector of services and has been the source of innovations adopted throughout the continent. In March 2017, Kenya became the first country to sell government bonds through mobile phones (BBC, 2017).

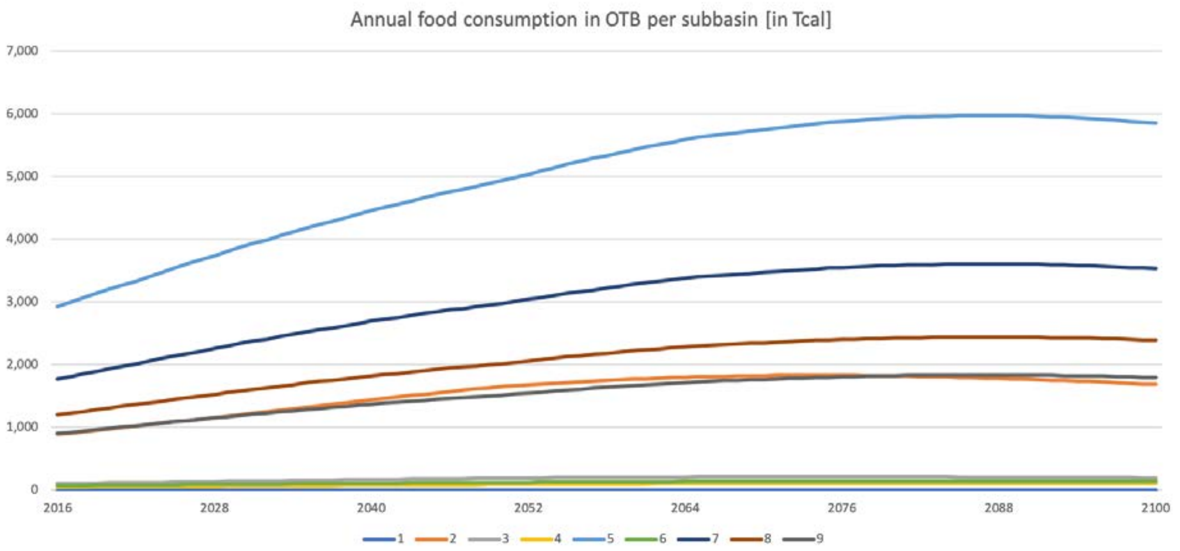

Figure 38 – Annual food requirements in OTB per sub-basin in Tcal per year.

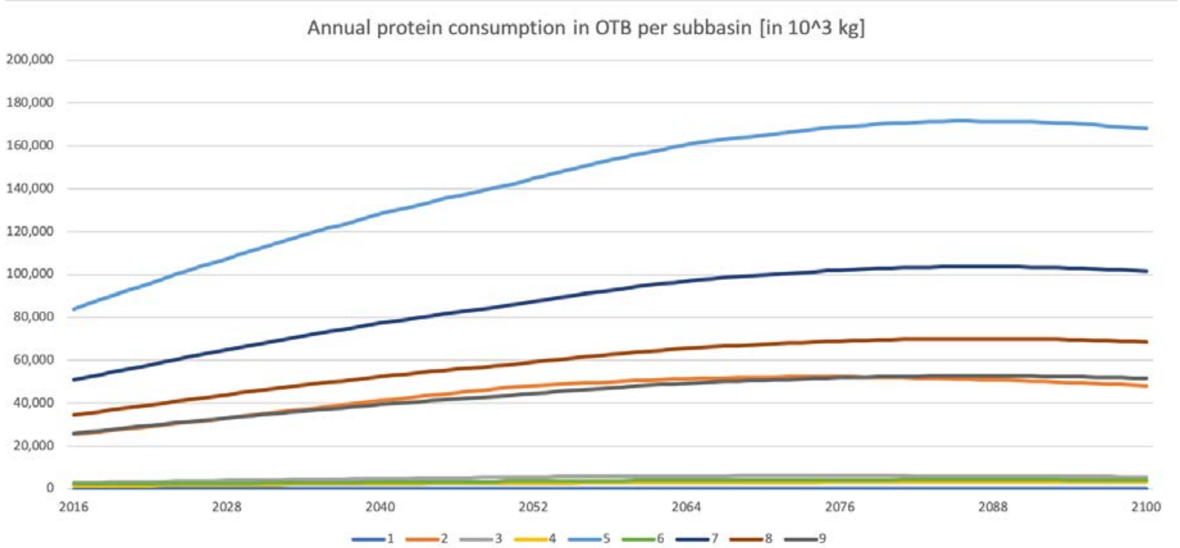

Figure 39 – Annual protein requirements in OTB per sub-basin in 10^3 kg

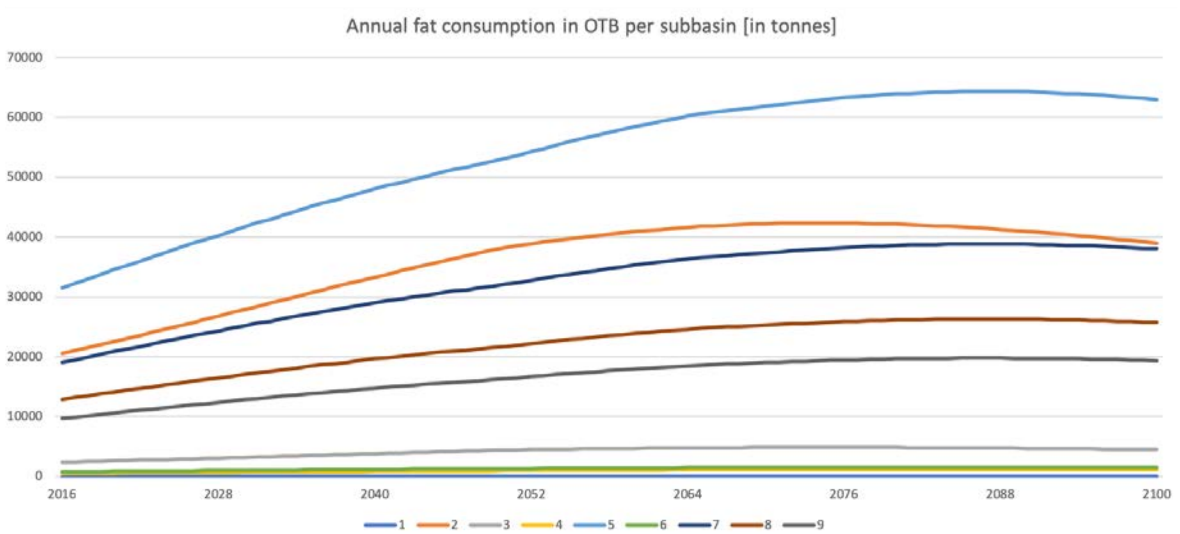

Figure 40 – Annual fat requirements in OTB per sub-basin in 10^3 kg

GDP growth

Figure 41 displays the GDP growth projections of the two riparian countries in the period from 2017 to 2023. Although Ethiopia doesn't diverge significantly from Kenya in terms of GDP production, it does diverge in terms of GDP per capita, as Ethiopia has twice the population of Kenya. However, in the next seven years, Ethiopia seems to grow faster than Kenya reaching $127 billion by 2023.

Moreover, in order to make comparisons with the other trends, GDP growth projections need to be run until 2100. However, due to lack of data after 2023, some assumption have been made. Firstly, it is assumed that both of the countries' GDP will grow with a rate 8,9% and 4,9% during the period 2023-2030, which derives from the average growth rate of the period 2000 to 2023. At this stage, both countries, and mainly Ethiopia, are expected to grow significantly fast due to their need for infrastructure and development.

Evidence from other countries shows that beyond a certain point, the rate of GDP growth decreases, thereby indicating a better-off economy. Based on a review of existing trends, this point has been narrowed down to the point at which the GDP reaches $230 billion; beyond this milestone, countries from different continents such as Canada, Brazil, Spain, Netherlands and Australia, follow similar GDP growth trajectories with an average around 2,3%. Hence, from 2030 to 2074 for Ethiopia and from 2040 to 2083 for Kenya, the assumed growth rate is 2,3%, while based on available data that there is an observable plateu in growth rates and so an assumption of 1% growth rate has been made for that point on.

As presented in Figure 42 the GDP of both countries is expected to grow significantly, exceeding $800 billion in Ethiopia and reaching almost $750 billion in Kenya. However, we should not forget that the world position of a country depends also on the inflation rates and on the growth of the other countries. In other words, by that time inflation may degrade the real value of the GDP reducing so, the consumers' purchase power stopping them from improving their living standards.

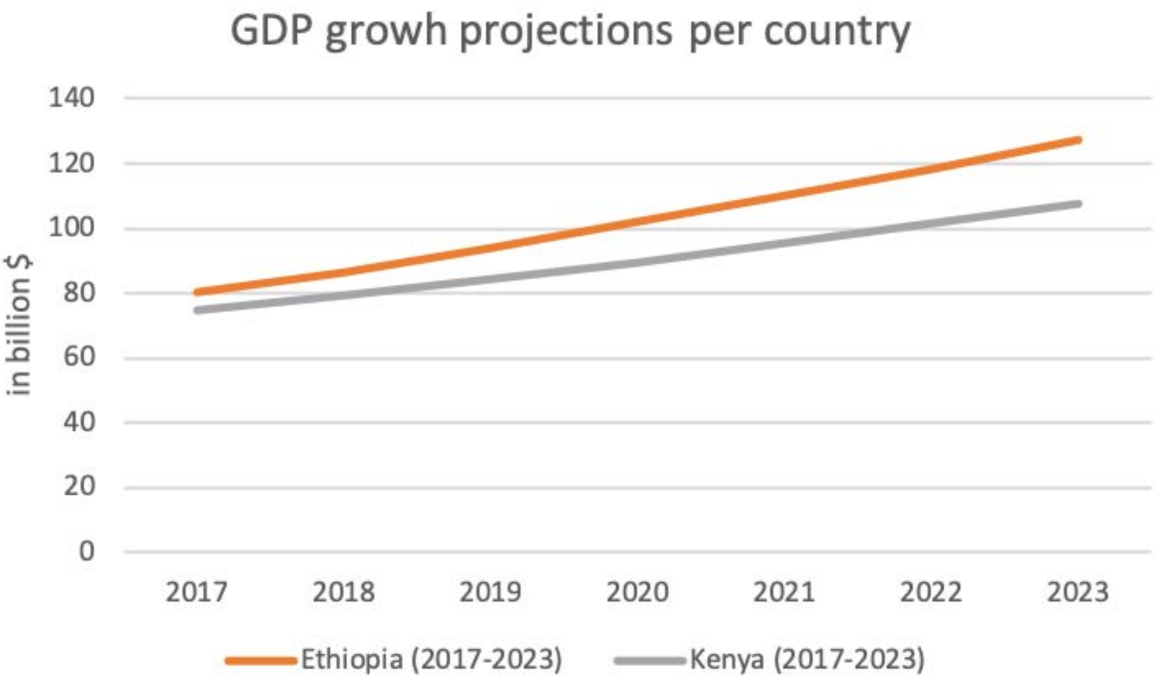

Figure 41 – GDP growth in OTB per country 2017-2023 (sources: World Bank (2018); IMF (2018))

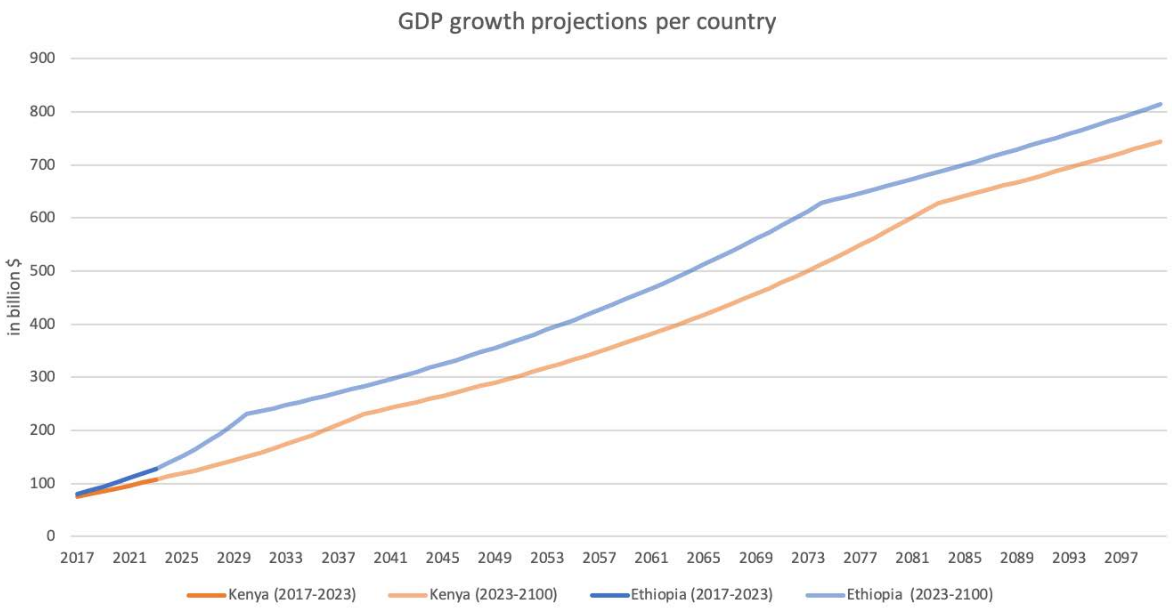

Figure 42 – GDP growth in OTB per country 2017-2100 (sources: World Bank (2018); IMF (2018))

In terms of WEF nexus, GDP growth can be constrained or accelerated by water, energy and food risks. Increasing GDP could increase further the demand for water, energy and food, as more and more people could afford to consume higher quantities of these goods. Consequently, an increased burden could be placed on the management of the resources, which except of smoothing people's lives, are also initial inputs for the economic growth. Hence, if they are not managed efficiently, they could even slow down the growth of the economy.

International trade

Ethiopia is relatively open to international trade, with a foreign trade-to-GDP ratio of 31,4% in 2017 (World Bank, 2018). It is a member of the Intergovernmental Authority on Development (IGAD) and the Common Market for Eastern and Southern Africa (COMESA), but has not joined the free trade zone and, since March 2003, has been in the process of joining the World Trade Organisation (WTO). As part of this process, the government is restructuring its custom tariffs. In order to rationalise the opportunities for investment, it has introduced lower duties on raw materials and semi-finished products. Customs duties in Ethiopia are payable on imports by all consumers and entities that have no duty-free privileges. The rate of customs duty varies from 0% to 35% with an average rate of 17%. In recent years, Ethiopia has decreased customs duties on a wide range of imports but duties still remain exceptionally high on certain items such as vehicles. Other taxes may also be imposed on imports. These are excise duties on selected goods (e.g., tobacco), sur tax on many imports and the value added tax (15%) (Société Générale, 2019).

Ethiopia is a country historically in deficit, with the trade balance continuing to deepen due to its investment-led economy, which strongly encourages imports. The country's trade balance partially depends on climatic events, which occasionally forces Ethiopia, a large agricultural producer, to import grains during droughts. In 2017, the worth of exports was only $3 billion, while imports reached $16.7 billion, thus resulting in a trade deficit of nearly $13.3 billion. Ethiopia mainly exports agricultural, such as coffee, oil seeds and flowers and mining products such as petroleum products and gold, with the U.S., Saudi Arabia and Germany as the main partners. The country mainly imports machinery and aircraft, metal and metal products and electrical materials. The main countries of origin are China, U.S., India and Kuwait.

Kenya is a country largely open to international trade, which accounts for 37,2% of its GDP in 2017 (World Bank, 2018). The country remains committed to trade liberalisation through its membership in the WTO, the COMESA and the East African Community (EAC), which includes Kenya, Tanzania, Uganda, Rwanda and Burundi. Together with the latter two, Kenya signed an agreement to establish a new monetary union in December 2013. Negotiations continue between the EAC and the EU to find an economic agreement, while Kenya signed many bilateral trade agreements and is currently in negotiation to sign more of them. After an unsuccessful first attempt, most tariff barriers have been eliminated and customs duties are not very high. They range from 0% for raw materials to 50% for certain products such as matches, with raw materials, capital goods, energy-saving bulbs or tractors for agriculture are exempted from customs duties (Société Générale, 2019).

Kenya imports three times more than it exports, which translates into a trade balance that is largely in deficit. This situation persists, although with a downward trend, as a result of imports related to infrastructure modernisation and oil exploration. The export of the first barrels should not allowed to significantly reduce the trade deficit within the coming years. In 2017, the deficit deepened (more than USD 11 billion), as exports, +3% in comparison with 2016 rates, are growing less rapidly than imports, +20,5% in comparison with 2016 rates. The driving force of Kenya's exports are the agricultural products, such as tea, coffee, vegetables and flowers, while imports are dominated by oil products, vehicles and manufactured products. The country's main export partners are Uganda, Tanzania, the Netherlands, the U.S., the U.K., Zambia, Pakistan and the UAE. Its main import partners are India, China, UAE, Japan, Saudi Arabia, Egypt, and South Africa.

Ethiopia in alignment with its economic development, the SDGs and its opening to the markets will present a slight increase in the coming years, while after it will keep on increasing with a lower rate, due to increased competition with an average rate deriving from Least Developing Countries trend, where Ethiopia is ranked as well. On the other side, the fact that Kenya is considerably open to international trade, which in addition with MOIED (2015) plans for making Kenya a "middle-income country providing a high-quality life to all its citizens by the year 2030", will drive international trade to increase until 2030. After that point it will keep on increasing, but in a slower pace due to increased competition in the market. The graph of these projections can be seen in Figure 43.

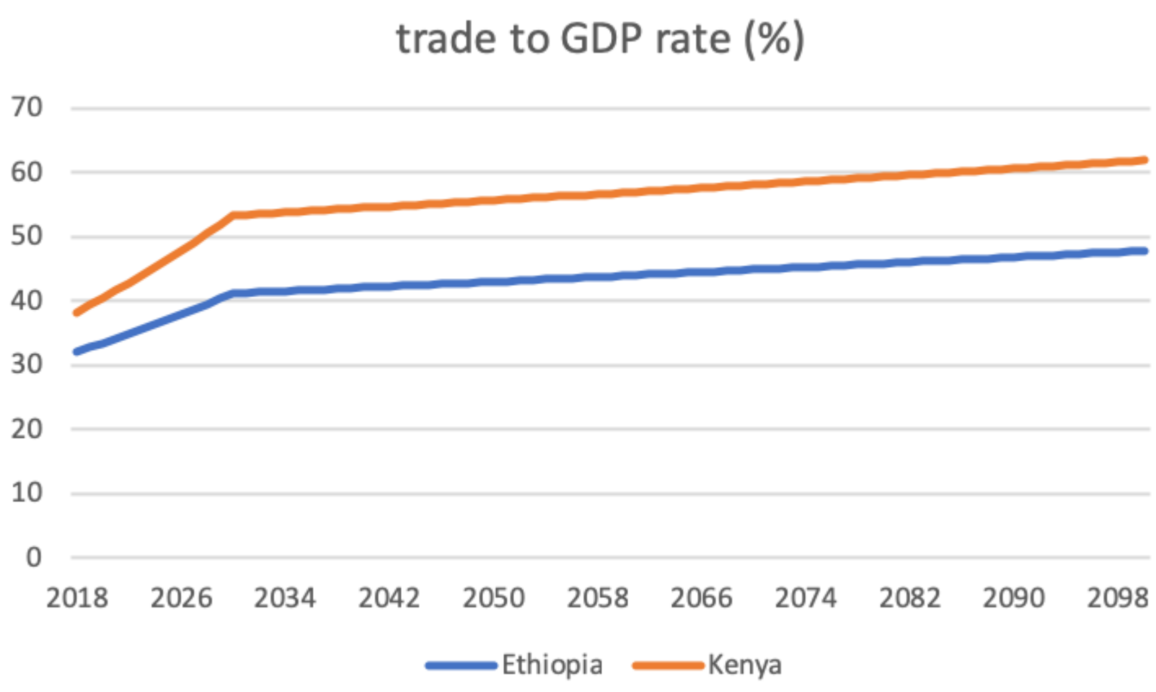

Figure 43 – trade to GDP rate projections in OTB per country

Lastly, increased trade could also affect the WEF nexus of a country. As described minutely below, water and energy are significant inputs of all sectors. Hence, increased demand for exports of a good or service would increase further its production and so, the use of its inputs. For example, Kenya is expected to increase significantly its trade to GDP rate, probably due to increased tea and coffee exports, which will be followed by further exploitation of water and energy necessary for their production.

GDP composition

Firstly, the motive powers of the production should be investigated. A good indicator of them is the GDP composition, as the distribution gives the percentage contribution of agriculture, industry, and services to total GDP. The data presented in Figure 44 are taken from World Bank (2018) and they show that the services sector is the leading sector of the economy in both countries followed by the agriculture sector. Agriculture includes farming, fishing, and forestry, industry includes mining, manufacturing, energy production, and construction, while services cover government activities, communications, transportation, finance, and all other private economic activities that do not produce material goods.

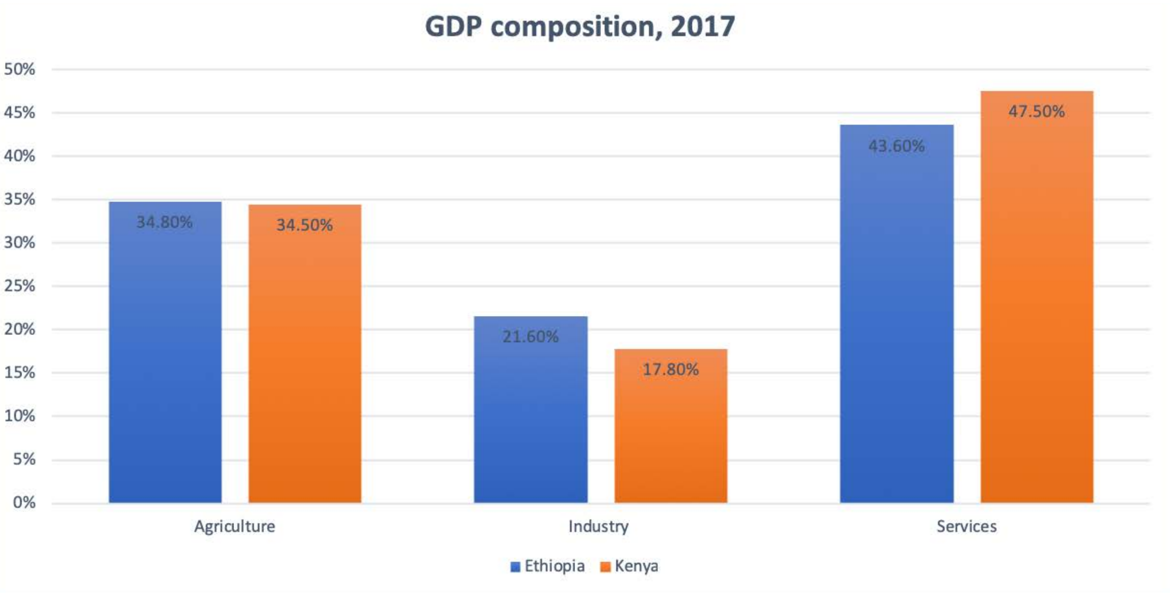

Figure 44 – GDP composition in OTB per country (source: CIA, 2019)

Ethiopia

The shift in political institutions in 1991 was followed by major economic reforms enclosing currency devaluation, trade liberalization, deregulation of markets, removal of restrictions on private sector participation, and modest privatization and reform of State Owned Enterprises.

There is broad consensus that the rapid economic growth in Ethiopia since 2000 is largely driven by public investment in infrastructure (World Bank, 2009). The latter include not only expansion of road networks but also construction of hydroelectric power plants and transmission lines, airports, telecommunication systems, health and education facilities, and most recently railways.

During the last 40 years, agriculture in Ethiopia tends to decrease reaching almost 35% of the GDP in 2017, while in 80s and 90s it was counting for more than the 50% of the GDP reaching 63% in 1992. Complementary, services have increased significantly their role in the GDP composition, while although mining and manufacture until 2014 remained stable with small fluctuations around 12% of the GDP, after 2014 they were followed by a rapid increase reaching 21,6% of GDP in 2017 (World Bank, 2018). Faster growth in services is attributed to increased public and private spending on education and health sectors, expansion of financial services as well as growth in distributive services such as transportation and domestic trade. The reason why growth in services exceeded that of industry is a critical question which has implications on the sustainability of Ethiopia's rapid economic growth.

According to the Ethiopian Government portal (2018), the government's long-term economic development strategy – Agricultural-Development-Led-Industrialization (ADLI) – is geared toward the transformation of the economic structure. The strategy comprises an export-led external sector, and internal emphasis on agriculture to supply commodities for exports, domestic food supply and industrial output, and expand markets for domestic manufacturing. The development strategy is supported by an economic reform program developed in cooperation with the World Bank and the International Monetary Fund (IMF) and by a series of structural adjustment programmes.

However, considering the historically low manufacturing base in Ethiopia, the intensity of firm-level investment will unquestionably play a critical role in industrial expansion. Particularly, the weak private investment rate in alignment with the rate of expansion of the manufacture sector and the export of the manufacture products could hold back the growth of the industry. Given also the fact that the mining sector accounts only for 1% of the GDP and that major infrastructure has already taken place, the industry sector within the following decade is not expected to grow dramatically.

In terms of infrastructure, great change has been noted within the last years with a massive increase in funds allocated for road construction and a significant investment in new and upgraded airports, which facilitate the transportation of goods and people. Consequently, the tourism will be boosted further as noted already with an encouraging increase in passengers. According to Shiferaw (2017), the Ethiopian economy has been growing rapidly since 2000 and long-term plans are under way that may lift the country to a lower middle-income status by 2020. However, Ethiopia in order to sustain a strong growth momentum, it should focus its weaknesses first, most of them affect the manufacturing and so the industry sector.

Kenya

The Ministry of Industrialization and Enterprise Development (MOIED) of Kenya has developed a strategic program aiming to accelerate the industrialization of the country. In particular, the program is guided by Kenya Vision 2030, the country's economic development blueprint that aims to transform Kenya into a newly industrializing "middle-income country providing a high-quality life to all its citizens by the year 2030" (MOIED,2015). Hence, according to this strategy, Kenya's industrial activity could rise significantly by 2030 and increase its share in the GDP composition.

In the last years, industrial investments in Kenya have led to mixed results, with new companies entering the Kenyan market and others relocating to other regional markets. This changing status quo can be explained by the competitive environment created domestically and complemented by regional integration initiatives to make EAC a common investment area, as well as by investment promotion, and liberalization.

The agro-processing, textiles, leather and construction materials sub-sectors have been earmarked as priority sectors in Kenya's industrial transformation programme. Generally, these subsectors are labour-intensive and could potentially add value to spur growth. However, the share of medium and large firms is less than 5 per cent but their contribution to sector's GDP is above 60 per cent, while about 95 per cent of manufacturing firms are micro and small, contributing only about 20 per cent of the sector's GDP. Hence, the manufacture sector is dominated by micro and small enterprises, which are characterized by low quality jobs and under-employment, increasing further so, the poverty in the country. Competitiveness is further hampered by relatively high cost of production, including power outages and high electricity tariffs compared to regional markets. Additionally, Kenya has to focus on reducing the cost of doing business to secure and attract Foreign Direct Investments (FDIs). For instance, reduction of energy cost and supply of stable and quality power are crucial in boosting efficiency and productivity in the industrial sector.

Although the tourism sector in Kenya plays a key role in the economy, it is still to be exploited. Kenya receives a high volume of tourists compared to other EAC countries without though increasing proportionally its revenues. It contributes around 10 percent to GDP and it is lying below the annual targets but on a recovery path. In particular, its slow growth is caused by terrorism-related insecurity, which has deterred major tourist source markets in North America and Europe, and by market price fluctuations, which led to increased competition in the region, political instability and the recent global recession (KIPPRA, 2017). Kenya took initiatives to boost tourism marketing but it procrastinates in implementing flagship projects targeted to accelerate tourism. For example, Kenya, Rwanda and Uganda have adopted the EAC common visa to simplify the Visa application procedure to visitors. The three countries have also launched a portal to jointly market their tourism products online. However, in order Kenya to strongly support strong recovery in the tourism sector, it will need to focus not only in the marketing, but in the necessary infrastructure as well.

On the other hand, the agriculture sector which is a significant contributor to the GDP of Kenya is highly driven by the weather conditions. In particular, over-reliance on rain-fed agriculture has increased the vulnerability of agriculture to weather shocks, with extreme events such as drought becoming more frequent. Consequently, as KIPPRA (2017) presented, the sector performance has been greatly constrained by disrupting production of food crops and livestock. The MTP II aimed to increase irrigated land by 404,800 hectares in order to reduce agriculture dependence on rainfall. By 2016, 26,101 hectares had been irrigated, however, without meeting the expectations. Achieving the irrigation target was constrained by funding levels.

Concluding, considering the full spectrum of the economic activities of Kenya, in a Business-as-Usual scenario (SSP2), no significant change would be noted in the short-term, due to the lack of the necessary structures for growth, such as creating a friendly environment for medium and large industrial firms to grow, or investing on touristic infrastructure. Lastly, infrastructure development could have significant multiplier effects through linkages with other sectors of the economy, leading to a higher GDP and an improved way of living for the citizens.

GDP composition projection

Following the analysis above, the projection of the GDP composition for both countries until the end of the century can be seen in Figure 45. The role of the agriculture in both countries will follow the global trend of counting less and less of the GDP, due to the fact that an increase in agriculture will not be greater than the corresponding one in the GDP. In particular, in the SSP2 scenario Ethiopia and Kenya will follow the average pattern that most developing countries do, where its GDP share will keep on decreasing with an average rate of 2,4 until it reaches 10% of the GDP, where usually the agriculture share stabilizes and from this point onward it will remain stable. However, Ethiopia is expected to notice an increase in the agricultural sector until 2030, due to ADLI strategy of the Ethiopian Government.

The services, which seem to be increasing in both countries, will keep on increasing. Here, someone can easily see from World Bank (2018) that the pattern between low- and middle-income countries and middle-income countries is very similar, with an average increase in the proportional share of the services being 0,5%. If not any great change in the economy of the countries occur, the industry sector will keep on increasing for the next 50 years reaching 26% of the GDP and then its share will slightly decrease, since the growth within the sector will not be enough to outstrip the general growth of the economy. However, in the Ethiopia, where the industry sector share of GDP has been dramatically increased in the last few years due to investments on infrastructure such as roads and airports, it is not expected to increase further within the next decade due to low private investment rates under the SSP2 assumptions.

Employment

Over the past 20 years, poverty in Ethiopia dropped by roughly 45 percentage points. However, approximately 25% of Ethiopians, i.e. 25 million people, still live in extreme poverty, which is defined as living on less than US$1.90 per day. On its current trajectory, according to Donnenfeld et al. (2017) Ethiopia is expected to reduce the proportion of the population living in extreme poverty to 10% by 2030, but that progress would still leave nearly 15 million people living in extreme poverty.

In terms of education in 2011, only 50% of the population being above 25 years old in Kenya and 24% in Ethiopia completed the primary education. In Kenya the educational attainment was achieved equally by both genders, while in Ethiopia the female students predominated over the male students, which were only 37% of the total (The World Bank, 2018).

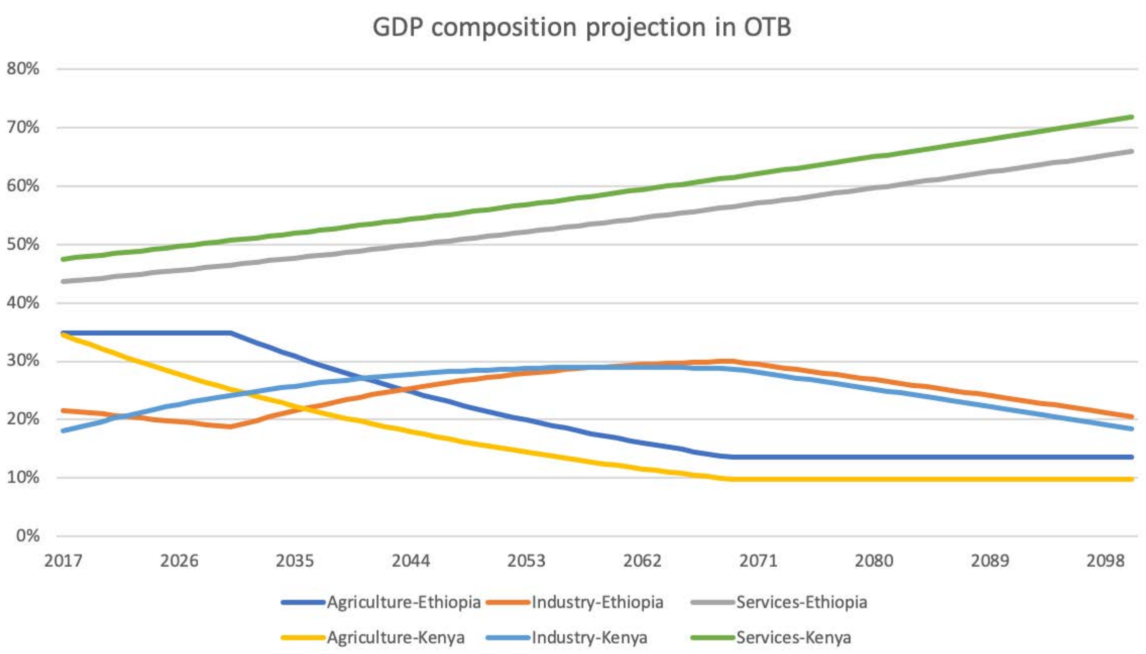

Figure 45 – GDP composition projections in OTB per country (source: World Bank, 2018)

Although the unemployment rate in Kenya seems to not fluctuate that much being 11,4% of the total labor force in 2018, in Ethiopia it was only 5,3% in 2018, which is significantly less than its former peak value in 1999 (8,7%), being so much lower than Kenya's corresponding term (The World Bank, 2018). Furthermore, both countries seem to give equal opportunities to both genders, with Kenya's workforce being composed by 48,4% female employees and Ethiopia's by 47,3% in 2018. Considering also their historical data from The World Bank (2018), one can identify the continuity of this trend, since in 1990 43,1% and 48,2% of Ethiopia's and Kenya's labor force correspondingly were women.

However, in terms of employment Ethiopia's leading force is the agriculture Sector followed by services, while for Kenya the employment composition follows the same pattern with its GDP composition. As presented in Figure 46, Kenya's workforce is more uniformly distributed than Ethiopia's, where the majority of people is occupied at its comparatively less productive sector, the agriculture.

In 2017, 9,3% of the total employment has been working within the industry sector of Ethiopia and 14,2% within the industry sector of Kenya (Figure 46). However, one should not forget that Ethiopia has twice as many inhabitants as Kenya leading to an extra burden in having a greater share of the total employment independently from its share in the GDP composition, as seen in Figure 44. Moreover, according to the World Bank (2018) Kenya seems to occupy on average 14% in the industry with small fluctuations from 12% to 16% during the period from1991 to 2018 declaring so, stability in the industry sector. However, Ethiopia has increased significantly its employment share from 2% in 1991 to 9,6% in 2018, which is probably paired with the general economic growth of the country. Tourism sector occupies 9 percent of the total employment (KIPPRA, 2017).

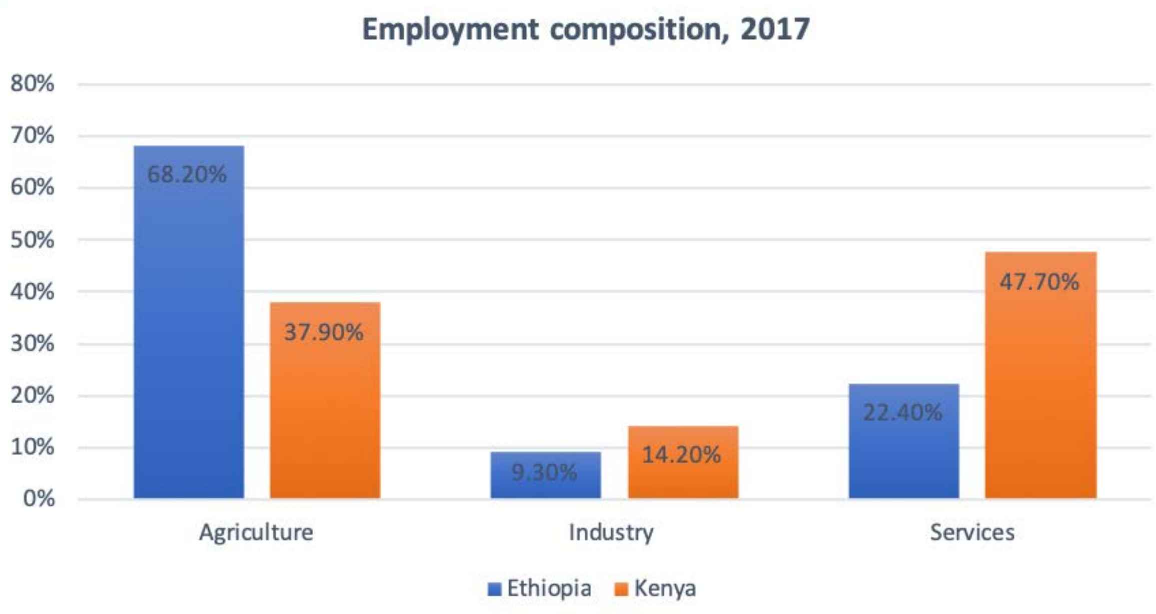

Figure 46 – Employment composition in OTB per country (source: The World Bank, 2018)

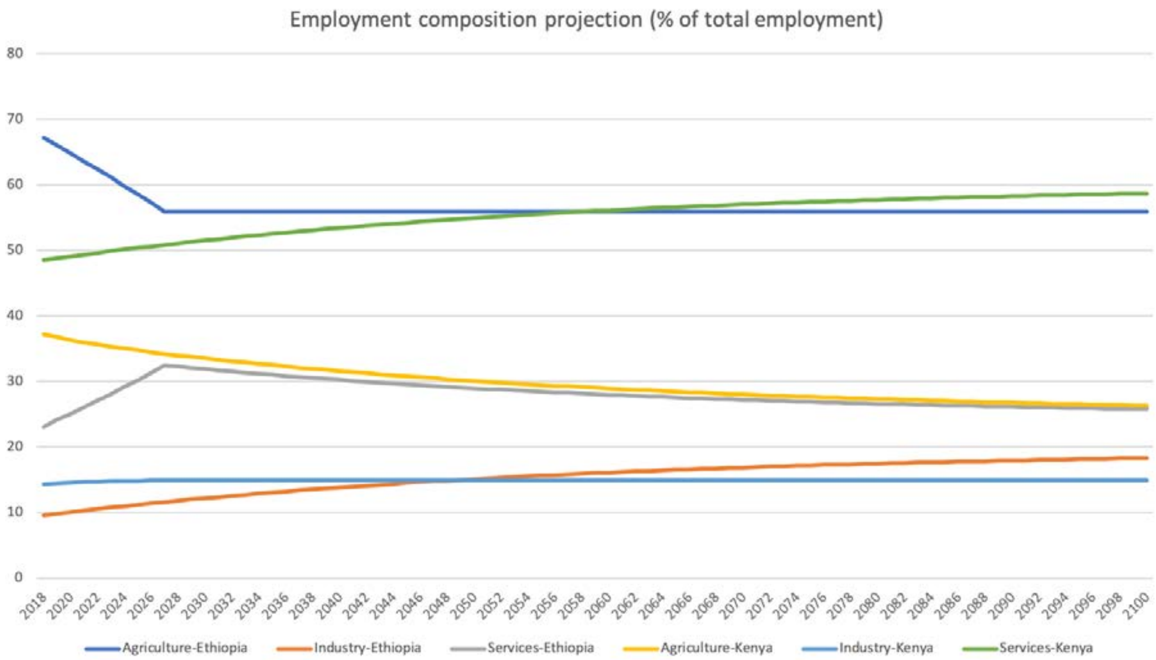

Figure 47 – Employment composition projection in OTB (% of total employment)

In a global scale, the share of employment in service sector in total employment is steadily increasing during the last 30 years expanding from 33% to 51%. On the other side, the share of employment in agriculture in total employment is constantly decreasing reaching 26% in 2018, while the employment in industry sector seems to fluctuate around an average of 22,5% (World Bank, 2018a). According to SSP2 assumptions, where the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns, employment composition projections will also follow the historical trends. Hence, a linear regression model with one lag (time series) is used as the appropriate tool for this example tracing data from the period 2000 until 2017, due to political instability before the 21st century.

The projection of the employment composition for both riparian countries until 2100 can be seen in Figure 47. In the long-run, all sectors tend to reach a plateau after 2050, declaring no significant change in the composition of employment. In particular, the employment at the agricultural sector of Ethiopia seems to stabilize at 55%, in alignment with the average share of the Sub-Saharan African countries, which doesn't fall under 57%. In general, no great change is expected in the final share of the riparian countries, with Agriculture providing employment to most inhabitants, followed by the service sector.

Water

The water use associated with the industrial, agricultural and service sectors does not differ significantly as in ZRB case. In contrast with the countries around ZRB, the industry sector of Ethiopia and Kenya seems not to be as developed as the agriculture, which consumes the majority of water in the basin. In 2017, 5,74 and 2,65 billion cubic meters of freshwater were consumed in Ethiopia and Kenya respectively for agriculture purposes. Agriculture contributes approximately 34% of the GDP for both riparian countries. On the other side, the industry sector, which accelerated in the last years, is not based on the water use to develop as much as in the Zambezi case. According to IFAD (2016), only one per cent of the potential of Ethiopia's vast water resources for irrigated agriculture and hydropower generation have been developed.

In order to compare the annual water consumption of the three sectors, we can consider the average water use in 2017 of the two riparian countries in each sector. Apparently, most freshwater withdrawals are consumed by the agriculture sector, which on average needs 2,65 billion cubic meters per year, while the service sector needs 0,88 billion cubic meters and the industry sector less than 0,2 billion cubic meters. In order to come up with the water use consumption per sector and per country, data from World Bank (2018) are used for annual freshwater withdrawals per sector to calculate the water use in billion cubic meters per 1 percent of added value in the GDP. Due to lack of data, this step was necessary in order to get an average water use per country and compute the current values. Then, this value was multiplied with the current share of the sector to the GDP giving the total water use per sector and per country. However, a limitation of this case is that the latest available data are in years 2005 for Ethiopia and 2010 for Kenya, which may explain the low values of water use of the industry sector, as a water intensive industry such as the Hydropower generation in Ethiopia accelerated in 2010 and could impact the average water consumption of the sector (IHA, 2017). For that reason, water projections per sector in this case are dominated by high uncertainty and they better be avoided.

Energy use by industry and mining

The energy sector of Ethiopia is one of the least developed in the world with 90 per cent of needs being met from biomass fuels, particularly wood, charcoal and animal dung (IFAD, 2016). However, according to IHA (2017) Ethiopia aimed to quadruple installed capacity by prioritising large hydro developments and achieving total power installed capacity of 10,000 MW by 2015, due to its 2010 Growth and Transformation Plan I (GTP-I), while the government published the GTP-II for 2016-20, with the objective of reaching total installed capacity over 17,208 MW. Hydropower is set to make up about 90 per cent of the power supply.

From Deliverable 2.1, the 2016 power sharing agreement provides a mandate for the Kenya-Ethiopia Electricity Highway Project (or the Eastern Electricity Highway Project), which will see the construction of a 1,000km power line to run from Ethiopia to Kenya to be completed by 2018. The agreement is built upon an MoU signed in 2006 between the Ethiopian Electric Power Corporation and the Kenya Electricity Transmission Company for the joint development of the project. The environmental and social impact assessment report was approved in 2012, although it has been criticised as it was conducted after any objection could be made. Following a World Bank loan of US$684 million, construction began in June 2016. While the 2016 agreement is not yet publicly available, it is reported that the agreement will allow Ethiopia to supply Kenya with 400 megawatts of hydro-power at less than 1 US cent/kwh. (World Bank, 2019; European Commission, 2019). The hydro-power source or sources that will supply this transmission line is not officially stated, although the World Bank modified an official project report specifying that power would be sourced "from Ethiopia's Gilgel Gibe hydropower scheme", changing the reference to the dam in its next report instead to "Ethiopia's power grid" (MININFRA, 2016; KETRACO, 2012).

2.3.6 Summary of Middle of the Road Scenario (SSP2)

Society: This path follows a pattern of action that is consistent with the experience of the last century. Under this scenario the OTB can expect to see the total population living within the basin after considering urbanization trends to reach 21.9 million people by the end of the century with 500 thousand of them being due to urbanisation assumptions. Education levels are moderate, thus limiting the level of the social and human capital of the riparian countries, but explaining the significant increase in the population.

Economy: In SSP2 although all countries are developing, some of them are making greater progress than the others. Given the historical patterns, the forecasting shows that Kenya, which is relatively poorer in absolute values than Ethiopia is expected to increase with a slower pace (around 6,5%) than Ethiopia, which can accelerate with rate up to 8,9%. Hence, existing inequalities are increasing more and more creating a greater gap between developing and developed world. Employment will also be rapid following the significant economic development of the countries.

Climate Change: Limited pro-active initiatives are considered from both Government and institutions in SSP2. The world is semi-open globalised, while the policies do not prioritise sustainability and the institutions are modestly effective. On top of that, extensive use of fossil fuels leads to continued degradation of the environmental assets, while the challenge to mitigate or adapt to these effects is moderate.

WEF nexus: The future drivers and scenario under SSP2 suggest that water, energy and food consumptions within OTB are expected to increase significantly by 2100, due to high population growth. By the end of the century, the total water use within the OTB is expected to increase from approximately 120 million m^3 at present, to 238 million m^3, while the total energy consumption within OTB is expected to reach about 74 TWh/year, which is twice as much as it is today. The total expected food requirements in OTB in 2100 will reach 15,6 Tcal/year, with Ethiopia consuming 88% of them. In terms of protein and fat intakes, the total requirements will reach 0.45 Megatonnes and 0.19 Megatonnes, with Ethiopia consuming 87% and 77% respectively.

2.3.7 Elaboration of SSP1 and SSP5

While the previous sections depict the SSP2 scenario, where global development follows a middle of the road path; this section considers two alternative futures under SSP1 and SSP5. SSP1 is perceived as the sustainable pathway focusing on the role of the environmental services in the economy, while SSP5 is the economically driven scenario, which although recognizes the economic impacts of the environmental degradation on the economy doesn't take pro-active actions, but it focuses on technology improvements able to mitigate the skyrocketed emissions of the human activity.

Sustainability conscious Scenario (SSP1)

Society: SSP1 envisions a development path with increased investment in education and health. Hence, greater access to education is leading to a relatively rapid demographic transition, due to birth controls and lower child mortality rates, which tones down the moderate population growth noted in SSP2, and also increases the human and social capital of the economy (Jones and O'Neil, 2016). By contrast, urbanization is assumed to be rapid in SSP1, which drives high income growth. Under this scenario urbanization is desired given the high efficiency that compact urban areas may achieve.

Economy: The main feature of the economic trajectory under SSP1 is the achievement of development goals while following a path of sustainability that moves towards a less intensive use of resources. As presented in Table 1 the economic development in SSP1 is expected to be high, with GDP growing more rapidly than the one illustrated in Figure 42. The drive of economic growth in this scenario is the fact that the human-wellbeing is redefined in SSP1 considering the environmental services, which are included in the economic development initiatives and in the overall shift of the economy to environmentally friendly actions with the help of rapid technology improvements. Employment in SSP1 will also be even more rapid than in SSP2, following the great economic development of this path.

Climate Change: In SSP1 sustainable development is the central focus of all policies across the world, which is connected in decision making with strong and effective institutions. Renewable sources of energy lead to an optimal treatment of the natural capital, while the need for mitigation or adaptation remains low.

WEF nexus: Water-Energy-Food (WEF) nexus projections in SSP1 result in a different pattern as a result of different population inputs, the increased value of ecosystem services and a more sustainable energy policy than in SSP2. In particular, since the overall population will decrease and the urbanization levels will remain as high as in SSP2, the final population within the basin will be significantly lower and hence the needs for water, energy and food will not increase dramatically.

Fossil fuel-driven Scenario (SSP5)

Society: Similar to SSP1, SSP5 envisions a development path with increased investment in education and health. Hence, greater access to education is leading to a relatively rapid demographic transition, due to birth controls and lower child mortality rates, which tones down the moderate population growth noted in SSP2, and also increases the human and social capital of the economy (Jones and O'Neil, 2016). By contrast, urbanization is assumed to be extremely rapid in SSP5, driving high income growth. Cities attract migration due to other reasons from SSP1, such as rapid technological change allowing for large-scale engineering projects to develop desirable housing.

Economy: The main characteristic of this narrative is the rapid development of the economy and the intensive use of fossil fuels. As presented in Table 1 the economic development in SSP1 is expected to be high, with GDP growing more rapidly than the one illustrated in Figure 42. However, the economic strategy of this scenario differs considerably than the SSP1 and SSP2, letting so GDP growth rates take their highest possible values. Innovation and investments are the most preferable options in SSP5, where technological progress and competitive markets drive growth. In alignment with SSP1, employment in SSP5 will also be even more rapid than in SSP2, following the great economic development of this path.

Climate Change: In SSP5 free markets and emphasis on human capital drive the economy under a strongly globalised status quo administrated by effective institutions. High fossil-fuel reliance in alignment with the high economic growth leads to higher GHG emissions and so, higher mitigation challenge. However, although the dominance of fossil fuels impacts significantly the environment, it doesn't degrade it more than SSP1, due to high mitigation policies, which control environmental processes through highly engineered systems, nevertheless with no focus on adaptation.

WEF nexus: Water-Energy-Food (WEF) projections in this scenario would also diversify as compared to SSP2 ones, as a result of different population inputs, industrial water demand and climate change adaptation measures. Likewise the SSP1 case, the population per country will decrease, thus inducing a decrease of water, energy and food needs per person. However, in this case the urbanization levels are more rapid than the other two paths, which means that the final population within the basin can be as much as in SSP2, ultimately leading to similar needs for water, energy and food.

2.4 SUMMARY AND CONCLUSIONS

This section presented extensively projections regarding different aspects of the SSP2 scenario and then it compared them to SSP1 and SSP5 scenarios for two case studies. The SSP2 scenario, illustrates the case, where the global development follows a middle of the road path, with most variables taking moderate values; the SSP1 describes a sustainable pathway focusing on the role of the environmental services in the economy, while SSP5 is focus on the economic progress only, where negative externalities on the environment are treated as a cost and hence mitigated. Demographic and economic indicators have been populated and forecasted, among which are lying population projections per country/major and potentially major city/sub-basin with and without urbanization, Water-Energy-Food (WEF) projections per country/sub-basin, GDP, trade to GDP, GDP composition and employment per sector projections until 2060 for ZRB and until 2100 for OTB case study.

In demographic terms, the total population living within OTB and ZRB is clearly affected by a moderate urbanization trend as assumed in SSP2, while education levels are moderate limiting so, the social and human capital of the riparian countries. In SSP1 and SSP5, access to education is greater leading so, to birth control, which tones down the moderate population growth noted in SSP2, and also increases the human and social capital of these economies. By contrast, urbanization is assumed to be rapid in both SSP1 and SSP5, which drives high income growth. Note, however, that in SSP1 urbanization is desired given the high efficiency that compact urban areas may achieve, while in SSP5 cities attract migration due to other reasons, such as rapid technological change allowing for large-scale engineering projects to develop desirable housing.

In economic terms, in both CS although all countries are developing, some of them are making greater progress than the others, driving existing inequalities to increase more and more and leave a greater gap between developing and developed world. However, although the economic development in both SSP1 and SSP5 is expected to be high, it will be more balanced than in SSP1 scenario decreasing so, existing inequalities. Note, though that the high economic growth illustrated in the former scenarios is originated from two diametrically opposed strategies. Human-wellbeing is redefined in SSP1 considering the environmental services, which lead development initiatives and the overall shift of the economy toward environmentally friendly actions with the help of rapid technology improvements. On the other side, innovation and investments are the most desirable options in SSP5, where growth is driven by technological progress and competitive markets. However, high fossil-fuel reliance in alignment with the high economic growth leads to higher GHG emissions and hence, higher mitigation challenge.

Lastly, in terms of Climate Change, limited pro-active initiatives are considered from both Government and institutions in SSP2. The semi-open globalised political environment in addition with the modestly effective institutions fail to prioritise policies regarding sustainability. On top of that, extensive use of fossil fuels leads to continued degradation of the environmental assets, while mitigation and adaptation challenges are moderate. In contrast, in SSP1 sustainable development is the central focus of all policies across the world, which is connected in decision making with strong and effective institutions. Renewable sources of energy lead to an optimal treatment of the natural capital, while the need for mitigation or adaptation remains low. In SSP5 free markets and emphasis on human capital drive the economy under a strongly globalised status quo administrated by effective institutions. The dominance of fossil fuels impacts significantly the environment, but it doesn't degrade it more than SSP1, due to high mitigation policies, which control environmental processes through highly engineered systems, nevertheless with no focus on adaptation.

The results of this section will feed into WP3 and WP5 to assess the overall impact of this future scenario on the two CS. The WP3, which focuses on the development, calibration and validation of the models to be used in the simulation of the WEF nexus, will use demographic, water, energy, food projections and also some general economic plans, while the WP5, which aims at the development of the robust Decision Analytic Framework (DAF) to explore alternative pathways (i.e. temporal sequence of actions) for advancing water management strategies under baseline and future scenarios, and identify efficient/robust pathways to be negotiated in the Negotiation Simulation Lab (WP6), will use also consider the pathways analysed above.

This study has potential limitations. The projections taken place in the model are based on international organisations and studies. Moreover, the lack of data constituted necessary the use of proxies of other similar cases, simplifying so, the individuality of each country. Last but not least, the long-term time horizon is accompanied with great uncertainty. The projections are therefore subject to biases and confounding that may have influenced the results of this section. The breakdown in shorter terms of the indicators analysed in this study could give a more precise understanding of the future situation in the two CS.

3. CLIMATE CHANGE SCENARIOS

In this chapter, we describe the methodology employed to develop downscaled future climate scenarios for the Zambezi and Omo-Turkana basins. We employ a gridded stochastic weather generator fitted to the present climate and adapted to the future climate using the climate trajectories simulated for each of the two case study catchments by an ensemble of climate models.

In section 3.1, we introduce the concept of stochastic weather generators, followed by a description of the weather generator used in this study, and an assessment of the model performance for the case study catchments. In section 3.2, we analyse the climate trends from the climate model ensemble and those simulated by the weather generator to conclude then with a discussion about the potential impact on water resources in the basins.

3.1 METHODOLOGY

As outlined in the Description of Action (DoA), the basin scale future climate scenarios are obtained in DAFNE by means stochastic downscaling of the climate trajectories simulated by General Circulation Models (GCMs) and Regional Climate Models (RCMs). This approach allows (a) overcoming the spatial coarse resolution of GCMs and RCMs, as compared with the spatial resolution of the hydrological and other (e.g. crop, ecosystem service) models forming the integrated WEF model and (b) generating ensemble scenarios that account for the inherent (stochastic) variability of climate, which cannot be represented by the single deterministic runs of climate models. Both the consistency of the spatial resolution and accounting for the natural variability of climate on top of the climate signal are an element of novelty for studies focusing on African river basins. Because of this approach it is possible to explore the full uncertainty of climate trajectories, which consists also of the natural climate variability, thus leading to more robust results about the impacts of climate change and how these can influence the development pathways.

3.1.1 Stochastic Weather Generators

The impacts of climate change on the hydrological cycle are complex and highly uncertain especially with regard to the variability induced at regional changes. Both complexity and uncertainty are accentuated by the coarse resolution of climate models, which are not yet able to capture the fine scale climate heterogeneities, neither in space nor in time, and are limited to one deterministic simulation trajectory. The misrepresentation of spatial climate variability on short timescales and at spatial resolution comparable with that of catchment scale hydrological processes, as well as the lack of ensured inter-variable consistency are key concerns for hydrological applications and in the context of water resources assessment under future climate scenarios.

Weather generators (WGs) are effective tools in efforts to overcome some of these limitations. WGs are numerical tools designed to produce synthetic time series of various meteorological variables of theoretically infinite length for a given climate and location. Most of the existing WGs are designed for station-scale applications or as multi-station generators, and simulate climate variables at daily or coarser temporal resolution (e.g. Keller et al., 2015). However, high temporal and spatial resolution climate data are needed to provide more realistic forcing for local hydrological climate impact assessments (Kerr, 2011), to allow a spatially explicit analysis of the impact of climate variability on basin hydrology. In particular, an ensemble of high- resolution climate data that represents the natural (stochastic) climate variability is essential to properly estimate the uncertainty derived from the chaotic nature of climate, and how this propagate throughout the catchment response and/or hydraulic infrastructures such as reservoir levels (Fatichi et al., 2015) or streamflow prediction (Peleg et al., 2015). Gridded stochastic WGs (Peleg et al. 2017; Peleg et al. 2019) are a suitable tool to generate multiple realizations (ensembles) of different climate variables at high spatial and temporal resolution, while reproducing the spatial climate variability and the natural climate variability. The ensembles of stochastically generated time series allow researchers to investigate natural variability at the local and catchment scale with spatial and temporal resolutions that are coherent with the typical scales of advanced hydrological models and of water resources problems. For the specific use of weather generators as a downscaling tool, the calibrated parameters of the generator are perturbed with changes derived from climate models, as illustrated in the following sections.

3.1.2 AWE-GEN-2d and basin scale stochastic downscaling methodology

This section introduces the concept of Factors of Change (FC), followed by a brief description of fitting the AWE-GEN-2d model for the case study basins, and finally an overview of the application of FC to produce future scenarios. Figure 48 gives a sketch of the downscaling methodology applied in the project, with specific reference to the precipitation component, which drives the modelling of the other meteorological variables. In the specific context of DAFNE, where ground and weather radar data could not be made available to the project, satellite derived rainfall is used to calibrate the AWE-GEN-2d precipitation sub-component, then multiple realizations of gridded precipitation can be simulated to represent realizations of the present climate (steps 1, 2 and 3 in Figure 48). Subsequently conditioned realizations of the other variables are computed at the same spatial and temporal scale.

The FCs computed from the climate model ensemble can then be applied to additional realizations of the present climate to produce future climate realizations at the same space and time scales (steps 4, 5 and 6 in Figure 48).

Determining factors of change from climate model ensemble

The FC are calculated by comparing the climate variables simulated by an ensemble of RCM-GCM climate models during a historical control period, and a range of 30-year time windows for the future climate simulated by the same climate model pairing. Figure 49 shows the ensemble members available for the RCP4.5 trajectory, while the window periods for computing the FC are illustrated in Figure 50. The number of available climate models for RCP4.5 is 22, as some of the models did not have appropriate simulations available.

The FC are computed for each ensemble member for a number of permutations of different seasons, time windows and RCPs (see Table 4). As explained in chapter 1, we focus primarily on RCP4.5 in this report. However, in a repetition of the work shown in section 3.2.1 we computed the FC for RCPs 2.6, 4.5 and 8.5 for rainfall and temperature over the basins.

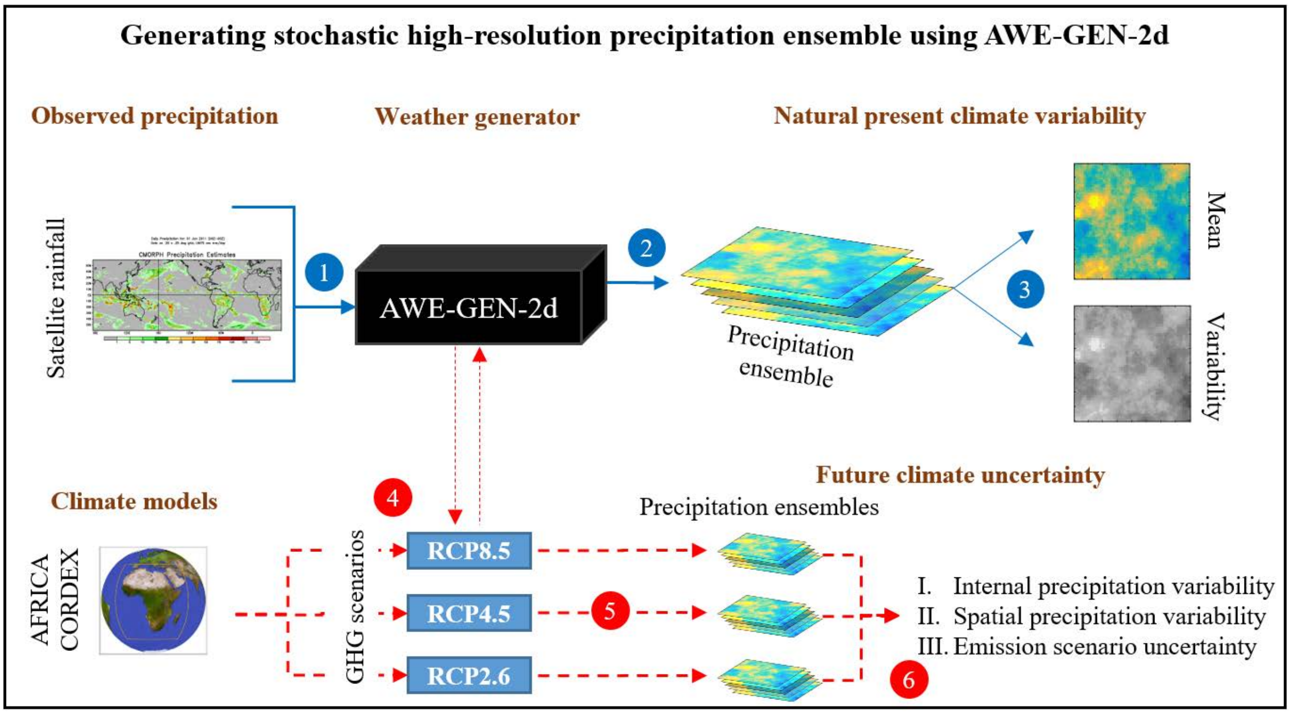

Figure 48 – Flowchart of the methodology used to generate stochastically downscaled scenarios. Here the focus is on precipitation, which drives the modelling of the other meteorological variables simulated by AWE-GEN-2d. The same concept of ensembles describing the various sources of uncertainty applies to the remaining simulated variables.

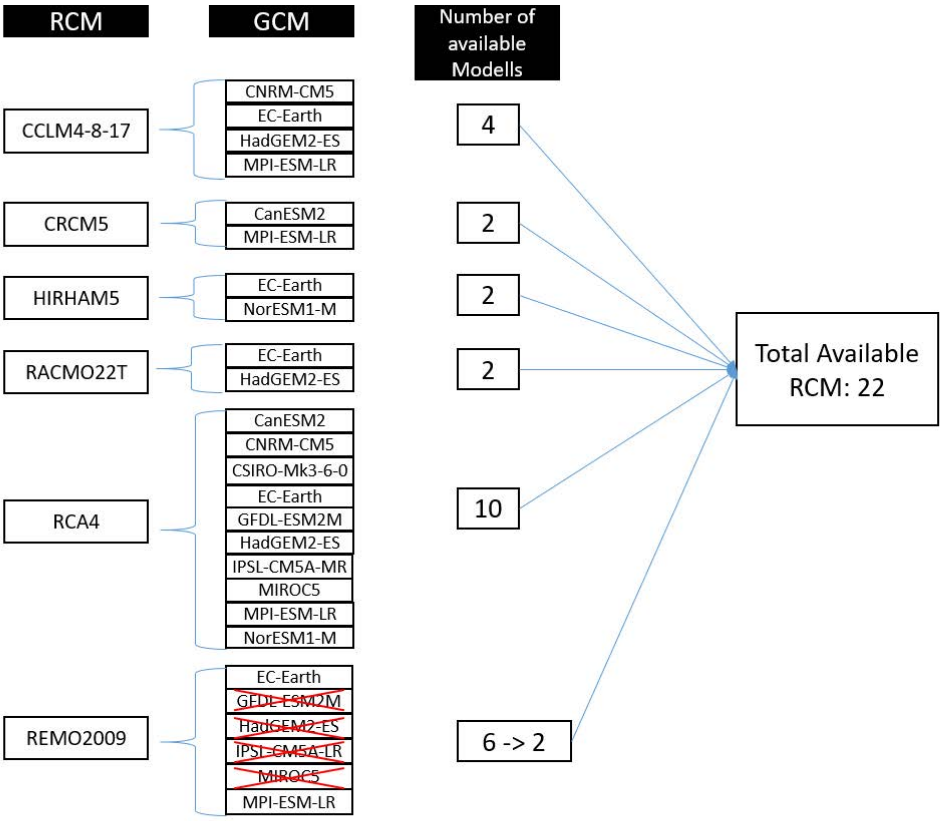

Figure 49 – Ensemble of RCM/GCM paired models of the CORDEX Africa experiment used in the analysis of the selected RCP4.5 future climate (2006-2095) for each of the CS basins. Four of the ensemble pairs were rejected, either because no RCP4.5 simulations were available, or because the member was a gross outlier (as determined by comparing the individual member's performance in a number of metrics, to the overall ensemble performance). Thus, reducing the ensemble from 26 to 22 models for this RCP.

Depending on the climate variable under consideration, FC can be a product factor (e.g. for precipitation statistics), in such a case the ratio between statistics for future and control realizations are used to modify the observed statistics as:

$$S(h)_v^{FUT} = \frac{S(h)_v^{CLM,FUT}}{S(h)_v^{CLM,CON}} S(h)_v^{OBS} , \quad (1)$$

where *S* is a statistical property (e.g. *mean*), *h* is the time aggregation (e.g. *hourly*), the subscript *v* is the climate variable (e.g. *precipitation*), the superscript *FUT* and *CON* denote future and control realizations (respectively), *CLM* denotes the climate model (*RCM-GCM pair*), and *OBS* denotes the observed data. Alternatively, FC can be an additive factor (also known as delta-change, e.g. for temperature statistics), in such a case the difference between statistics for FUT and CON realizations are used to modify the observed statistics as:

$$S(h)_v^{FUT} = S(h)_v^{OBS} + \left(S(h)_v^{CLM,FUT} - S(h)_v^{CLM,CON}\right) \quad (2)$$

with the same notations as above.

The FCs calculated according to equations 1 and 2 for each combination of RCP, season and climate model ensemble member (Table 4) were stored, and used to reconstruct a seasonally varying Multi-Model Mean (MMM) trajectory for each RCP. We then used the RCP 4.5MMM to generate downscaled future scenarios using AWE-GEN-2d, as described in the sections which follow.

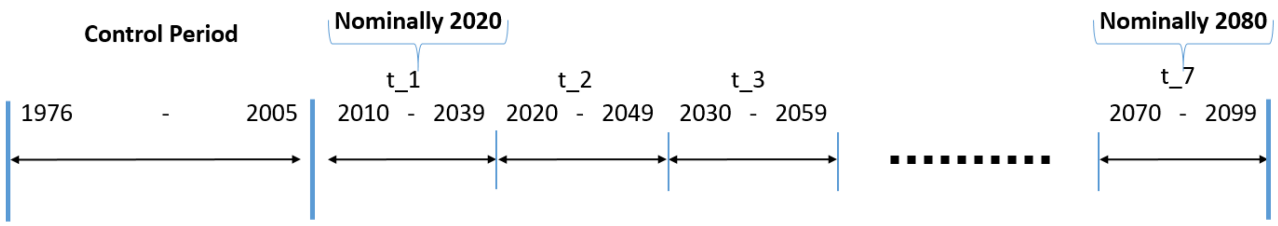

Figure 50 – Illustration of the 30-year time windows used to develop the FCs relative to the control period for each RCP. Note that in the remainder of this chapter we refer to the 30-year periods using a nominal date (e.g. Future climate 2080 for the 2070-2099 period).

Methodology for calibrating AWE-GEN-2d at basin scale

A detailed description of the AWE-GEN-2d model, it's calibration parameters and input data requirements can be found in Peleg et al. (2017). Since the model has a relatively complex set of input requirements, we provide only a brief summary of the steps applied to fit the model for the ZRB and OTB case study basins. Essentially the inputs for calibration were satellite derived gridded precipitation and reanalysis model temperature time series, in order to fit the main model parameters as described below.

The parameters influencing the precipitation distribution were derived using the CMORPH (Xie et al., 2017) precipitation product. These include the temporal sequencing and lengths of wet and dry spells, as well as the seasonally varying rainfall distribution parameters describing the distribution of rainfall amounts at each grid location. In addition, spatial properties are characterized such as the spatial correlation structure of the rainfall for a given hourly simulation time step, as well as properties for the entire simulation domain like Wetted Area Ratio (WAR) and Mean areal precipitation (IMF). The other primary input used was near surface air temperatures from the MERRA-2 reanalysis product (Gelaro et al., 2017). The performance of the fitted model is assessed in section 3.1.4.

Once the model has been fitted to the present climate, the FC's are applied to produce new model realizations for the future climate, by a combination of post-processing the precipitation and temperature fields, which in turn condition the other simulated variables using the sub-models of AWE-GEN-2d.

3.1.3 Summary of the generated scenarios

Using the methodology described in the previous sections, we developed climate scenarios based on a three phase approach. *First*, we analyse an ensemble of 22 Regional Climate Model (RCM) and General Circulation Model (GCM) pairs. Using the ensemble, we develop a time series of Factors of Change (FC) by comparing the changes in meteorological variables (e.g. precipitation, temperature) between a historical control period (1976-2005) and moving windows of with matching 30 years length for simulations of the future climate under RCP4.5 forcing. *Second*, we fit a stochastic gridded weather generator (AWE-GEN-2d; Peleg et al., 2017) using the present observed climate for each of the study basins, and generate an ensemble of plausible gridded present climate sequences at high spatial and temporal resolution. Simulations are generated for the following meteorological variables – precipitation, near surface air temperature, solar radiation, wind speed and relative humidity. *Thirdly*, we apply the FCs to the AWE-GEN-2d simulations to produce a set of future climate forcing grids for the DAFNE modelling chain using the methodology described in Peleg et al. (2019).

Table 4 – Table outlining the groupings of season, time-periods and RCM/GCM pairs considered in the analysis of future changes in each relevant climate variable. All permutations of these groupings were included in the analysis, and stored for later use.

Season	
DJF	December, January, February
MAM	March, April, May
JJA	June, July, August
SON	September, October, November
Control period and Future time windows	
Present	1976-2005
Future 2020	2010-2039
Future 2030	2020-2049
Future 2040	2030-2059
Future 2050	2040-2069
Future 2060	2050-2079
Future 2070	2060-2089
Future 2080	2070-2099
Number of RCM-GCM ensemble members	
For Control Period	26
For RCP 2.6	13
For RCP 4.5	22
For RCP 8.5	23

To date we have produced for the ZRB:

- An ensemble of 30 members of gridded time series at 8km horizontal spatial resolution and hourly temporal resolution,
- for the period 2020-2099,
- using different FCs for each of the 7 decades based on the RCP4.5 ensemble;

while for the OTB we have produced an intermediate scenario used in this deliverable D2.2, as the final OTB scenarios, equivalent to those of the ZRB, are being completed at the time of writing. This intermediate OTB scenario consists of:

- Precipitation at 269 locations inside the OTB (virtual stations used by the hydrologic simulations already produced in the past months) at daily resolution,
- and temperature at 69 locations inside the OTB (again virtual stations) at daily resolution,
- for the period 2020-2099,
- using different FCs for each of the 7 decades based on the RCP4.5 ensemble.

3.1.4 Model performance and validation for the present climate

In this section, we present performance and validation results for the AWE-GEN-2d model developed for each of the case study basins. These results are for the present climate, which the models have been calibrated to mimic. The models have been fitted according to the methodology outlined in section 3.1.2. We use the term performance to mean how well the model can reproduce it’s calibration data, and validation in the usual sense of a comparison with data not used in the calibration. The model performance for reproducing precipitation over the domain is evaluated against the gridded reference dataset used to calibrate the model (CMORPH), as insufficient local ground observations were available from the data agencies to allow a spatial analysis. Some of the other variables (temperature, solar radiation) could be compared to independent climatological products that were not involved in the model calibration. The reference datasets themselves are, of course, estimates of reality, and we estimate the deviations of the fitted AWE-GEN-2d model to be within the same order of magnitude as the uncertainty associated with these reference data. Where possible we have also validated the model results against observed records at meteorological stations, in order to build confidence in the fitted models. Unfortunately records of many of the modelled variables are generally scarce in the study basins, and data acquisition remains an ongoing process to build further confidence in the model.

Zambezi River Basin

In figures 51 and 52 we compare the simulated model outputs with CMORPH, at the basin scale for annual and monthly precipitation. Figure 51 shows the mean annual precipitation totals for ZRB. There is a good correspondence between the observed and simulated annual total, especially considering that the calibration is done using hourly rainfall distributions for each grid cell. Differences are in the order of 10 % at this time scale. Figure 52 compares the monthly distributions of rainfall hours for each month. Once again, the simulations capture the general character of the rainfall in a consistent way across all seasons. No comparison is shown for the dry season of May to October, since these are mostly uninteresting.

Figure 53 shows that the seasonal variation in two important parameters of the precipitation component of AWE-GEN-2d are well represented for the ZRB at the monthly scale. These are the Wet Area Ratio (WAR) and Mean areal precipitation amount (IMF).

Figures 54 through 56 make comparisons between simulated and independent estimates of temperature, solar radiation and relative humidity respectively. Once again, although there are some model biases, these are small percentage differences.

We were also able to carry out a limited number of local validations for some of the modelled variables. Two cases are represented in figures 57 and 58 for Lusaka and Lilongwe. The model produces good simulations of the seasonal (monthly) cycle, and the diurnal cycles of temperature and solar radiation look reasonable, but we did not find ground data for validation. Overall, we are satisfied with the model calibration given the limited high resolution data available.

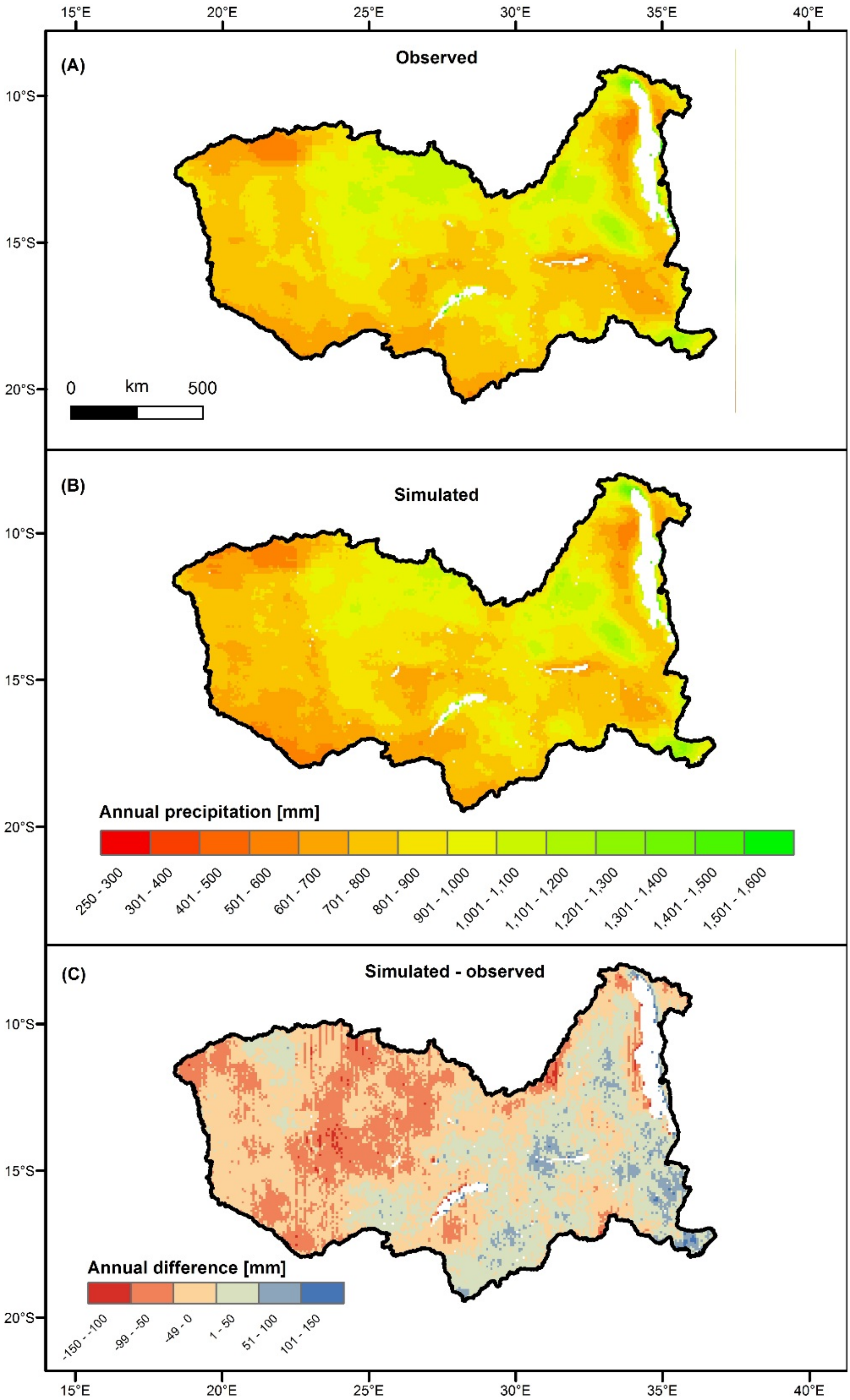

Figure 51 – Comparison of mean annual precipitation depth for observed (CMORPH), and simulated (AWE-GEN-2d). Although some relatively large annual differences are shown, this is mostly related to spatial mismatches rather than a generally different character of the rainfall between observed and simulated.

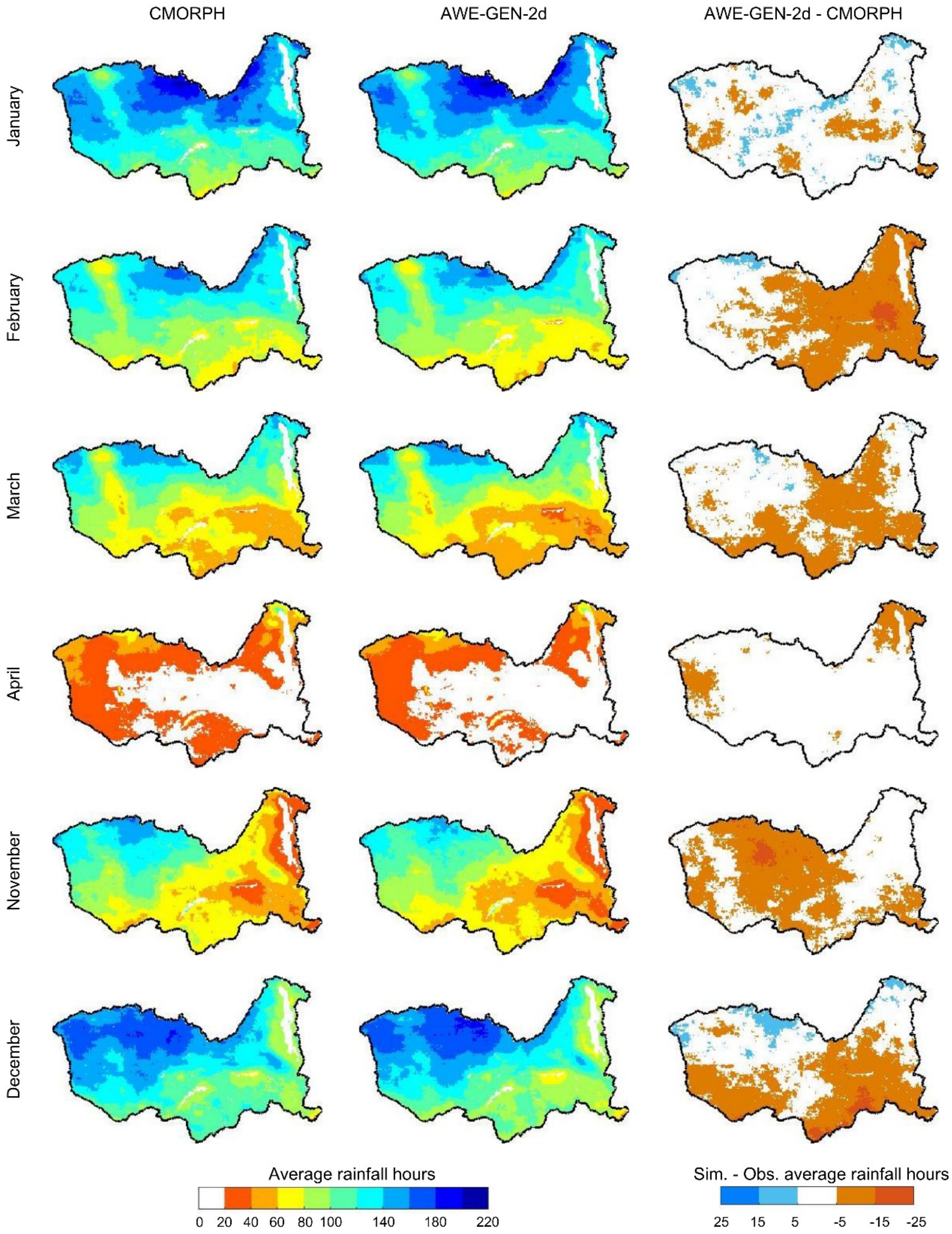

Figure 52 – Comparison of the average number of rainfall hours per month for observed (CMORPH), and simulated (AWE-GEN-2d). The months of May through October have been omitted from the figure, as they are generally very dry, making the comparison uninteresting (however this behaviour is well captured by the model). The difference maps in the rightmost column show that AWE-GEN-2d typically underestimates the number of wet hours, but this is usually by less than 15%.

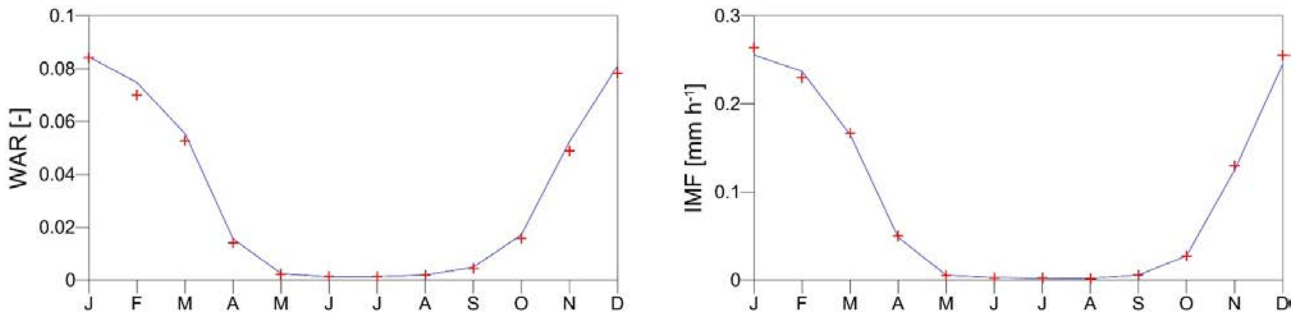

Figure 53 – Seasonally averaged performance of the simulated (AWE-GEN-2d) relative to observed (CMORPH) for two primary precipitation related metrics, Wet Area Ratio (WAR) and Mean areal precipitation (IMF). These parameters are computed over the entire model domain.

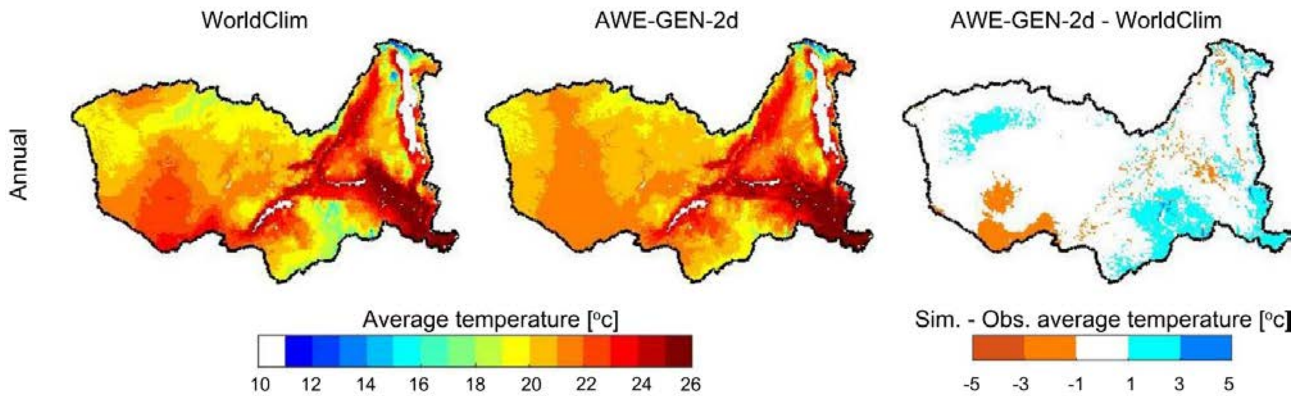

Figure 54 – A qualitative comparison of the mean annual temperature between observed (WorldClim – Fick and Hijmans, 2017), and simulated (AWE-GEN-2d). The WorldClim dataset was not used in the model calibration, which was based on temperature from the MERRA-2 reanalysis product (Gelaro et al., 2017). The mean annual temperature according to WorldClim is generally well captured by AWE-GEN-2d across the ZRB.

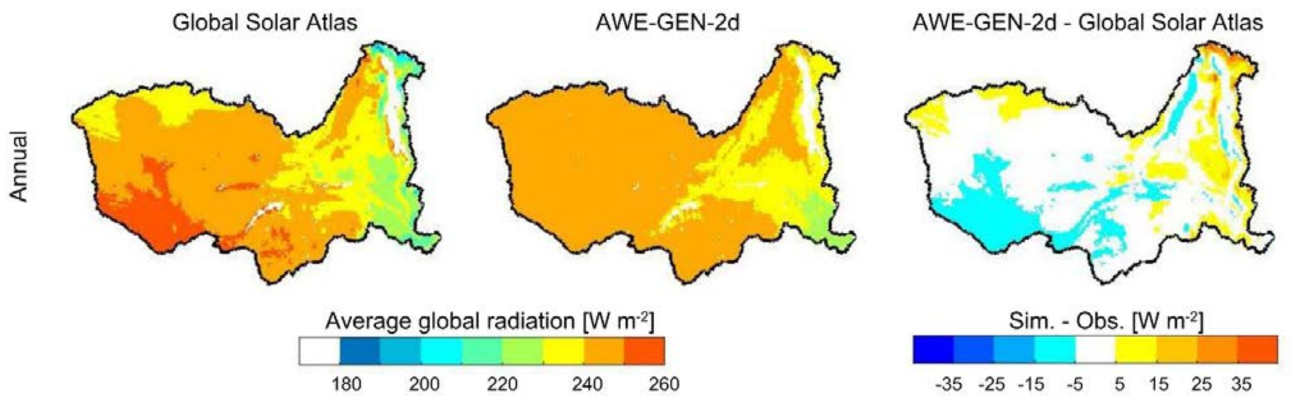

Figure 55 – Comparison of the average annual solar radiation between observed (Global Solar Atlas – GSA, 2018), and simulated (AWE-GEN-2d). AWE-GEN-2d captures the general character of this variable, but misses some of the details in spatial variability.

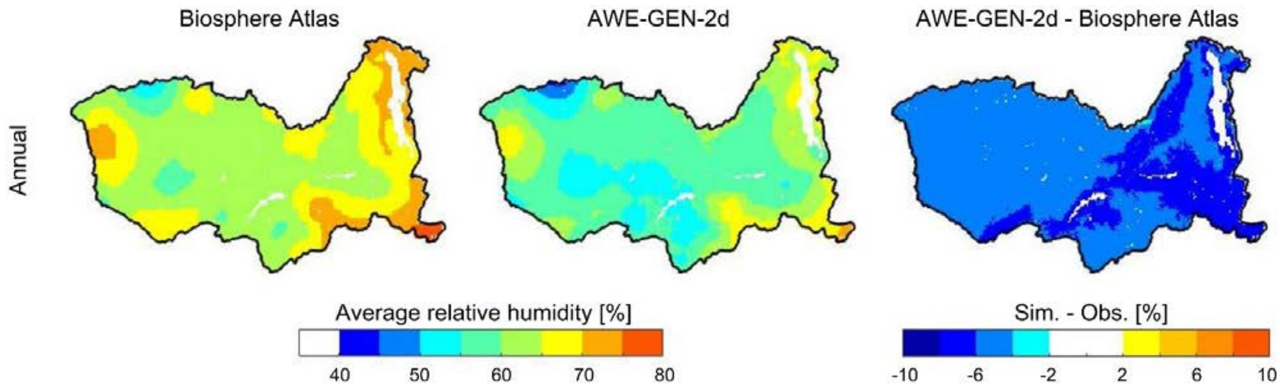

Figure 56 – Comparison of the annual mean relative humidity between observed (Biosphere Atlas – New et al., 1999; New et al., 2000), and simulated (AWE-GEN-2d). There is a consistent small underestimation of relative humidity by the model.

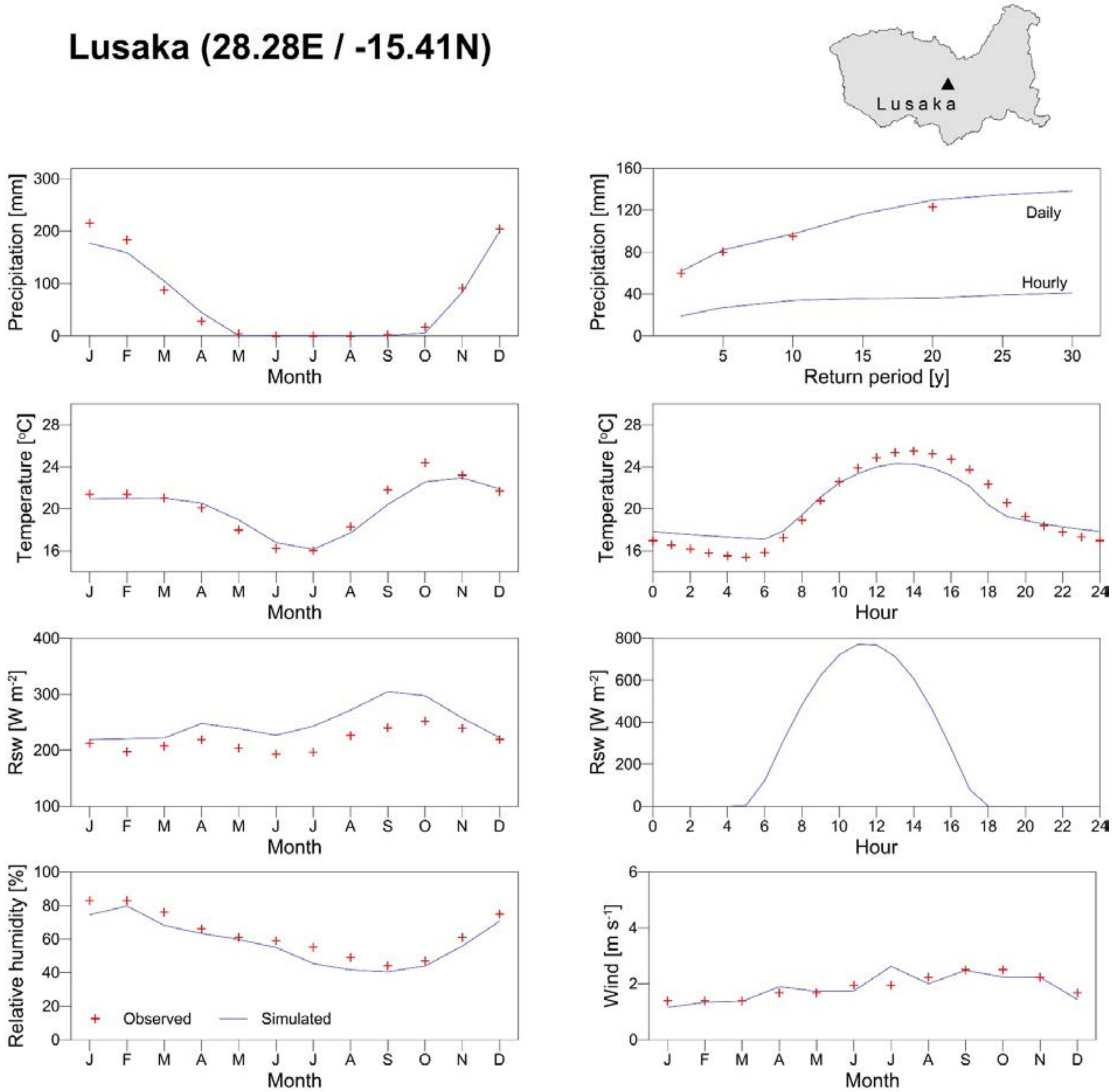

Figure 57 – Validation of AWE-GEN-2d simulated variables against observations available at the Lusaka (variables compared to the simulation are obtained from several sites in the vicinity). The fit is generally reasonable for the monthly means, although the radiation is underestimated. The fit is good for the diurnal cycle of temperature at this location.

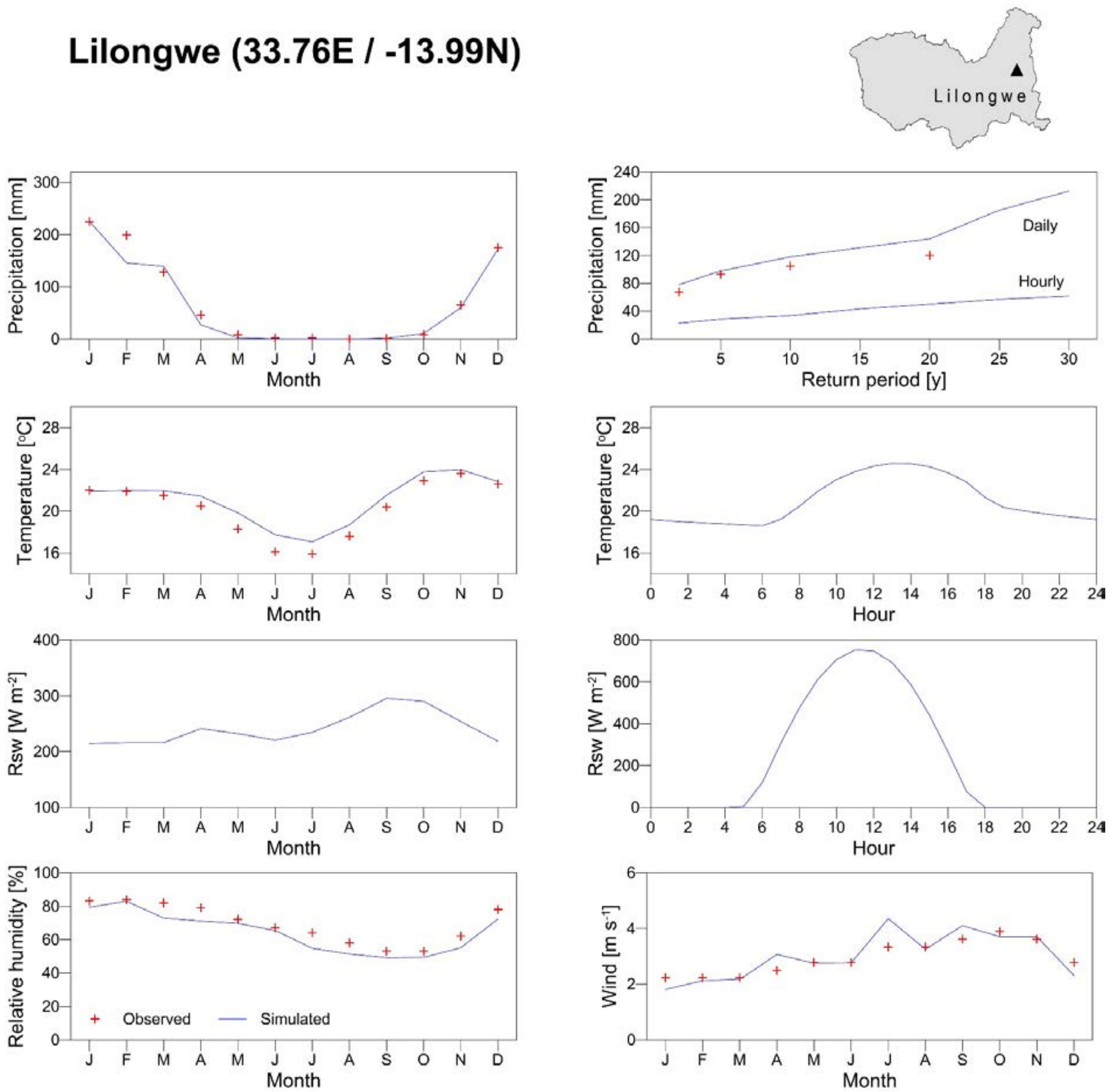

Figure 58 – Validation of AWE-GEN-2d simulated variables against observations available at the Lilongwe (variables compared to the simulation are obtained from several sites in the vicinity). The fit is generally reasonable for the seasonal cycle, and appears reasonable for the diurnal cycle, but we could not validate this.

Omo-Turkana Basin

In this section we show a similar qualitative validation for the AWE-GEN-2d model fitted for the Omo-Turkana. Figure 59 gives a comparison of the mean annual precipitation between the simulated and observed (CMORPH). Lake Turkana is masked out because the satellite rainfall retrievals over inland water bodies are known to be unreliable (e.g. Tian and Peters-Lidard, 2007). There is a generally good agreement at this temporal scale, showing the model has been satisfactorily calibrated.

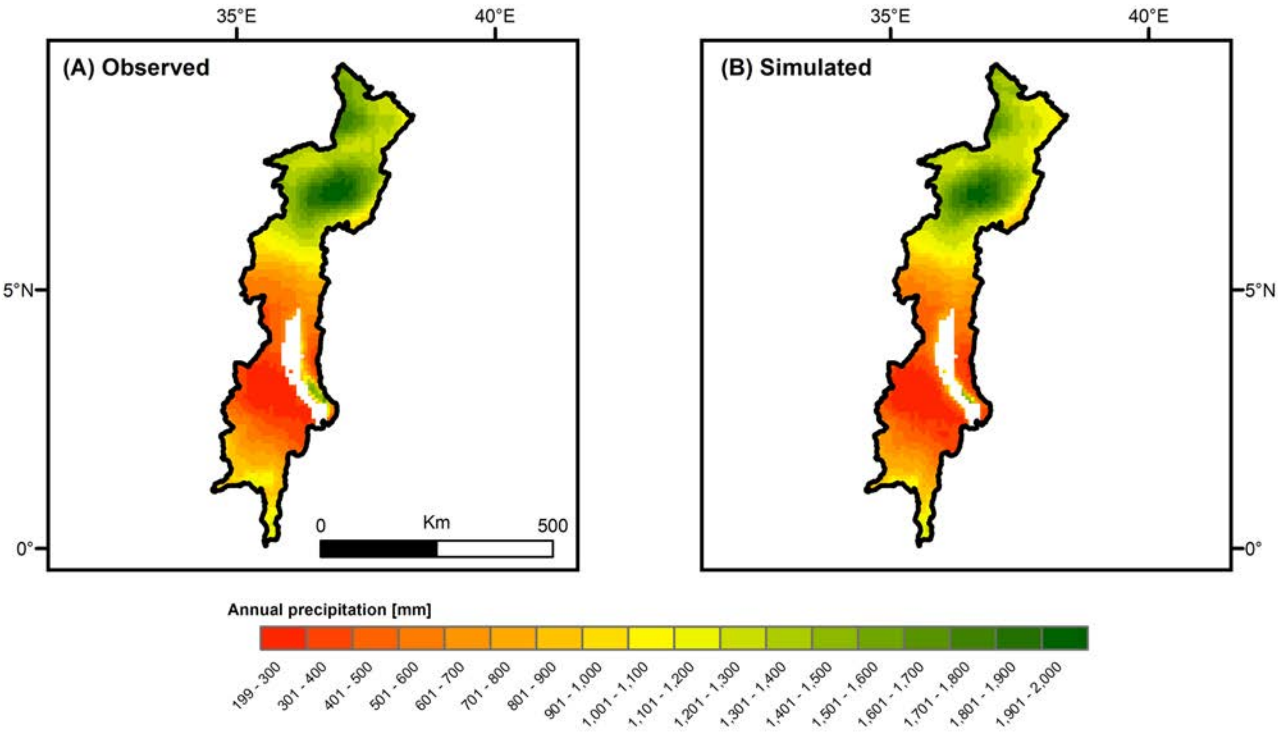

Figure 59 – Validation of mean annual precipitation depth for the OTB. Comparison of mean annual precipitation depth for observed (CMORPH), and simulated (AWE-GEN-2d). It's clear that the general patterns of precipitation are well captured, especially the strong North to South precipitation gradient.

In Figure 60 we compare the spatial distributions of the average number of rainfall hours in each month. Apart from some anomalies around Lake Turkana, the patterns are very similar for all months. April and May show some bias in the number of rainfall hours, which are higher than the observed. However, this bias appears to be compensated for in a reduced intensity of rainfall, because the annual totals match so well.

A qualitative comparison of the mean annual temperature between observed (WorldClim – Fick and Hijmans, 2017), and simulated (AWE-GEN-2d) is given in Figure 61 (left panel), while the right-hand panel shows the average global radiation between observed (Global Solar Atlas; GSA, 2018), and simulated (AWE-GEN-2d). The general distribution of both variables is well captured, and neither WorldClim nor GSA are used in the calibration process.

Overall these qualitative validations give confidence in the AWE-GEN-2d model for the OTB. However, a more thorough validation has not yet been completed for this basin. This is mainly due to data scarcity.

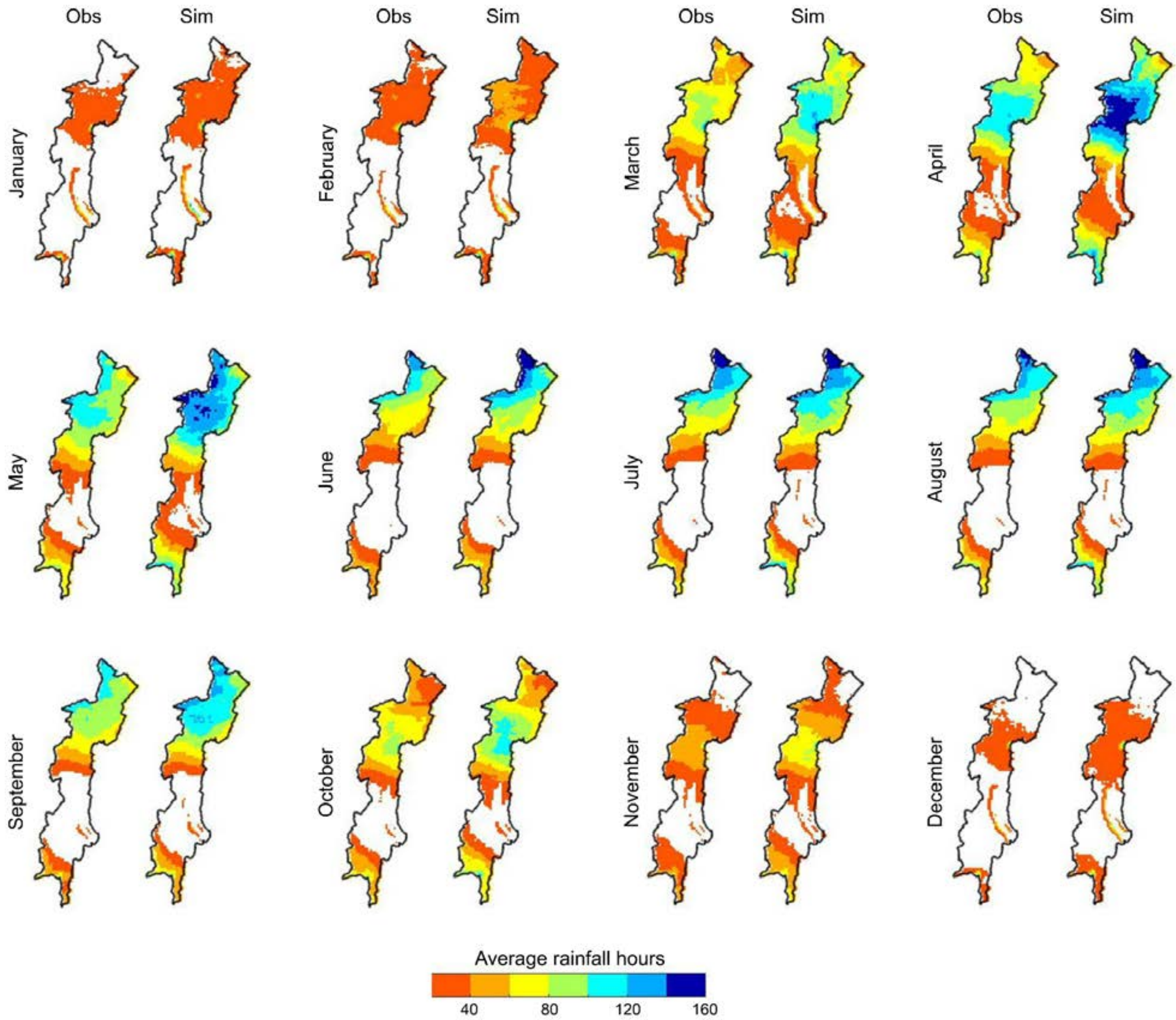

Figure 60 – Validation of the average number of rainfall hours by month the OTB. Observed (CMORPH), and simulated (AWE-GEN-2d).

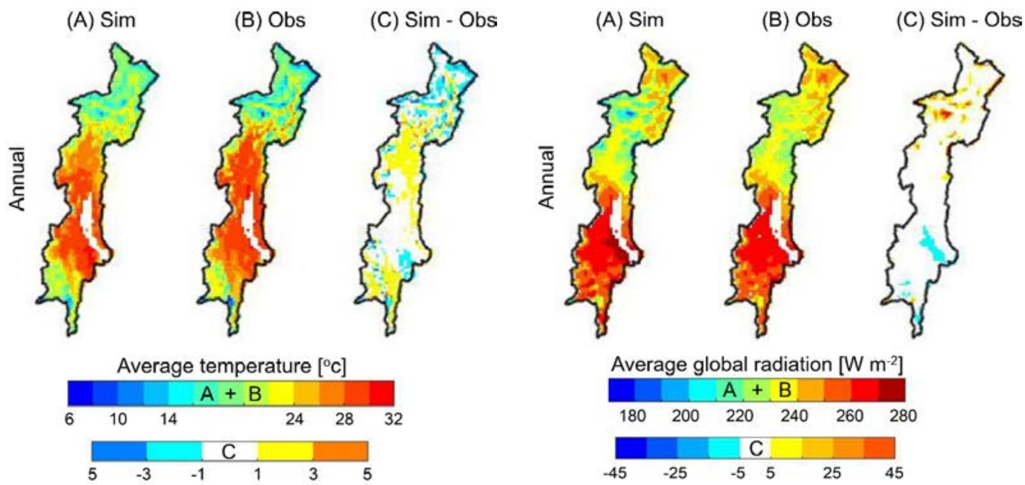

Figure 61 – Left panel: Comparison of average temperature for simulated (AWE-GEN-2d) and observed (WorldClim). Right panel: Comparison of the average global radiation between observed (Global Solar Atlas), and simulated (AWE-GEN-2d).

3.2 FUTURE CLIMATE FORCING

In this section, we discuss the main climate trends for precipitation and temperature identified for the two basins by the climate model ensemble. This is followed by a discussion of the expected impacts on streamflow in the case study catchments.

3.2.1 Climate trends

To simplify the interpretation of trends we focus on the computed factors of change for precipitation and temperature since they have a strong influence on the overall catchment water balance. Precipitation being the water input, and temperature being an important influence on evaporation. We find that the trends in each basin are actually quite dissimilar.

Zambezi River Basin – Climate models scenarios (seasonal trends)

For the ZRB, we note from Figure 62 that the climate model ensemble predicts a relatively small (less than 15 %) change in precipitation for all seasons, and not much difference between mid-century (2030-2070) and late century (2070-2100). For the DJF and MAM seasons, the ensemble median predicts almost no change in rainfall. While for the SON season a slight reduction of rainfall is predicted in the southern regions of the basin, this is probably due to a northward shift of the Intertropical Convergence Zone (ITCZ) expected by the models. We did not analyse the JJA season because this dry period of the year in the ZRB receives almost no rain.

In terms of the seasonal temperature trends shown in Figure 63, the models predict a consistent warming over the entire basin from mid to late century of 1.5-2 °C, rising to 2.5-3 °C by the end of the century. Interestingly, over the entire range of the ensemble the SON season is expected to warm more than the other seasons, which ties in well with the expected reduction in rainfall discussed above.

Omo-Turkana Basin – Climate models scenarios (seasonal trends)

In the OTB the ensemble median change factor for precipitation (Figure 64) predicts very little change in precipitation for the seasons MAM and JJA with an increase in rainfall amount expected for the remainder of the year (SON and DJF). This increase is expected to be in the range of 15-30 percent for DJF, which should result in more water input to the basin. There is a degree of variation between the models, with some members predicting a rainfall decrease in the order of 15-30 %, while others predict an increase as large as 50 % in the DJF season. Since rainfall is a difficult variable to model, this level of uncertainty in precipitation forecasts is expected. However, it is clear that the general trend expects a climate with higher rainfall in this region.

The expected temperature trends shown in Figure 65 for the OTB are fairly typical, with a steady increase from mid to late century.

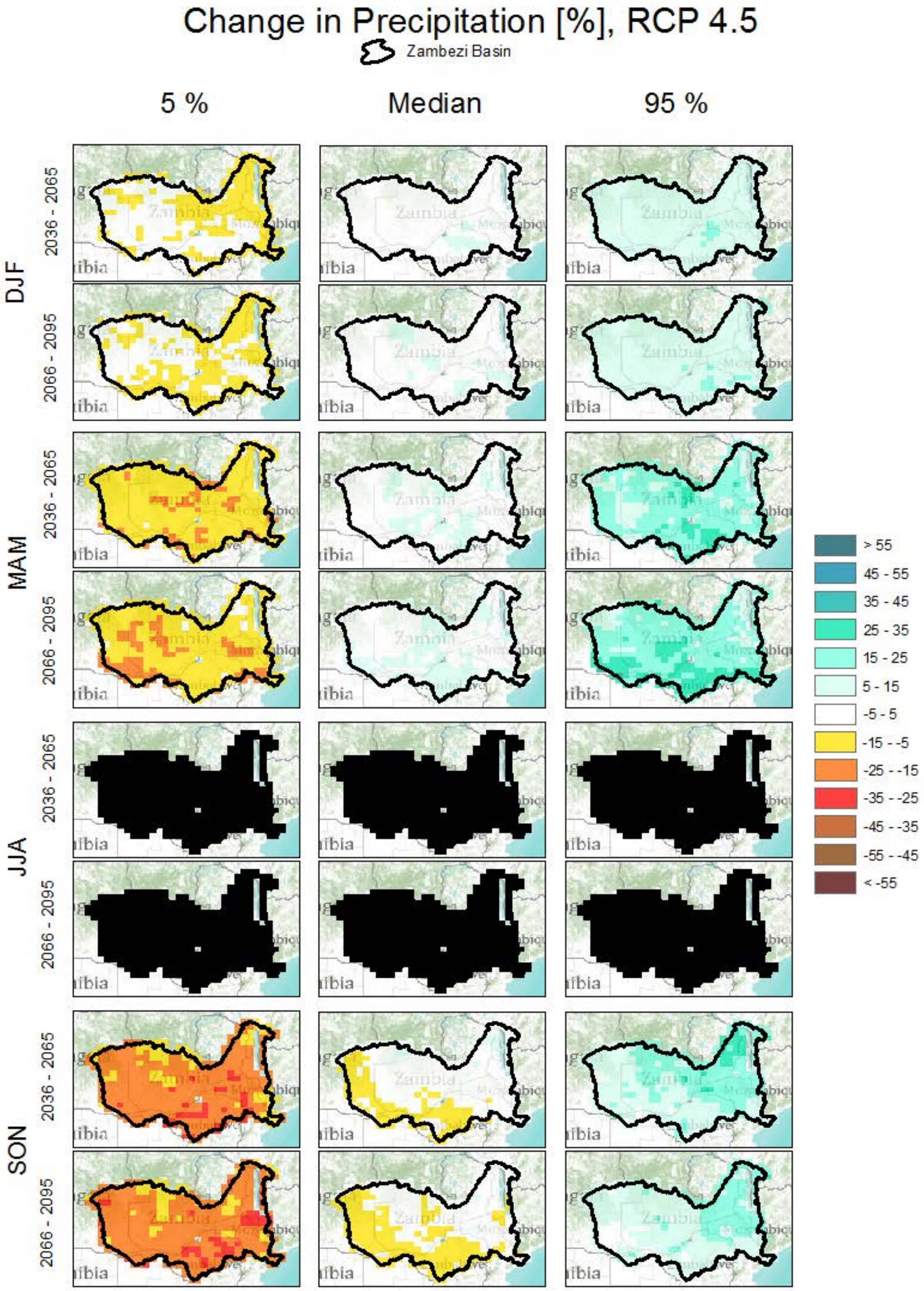

Figure 62 – Expected percentage change in seasonal precipitation amount in the ZRB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble. No analysis carried out for the JJA season due to extremely low rainfall in this season.

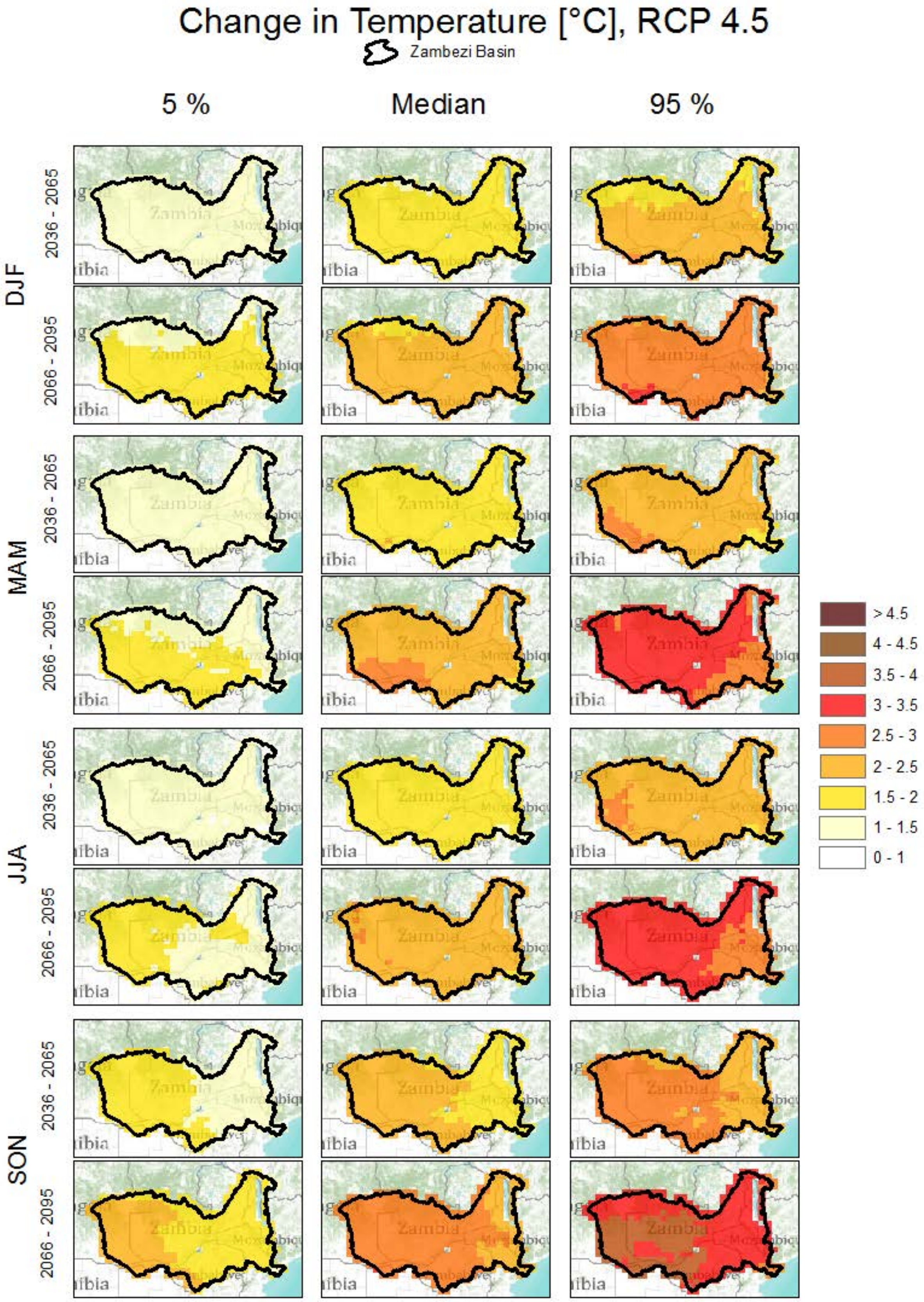

Figure 63 – Expected percentage change in seasonal average temperature in the ZRB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble.

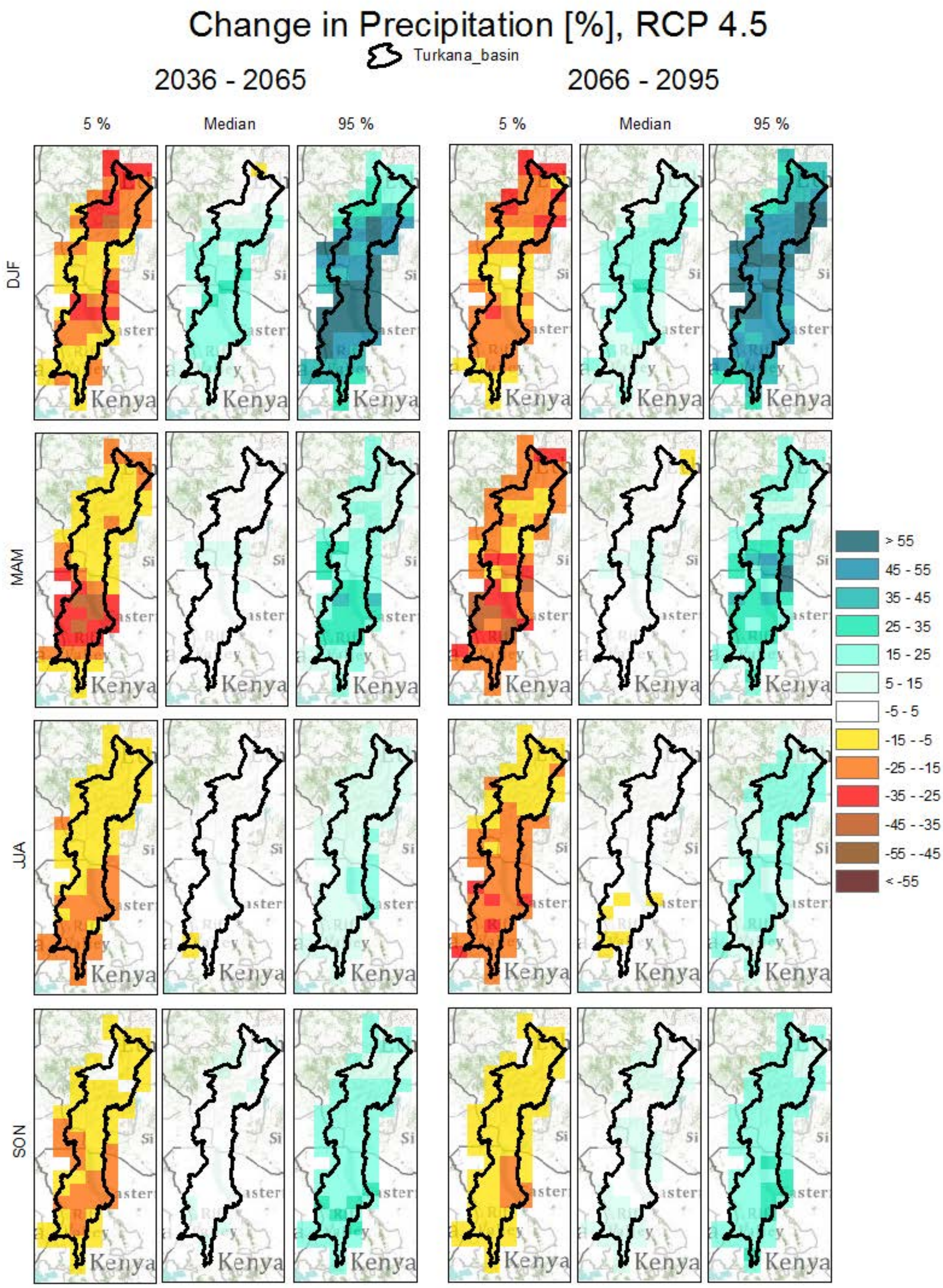

Figure 64 – Expected percentage change in seasonal precipitation amount in the OTB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble.

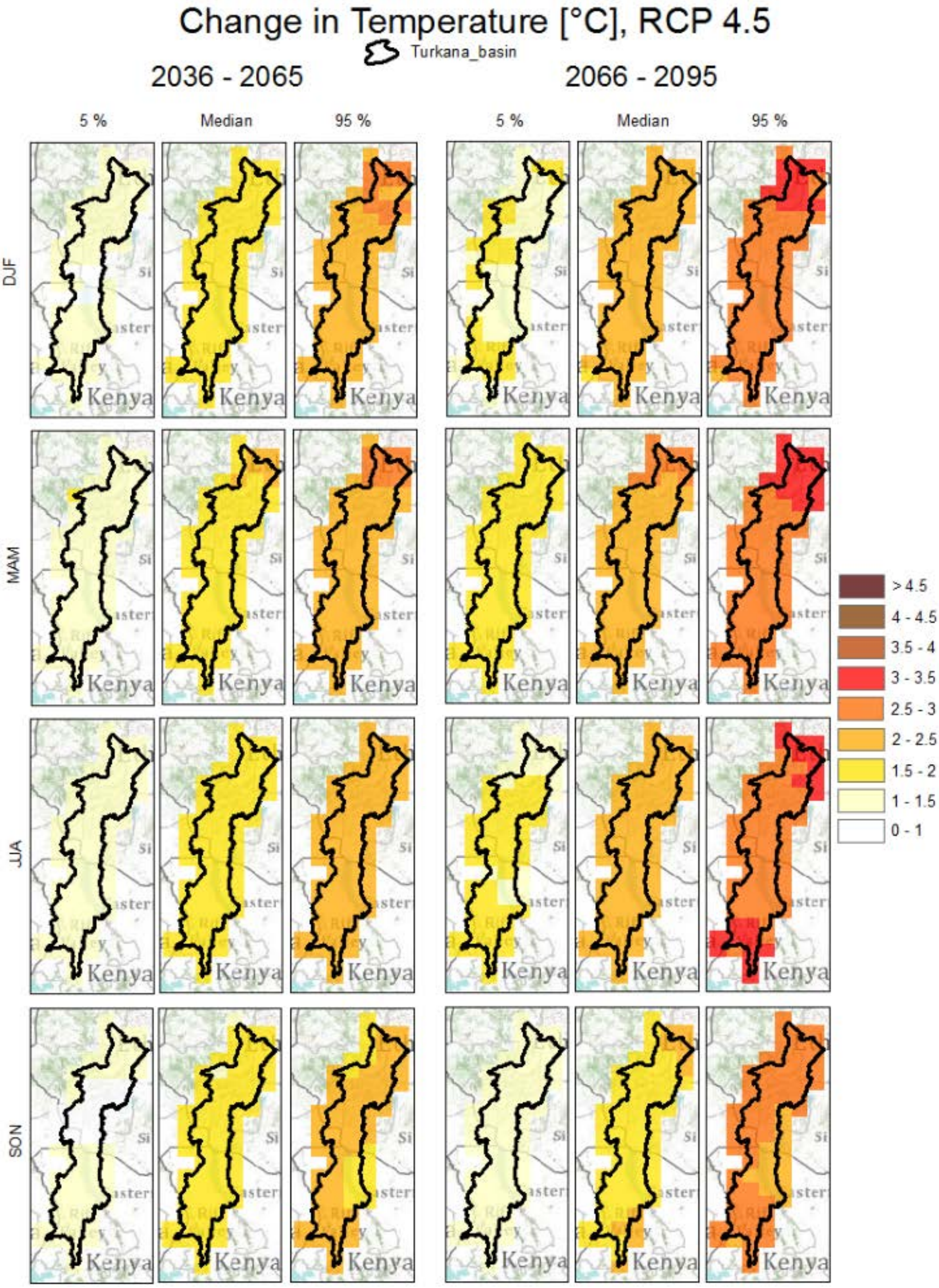

Figure 65 – Expected percentage change in seasonal average temperature in the OTB for RCP 4.5 during future time windows 2036-2065 and 2066-2095, for the 5/50/95th percentiles of the RCM/GCM ensemble.

Zambezi River Basin – AWE-GEN-2d downscaled scenarios (detailed trends)

In this section we present a summary of climate indices computed for the ZRB based on the detailed AWE-GEN-2d climate simulations, as an illustration of the increased flexibility and level of detail that is possible relative to the coarse climate model simulations. Table 5 gives a summary of the calculated indices to ease interpretation of figures 66 through 73 in the following. The indices presented are ones that could have obvious impacts on agriculture, water resources and natural hazards like flood and droughts. We present them in an indicative way, without detailing all possible consequences for the case study basins. Further detail will emerge as the project progresses.

Table 5 – Summary of the climatic index abbreviations used in figures 66 through 73 below.

Abbreviation	Definition	Unit
TXx	Hottest day of the year: annual maximum of daily Tmax	°C
TNn	Coldest night of the year: annual minimum of daily Tmin	°C
TNx	Warmest night of the year: annual maximum of daily Tmin	°C
TXn	Coldest day of the year: annual minimum of daily Tmax	°C
TXx7d	Hottest week of the year: maximum 7-day mean of daily Tmax	°C
TX>25C	Summer days: annual number of days with Tmax > 25 °C	days
TX>30C	Hot days: annual number of days with Tmax > 30 °C	days
TN>20C	Tropical nights: annual number of days with Tmin > 20 °C	days
TXp95%	95th percentile of daily Tmax	°C
TXp99%	99th percentile of daily Tmax	°C
TNp5%	5th percentile of daily Tmin	°C
TX95P	Hot days: annual days with Tmax > TXp95% of present climate	days
TX99P	Very hot days: annual days with Tmax > TXp99% of present climate	days
MEA	Mean daily rainfall	mm d^{-1}
INT	Wet-day intensity: mean rainfall amount on wet day	mm d^{-1}
Rx1h	Maximum of 1-hour rainfall	mm h^{-1}
Rx1d	Maximum of 1-day rainfall	mm d^{-1}
Rx5d	Maximum of 5-day rainfall	mm $5d^{-1}$
Rp90%	90th percentile of daily rainfall	mm d^{-1}
Rp95%	95th percentile of daily rainfall	mm d^{-1}
Rp99%	99th percentile of daily rainfall	mm d^{-1}
x1h.YY	YY-year return periods of hourly rainfall (YY={5,10, 20 and 50})	mm h^{-1}
x1d.YY	YY-year return periods of daily rainfall (YY={5,10, 20 and 50})	mm d^{-1}
x5d.YY	YY-year return periods of 5-day rainfall (YY={5,10, 20 and 50})	mm $5d^{-1}$

Temperature

Figures 66 through 69 illustrate the differences in a selection of temperature indices between the AWE-GEN-2d simulated present climate (1976-2005), and the end of century climate (2070-2099) using the RCP4.5 factors of change. The general behaviour is one of an increase in the mean of the temperature distribution, as expected based on the factors of change (Figure 63). The implication of this general shift in the distribution is to increase the number of hot days and nights (Figure 66), as well as increasing the extremes (figures 67 and 68), and their frequency of occurrence (Figure 69). All of these changes have a variety of implications for many sectors, especially agriculture and the environment.

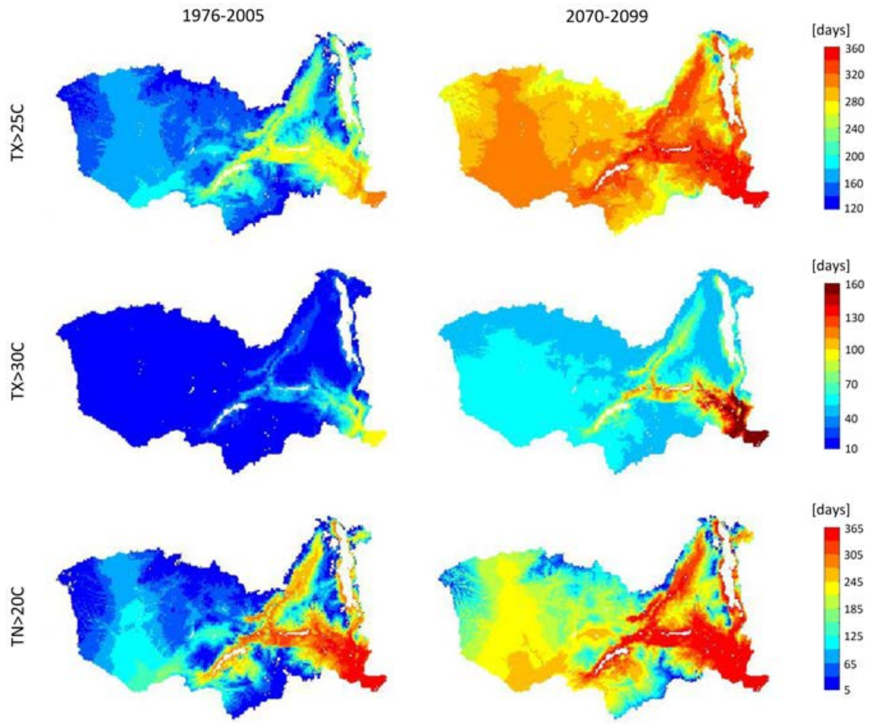

Figure 66 – Potential change in the annual number of summer days, hot days and tropical nights (as simulated by AWEGEN-2d) for the present climate (left-hand panels) compared to the end of century climate (right-hand panels). Note that the colour scale is not the same for each row. Refer to Table 5 for a more detailed interpretation of the abbreviations used.

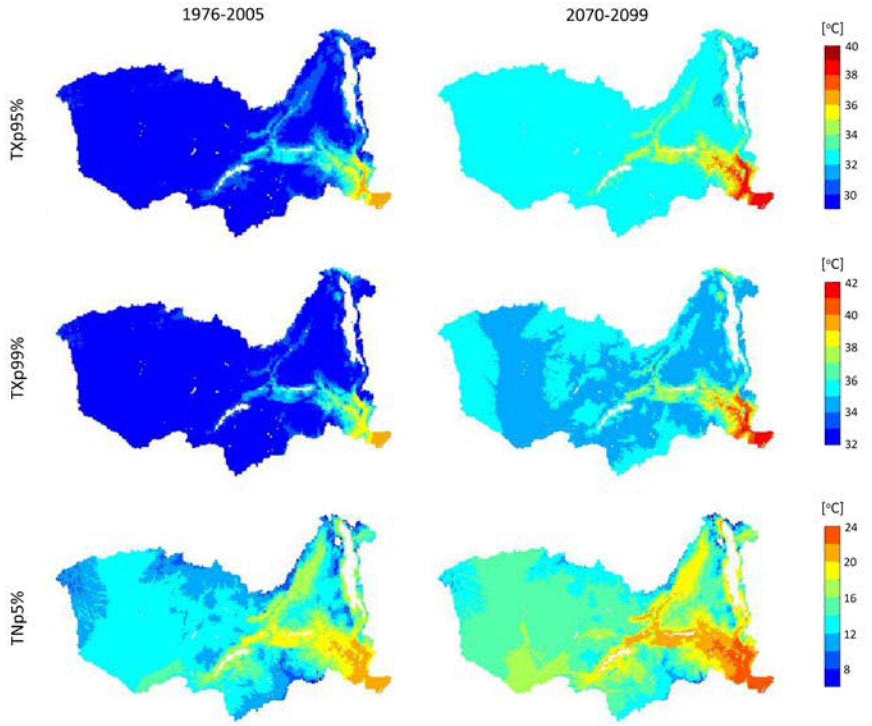

Figure 67 – Potential change in the 5/95/99th percentiles of daily temperature (as simulated by AWEGEN-2d) for the present climate (left-hand panels) compared to the end of century climate (right-hand panels). Note that the colour scale is not the same for each row. Refer to Table 5 for a more detailed interpretation of the abbreviations used.

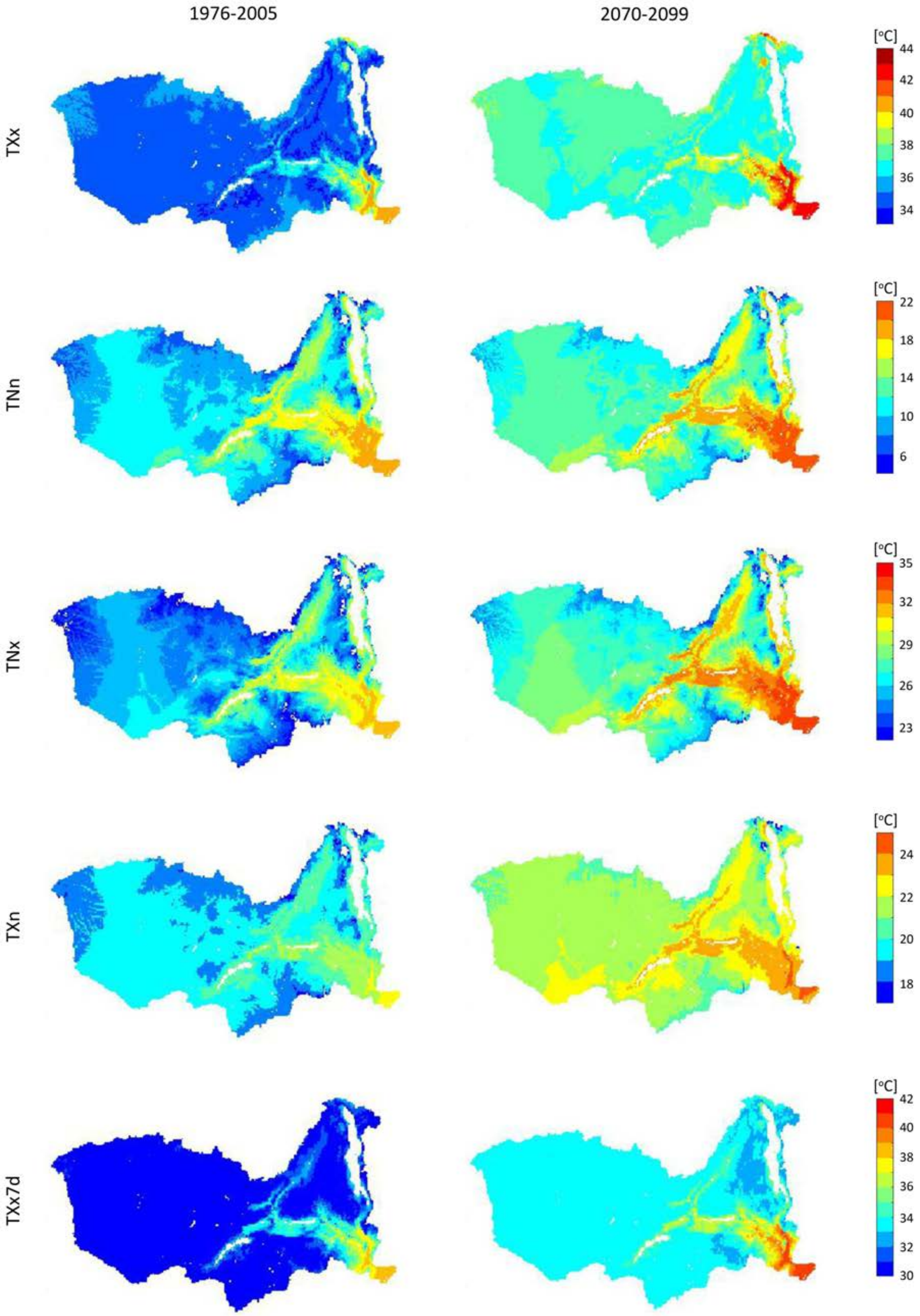

Figure 68 – Potential change in the annual hottest day, coldest night, warmest night, coldest day and hottest week (as simulated by AWEGEN-2d) for the present climate (left-hand panels) compared to the end of century climate (right-hand panels). Note that the colour scale is not the same for each row. Refer to Table 5 for a more detailed interpretation of the abbreviations used.

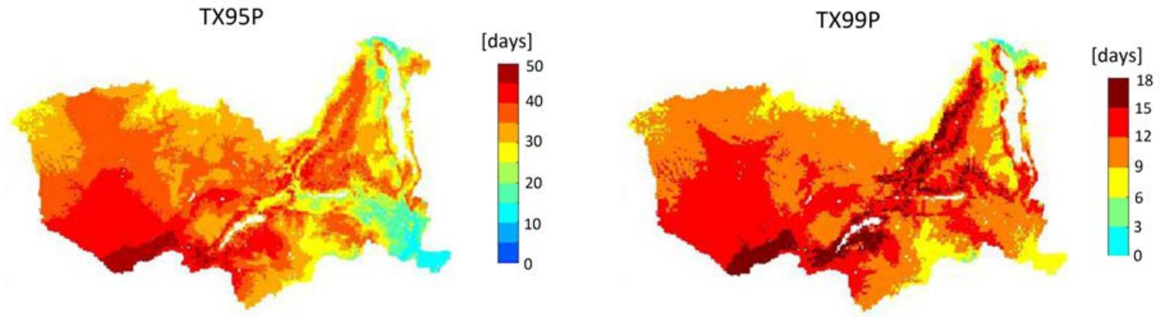

Figure 69 – Potential change in the annual number of hot days (left-hand panel) and very hot days (right-hand panel), as simulated by AWEGEN-2d for the end of century climate compared to the present climate. Note that the colour scale is not the same for each panel. Refer to Table 5 for a more detailed interpretation of the abbreviations used.

Precipitation

Figures 70 through 73 illustrate the differences in a selection of temperature indices between the AWE-GEN-2d simulated present climate (1976-2005), and the end of century climate (2070-2099) using the RCP4.5 factors of change. In Figure 70 the maximum hourly, daily and 5-day rainfall totals under present and future climate conditions are compared, there is no significant change in the hourly rainfall amount, however some differences in the daily and 5-day maximums are possible. A closer look at the upper etremes of the daily rainfall distribution (Figure 71) shows a general increase in the extremes of daily rainfall over the basin. The increase in rainfall extremes has implications for flash flooding, and soil erosion processes. Figures 72 and 73 show that the changes in less extreme events (5 to 50 year return periods) are not changed in a significant way between the present and end of century climates, which is consistent with the climate model ensemble (Figure 62).

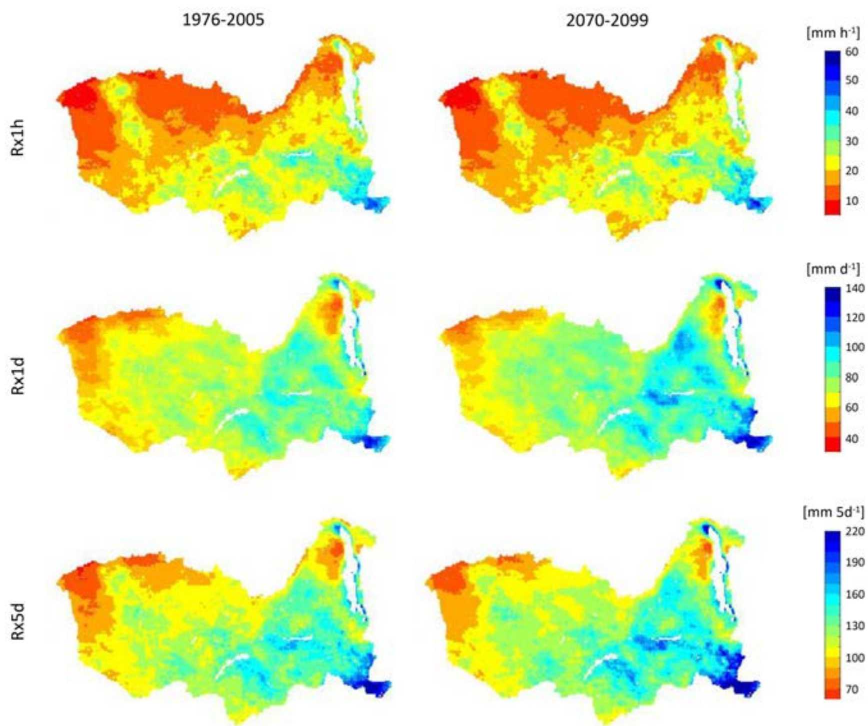

Figure 70 – Potential change in the 1-hour, 1-day and 5-day maximum rainfall (as simulated by AWEGEN-2d) for the present climate (left-hand panels) compared to the end of century climate (right-hand panels). Note that the colour scale is not the same for each row. Refer to Table 5 for a more detailed interpretation of the abbreviations used.

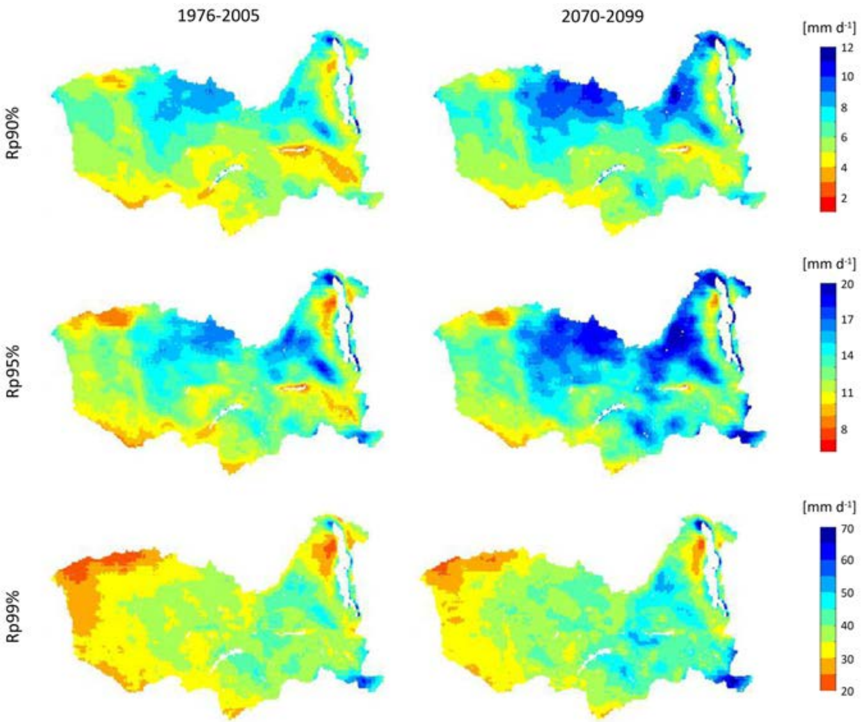

Figure 71 – Potential change in the extremes (90/95/99th percentiles) of daily rainfall, as simulated by AWEGEN-2d for the present climate (left-hand panels) compared to the end of century climate (right-hand panels). Note that the colour scale is not the same for each row. Refer to Table 5 for a more detailed interpretation of the abbreviations used.

3.2.2 Expected Impacts on Water Resources

In this section we give a, mostly, qualitative description of the expected impacts on water resources of the climate trends identified in section 3.2.1. For the Omo-Turkana basin, we were also able to perform hydrological simulations using preliminary climate trajectories, to assess the impacts of a changing climate.

Zambezi River Basin

As noted in section 3.2.1 there are no significant precipitation changes expected for most seasons, however the potential decreases over the southern and western parts of the catchment in SON could have an important impact in the stream flow volumes of the main channel, due to the large area over which this small reduction is expected to occur. This reduction in rainfall in combination with generally increasing temperatures would be expected to result in greater sensitivity of the water balance to drought conditions in a similar manner to the effects seen in a recent study of the Colorado river (Xiao et al., 2018).

The impacts of a reduced volume of available water would obviously have important impacts in all sectors of the nexus. This can be assessed in an integrated way by the combined WEF nexus model being developed in deliverable D3.5.

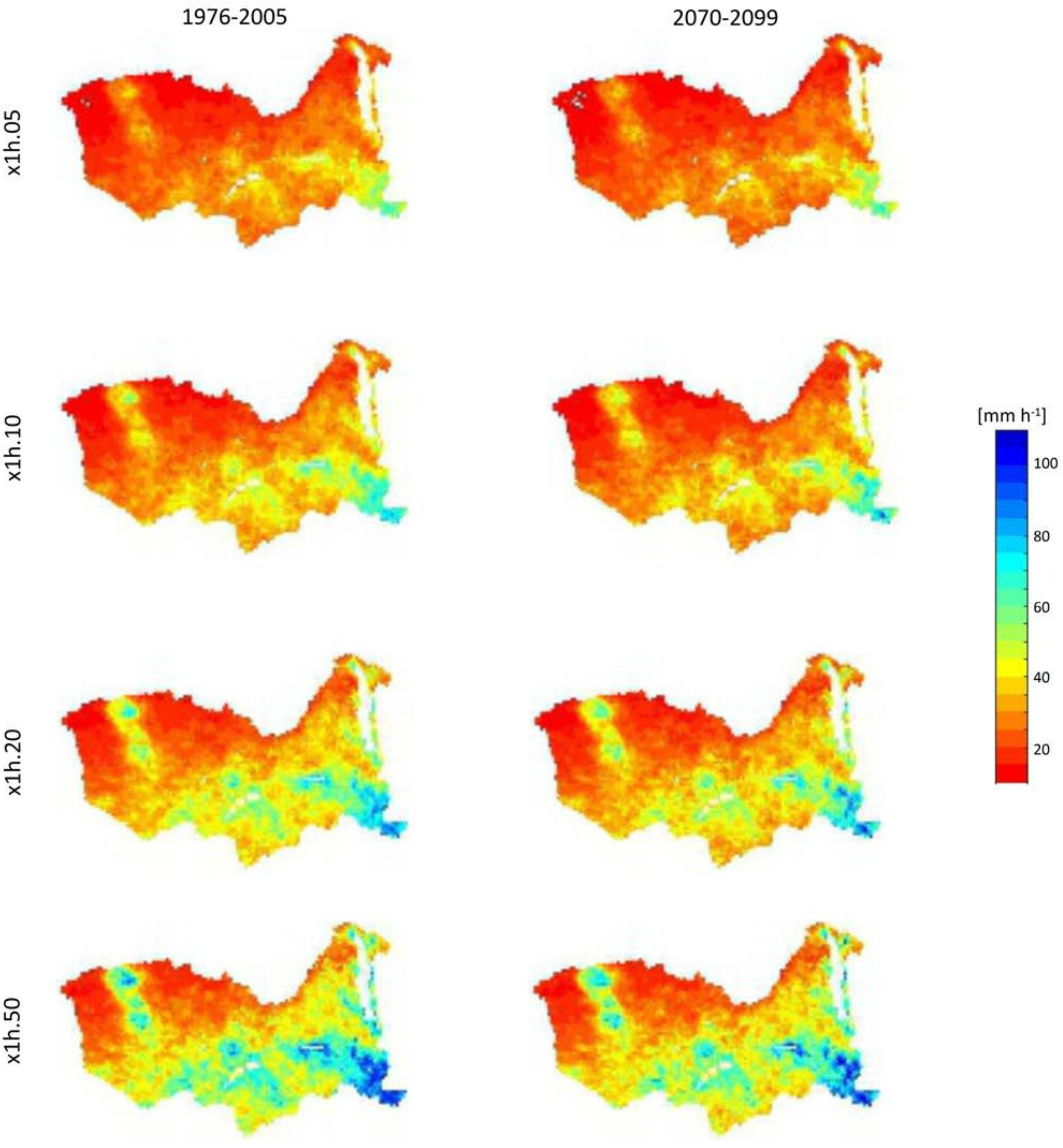

Figure 72 – Potential change in the 5/10/20/50 year return period hourly rainfall, as simulated by AWEGEN-2d for the present climate (left-hand panels) compared to the end of century climate (right-hand panels). Refer to Table 5 for a more detailed interpretation of the abbreviations used.

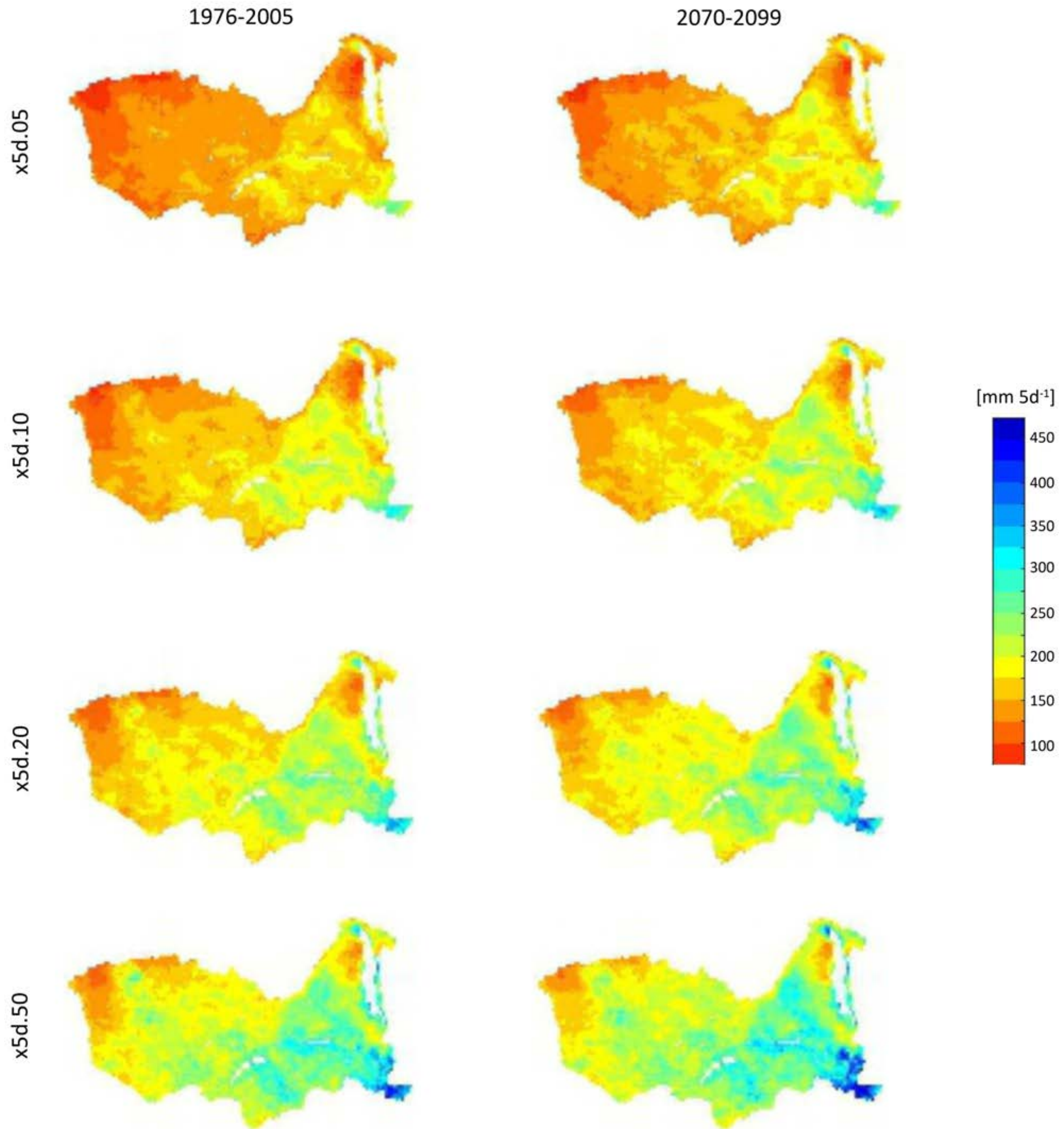

Figure 73 – Potential change in the 5/10/20/50 year return period 5 day rainfall, as simulated by AWEGEN-2d for the present climate (left-hand panels) compared to the end of century climate (right-hand panels). Refer to Table 5 for a more detailed interpretation of the abbreviations used.

Omo-Turkana Basin

The water resources in OTB are expected to be impacted in a positive way by the predicted increase in precipitation amount, unless this is counteracted by an increased evaporation of similar magnitude. Our simulations using a preliminary future trajectory (detailed below) indicate that this will not be the case, and that there will be an increased volume of water generated in the Omo catchment.

In order to perform a quantitative assessment of the climate trends on the OTB basin hydrology, we developed an intermediate future climate by applying the Factors of Change calculated for RCP4.5 to the historical forcing data time series. This assessment allows us to verify that the qualitative effects that are expected based on the analysis in section 3.2.1, do in fact translate to the model outputs. At the time of writing the outputs of the AWE-GEN-2d model for OTB are being processed to allow a more robust analysis along the lines of that described here.

The hydrological model (TOPKAPI-ETH) configuration for the OTB driven by precipitation and temperature derived meteorological forcing time series on a network of virtual stations derived from gridded datasets (see Figure 74). The two different grid spacing's are a function of the spatial resolution of the input datasets – TRMM3B42 (Huffman et al., 2007) in the case of precipitation, and MERRA-2 (Gelaro et al., 2017) for temperature.

We applied the FC methodology outlined in section 3.1.2, to the time series of precipitation and temperature used to force the TOPKAPI-ETH model of the OTB. As an illustration, Figure 75 shows the time series of present climate (historical) and future climate daily precipitation for a single virtual station (indicated in Figure 74 as a larger red marker). The distribution of daily rainfall values for present and future climates for the same station is presented in Figure 76. Similarly, figures 77 and 78 present the time series and daily distributions for temperature, for a single virtual station close to the precipitation station (once again indicated in Figure 74 as a larger red marker).

Using the end of century time series derived by applying the appropriate seasonally and spatially varying FC for each virtual station, we ran hydrological simulations for two configurations of the hydrological model. Summarised results of the simulations are presented in figures Figure 79 through Figure 82.

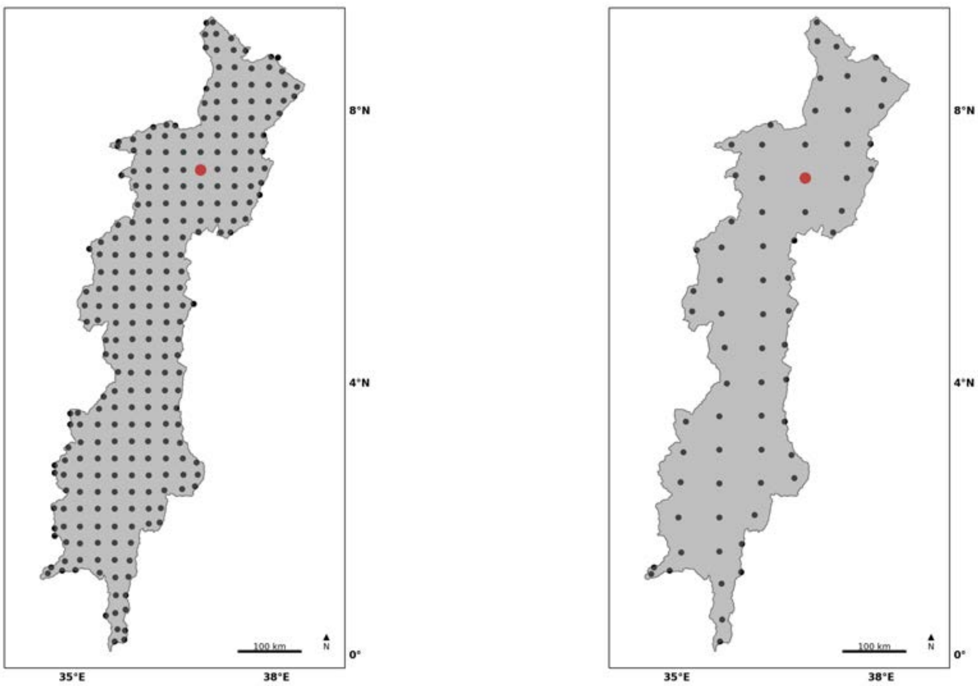

Figure 74 – Virtual precipitation (left) and temperature (right) stations used to force the TOPKAPI model. The larger red markers indicate the locations of the stations considered in figures 75 through 78.

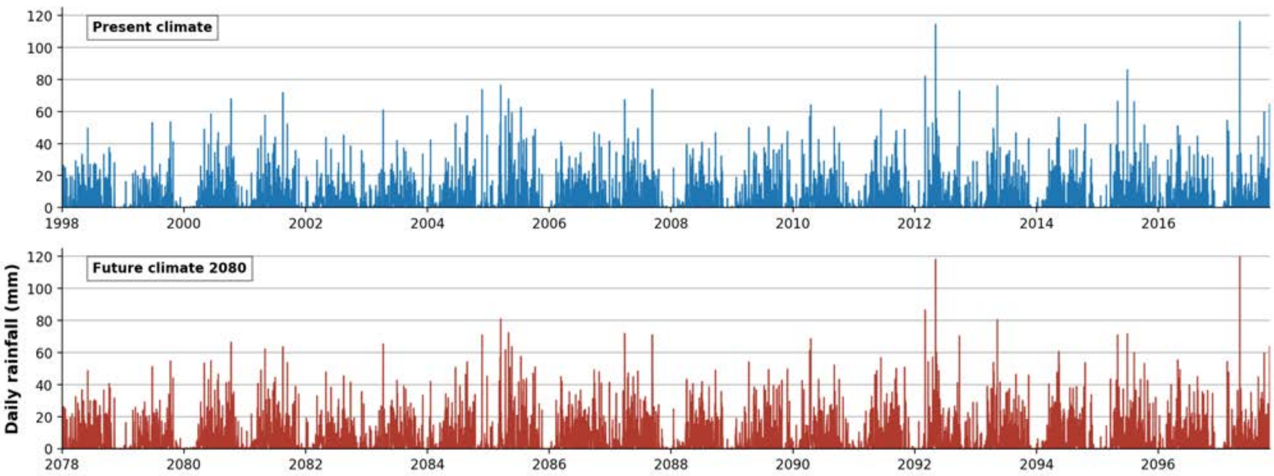

Figure 75 – Comparison between the time series of daily precipitation for the present climate (top panel – blue) and future climate (bottom panel – red) at a single virtual station (indicated in Figure 74 as a larger red marker). The character of the time series is changed by the quantile transformation, in this case it is primarily a shift in the mean of the distribution.

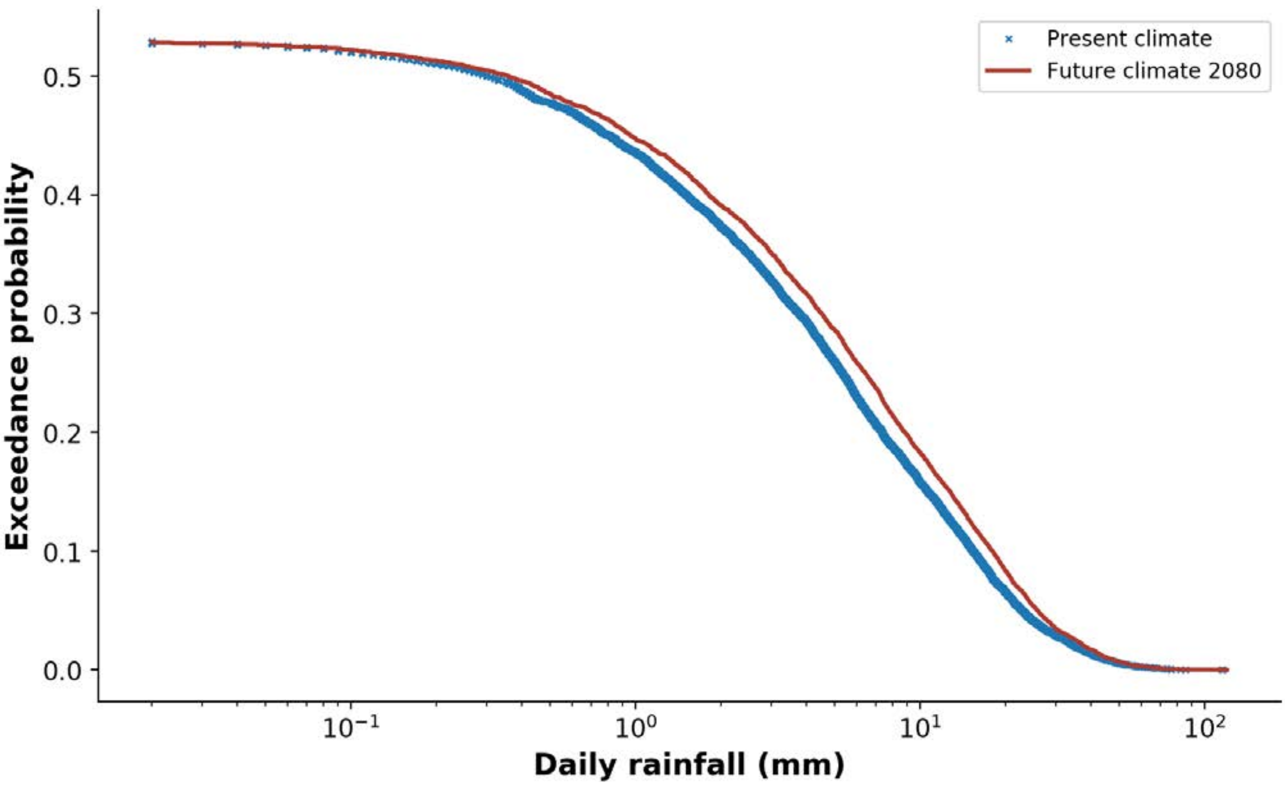

Figure 76 – Distribution of daily rainfall values for present and future climates for the same station presented in Figure 75. Note the logarithmic scale for the rainfall axis. In the case of this single station the distributional shift is not very large, however the cumulative effect over the 20 year simulation period (and all stations) results in a significant increase in total precipitation volume (see Figure 81).

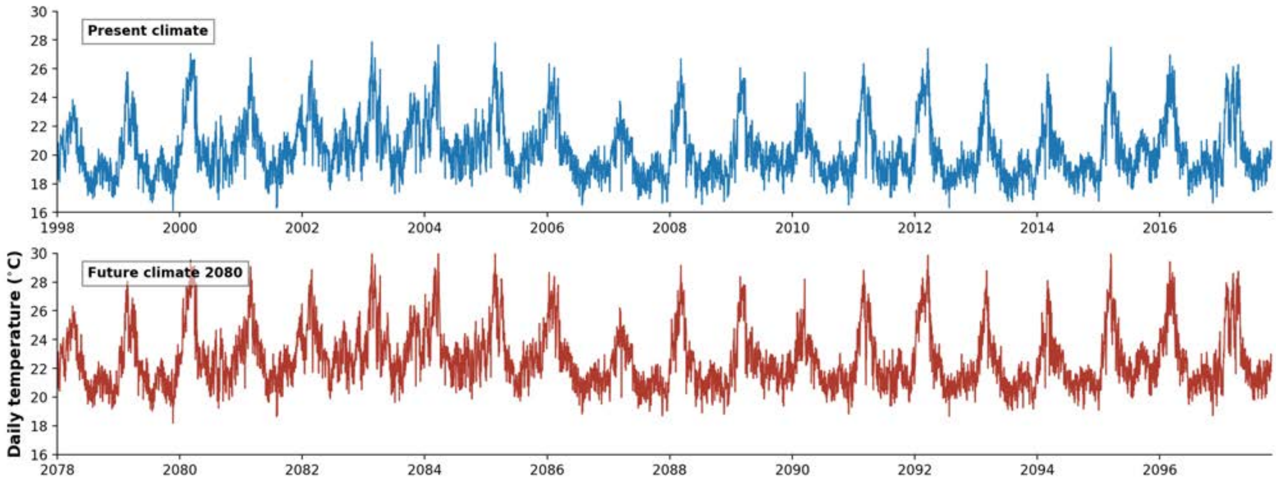

Figure 77 – Comparison between the time series of daily mean temperature for the present climate (top panel – blue) and future climate (bottom panel – red) at a single virtual station (indicated in Figure 74 as a larger red marker). The character of the time series is not changed, because the FC computed for temperature is a proportional change.

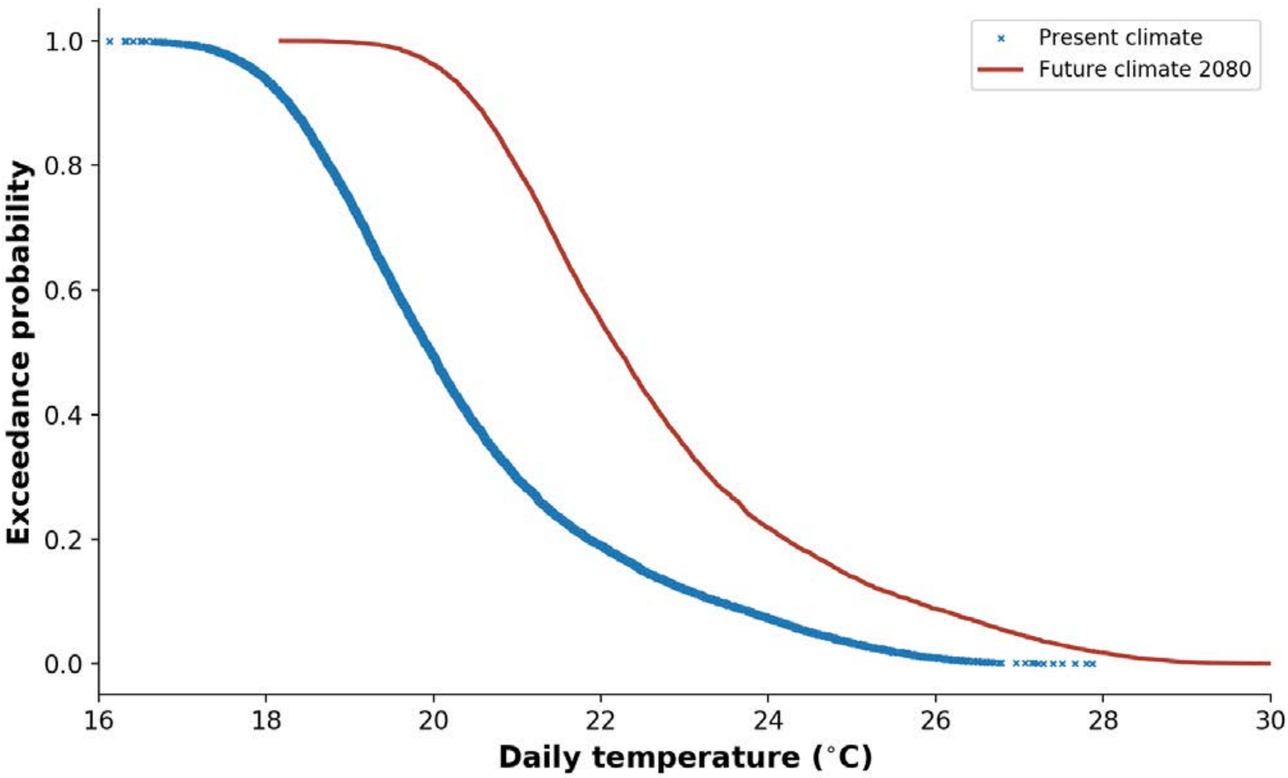

Figure 78 – Distribution of daily temperature values for present and future climates for the same station presented in Figure 77.

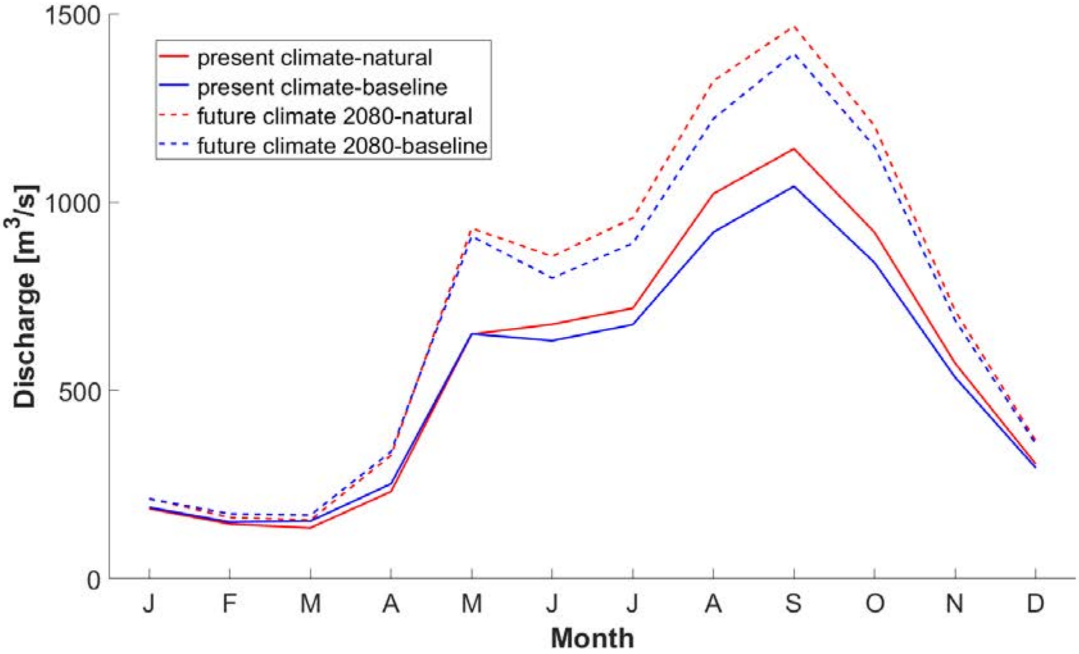

Figure 79 – Seasonal flow distribution entering lake Turkana from the Omo catchment. The solid lines show the distribution for the present (observed) climate, where "natural" refers to a hypothetical model configuration with no reservoirs in the catchment, while "baseline" refers to a configuration that includes the Gibe I and Gibe III reservoirs. The dashed curves show the effect of running the same simulations with the future climate forcing. The general increase in future precipitation results in a significant increase in the run-off volume.

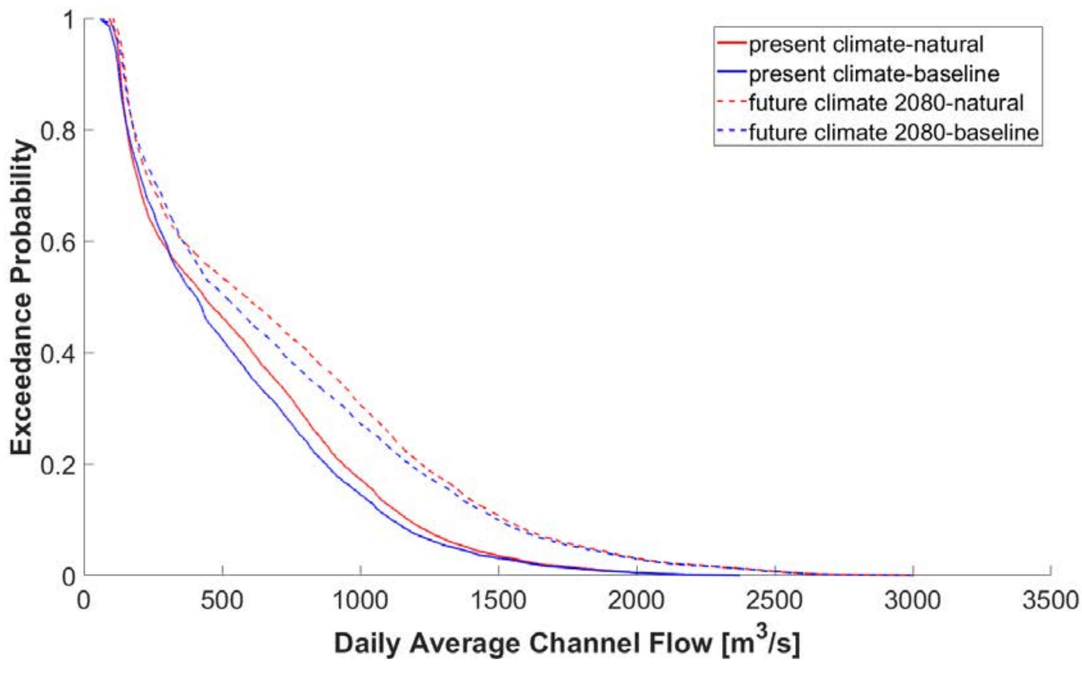

Figure 80 – Distribution of the daily flow rates for the location presented in Figure 79.

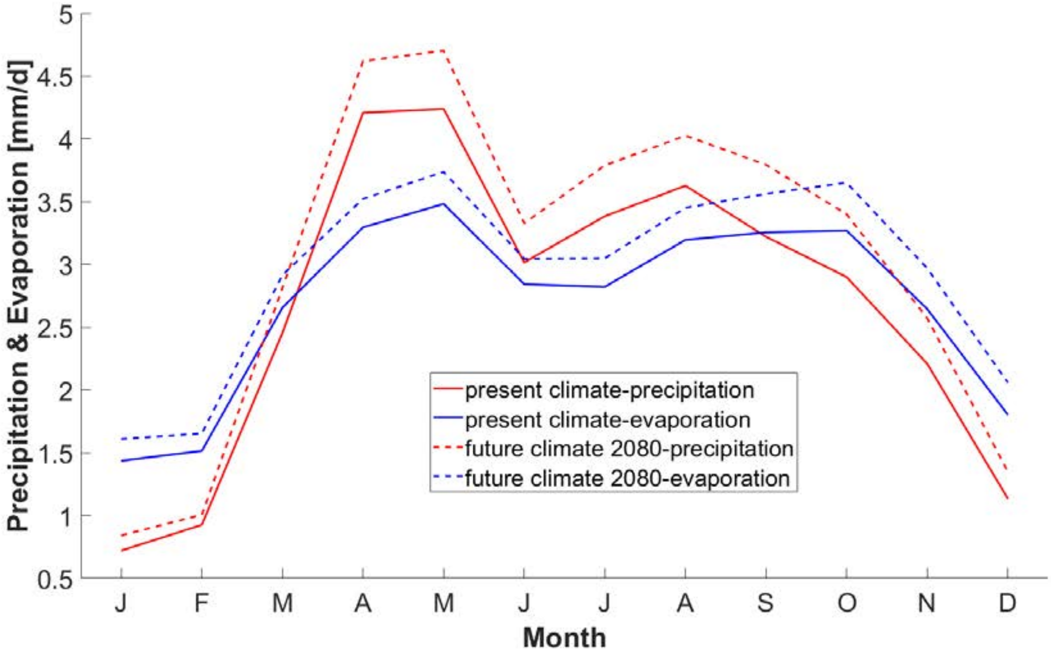

Figure 81 – Seasonal distribution of precipitation and evaporation as an average for the OTB (including Lake Turkana). For the present climate, there is an approximate balance between precipitation and evaporation volumes, which results in a relatively stable level in Lake Turkana. For the future climate simulations, the precipitation is no longer balanced by evaporation.

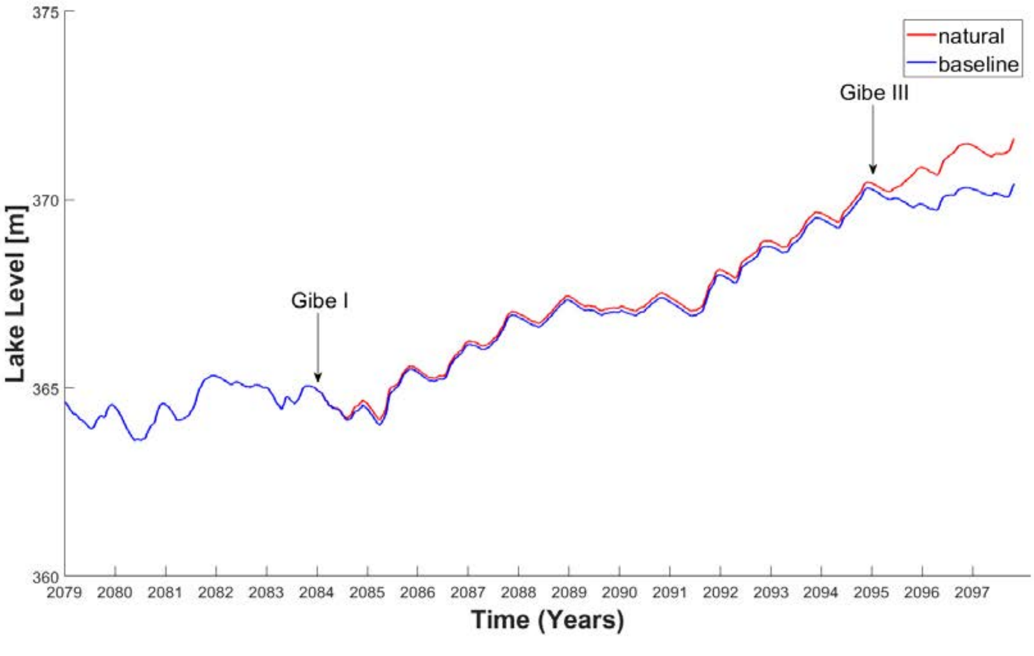

Figure 82 – Simulated trajectory of Lake Turkana level for natural conditions (no dams), and the baseline catchment configuration (Gibe I and Gibe III), under future climate forcing. It is clear that the increased evaporation due to temperature increases doesn't compensate for the increased volume of runoff caused by increased rainfall (see Figure 81 for an explanation). We are working to improve the storage volume relationship for Lake Turkana, in order to better understand this behaviour, however it is clear that the increased precipitation predicted by the climate scenarios introduces a significant increase in the available runoff volume simulated by the model. The references to Gibe I and Gibe III are included because we ran a simulation configuration that includes the introduction of the dams at the same relative timing as the historical simulations.

4. FUTURE HYDROPOWER AND HYDRAULIC INFRASTRUCTURES

In this chapter, we introduce the African power sector in section 4.1, before expanding on the Southern African Power Pool (SAPP) in section 4.2, and the planned and potential hydropower potential in the ZRB in section 0. Moving to the East African Power Pool in section 4.4, we discuss plan infrastructural development in section 4.5.

4.1 AFRICA POWER SECTOR

Africa presents a very small power sector when compared with its geographic extension and population, and while its domestic energy production potential could overtop the internal energy demand, as of 2014, more than two-thirds of the African population did not have access to electricity (IEA, 2014).

If we focus on the supply side, Africa can be divided into five different macro-regions according to the major sources of energy supplying electricity to the main demand sectors of each region. These macro-regions are usually called power pools, acting as specialized agencies of their respective Regional Economic Community (REC) (ICA, 2016):

- **Central Africa Power Pool (CAPP)** for the Economic Commission for Central Africa States (ECCAS): it consists of 10 member countries and experienced a growth in both installed power capacity (from 5,345 MW to 6,299 MW) and associated electricity consumption (from 15,238 GWh to 24,744 GWh) from 2008 to 2013.
- **Comité Maghrébin de l'Electricité (COMELEC)** for the Union of Maghreb Arab (UMA): it consists of 5 member countries and experienced a growth in both installed power capacity (from 24,027 MW to 36,367 MW) and associated electricity consumption (from 160,322 GWh to 120,200 GWh) from 2009 to 2013.
- **Eastern Africa Power Pool (EAPP)** for Common Market for Eastern and Southern Africa (COMESA): it consists of 11 member countries and experienced a growth in both installed power capacity (from 38,513 MW to 54,311 MW) and associated electricity consumption (from 162,322 GWh to 232,505 GWh) from 2008 to 2013.
- **Southern Africa Power Pool (SAPP)** for SADC: it consists of 11 member countries and experienced a growth in both installed power capacity (from 55,948 MW to 61,859 MW) and associated electricity consumption (from 260,081 GWh to 269,375 GWh) from 2008 to 2015. It was created in 1995 and is now the most developed power pool in Africa.
- **West Africa Power Pool (WAPP)** for ECOWAS (ICA, 2011): it consists of 14 member countries and experienced a growth in both installed power capacity (from 14,669 MW to 19,648 MW) and associated electricity consumption (from 46,936 GWh to 50,634 GWh) from 2008 to 2015.

4.2 SOUTHERN AFRICAN POWER POOL (SAPP)

The Southern African Power Pool (SAPP) was created in August 1995 at the Southern African Development Community (SADC) summit held in Kempton Park, South Africa. It consists of twelve member countries, represented by their respective electric power utilities organized through SADC (SAPP, 2015). The primary aim of the SAPP is to provide reliable and economical electricity supply to the consumers of each of its members, based on reasonable utilization of natural resources and the effect on the environment. In particular, all its members have committed to create a common market for electricity in the SADC region and let their customers benefit from the advantages associated with this market. In doing so, the utilities from member countries work under the right of equal and fair participation, from sharing information and lessons learnt to technical wheeling and mutual support (SAPP, 2016).

At the utility scale, it is important to note that the Republic of South Africa (RSA) presents the biggest contribution to the installed capacity in the SAPP amounting to 75.9% of the total. This means that the RSA is a fundamental stability factor for the regional grid system. At the SAPP level, after coal hydropower provides the second largest installed capacity, equal to 21% of the total. On the electricity production side, on average hydropower generates 14.1% of total electricity produced in the whole SAPP, nuclear 4.4%, whereas thermal (i.e., oil, gas and coal) is responsible for 81.4%. The contribution from other renewable sources (e.g., solar, wind) is negligible (The World Bank, 2016).

Despite installed capacity is growing fast in some member countries (1,237 MW of new generation capacity on annual average over the last 11 years), there is still a relatively large shortfall at the SAPP level. As at 31st March 2015, SAPP had an operating capacity of 46,910 MW against a demand of 49,563 MW that includes peak demand, suppressed demand, and reserves. This corresponded to a generation capacity shortfall of 8,247 MW, i.e. 16.6% of demand was unserved, taking into account generation capacity reserve requirements. In order to face this issue, a large amount of planned new capacity is supposed to be commissioned between 2015 and 2019, totaling 24,062 MW within the whole SAPP (SAPP, 2015).

As for the future electricity demand, Figure 83 shows the projections of future yearly energy consumption [GWh] at the national scale for all the countries belonging to the SAPP (for further details on the methodological approach employed to generate these projections, we refer to *Deliverable 5.1*). As can be observed, all the nations but South Africa experience a slightly exponential increase in their energy demands in the future. On average, Angola (dark blue), Tanzania (pink) and Zambia (light blue) are characterized by the highest rise in their energy consumption rates, equal to a +2% increase per year. The only exception is made for South Africa (dark red), whose future energy consumption projection is characterized by a downward parabolic behavior. In particular, an increase in its energy demand is estimated up to 2050, driven by a large population growth. After this breakpoint, its population will start decreasing, causing energy consumption rates to diminish consequently. Yet, the South African future energy demand is expected to rise by +0.3% on average across the entire time horizon.

Figure 84 displays the energy demand projections at the SAPP scale, where it is highlighted the share of each nation to the total demand of the power pool on an yearly time-step. As can be observed, South Africa (dark red) is responsible for the largest energy consumption, covering about 70% of the SAPP future energy demand on average. Yet, its consumption share is likely to decrease from 77% in 2015 down to 62% in 2060 of the overall demand. Zambia (light blue) presents an opposite trend with respect to South Africa and is the second-largest energy consumer within the SAPP in the future. In particular, its energy demand share is likely to increase from 8% in 2015 to 16% in 2060 of the entire power pool consumption, covering about 12% of the SAPP future energy demand on average. As already discussed in Figure 83, the same increasing trend of energy consumption share forecasted in Zambia can be observed in all the other countries belonging to the SAPP, except for South Africa.

For further details on the Africa power sector and the five power pools it comprises, we refer the reader to *Deliverable D2.1*.

4.3 HYDROPOWER INFRASTRUCTURES IN THE ZAMBEZI RIVER BASIN

The eight nations belonging to the Zambezi River Basin (ZRB), namely Angola, Botswana, Mozambique, Malawi, Namibia, Tanzania, Zambia and Zimbabwe, are also state members and operate within the SAPP. In this deliverable, we present an overview of: (i) the current and future installed hydropower capacity in the basin; (ii) the technical sheets collected for both the under construction and planned hydropower plants.

Within the ZRB, on average hydropower currently generates 78.4% of total electricity produced, whereas thermal sources are responsible for 21.5%. Other renewable sources contribution is negligible. The lion's share of the electricity produced comes from Mozambique (27.4%), Zambia (27.3%) and Zimbabwe (24.9%). As far as installed capacity is concerned, the current hydropower capacity sums up to 5,415 MW, updated at 2016. By the end of 2023, an additional 8,394 MW new hydropower generation capacity will be commissioned (Figure 85), corresponding to 155% of the current operating one.

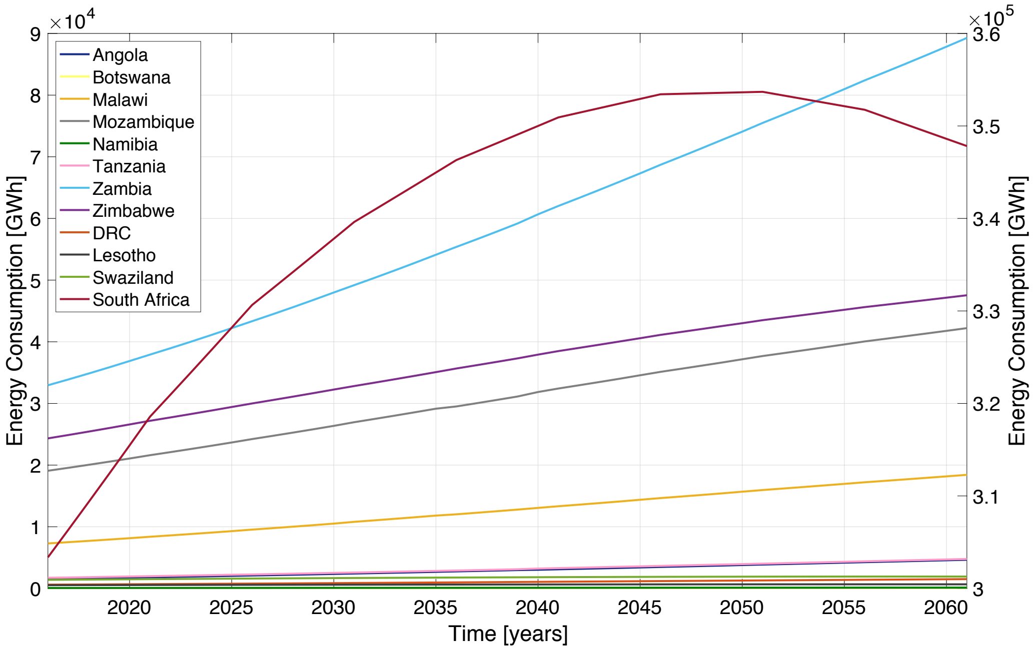

Figure 83 – Projections of future yearly energy consumption [GWh] at the national scale over the 2015-2060 time horizon for all the countries belonging to the Southern African Power Pool. Each color refers to a specific nation within the SAPP. Secondary y-axis refers to South Africa only, as its energy demand data are one order of magnitude bigger with respect to all the other countries.

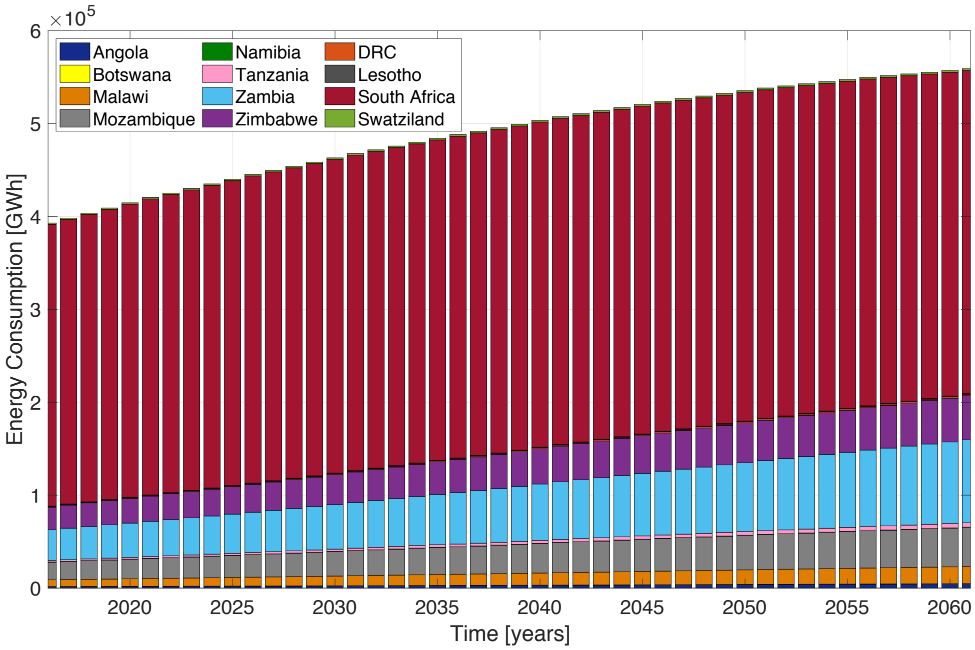

Figure 84 – Projections of future yearly energy consumption [GWh] over the 2015-2060 time horizon at the entire Southern African Power Pool scale. Each color refers to one specific nation's contribution to the total energy consumption within the SAPP each year.

Both the existing and planned hydropower plants within the ZRB are summarized in Table 6 in terms of their installed capacity [MW], status (i.e., operating, under construction, planned) and expected completion date (in case of planned infrastructures). In addition, they are geographically located and classified according to their installed capacity in Figure 86 (Cervigni et al., 2015). Their upstream-downstream relationship is instead highlighted in both Figure 87 and Figure 88, where an elevation profile of the ZRB and the future topologic scheme of the system are respectively outlined. In particular, Figure 87 shows the high hydropower potential of the basin due to its rapid elevation changes that guarantee significant hydraulic heads, and thus high hydropower production. The peculiar orography of the ZRB therefore justifies the large number of planned hydropower plants in the near future, displayed in orange and red in Figure 88. Here, a distinction must be made between hydropower reservoirs, namely regulated natural/artificial lakes that can be operated either annually (e.g., Itezhi-Tezhi) or as carry-over reservoirs for several years (e.g., Cahora Bassa), and pondages, i.e. smaller regulated reservoirs that can be operated only over relatively short periods (e.g., weekly, such as Tedzani) (The World Bank, 2010).

As it can be observed from the rows highlighted in red in Table 6, the existing hydropower plants within the Lunsemfwa sub-catchment (i.e., Mulungushi and Mita Hills dams located on the Lunsemfwa river entering the Zambezi right upstream of Lake Cahora Bassa) have a negligible capacity, only 1% of the total installed hydropower capacity of the Zambezi river basin.

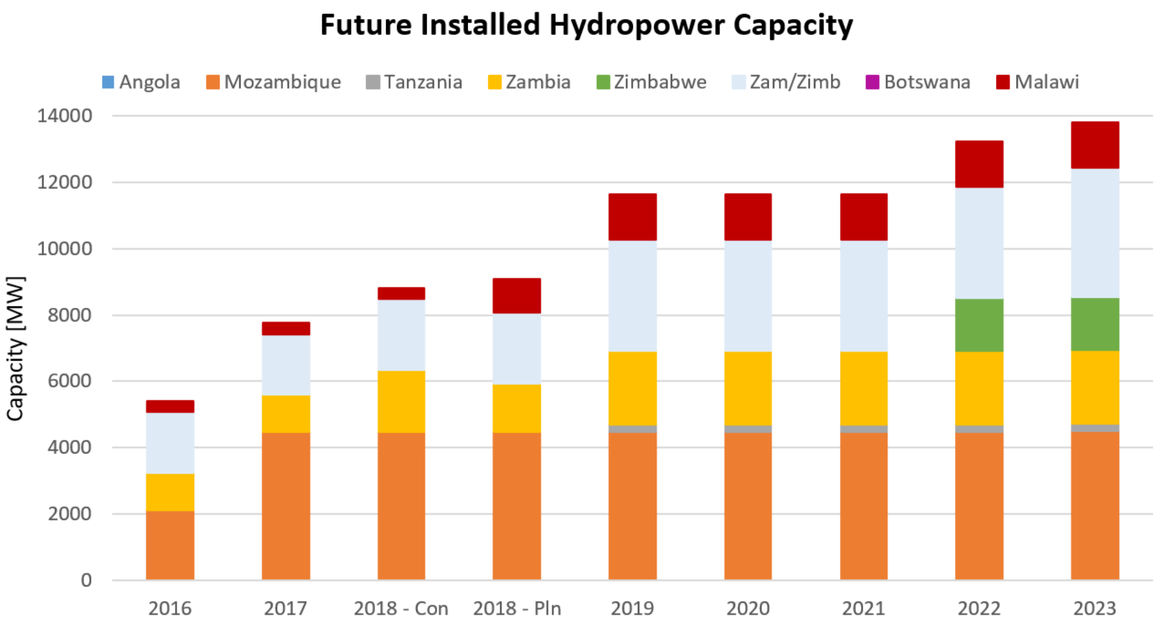

Figure 85 – Planned new hydropower capacity [MW] to be commissioned by the end of 2023 in each of the states belonging to the Zambezi river basin (Cervigni et al., 2015).

Table 6 – Existing and future hydropower plants within the Zambezi river basin. The rows highlighted in orange identify the projects that were supposed to be operating by 2016 but that are still in the planning phase. The rows highlighted in red refer to the two existing hydropower plants (i.e., Mulungushi and Mita Hills) on the Lunsemfwa river that can be neglected due to their low installed capacity.

COUNTRY	HYDROPOWER NAME	CAPACITY [MW]	STATUS	EXPECTED COMPLETION
				EXISTING HYDROPOWER
Mozambique	Cahora Bassa	2,075	HC	-
Malawi	Nkhula Falls	122	HC	-
Malawi	Kapichira	132	HC	-
Malawi	Tedzani	88	HC	-
Zambia	Victoria Falls	108	HC	-
Zambia	Kafue Gorge Upper	990	HC	-
Zambia	Itezhi-Tezhi	120	HC	-
Zambia	Mulungushi	32	HC	-
Zambia	Mita Hills	24	HC	-
Zambia/Zimbabwe	Lake Kariba	1,470	HC	-

(Table 6 continued)

Zambia/Zimbabwe	Kariba North Extension	360	HC	-
				FUTURE HYDROPOWER
Malawi	Khlolombizo	240	PLN	2018
Malawi	Songwe I,II and III	340	PLN	2014
Malawi	Lower Fufu	100	PLN	2015
Tanzania	Rumakali	222	PLN	2019
Mozambique	Mphanda Nkuwa	1,500	PLN	2017
Mozambique	Boroma	444	PLN	2025
Mozambique	Lupata	654	PLN	2025
Mozambique	HCB North Bank	850	PLN	2015
Zimbabwe	Batoka Gorge	1,600	PLN	2022
Zambia	Kafue Gorge Dam Lower	750	CON	2018
Zambia	Mulungushi Expansion	80-100	PLN	n.a.
Zambia	Muchinga	240-330	PLN	n.a.
Zambia	Ndevu Gorge	235-240	PLN	2022
Zambia/Zimbabwe	Devils Gorge	1,240	PLN	2019
Zambia/Zimbabwe	Kariba South Extension	300	CON	2018
Zambia/Zimbabwe	Mpata Gorge	543	PLN	2023

HC = Operating; CON = Under Construction; PLN = Planned

The technical characteristics of both the future hydropower plants in the ZRB are available on the internal project data repository and in the Appendix of this report. Variables highlighted in red refer to either missing data or data that still needs to be validated by the utility managing the power plants. It must be noticed that the list of hydropower stations here classified is not exhaustive but reflects the availability of information that could be collected from both scientific papers and grey literature (e.g., technical reports) via traditional information channels. In the following sections, we briefly describe the following future hydropower infrastructures:

- Kafue Gorge Lower (Zambia);
- Ndevu Gorge (Zambia);
- Muchinga (Zambia);
- Mulungushi (Zambia);
- Devil's Gorge (Zambia/Zimbabwe);
- Mpata Gorge (Zambia/Zimbabwe);
- Batoka Gorge (Zambia/Zimbabwe);
- Mphanda Nkuwa (Mozambique);
- Boroma (Mozambique);
- Lupata (Mozambique);
- Lower Fufu (Malawi);
- Songwe I, II, III (Malawi);
- Kholombidzo (Malawi);
- Rumakali (Tanzania);

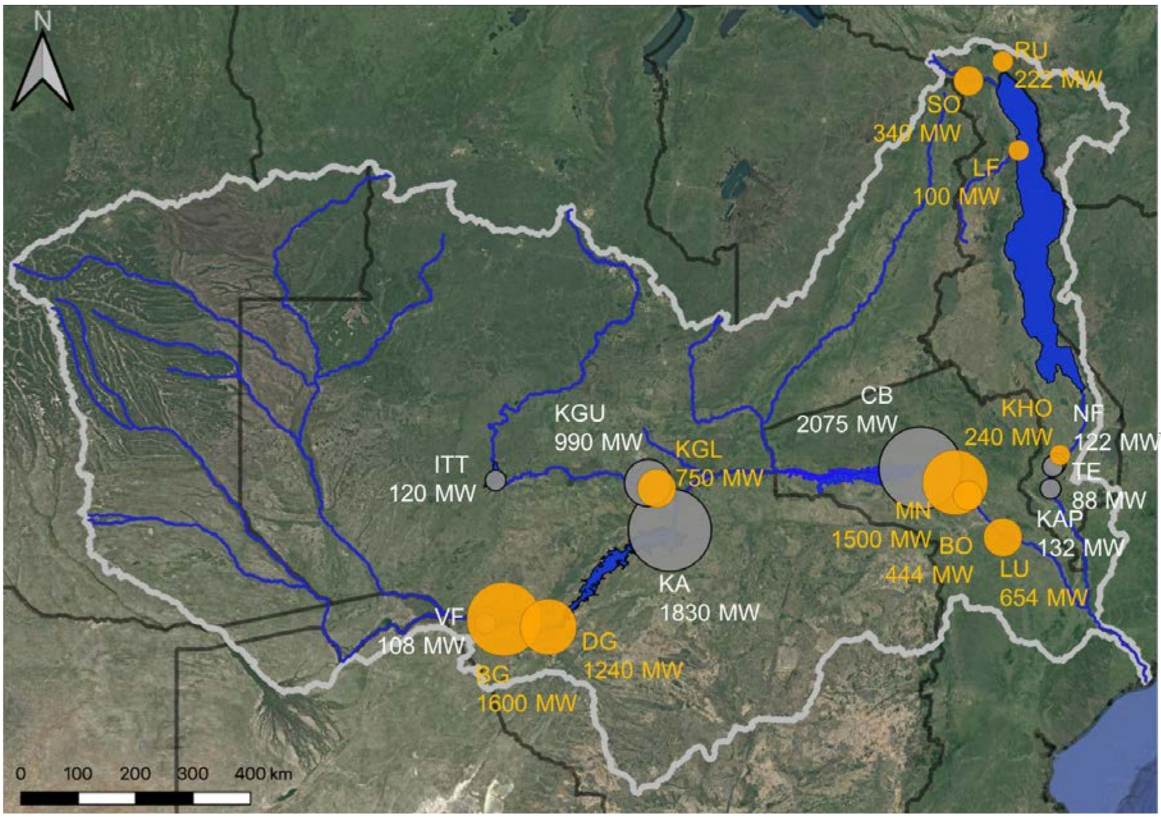

Figure 86 – Geographical location of both the existing (grey) and planned (orange) hydropower infrastructures within the Zambezi river basin. The marker size is proportional to the installed capacity [MW].

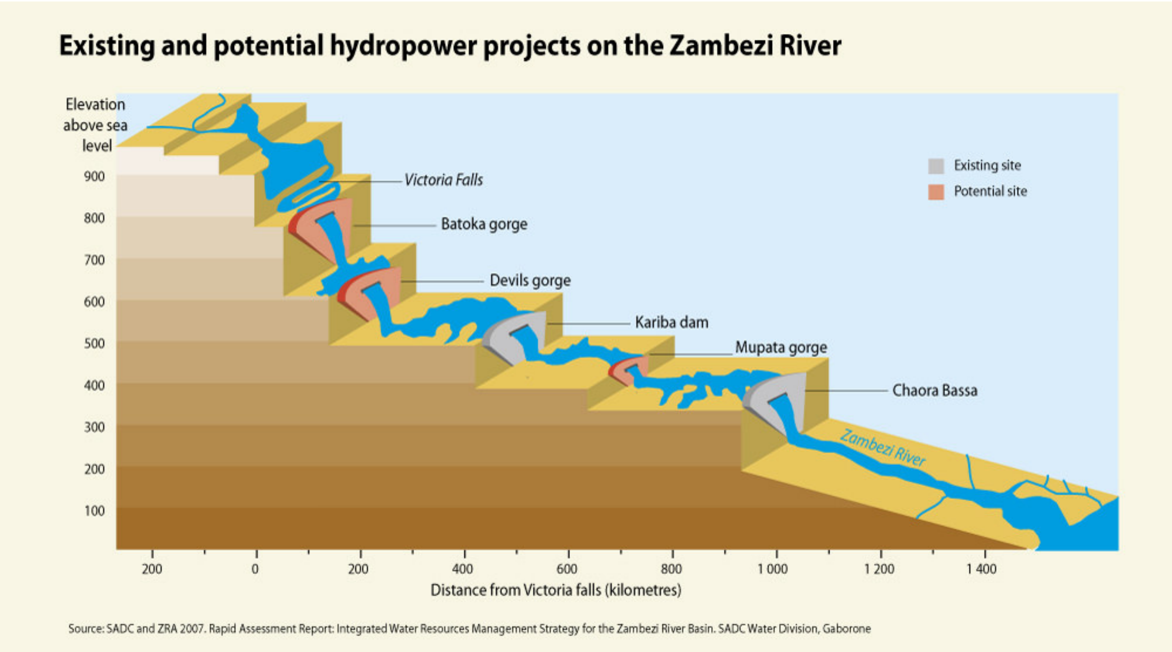

Figure 87 – Elevation profile of the major existing (grey) and planned (red) hydropower plants along the Zambezi River Basin (SADC, 2007).

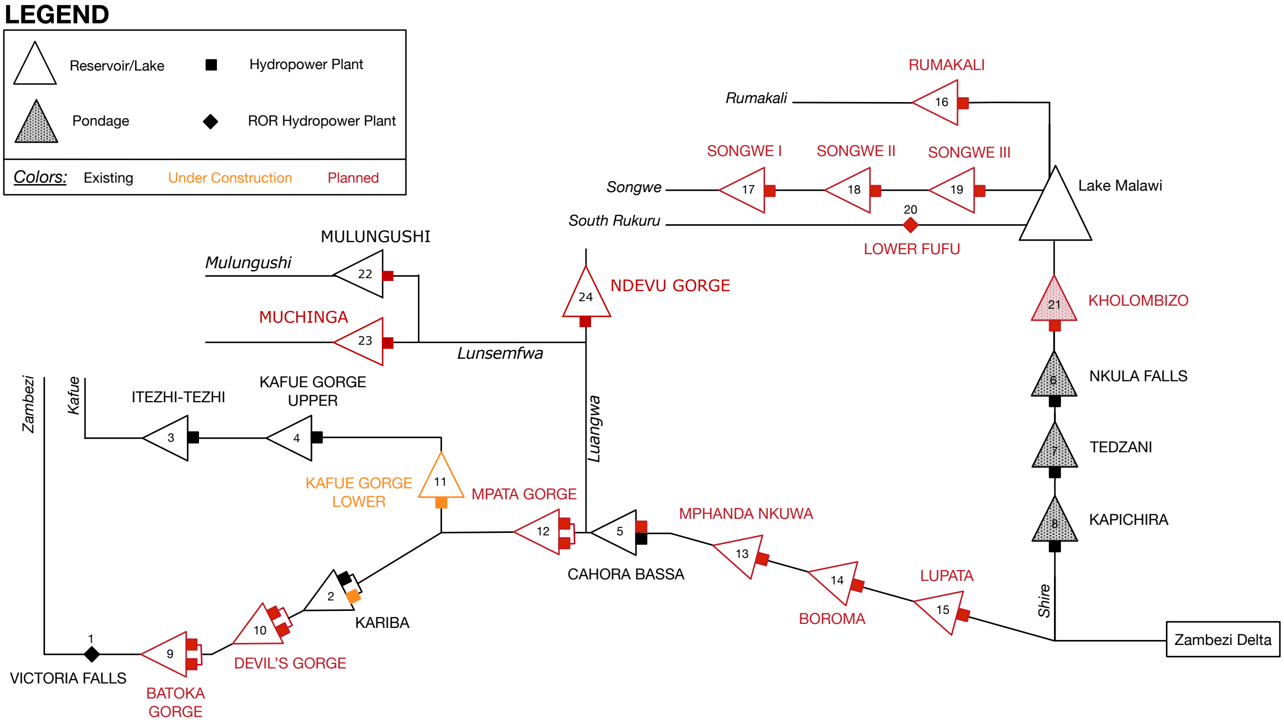

Figure 88 – Topologic scheme of the Zambezi river basin showing the future state of the system.

4.3.1 Kafue Gorge Lower – Zambia (under construction)

The Kafue Gorge Lower project was first analyzed in the mid 1970s, but only in 2006 ZESCO completed an environmental impact assessment. The site selection is located in the Kafue Gorge, 65 km upstream from the confluence of the Kafue and the Zambezi River and about 5.9 km downstream the existing Kafue Gorge Upper water outlet (ZESCO, 2006). The Kafue Gorge Lower project includes the construction of a concrete-face rock fill dam and a surface powerhouse housing five 150 MW generator units, for a total nameplate capacity of 750 MW. Since October 2015, this project is being developed under a Private Public Partnership between ZESCO and SINOHYDRO Corporation, a Chinese company, with the former operating the dam. The project is supposed to be fully commissioned in 2019 (“Kafue Gorge Lower (KGL) Power Station, Zambia”, 2015).

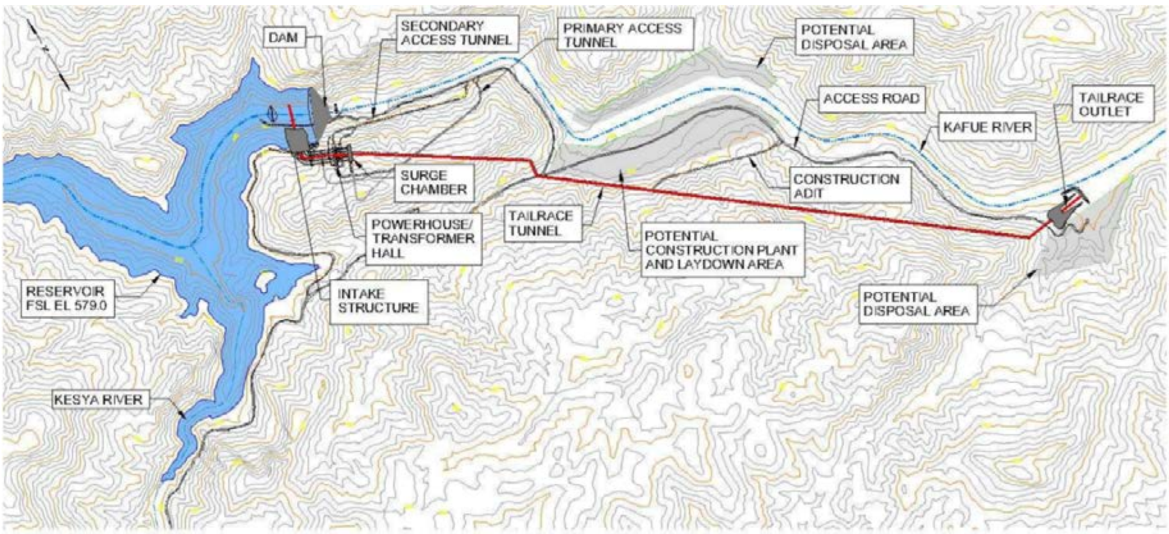

Figure 89 – The Kafue Gorge Lower hydroelectric project (Basson, 2010).

4.3.2 Ndevu Gorge – Zambia

The Ndevu Gorge dam and associated hydropower plant has been proposed by the MDH South Africa (Pty) Limited and will be located on the Luangwa river, upstream of the Lunsemfwa-Luangwa rivers confluence. The Ndevu Gorge primary dam is supposed to impound a 165 km-long lake, thus requiring a water supply level of 78 m at fully capacity, based on the bathymetry of the chosen location. A secondary dam wall will thus be needed in order to prevent the primary wall to be bypassed. The Ndevu Gorge reservoir will inundate various surrounding areas, among which the most important is the South Luangwa National Park, whose 30% of total areal extent will be flooded (Conlen et al., 2017). In the end, the Ndevu Gorge hydropower project will generate 235-240 MW of power and cost USD1.26 billion (Lusaka Times, 2017).

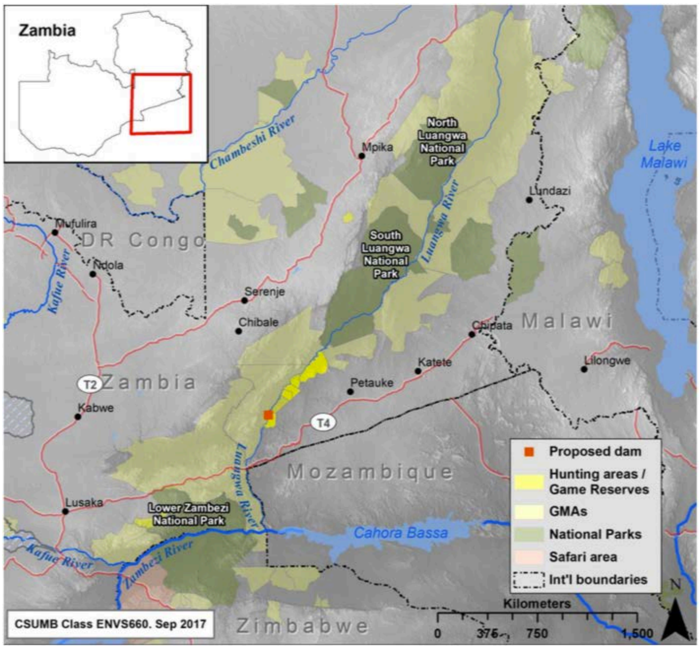

Figure 90 – Location of the Ndevu Gorge hydropower project along the Luangwa river (Conlen et al., 2017).

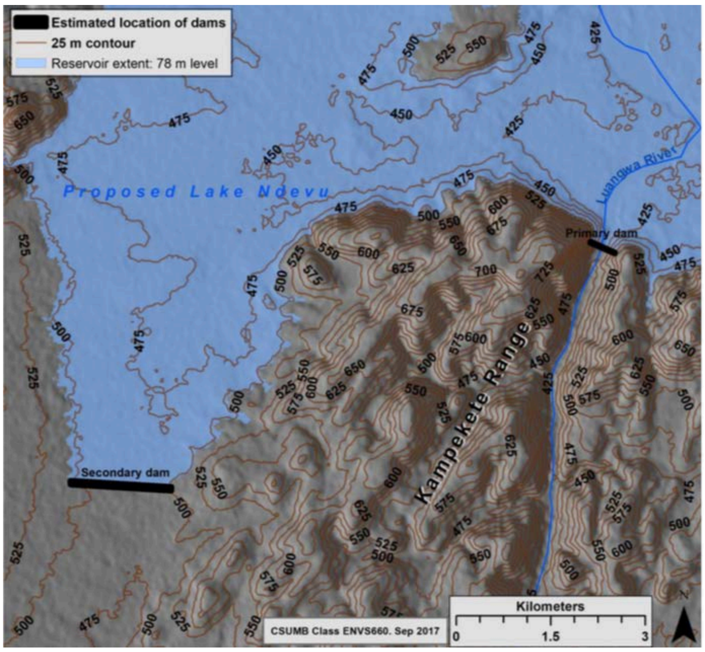

Figure 91 – Estimated position of the primary and secondary Ndevu Gorge dam walls needed for guaranteeing a 78 m fully supply level in the Lake Ndevu reservoir (Conlen et al., 2017).

4.3.3 Muchinga – Zambia

The Muchinga Power Company Limited is studying the potential construction of a 240-330 MW hydropower project (namely, Muchinga hydropower plant) on the Lunsemfwa river, located about 35 km downstream of the existing Mita Hills dam and 25 km downstream of the existing Lunsemfwa hydropower station. In particular, the Lunsemfwa river flows currently regulated by the upstream Mita Hills dam will be transferred to the Mkushi reservoir on the Mkushi river[2] through a transfer tunnel, summing up to the volume of water drained from the Mkushi Basin. The releases from the Mkushi dam will then be transferred back through a 7.8 km headrace tunnel first and three penstocks later to the Muchinga powerhouse located on the eastern bank of the Lunsemfwa river. This latter is planned with 3 Francis units, each one in the range of 80-110 MW installed capacity. The Muchinga hydropower scheme will be operated in order to maximize hydropower production, thus to maintain as high reservoir levels as possible (i.e., high hydraulic head) but low enough to provide enough storage to minimize spilled volumes (ERM, 2013).

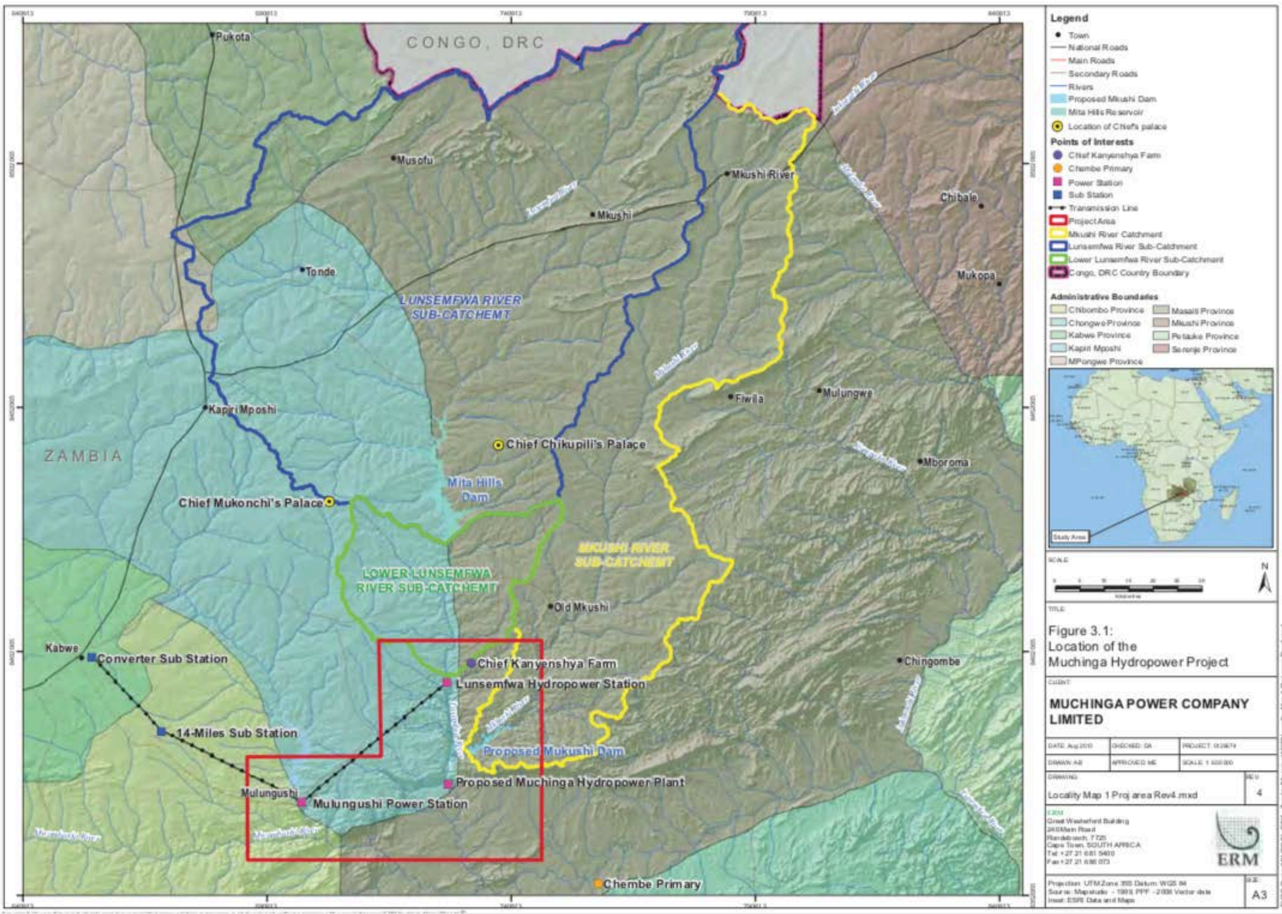

Figure 92 – Location of the planned Muchinga hydropower project, situated at the southern limits of the Mita Hills (blue), Mkushi (yellow) and Lunsemfwa (green) catchments (ERM, 2013).

[2] The Mkushi dam will be located on the Mkushi river, about 6 km upstream of the Mkushi and Lunsemfwa rivers confluence, in order to avoid the national monument of the Wonder Gorge situated very close to this confluence point.

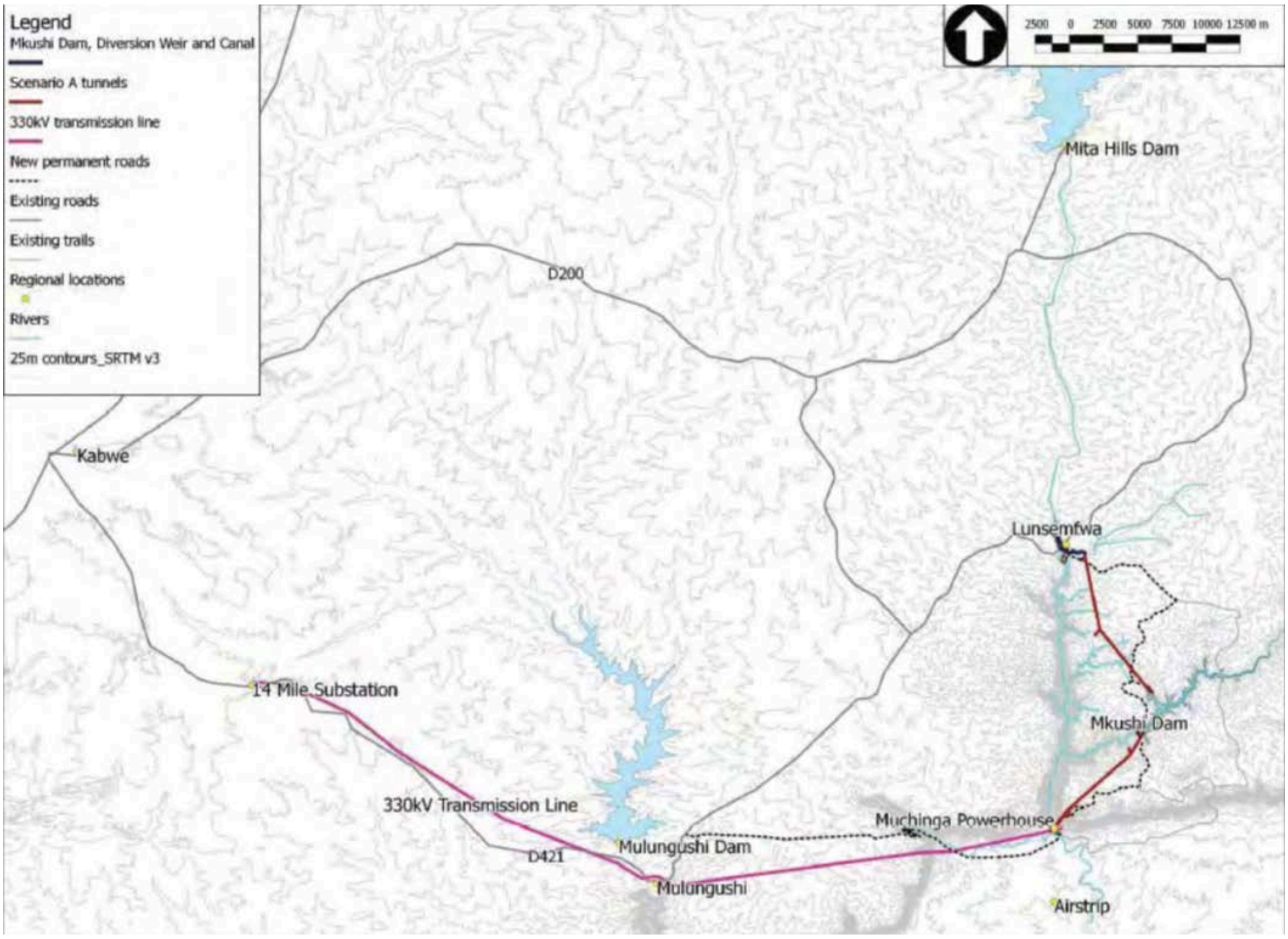

Figure 93 – Planned project infrastructure for the planned Muchinga hydropower plant. It can be observed a: (i) transfer tunnel from Lunsemfwa to Mkushi dam; (ii) 7.8 km headrace tunnel from Mkushi dam to Muchinga powerhouse on the Lunsemfwa river; (iii) future transmission lines (ERM, 2013).

4.3.4 Mulungushi – Zambia

The Lunsemfwa Hydro Power Company Limited is studying the potential development of a 80-100 MW hydropower project (namely, Mulungushi hydropower plant) on the Mulungushi river, located about 60 km to the south-east of Kabwe. This project will consist in the construction of a new 80-100 MW surface powerhouse next to the existing 30 MW Mulungushi hydropower station, which will then be dismissed. No additional impoundment will be necessary as the existing Mulungushi dam will provide enough water storage for the new enlarged Mulungushi hydropower plant (ERM, 2013).

4.3.5 Devil's Gorge - Zambia/Zimbabwe

The Devil's Gorge hydropower plant is supposed to be built between the planned Batoka Gorge and the tail end of the existing Kariba dam along the Zambezi river, just downstream of the Gwayi/Zambezi rivers confluence. The Devil's Gorge will be a bilateral project between Zambia and Zimbabwe, as it would include north (Zambia) and south (Zimbabwe) bank power stations, each with a capacity of 600 MW. Earliest studies on the potential of this site for hydropower development have been first undertaken in the 70s and later on in the 90s with the Batoka Gorge Hydroelectric Scheme Feasibility Study (ZRA, 2018). However, the Devil's Gorge project has been considered economically unfeasible and postponed indefinitely according to the World Bank (2010).

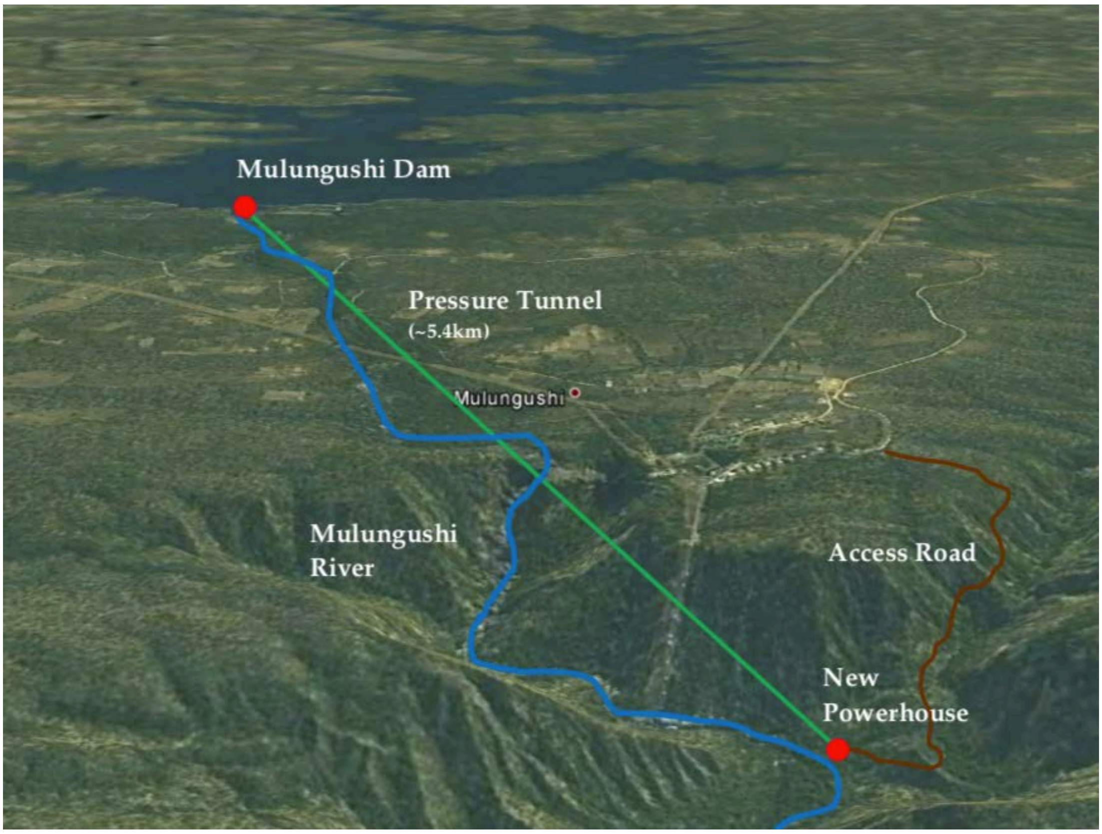

Figure 94 – Aerial layout of the planned Mulungushi hydropower project on the Mulungushi river (ERM,2013).

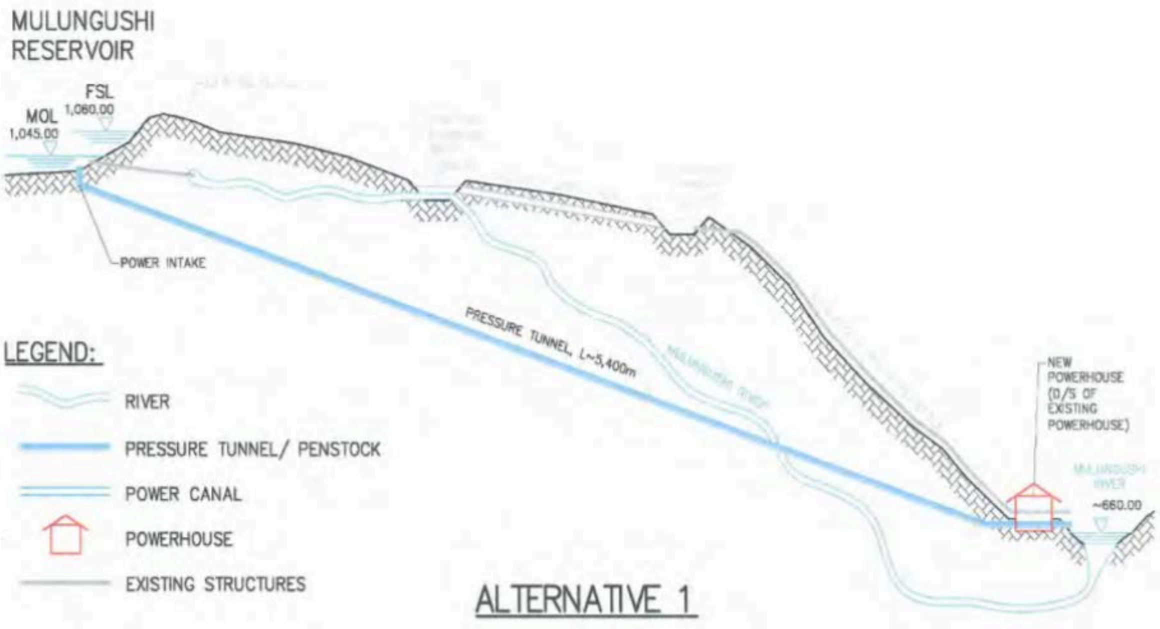

Figure 95 – Cross-sectional layout of the planned Mulungushi hydropower project. Alternative 1 has been selected among other 3 alternatives evaluated in terms of their net benefit (i.e., input costs relative to their power generation capacity) (ERM, 2013).

4.3.6 Mpata Gorge - Zambia/Zimbabwe

The Mpata Gorge hydropower plant is supposed to be located at the downstream end of the Mupata Gorge that lies between the existing Kariba and Cahora Bassa dams along the Zambezi river.

The Mpata Gorge will be a bilateral project between Zambia and Zimbabwe, as it would include the construction of two surface power-stations, one on each bank of the river (i.e., north - Zambia and south - Zimbabwe), just downstream of the dam for an overall installed capacity of 1200 MW. Earliest studies on the potential of this site for hydropower development have been first undertaken in the 80s (ZRA, 2018). However, the Mpata Gorge project has been reserved as one of potential sites for future hydropower development in the basin because it would inundate both the UNESCO World Heritage Site of Mana Pools on the south bank (Zimbabwe) and the Lower Zambezi National Park on the north bank (Zambia) (World Bank, 2010).

4.3.7 Batoka Gorge - Zambia/Zimbabwe

The Batoka Gorge hydroelectric project lies on the Zambezi River, approximately 50 km downstream of the Victoria Falls and upstream of the existing Kariba Dam, across the boundary between Zambia and Zimbabwe. If it were operated in conjunction with Kariba Dam, it would enable this latter to significantly reduce its flood season output and consequently build up reservoir storage for the dry period (Tilmant, 2012).

The Batoka Gorge bilateral scheme includes the construction of a Roller Compacted Concrete gravity arch dam and two powerhouses of 800 MW each on each riverbank, for a total nameplate capacity of 1,600 MW. The Zambezi River Authority (ZRA) is the project proponent, whereas ZESCO and ZPC will operate the powerhouse in Zambia and Zimbabwe respectively (Zambezi River Authority, 2015).

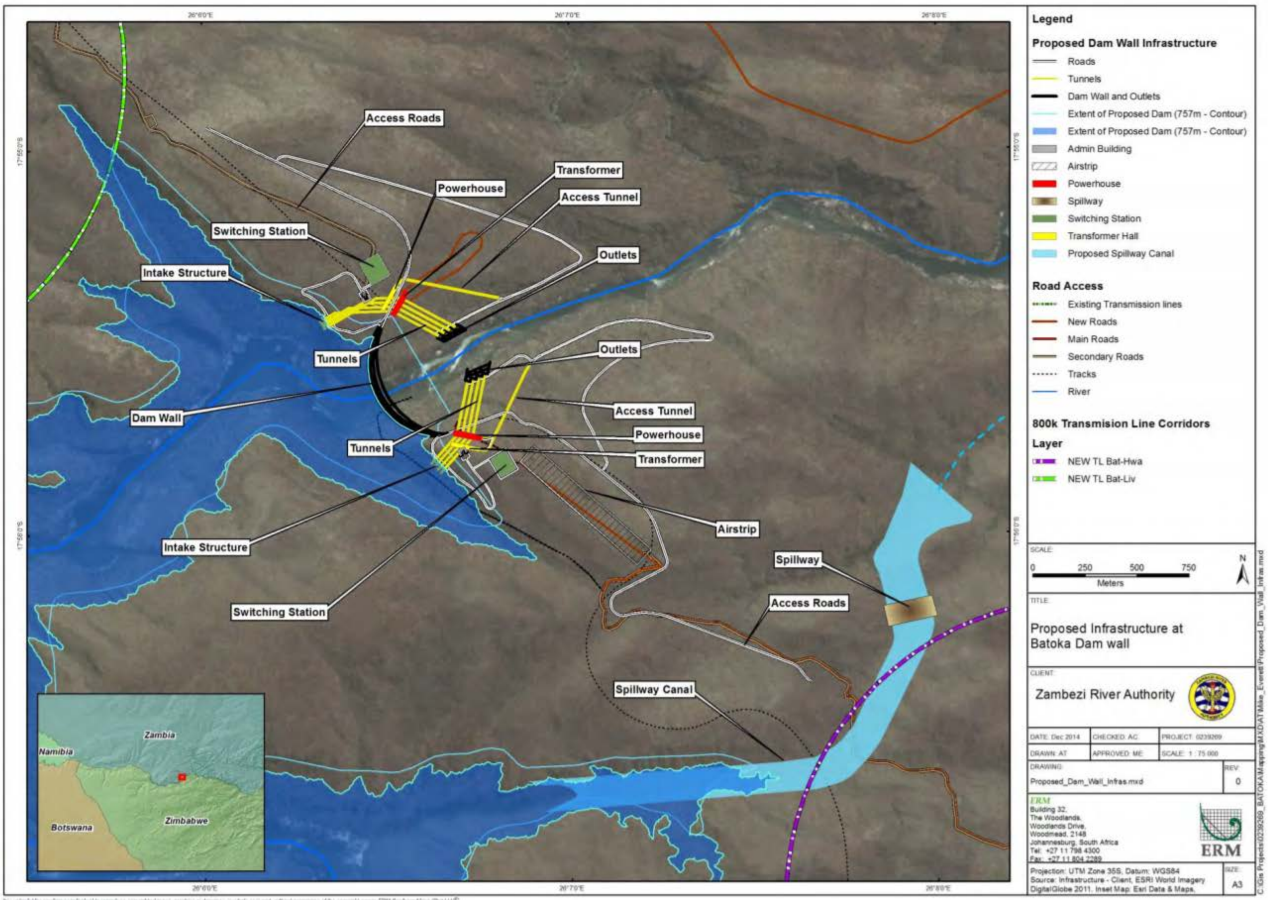

Figure 96 – The Batoka Gorge hydroelectric project. Source: Zambezi River Authority, 2015.

4.3.8 Mphanda Nkuwa – Mozambique

The Mphanda Nkuwa Dam is supposed to be located 60 km downstream of Cahora Bassa and 70 km upstream of the city Tete, along the Zambezi River. The project consists of a high roller-compacted concrete dam, whose 2,510 Mm^3 storage would correspond to 5% of the Cahora Bassa reservoir stored volume (COBA et al., 2009). The Mphanda Nkuwa will be operated as a run-of-river plant by EDM (Electricidade de Moçambique). If an extension to the Mphanda Nkuwa installed capacity were performed, the power station would likely operate in midmerit or peaking mode, which would require the construction of an additional reservoir downstream (i.e., Boroma) to regulate the fluctuating downstream river flows (The World Bank, 2010). The Mphanda Nkuwa project was supposed to be fully commissioned by 2017 (Cervigni et al., 2015), however the latest project stage recorded as of 2016 is the transaction support and financial close (PIDA, 2017).

Figure 97 – The Mphanda Nkuwa Project (COBA et al., 2009).

4.3.9 Boroma – Mozambique

The Boroma hydropower plant is supposed to be built along the Zambezi river within the Lower Zambezi region, downstream of both the existing Cahora Bassa reservoir and the proposed Mphanda Nkuwa hydropower dam (Stanzel et al., 2014). Only if this latter will be developed to its full potential (i.e., 2275 MW) and operated in either midmerit or peaking mode, the Boroma reservoir will be needed in order to re-regulate (i.e., stabilize) the associated fluctuating river flows downstream. Otherwise, the Mphanda Nkuwa plant will be operated as a run-of-the-river plant, which would not require any re-regulation downstream. If needed, Boroma itself will have an installed generation capacity of 444 MW (The World Bank, 2010).

4.3.10 Lupata – Mozambique

The Lupata hydropower plant will be located along the Zambezi river within the Lower Zambezi region, 230 km downstream of the existing Cahora Bassa reservoir and the planned Mphanda Nkuwa and Boroma projects (Stanzel and Kling, 2014). Even though the Lupata reservoir will be relatively limited for storage of peak flows with respect to the existing Kariba and Cahora Bassa reservoirs, it will: (i) considerably contribute to solving the power deficit in the region with its 654 MW of installed capacity; (ii) be operated to contribute to more natural flows in the Zambezi Delta (SADC, 2011).

4.3.11 Lower Fufu – Malawi

The Lower Fufu project consists of a high-head (i.e., over 300 m) run-of-the-river plant near Chiweta, which exploits the hydropower potential of the South Rukuru River and, through a connector, of the North Rumphi River, for a generation capacity range of 90 – 180 MW. The basic scheme will divert water from these two rivers via two small concrete intake dams and two tunnels, leading to a single underground powerhouse. The prefeasibility report carried out by Norconsult in 1996 calls for two tunnels of equal size for a total length of 15 kilometers, conveying up to 31 m^3/s of total flow to the hydropower plant. The combined discharge flow from this latter will be released into Lake Malawi. The Lower Fufu dam will be operated by ESCOM (The World Bank, 2010).

4.3.12 Songwe I, II, III – Malawi

The 340 MW Songwe Hydroelectric Project would be located on the Songwe River and would consist of three reservoirs and corresponding hydropower plants in cascade (Songwe I, II and III). The upper dam (Songwe I) would be on the border between Malawi and Tanzania, downstream of Bupigu settlements, whereas the middle and lower ones would be in Malawi (EAC, 2011). In particular, Songwe II would be near the Songwe River confluence with the Sofwe River, while Songwe III near the Songwe River confluence with the Manolo River.

The Songwe Scheme is a multipurpose project, since the three aforementioned hydropower plants should be designed for combined hydropower production and flood control. They would also be all operated by ESCOM and be fully commissioned by 2024 (The World Bank, 2010).

4.3.13 Kholombidzo – Malawi

The Kholombidzo hydropower plant is supposed to be located on the Shire river within the middle Shire River Basin, about 50 km downstream of the existing Kamuzu Barrage. In earlier studies (e.g., The World Bank, 2010), it has been identified as a potential least-cost solution for both expanding Malawi power generation system and increasing rural communities' access to electricity (USAID, 2014). The African Development Bank approved financing to the Government of Malawi after the original design of the proposed Kholombidzo hydropower plant was changed to a lower dam height, in order to prevent Kamuzu Barrage and 250 km^2 of upstream land to be inundated and 8000 people resettled. The current project will then produce 140-280 MW during the dry/rainy seasons, instead of the initially proposed 160-370 MW. If approved and constructed, the Kholombidzo infrastructure will become the first hydropower facility among the Shire river hydropower plants cascade (USAID, 2014).

Figure 98 – Kholombidzo Falls (USAID, 2014).

4.3.14 Rumakali - Tanzania

The Rumakali Hydropower Project would be located on the Rumakali River, 85 km west of Njombe in the Iringa Region of south-western Tanzania. In 1997/1998, SWEDPower/NORConsult carried out a first feasibility study on the construction of a 222 MW hydropower plant, which Studio Pietrangeli, Rome later upgraded to 520 MW (SMEC, 2013). The new hydroelectric scheme consists of a rockfill storage dam on the river, an intake close to the dam and a system of underground tunnels and penstocks carrying water to an underground powerhouse (The World Bank, 2010). Artificial waterways (e.g., canals, tunnels) will transfer water from four adjacent basins besides Rumakali to the main reservoir of the Rumakali dam (SMEC, 2013). This latter will be operated by TANESCO.

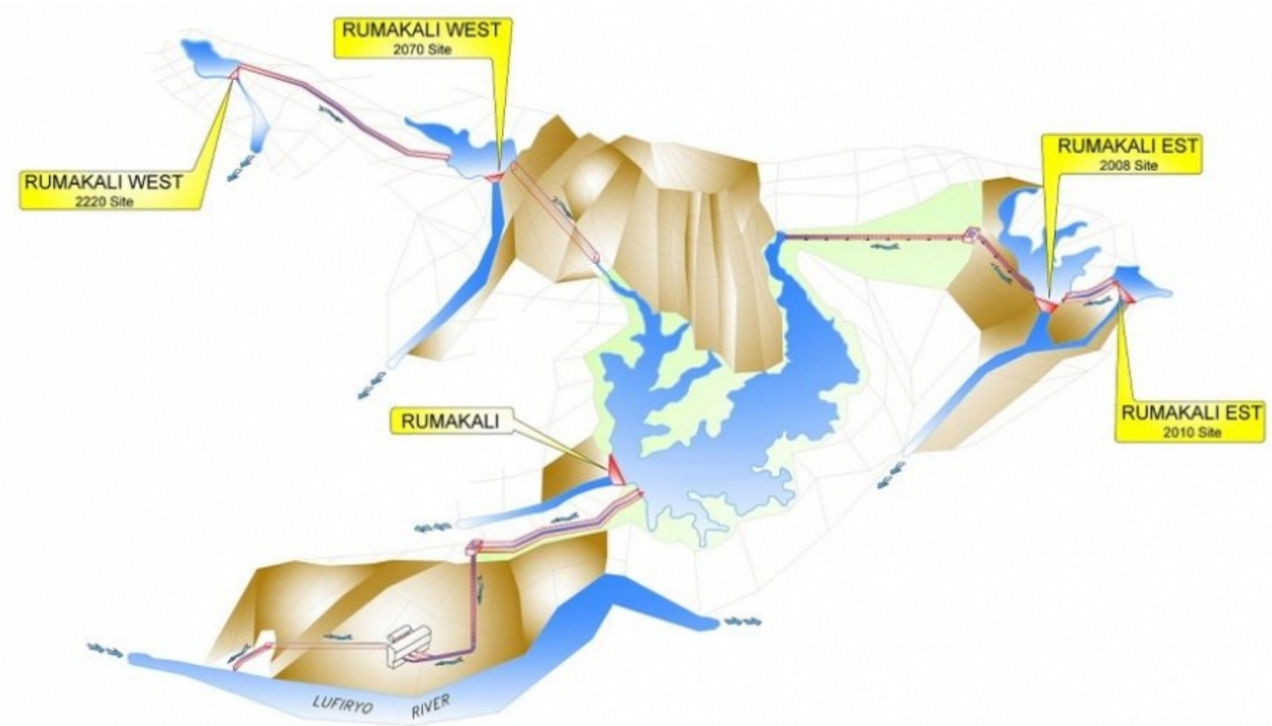

Figure 99 – The Rumakali Hydropower Project. It is supposed to exploit five catchments, whose water is transferred to the main reservoir of the Rumakali Dam through artificial water ways (i.e., canals, tunnels and pipelines) (SMEC, 2013).

4.4 EASTERN AFRICA POWER POOL (EAPP)

Eastern Africa is one of the fastest growing socio-economic realities of the world, with a population expected to grow five-fold by the end of the century according to UN projections. The impressive growth in energy demand is balanced by recent discoveries of new fossil fuel reserves (e.g., Oil discovery in Turkana region (Johannes, Zulu, & Kalipeni, 2014), and unexploited renewable energy potential (e.g., geothermal and wind along the rift valley, and hydropower in the Ethiopian highlands).

The Eastern Africa Power Pool (EAPP) is the leading authority in charge of develop a regional planning around energy resources, drive public and private investments, and favor the integration of countries power sector to establish a regional electricity market. Current and projected energy demand of EAPP member states are reported in until 2030, displaying a growth factor of 3.5 in accordance to the EAPP Master Plan (IRENA, 2015). A disproportion in demand between member states is evident. Egypt, the second most populous country in Africa, accounts for the largest share of energy demand, and is projected to reach by 2030 the 75% of the total, while Burundi, Djibouti, Eritrea, Rwanda, and Somalia will together total less than 2%.

The International Renewable Energy Agency (IRENA, 2015) projects an increase in exploitation of renewable resources with a significant supply diversification. In the renewable-promotion scenario, wind power shows the biggest growth in installed capacity (60 GW), followed by hydro (30 GW), solar PV (8 GW), and geothermal (5 GW). In addition to the expansion of generation capacity, another key challenge for the EAPP is the expansion of the existent transmission lines, necessary to enable electricity trading between nations. It is part of EAPP development plan to expand the transmission line capacity at regional level by more than 10 GW by 2030. The extended network shows a substantial increase in the number of cross-boundary, high-voltage power lines to sustain regional energy exchange towards a strong integration of the countries' energy sectors (Gebrehiwot, 2013).

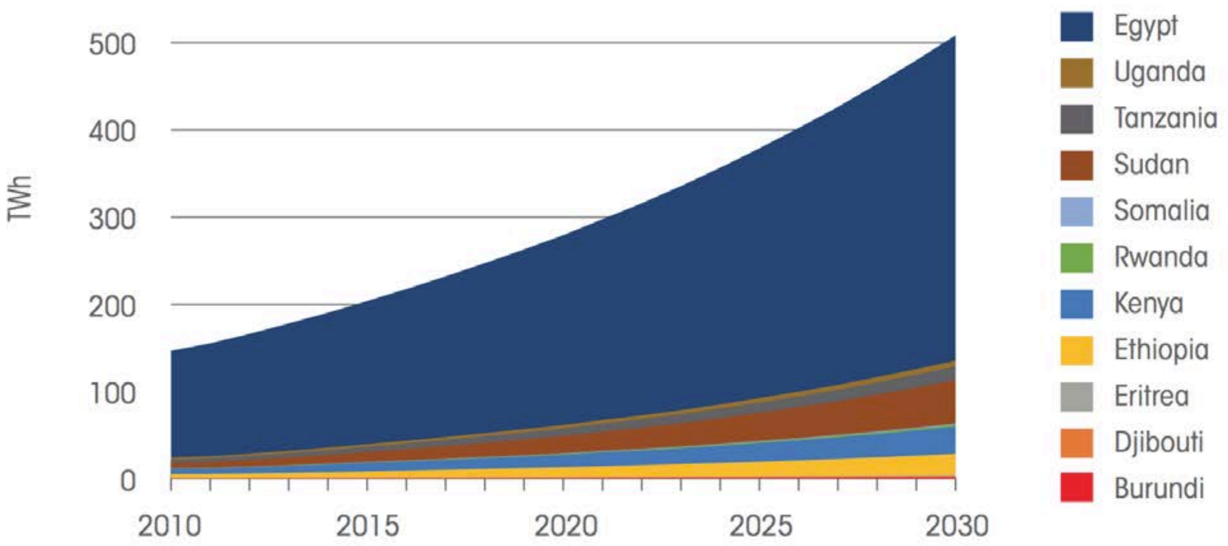

Figure 100 – Current and projected energy demand of EAPP member states from 2010 to 2030 (IRENA, 2015).

Ethiopia aims at becoming a regional power hub by exploiting its exceptional renewable energy resource potential. With the first 5-years plan (Growth and Transformation Plan, GTP-I) Ethiopia aimed at increasing the total installed capacity from the 2 GW existing before 2010 to 10 GW by 2015, achieved by prioritizing large hydro developments. In GTP-II, the aim is to reach a final installed capacity of over 17 GW. GTP-II favors a more balanced mix of energy sources, with investments in wind farms (300 MW Aysha, 100 MW Debreberhan and 150 MW Itaya currently under development) and geothermal energy (1,000 MW Corbetti geothermal power project commissioned in 2018). Nevertheless, hydropower will represent the biggest share of power generation, contributing around 90% of electricity to the Ethiopian grid (International Hydropower Association, IHA, 2017). More than half of Ethiopian hydropower potential (estimated to reach 45 GW) is distributed in two main river basins, the Blue Nile, and the Omo River basin.

The most ambitious dam construction project undertaken, yet to be completed, is the Grand Ethiopian Renaissance Dam (GERD), on the Blue Nile. With 6.450 GW, the dam will be the largest hydroelectric power plant in Africa when completed, as well as the 7th largest in the world (Elsanabary, 2015). The energy generated by GERD will act as a stabilizing backbone for the country electricity supply, and an energy surplus will be exported to Sudan and Djibouti, upon completion of massive transmission lines (CapitalEthiopia, 2017).

In Kenya, the current energy generation mix is dominated by hydropower and fossil fuel sectors, each accounting for above 35% of generation capacity, but the future energy mix is expected to drastically change as part of the Vision 2030, with most of the investments directed towards the generation of geothermal and wind energy, both abundant in the rift valley (Daniel M. Kammen, 2015). The largest wind farm is located in the eastern edge of lake Turkana with a 330 MW of installed capacity (Cookson, Kuna, & Golla, 2017). Large oil reserves were unexpectedly discovered in the same region, oil extraction started in 2018, but the pipeline that will allow large scale commercial export is still under construction (Paraskova, 2018).

Hydropower energy, on the other hand, is not expected to grow, as no new large hydroelectric projects are envisioned for the future. As a consequence, despite it is currently associated with the highest installed capacity, its share is estimated to drop to only 5% by 2030 (Kianji, 2012).

4.5 HYDROPOWER INFRASTRUCTURES IN THE OMO-TURKANA BASIN

In the Omo-Turkana basin, the Omo river presents a cascade of dams and power plants, Gibe I, II, and III with a combined capacity of nearly 2.5 GW. In addition, a new dam is currently under construction downstream the Gibe cascade, the Koysha dam, with an installed capacity of 2.2 GW. Electricity generated in the Omo river is targeting the export market, once the 1,000 km Eastern Electricity Highway Project (500 kV) will be completed, and will enable the transport of 2 GW to Kenya. On the Kenya side, a smaller dam, the Turkwel dam, is operating (Figure 101).

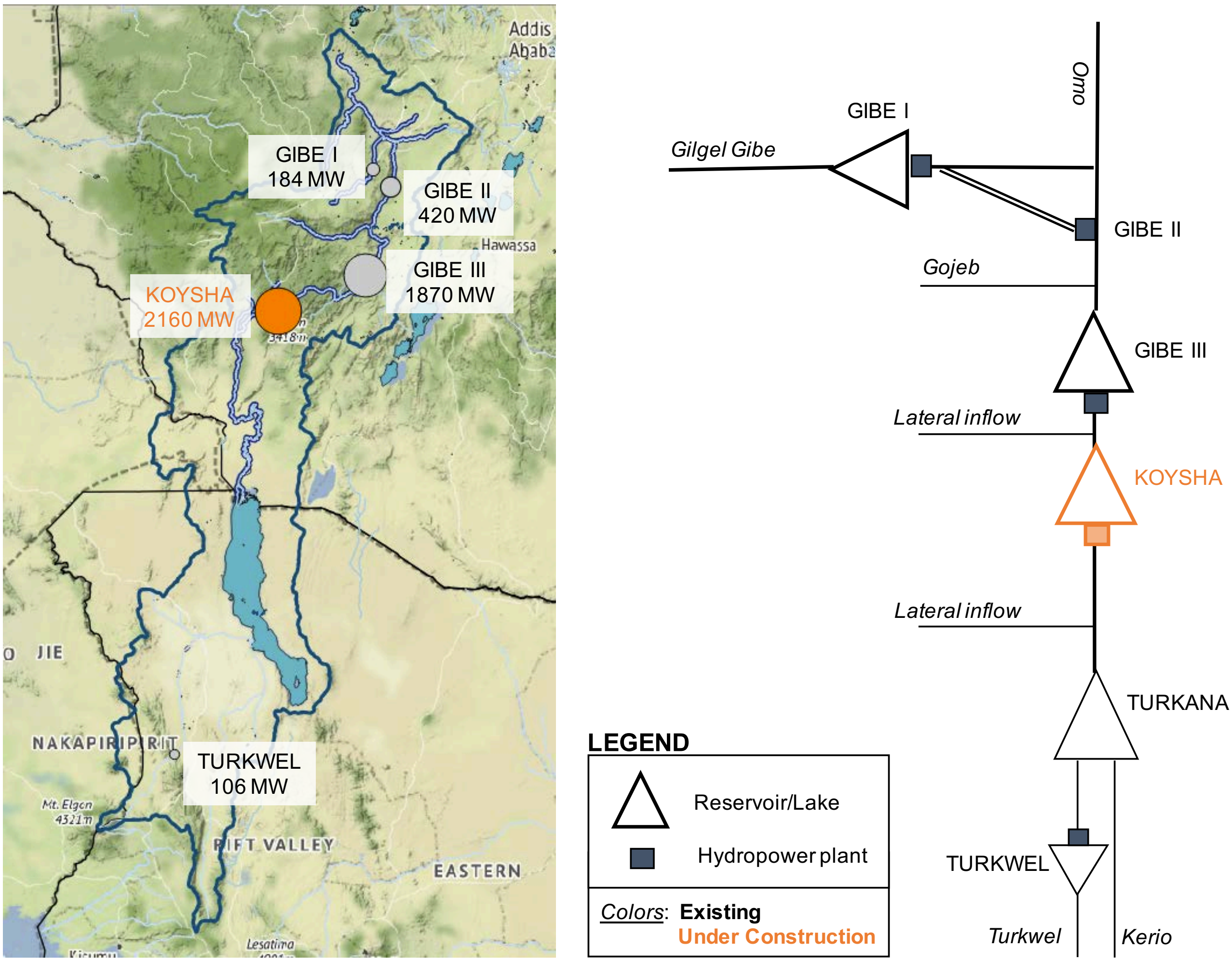

Figure 101 – Map (left) and topological scheme (right) of the existing (grey) and planned (orange) reservoir and HP plants in OTB. In the map, marker dimension is proportional to hydropower plant installed capacity.

4.5.1 Koysha Dam

Koysha is an under-construction dam located along the Omo river downstream Gibe III, and will be the fourth plant in a waterfall dam system on the Omo river (Figure 102) (Salini impreglio, 2017). The contract for the creation of the plant was signed on 28 March 2016 by Ethiopian Electric Power, which is financing the project, and by Salini Impregilo, appointed to build the plant. Additional funds estimated to be EUR 1.5 billion will be provided by an Italian financial institution named Servizi Assicurativi del Commercio Estero (SACE) (Fistum, 2016). Five years of work are envisaged for this massive project, including the construction of a 175 meter-high dam in Roller Compacted Concrete with a storage capacity of 6000 million cubic meters, and an outdoor electric power station guaranteeing an installed power of 2,160 MW and an annual production capacity of 6,460 GWh (Figure 103). According to plans, the dam should be completed in 2021 (Salini impreglio, 2017). The technical characteristics of Koysha are available on the internal project data repository and in the Appendix of this report.

Figure 102 – Koysha hydroelectric project upon completion (Woldemariam et al., 2016).

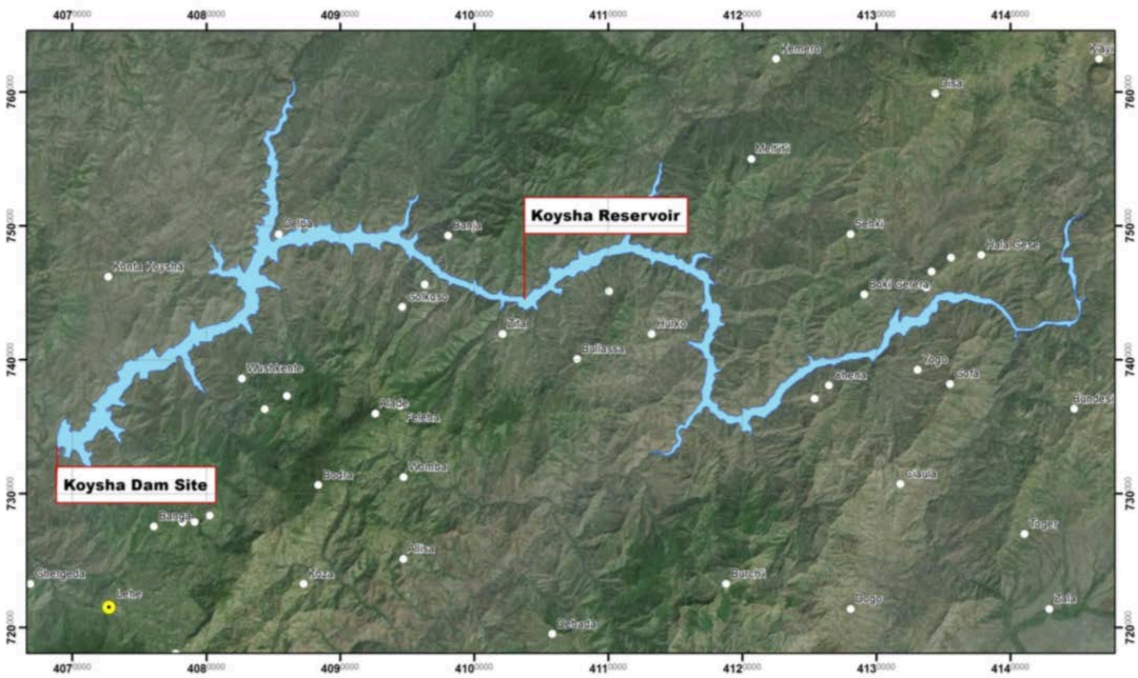

Figure 103 – Koysha dam site and reservoir upon inundation (Woldemariam et al., 2016).

5. AGRICULTURE, LIVESTOCK AND FISHERIES DEVELOPMENT

In this chapter, we assess the productivity of rain-fed and irrigated agriculture, livestock and fisheries developments as well as agricultural water requirements for a future scenario. In section 5.1, we describe the land and water that is used for rainfed and irrigated crop production, livestock production and fisheries in the ZRB and we present the results of modelling food production and its surplus and/or deficit. Section 5.2 presents the same for the OTB.

5.1 ZAMBEZI RIVER BASIN

In D2.1, we described current crop, livestock and fisheries production systems, their productivity and water use in the ZRB. In this section of D2.2, we assess agricultural developments that can be expected in the future. These changes are driven by a number of factors such as population growth and climate change. For simplicity, we will here take into account only one climate change scenario, i.e., RCP 4.5, and one shared socio-economic pathway (SSP), SSP2. The latter has been further elaborated on in section 2.2.6.

5.1.1 Land used for rainfed and irrigated crop production, land used for livestock production and water bodies used for fisheries

Crops

For crop production, we make a distinction between rainfed and irrigated agriculture. At the level of the eight riparian states of the ZRB, the proportion of agricultural land under irrigation is currently limited (Table 7). Given the low proportion of agricultural land that is irrigated, we assumed in D3.3 that all production values assigned to the land units (LUs) are related to rainfed agriculture. In D2.1, we converted these production values into calories and proteins and considered this the baseline scenario. In this report we consider the year 2020 to be the same as the baseline for rainfed crop production.

Table 7 – Percentage of agricultural land that is under irrigation in the riparian states of the ZRB.

Country	Agricultural irrigated land (% of total agricultural land)	Year of reporting	Source
Angola	0.15	2014	(cia, 2019)
Botswana	0.01	2014	(World Bank, 2019)
Malawi	0.53	2008	(World Bank, 2019)
Mozambique	0.08	2001	(World Bank, 2019)
Namibia	0.90	2002	(FAO, 2005a)
Tanzania	1.70	2002	(Tanzania National Bureau of Statistics, 2006; Makoi, 2019)
Zambia	1.05	2005	(FAO, 2005b)
Zimbabwe	1.07	2012	(cia, 2019)

We divided the ZRB into ten climate zones, according to the ten largest Global Yield Gap map climate zones (www.yieldgap.org), present in the basin (Figure 104). Climatic homogeneity within these zones was assumed. Within each of the ten climate zones, one point was selected based on the presence of LUs under crop production and of planned irrigation schemes around the point. Each of these ten points is assumed to be representative of the corresponding climate zone. For each of these ten points we used FAO's AquaCrop-model to simulate the expected yield for a number of crops for the years 2020-2089. In this way, the evolution of the expected yield as compared to 2020 was assessed for the RCP 4.5 scenario. When expected yield was obtained equal to 0 tonnes/ha this was interpreted as land not suitable for rainfed production of the considered crop in that year.

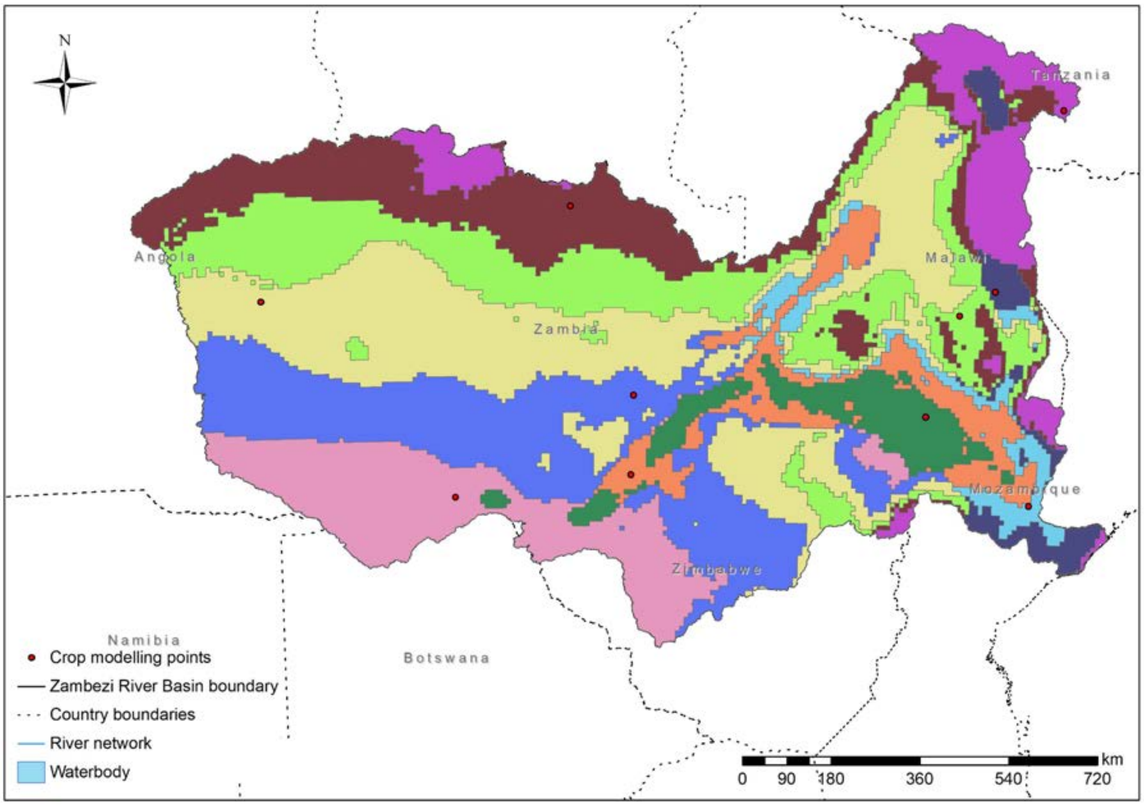

Figure 104 – Ten main climate zones in ZRB and corresponding locations for which crop yield was modelled.

Although rainfed agriculture dominates in the ZRB, irrigated agriculture currently is, and is expected to remain, important in terms of water consumption. According to Beck and Bernauer (2010) it is the second largest consumptive water user in the ZRB, using ca. 1.5 km³ of water per year. It was assumed that already operational irrigation schemes identified in D2.1 will remain operational in the future. Further, planned irrigation schemes within the ZRB were identified and –if possible– georeferenced by using literature (World Bank, 2010; AfDB, 2014; Malawi Government Department of Irrigation, 2014; Embassy of Japan in Zimbabwe, 2015; Republic of Zambia and World Bank, 2016; JICA, 2017; Ulimi Irrigation, 2017; Waalewijn, 2017; nrv-norvia, 2018). Information on the planned irrigated area, crop type to be cultivated, and date of commissioning of these schemes were collected. The irrigation schemes already operational and future planned irrigation schemes are mapped in Figure 105. The planned irrigation projects are mainly located near Lake Kariba and Lake Malawi, which both have the potential to serve as major water suppliers for irrigated agriculture. In D2.1 the area around Lake Malawi was identified as an area more densely populated than the rest of the river basin. This higher regional food demand is likely to act as an incentive to increase agricultural production.

Livestock

In D2.1, livestock head counts reported in D3.3 were related to current population numbers in order to calculate the proportion of energy and proteins derived from livestock products in the population’s diet. Further, the water consumption for livestock was calculated. In this report we assumed that livestock numbers will change proportionally with changes in human population numbers under the SSP2 scenario as reported in section 2.2.1. The exact LUs within the subbasins on which these human population changes will have an impact were however not identified.

Fisheries

In D3.3, national statistics on fish catch and aquaculture for the eight riparian states of the ZRB were reported. Lake Malawi, Lake Kariba and Lake Cahora Bassa were identified as the major water bodies for fish catch and aquaculture production in the ZRB. Since information on future developments and productivity of fisheries in the ZRB could not be found, we surmise that future fish catch and production will remain similar to the catch and production in the recent past and that the only changes are the result of fisheries and aquaculture in reservoirs which will be created through the construction of new dams. The building of dams related to hydropower generation results indeed in the creation of reservoirs which have a potential for fishing and aquaculture. Yields between 56.51 kg ha^{-1} $year^{-1}$ and 301.15 kg ha^{-1} $year^{-1}$ for African reservoirs are reported (Kolding and van Zwieten, 2012). MS16 identified the Kafue Gorge Lower as the only power plant currently under construction in the ZRB. The Kafue Gorge Lower has an expected reservoir area of 0.28 km² (Tilmant et al., 2012). Given this small area, its contribution to food energy and proteins was considered to be negligible. Further, 12 planned power plants with an associated reservoir were identified (Figure 106). The potential fish yield of these reservoirs was calculated and is presented in Table 8. Because of its relatively small area, and the unknown closure date, the Muchinga reservoir in Zambia was not further considered.

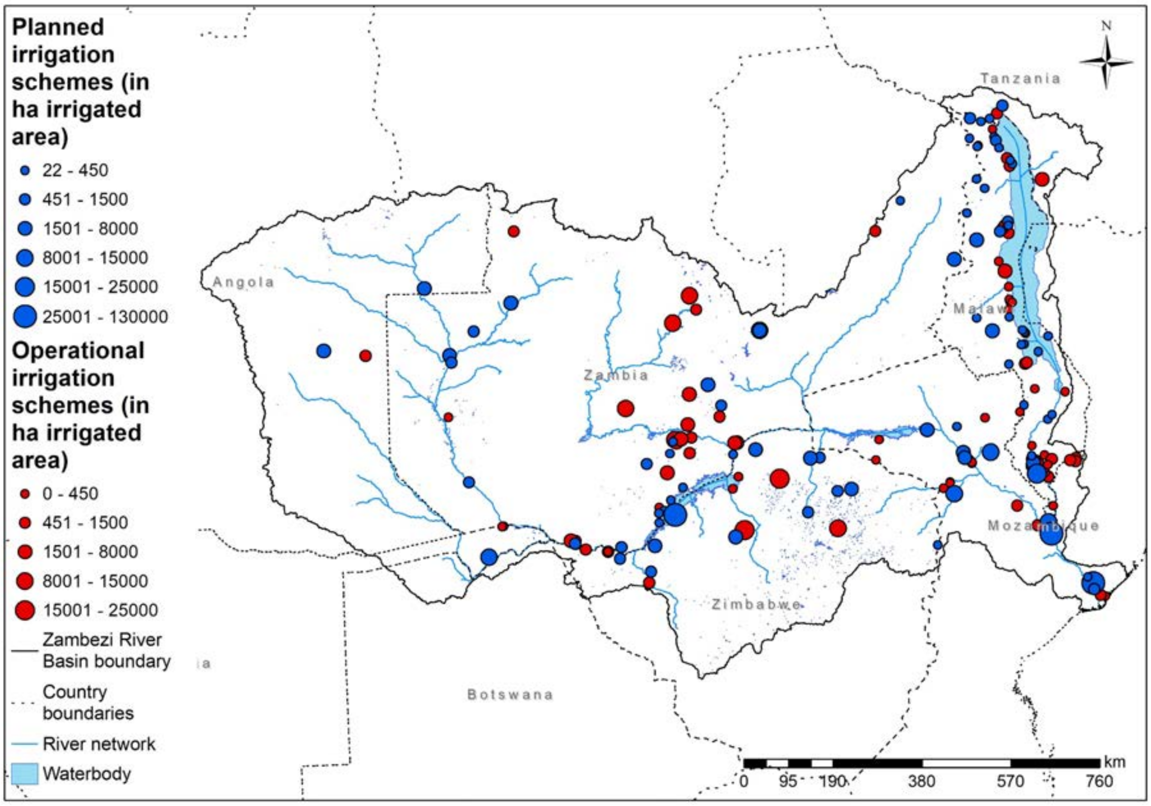

Figure 105 – Operational and planned irrigation schemes in the ZRB. The dot size reflects the scheme size.

5.1.2 Food production from crops, livestock and fisheries

Food production from harvested crops, livestock products, and fish catch and aquaculture were estimated in terms of produced food energy and proteins for the 67 subbasins corresponding to the HydroSHEDS[3] subbasins at Pfaffsetter level 5 (Figure 107). Each subbasin is identified by a unique code, based on the Pfaffstetter coding system. All calculations in this chapter were done for

[3] https://www.hydrosheds.org

the 67 HydroSHEDS Pfaffstetter level 5 subbasins. For readability of the graphs, the calculated values for each of the 67 subbasins were summarized for the 11 HydroSHEDS Pfaffstetter level 4 subbasins within the ZRB. For harvested crops and fish catch and aquaculture, this was done for the period 2020-2099. For livestock products, this was done for the same time period as for which demographic data were available, i.e. 2020-2060. By comparing the sum of these values per sub-basin with the human food requirements within that subbasin, we estimated food surplus or deficit for the period 2020-2060.

Table 8 – Planned hydropower plants, associated with a reservoir in the ZRB and fish production potential.

Hydropower plant	Country	Closure	Reservoir area [km²]	Potential fish yield [tonnes/year]
Ndevu Gorge	Zambia	2022	1510	8533 - 45474
Muchinga	Zambia	n.a.	5	6 - 30
Mulungushi	Zambia	n.a.	n.a.	n.a.
Devil's Gorge	Zambia/ Zimbabwe	2019	750	4238 - 22586
Mpata Gorge	Zambia/ Zimbabwe	2023	1230	6951 - 37041
Batoka Gorge	Zambia/ Zimbabwe	2024	23	130 - 693
Mphanda Nkuwa	Mozambique	2019	100	565 - 3012
Boroma	Mozambique	2025	30	170 - 903
Lupata	Mozambique	2025	n.a.	n.a.
Songwe (I, II, III)	Malawi	2024	57.1	323 - 1720
Kholombidzo	Malawi	2025	n.a.	n.a.
Rumakali	Tanzania	2019	13.2	75 - 398

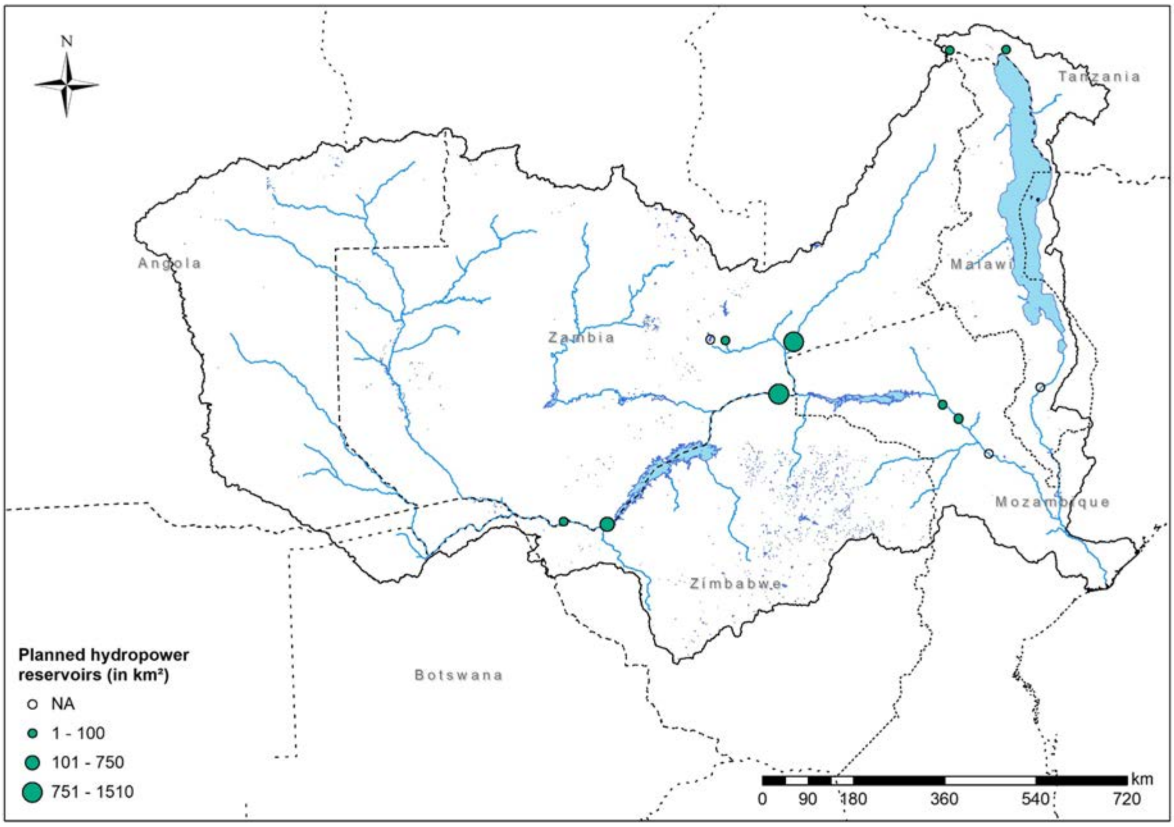

Figure 106 – Planned hydropower reservoirs in the ZRB.

Rainfed crops

In D3.3, statistics on the production of the 20 major crops were disaggregated and assigned to bio-physical LUs defined in terms of land use type and slope class covering the ZRB. Crop production was expressed in tonnes per year. In the case of multiple cropping cycles during one year, the corresponding production values were summed up. Of these 20 major crops, only 18 were retained here because seed cotton and tobacco were not considered to be food crops.

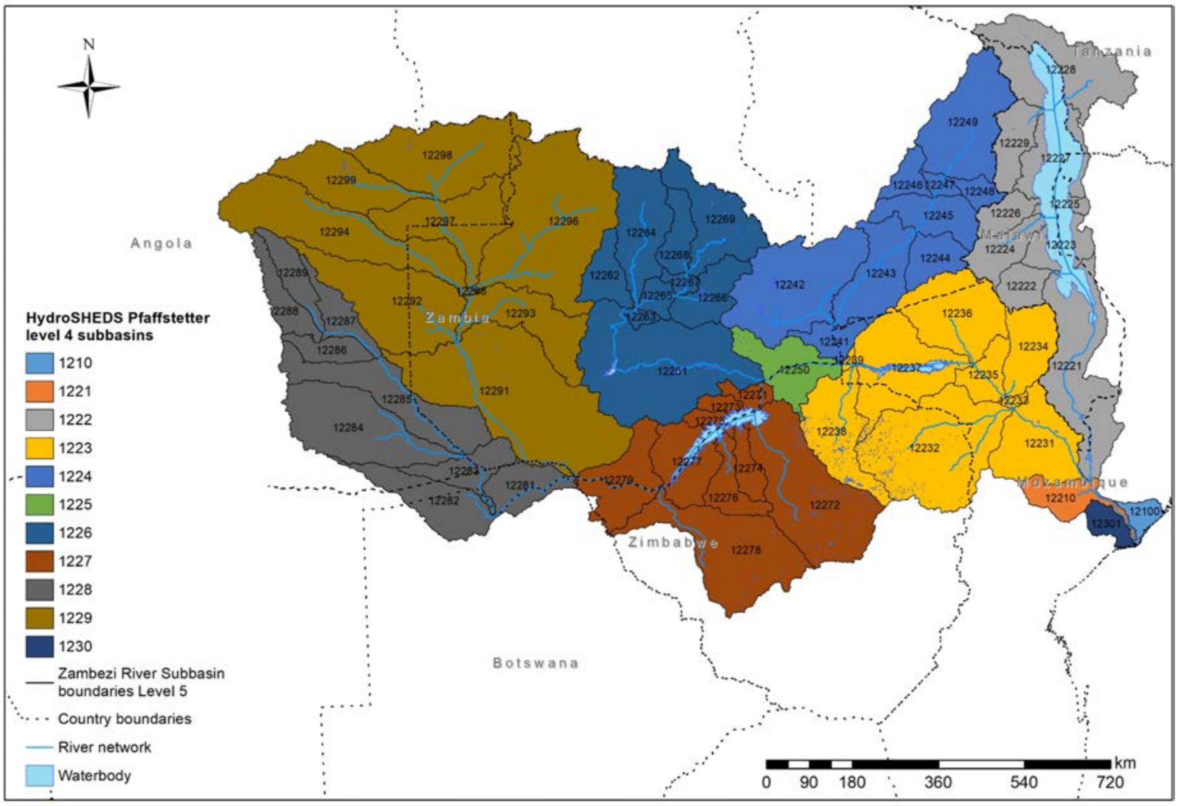

Figure 107 – HydroSHEDS Pfaffstetter level 5 subbasin boundaries and code and corresponding HydroSHEDS Pfaffstetter level 4 subbasins the ZRB. The HydroSHEDS Pfaffstetter level 5 subbasin numbers are displayed for each of the 67 subbasins within the corresponding subbasin. The HydroSHEDS Pfaffstetter level 4 subbasins are displayed in different colours.

The production values of 2020 were considered to be the same as the values calculated in the baseline scenario. To estimate future changes in rainfed crop production of these 18 crops in the ZRB, we used FAO's AquaCrop crop growth and yield prediction model to estimate the effect of climate changes on yield. To do this, for each of the ten '*crop modelling points'* (Figure 104), climatic and soil input data had to be gathered. Hourly climatic data for these ten 'crop modelling points' was extracted for RCP 4.5 from 8 km spatial resolution rasters for the period 2020-2099 (Section 3.1.3). The extracted climatic variables were surface relative humidity (in %), surface shortwave incoming radiation (in W/m²), surface air temperature (in °C), 2m wind speed (in m/s), and precipitation (in mm). Hourly data on surface relative humidity, surface shortwave incoming radiation, and 2m wind speed were converted into daily values by taking the 24 hour average. Hourly data on surface air temperatures were converted into daily minimum and maximum air temperatures by taking the daily minimum and maximum respectively. Hourly precipitation data was converted into daily data by taking the daily sum. Daily surface relative humidity, surface shortwave incoming radiation, surface minimum and maximum air temperature, and 2m wind speed were used to calculate the daily reference evapotranspiration (ETo) by using the Penman-Monteith equation (Allen et al., 1998). Elevation of the location of the virtual temperature stations, used to derive Atmospheric pressure, was derived from the 90m resolution Shuttle Radar Topography Mission (SRTM)-Digital Elevation Model (https://earthexplorer.usgs.gov/). Eventually time series of daily minimum and maximum temperature, ETo, and precipitation were obtained for the ten crop modelling points. In order to obtain the soil input data required by AquaCrop first a buffer zone with a radius of 10 km was created around each crop modelling point. Next the buffer zones were used to retrieve a selection of the available standard soil properties raster products from the SoilGrids-database (250 m resolution) (www.soilgrids.com). Finally the median value of the soil properties values of the concerned raster cells within each buffer zone was computed. SoilGrids is a project from the International Soil Reference Information Centre (ISRIC), and provides estimated soil characteristics per 250 metre raster cell for seven different soil layers, each having a specific thickness (0.05, 0.1, 0.15, 0.3, 0.4, 1.0, and 1.0 m). The soil characteristics that were selected, based on the soil input data required by AquaCrop, are:

– Soil organic carbon content in ‰ (g kg^{-1});
– Sand and clay content (weight %);
– Bulk density (kg m^{-3}) of the fine earth fraction (< 2 mm).

Soil organic carbon content was converted into soil organic matter content by using a conversion factor of 1.72. This resulted in one value for sand, clay and organic matter content and one value for bulk density per soil depth layer for each of the crop modelling points.

Soil hydraulic properties were estimated by the pedo-transfer functions proposed by Saxton et al. (2006). These functions estimate water content at permanent wilting point (PWP), at field capacity (FC) and at saturation (SAT), and saturated hydraulic conductivity (K_{sat}) from soil granulometric fractions, organic matter content and bulk density. Values of soil granulometric fractions and organic matter content used in the pedo-transfer function are the median values calculated for each crop modelling point.

The time series of climatic variables and the soil hydraulic variables were then used to model growth and yield of rain-fed maize and soybean by means of AquaCrop for the rainy seasons within the period 2020-2099, with linked simulation runs. D3.3 identified maize and soybean as the two most important crops of the 18 considered crop in terms of production in the ZRB. Due to the lack of basin-wide validation data, the crop parameters could not be calibrated. Therefore, the simulations were done by using the default crop parameters available in AquaCrop. The planting data was assumed to be 1 December, at the beginning of the wet season. This resulted in time series of seasonal maize and soybean yield estimates. These yield values were then used to calculate average changes in estimated yield for each of the ten climate zones compared to yield values modelled in 2020. These estimated average changes were used to assess the expected changes between 2021 and 2099 in yield values of the 18 crops identified in D3.3, under the RCP 4.5 climate change scenario. Crop production in 2020 was considered to be the same as in the baseline scenario. Production values for 2021-2099 were estimated by changing the baseline production values proportional to the simulated average changes in yield.

These projected production values per climate zone were summed per Pfaffstetter level 4 subbasin and converted into amount of calories (Figure 108) and proteins (Figure 109) based on energy and nutrient coefficients for the considered crops as derived from FAO (2001) and USDA (2018). These conversion values can be found in Table 9 and correspond to the ones used in D2.1.

In Figure 108 and Figure 109, it can be seen that when the area under rainfed crop production remains constant, energy and protein production from crops remains fairly stable under the RCP 4.5 scenario. In some subbasins, produced food energy and proteins are estimated to go slightly up (e.g., subbasin 1222 and 1223), while in others, produced food energy and proteins are expected to go slightly down (e.g, subbasin 1226 and 1227).

Irrigated crops

To estimate yield and irrigation requirements of irrigation schemes with a crop different from sugarcane, AquaCrop was used to model maize yield and corresponding net irrigation requirement in the ten crop modelling points. The planting data was assumed to be 15 May, at the beginning of the dry season. The net irrigation requirements were determined in such a way that the root zone depletion did not drop below 30% of the readily available soil-water in the root zone. Maize was selected because it has been identified as the crop with the highest production values in the ZRB. Further, maize is expected to remain an important irrigated crop in the ZRB in the (near) future as maize was reported to be the intended crop on the majority of the planned irrigation schemes for which this was reported.

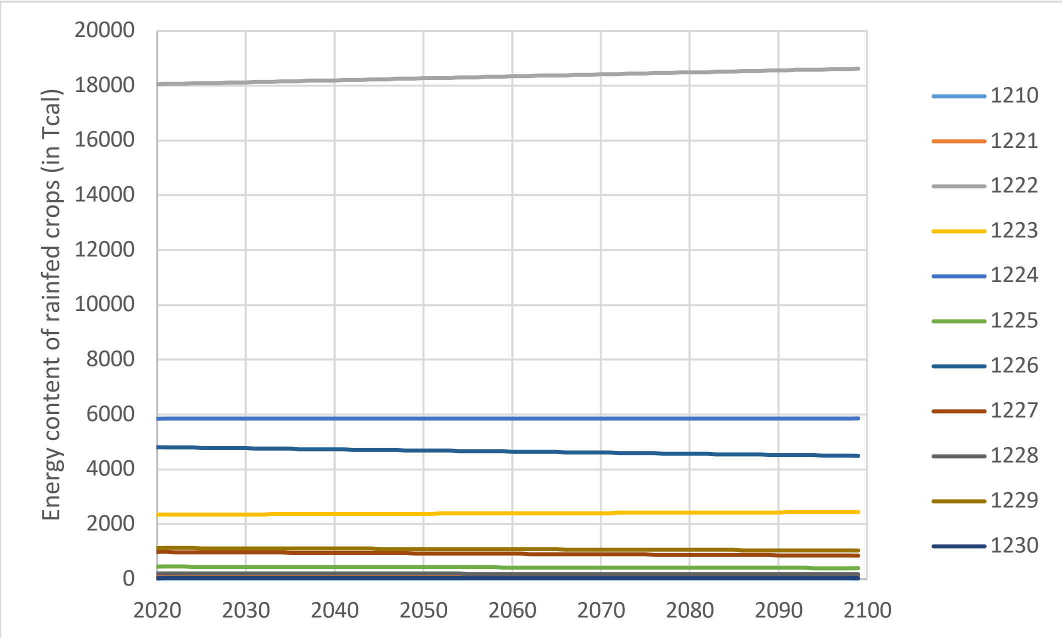

Figure 108 – Predicted energy content of harvested rainfed crops in terms of teracalories per year per Pfaffstetter level 4 subbasin in the ZRB under RCP 4.5.

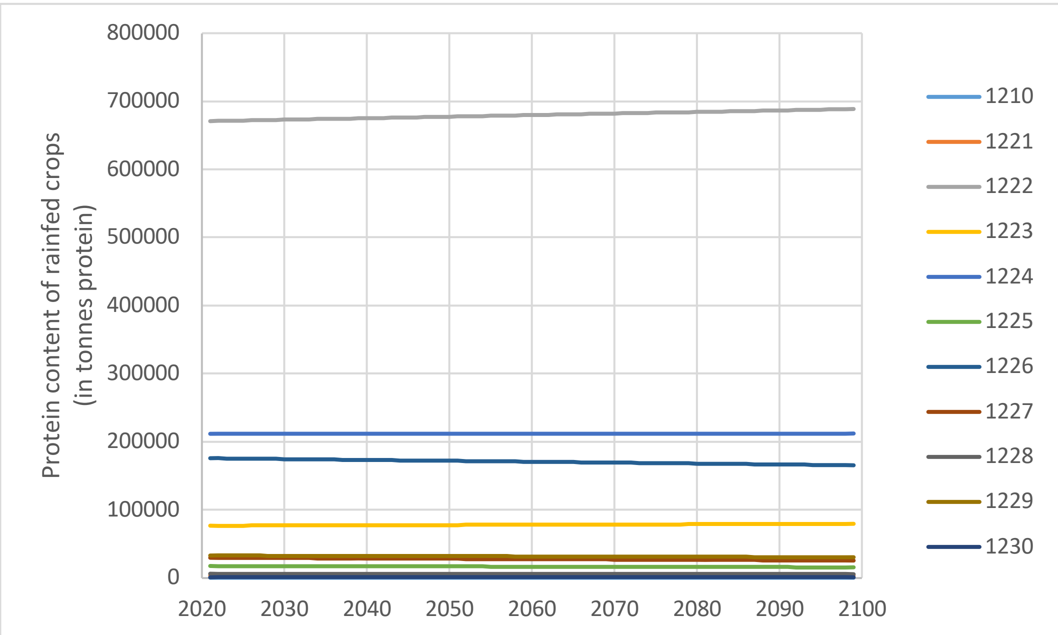

Figure 109 – Predicted protein content of harvested rainfed crops in terms of tonnes of protein per year per Pfaffstetter level 4 subbasin in the ZRB under RCP 4.5.

The modelled yield and irrigation water requirements per crop modelling point were assigned to all irrigation schemes within the corresponding climate zone (Figure 104). Since the crop production data collected in D3.3 and used in D2.1 cover both rainfed and irrigated crop production, modelled yield and production values and thus food energy and protein values of the current schemes are assumed to be already accounted for in Figure 108 and Figure 109. For planned irrigation schemes, only these that were reported to be operational by 2025 were used as they were considered 'short-term'. The realization of irrigation schemes for which the date of commission was unknown or later than 2025 was considered to be uncertain and they were therefore not included in this analysis. For these short-term planned irrigation schemes, modelled yield values were multiplied with planned irrigated areas and converted into food energy in terms of calories (Figure 110) and food proteins (Figure 111) by using the conversion values from Table 9.

Table 9 – Energy content (kcal) and protein content (grams) per 100g retail weight of 18 crops considered for ZRB (from FAO (2001) and USDA (2018)).

Crop	Energy content [kcal/100g]	Protein content [g/100g]	Crop	Energy content [kcal/100g]	Protein content [g/100g]
Bambara groundnuts	567	25.7	Pigeon peas	343	20.9
Barley	332	11	Potato	67	1.6
Beans	341	22.1	Rice	357	7.5
Cassava	109	0.9	Sorghum	343	10.1
Cow Peas	342	23.4	Soybeans	335	38
Groundnuts	567	25.7	Sugarcane	30	0.2
Maize	356	9.5	Sunflower seeds	308	12.3
Massango	340	9.7	Sweet potato	92	0.7
Millet	340	9.7	Wheat	334	12.2

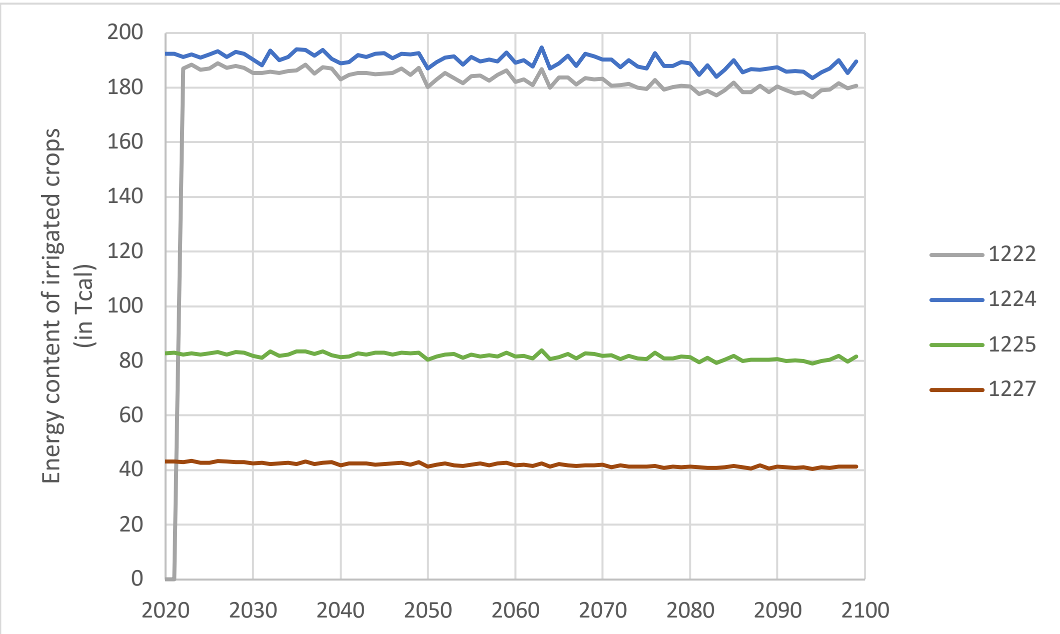

Figure 110 – Predicted energy content of harvested crops in terms of teracalories under short term planned irrigation schemes per Pfaffstetter level 4 subbasin in the ZRB under RCP 4.5.

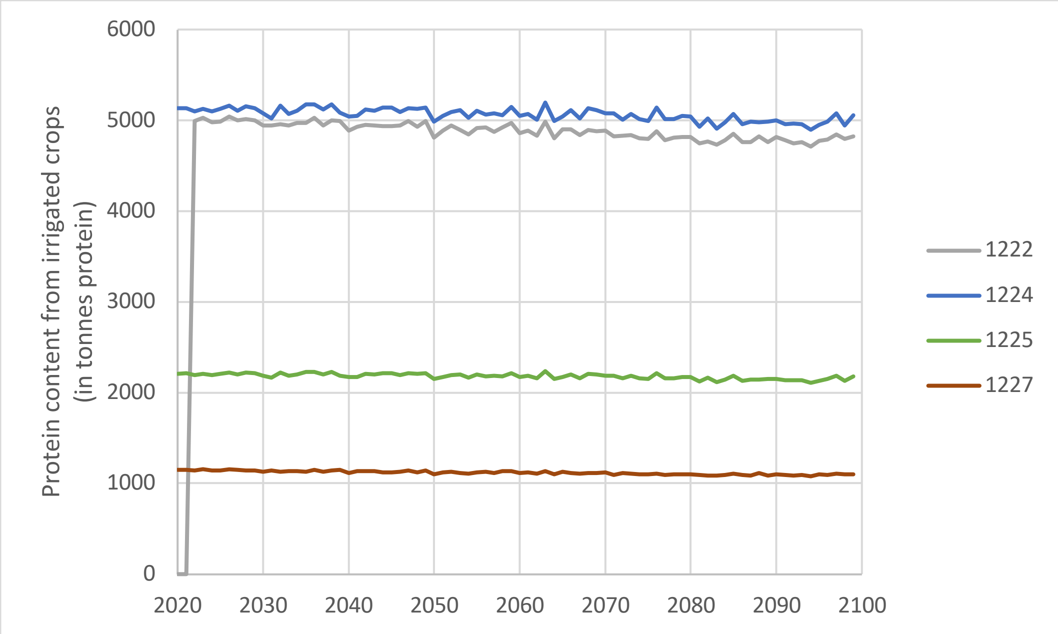

Figure 111 – Predicted protein content of harvested crops in terms of tonnes of protein under short term planned irrigation schemes per Pfaffstetter level 4 subbasin in the ZRB under RCP 4.5.

Short-term planned irrigation schemes were only identified in subbasins 1222, 1224, 1225, and 1226. Therefore, only these subbasins were included in Figure 110 and Figure 111. In Figure 110 and Figure 111 it can be seen that irrigated maize yield and thus produced food energy and proteins for the planned irrigation schemes in the ZRB are expected to go slightly down in the future under the RCP 4.5 scenario. Therefore, to obtain the same amount of food energy and proteins from irrigated agriculture, it is expected that under the RCP 4.5 scenario, more land and thus irrigation water should be used in order to keep food energy and protein output constant over time.

Livestock

In D2.1, statistics on livestock head counts and production reported in D3.3 were related to current population numbers in the subbasins, and the water consumption for livestock was calculated under the baseline scenario. By assuming that the relative contribution of livestock products to the calories and proteins in the population's diet as computed for the baseline scenario will remain stable in the future, estimations of total calories and proteins derived from livestock products based on population projections under the SSP2 scenario could be calculated for the time period 2020-2060 (Figure 112 and Figure 113). When total calorie and protein demand of a subbasin changes due to changing population numbers or changes in daily calorie or protein demand of one person, the energy and protein content of produced livestock products changes proportionally in that subbasin. Since population numbers and food energy and protein demands per subbasin in 2020 are similar to the baseline scenario, energy and proteins derived from livestock products in 2020 are also similar compared to the baseline scenario.

Under the assumption that livestock production values follow the same trend as population energy and protein demands, we can see that these variables are expected to increase in the future under the SSP2 scenario (Figure 112 and Figure 113). The total energy and protein content of livestock products under the baseline scenario were highest in subbasins 1124 and 1226, the Kafue and Luangwa subbasins. Under the SSP2 scenario, it is expected that these subbasins will remain the most important livestock and hence energy and protein from livestock producing subbasins.

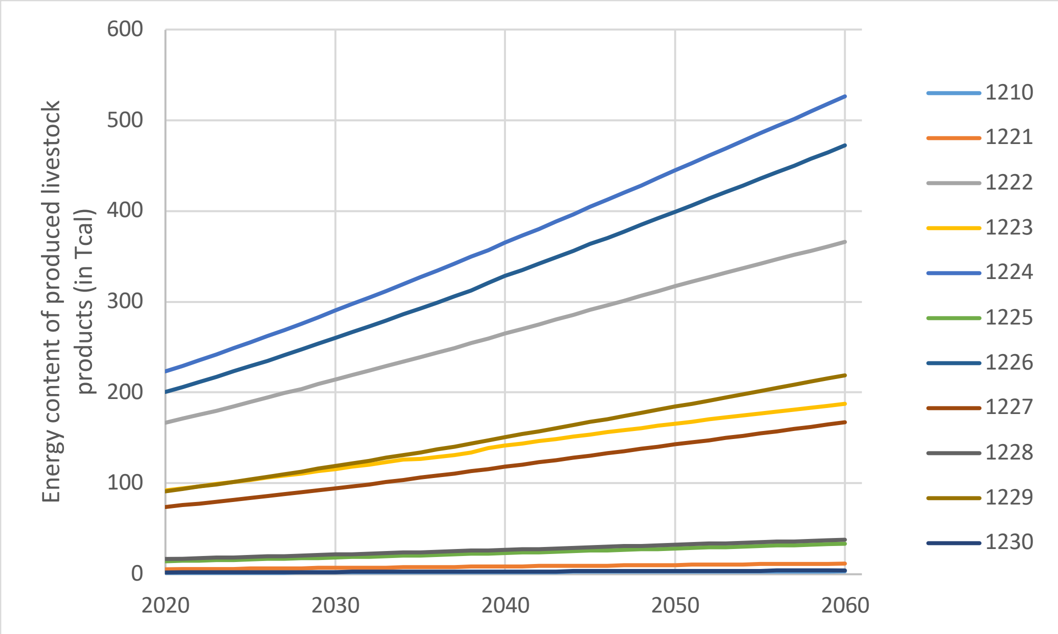

Figure 112 – Predicted energy content of livestock products in terms of teracalories per year per subbasin (Figure 107) in the ZRB under the SSP2 scenario.

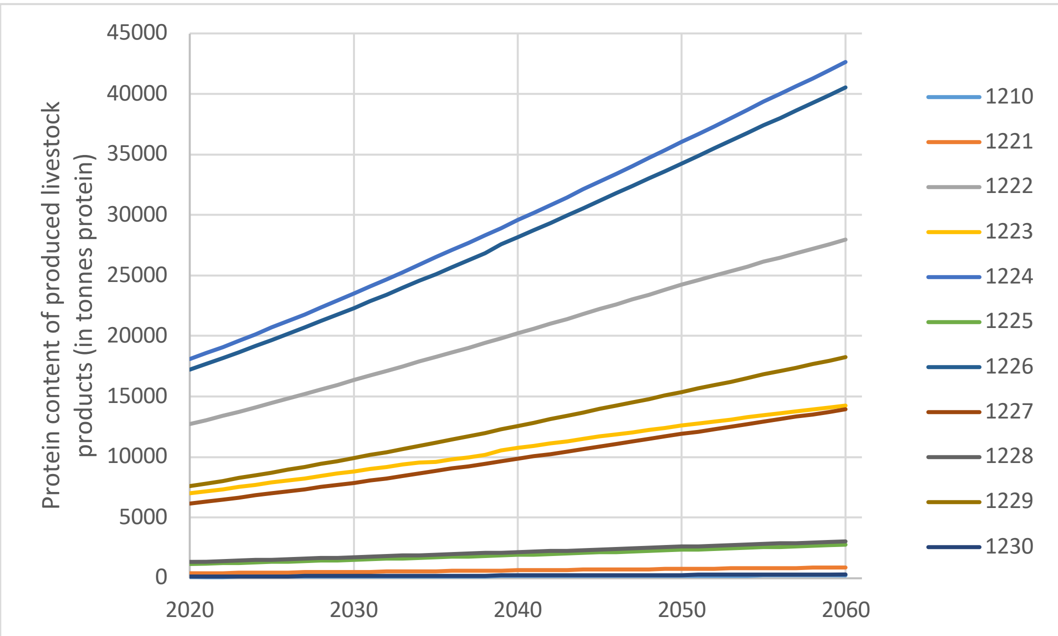

Figure 113 – Predicted protein content of livestock products in terms of tonnes of protein per year per sub-basin (Figure 107) in the ZRB under the SSP2 scenario.

Fisheries

We assumed that fish catch and aquaculture production will remain stable in the future and that the only changes in fish catch and production compared to the baseline scenario are the result of additional reservoirs (Figure 106). Therefore, the predicted production values from the planned hydropower basin were added to the baseline annual fish catch and production values and converted into amounts of calories (Figure 114) and proteins (Figure 115) based on the nutrient content of fresh fish as derived from FAO (2001). It was assumed that all fish caught and produced is pelagic fish. The energy and protein content is presented in Table 10.

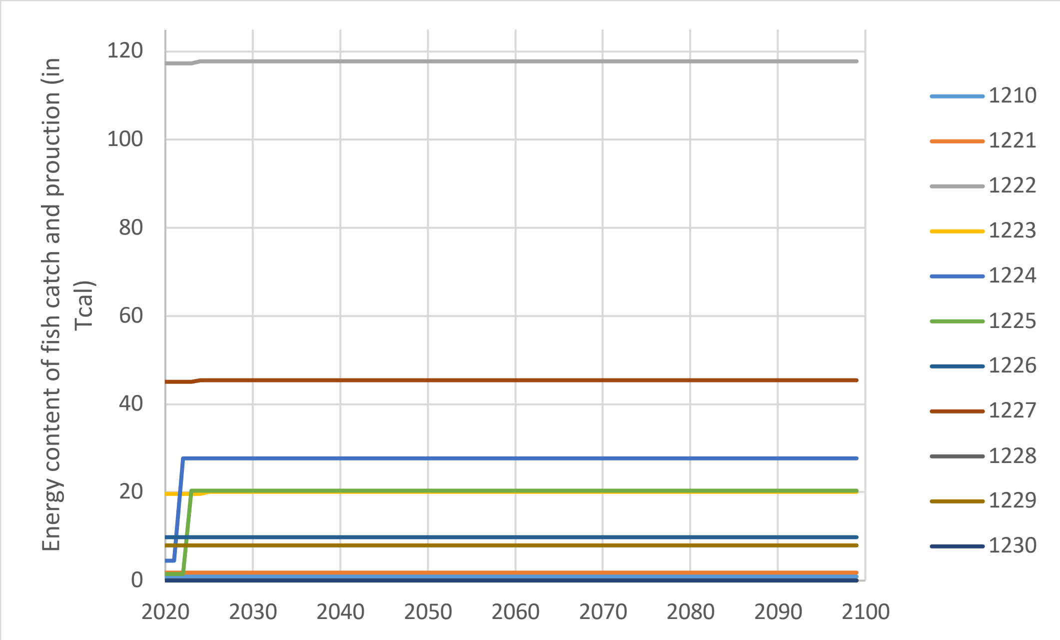

Figure 114 – Predicted energy content of fish caught and produced in terms of teracalories per year per Pfaffstetter level 4 subbasin in the ZRB.

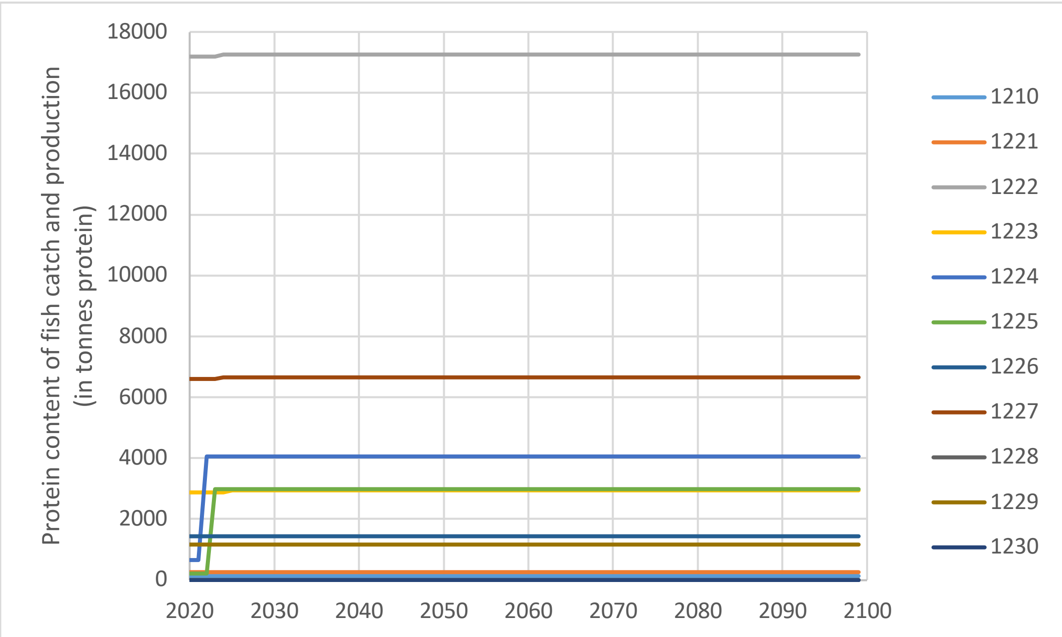

Figure 115 – Predicted protein content of fish caught and produced in terms of tonnes of protein per year per Pfaffstetter level 4 subbasin in the ZRB.

Table 10 - Energy (kcal) and protein (g) content per 100g retail weight of fresh fish (from FAO (2001)).

	Energy content [kcal/100g]	**Protein content [g/100g]**
Pelagic fish	86	12.6

Fish energy and protein production is mainly concentrated in the Malawian and Tanzanian part of the ZRB (subbasin 1222) but also in the northwest of Zimbabwe (subbasin 1227) around Lake Ka-riba. The most significant changes in fish energy and protein production compared to the baseline scenario can however be seen for subbasin 1224 and 1225. The new hydropower plants, of which the largest are located in these two subbasins, are expected to have a great impact from 2022 onwards on calories and protein produced by fish within these subbasins (Figure 114 and Figure 115).

Crops, livestock and fisheries combined

For each of the eleven Pfaffstetter level 4 subbasins in the ZRB, the sum of the total annual agricultural output in terms of amount of calories (Figure 116) and proteins (Figure 117) was calculated by adding the amounts of calories (respectively proteins) coming from harvested crops, livestock products and fish catch and production.

If the year 2020 is considered to be comparable as the baseline scenario, total energy content and protein content derived from agricultural products is not expected to change significantly under the RCP4.5 and SSP2 scenarios compared to the baseline scenario described in D2.1 (Figure 116 and Figure 117).

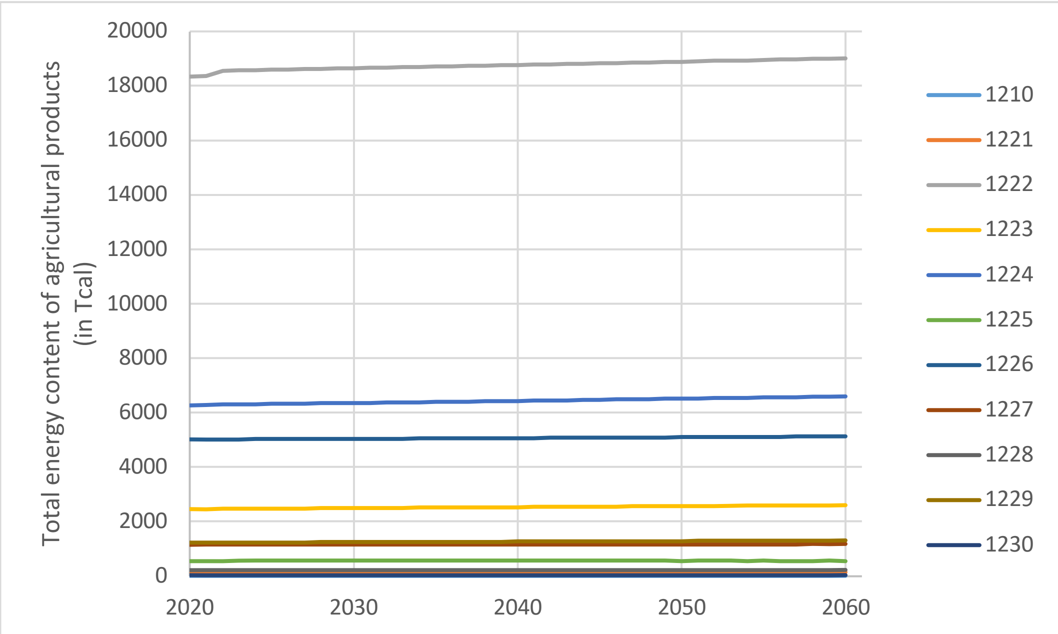

Figure 116 – Total estimated energy content of agricultural products in terms of teracalories per year per Pfaffstetter level 4 subbasin in the ZRB for the period 2020-2060 under the RCP4.5 and SSP2 scenarios.

5.1.3 Water use associated with irrigated crop production and livestock production

Crops

Although a proper assessment of crop water consumption will be provided through modelling results to be reported in D3.5, in this section, we carried out a first attempt to estimate water requirements for irrigated agriculture between 2020 and 2099 under the RCP 4.5 scenario. This was done for both existing and short-term planned irrigation schemes. To estimate net irrigation requirements, a distinction was made between irrigated land under sugarcane and land irrigated for other crops. For existing and planned irrigation schemes reporting a crop different than sugarcane, net irrigation water requirement was estimated by multiplying the reported areas under irrigation with the net irrigation requirement calculated by AquaCrop for irrigated maize (Figure 141). Gross irrigation water requirement was calculated by assuming an irrigation efficiency of 45%.

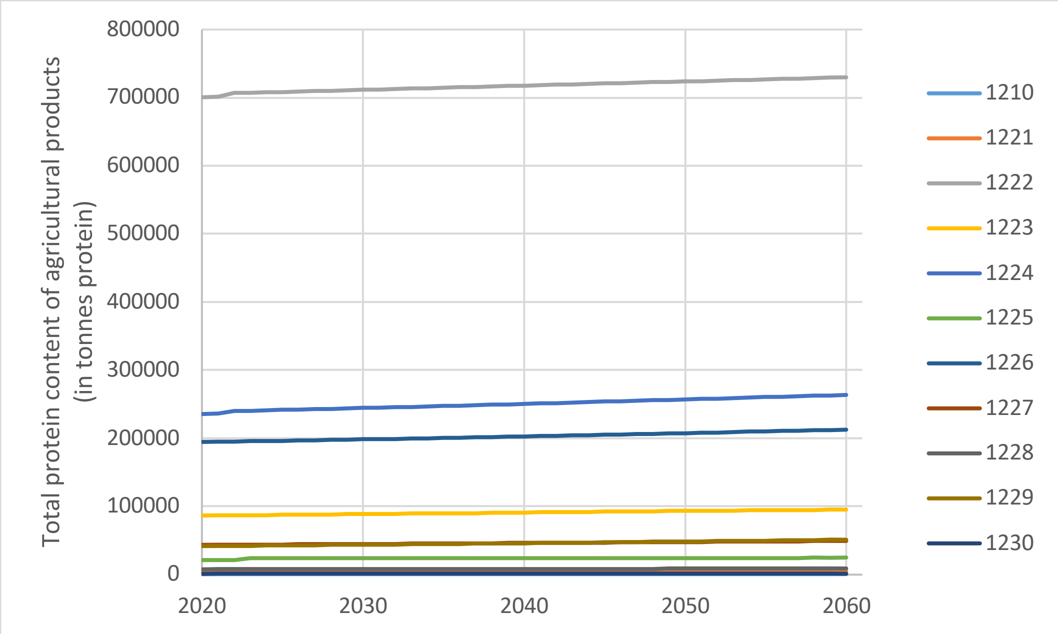

Figure 117 – Total estimated protein content of agricultural products in terms of tonnes of protein per year per Pfaffstetter level 4 subbasin in the ZRB for the period 2020-2060 under the RCP4.5 and SSP2 scenarios.

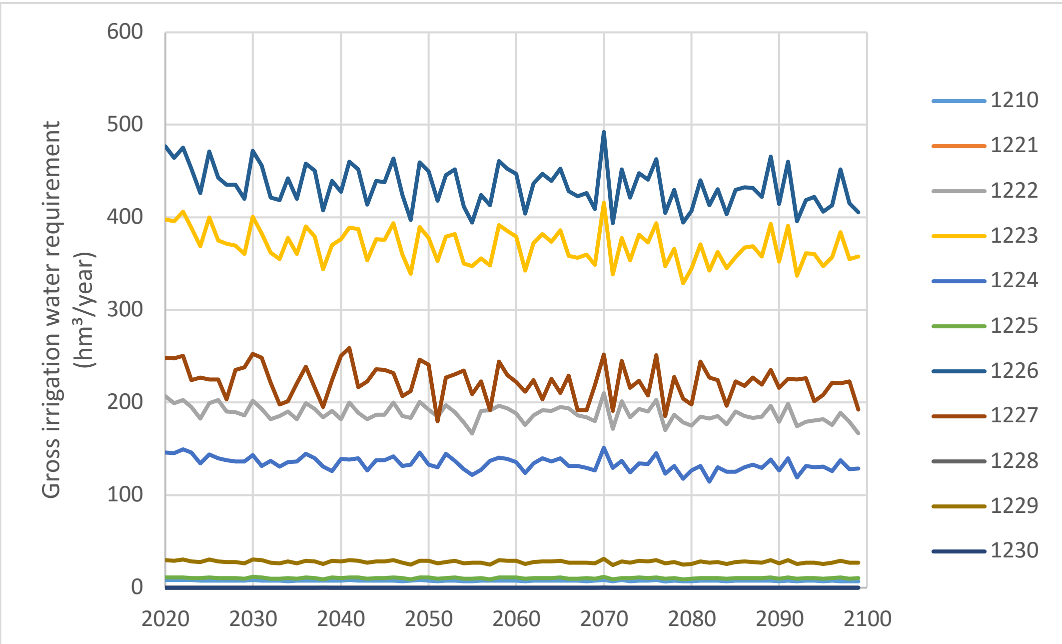

Figure 118 – Gross irrigation requirement for current and short-term planned irrigation schemes excluding sugarcane irrigation schemes per subbasin (Figure 107) in the ZRB in hm³/year.

Figure 118 shows the gross irrigation requirements for existing and short-term planned irrigation schemes with an intended crop different than sugarcane. Since only irrigation schemes planned to be operational before or by 2025 were considered here, the area under irrigation is stable for the majority of the considered time period. However, a downward trend in gross irrigation water requirements caused by the changes in the climate under the RCP4.5 emission scenario can be noted. The highest irrigation water requirements can be seen in subbasin 1226 (Kafue subbasin) and 1223, around lake Cahora Bassa.

Because of the high water demand of sugarcane and the abundance of the crop in the ZRB, we estimated water requirements of sugarcane irrigation schemes separately from irrigation schemes with a crop other than sugarcane. The identified operational and planned sugarcane irrigation schemes are illustrated in Figure 119.

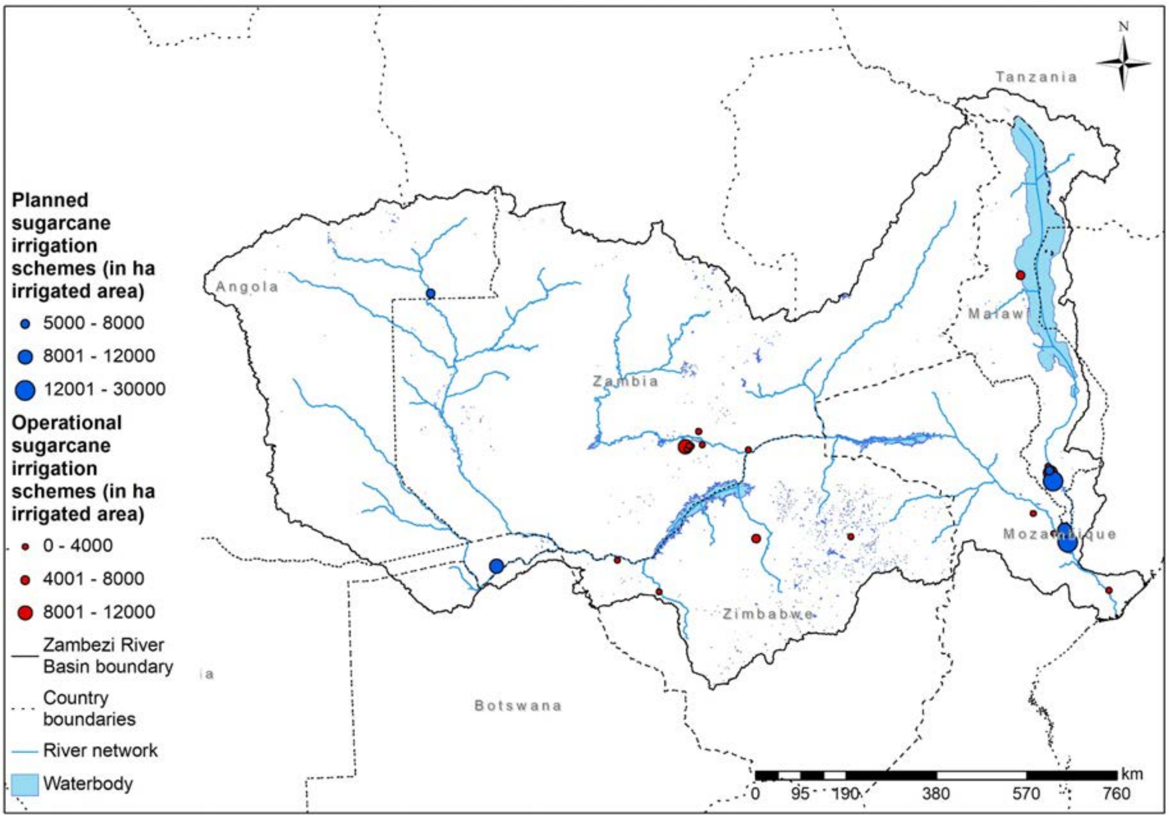

Figure 119 – Operational and future planned sugarcane irrigation schemes in the ZRB. Size of the dots reflects the size of the scheme.

We used AquaCrop to estimate net irrigation water requirements (and yield) of irrigated sugarcane in the ZRB, in the ten selected crop modelling points (Figure 104). The same soil and climatic inputs as described in section 2147483647.1.18, were used. Since sugarcane is planted all year round, we selected 1 January as the planting date. The net irrigation requirements were determined in such a way that the root zone depletion did not drop below 30% of the readily available soil-water in the root zone. Gross irrigation water requirement was calculated by assuming an irrigation efficiency of 45%. These gross irrigation water requirements were then multiplied with the area under irrigation.

In Figure 120, it can be seen that irrigation water requirements are highest in subbasin 1226 and 1222. These subbasins contain the large Mazabuka sugar estate in Zambia and the sugar-producing areas in Malawi and Mozambique. In all sugarcane producing subbasins, an increasing trend in irrigation water requirements can be seen. This can be explained by the changes in climatic variables under the RCP 4.5 scenario. These changes are expected to have a positive effect on sugarcane yield. For maize, these changes have a negative impact on predicted yields, which translates in a downward trend in irrigation water requirement (Figure 118).

Figure 121 shows the total water demand by irrigated sugarcane if all planned sugarcane developments were to be realized. The total estimated water requirement of operational and planned irrigated sugarcane is shown. This illustrated that there would mainly be an increase in irrigation water requirement in subbasin 1222, which includes the large planned sugarcane plantations in Malawi and Mozambique.

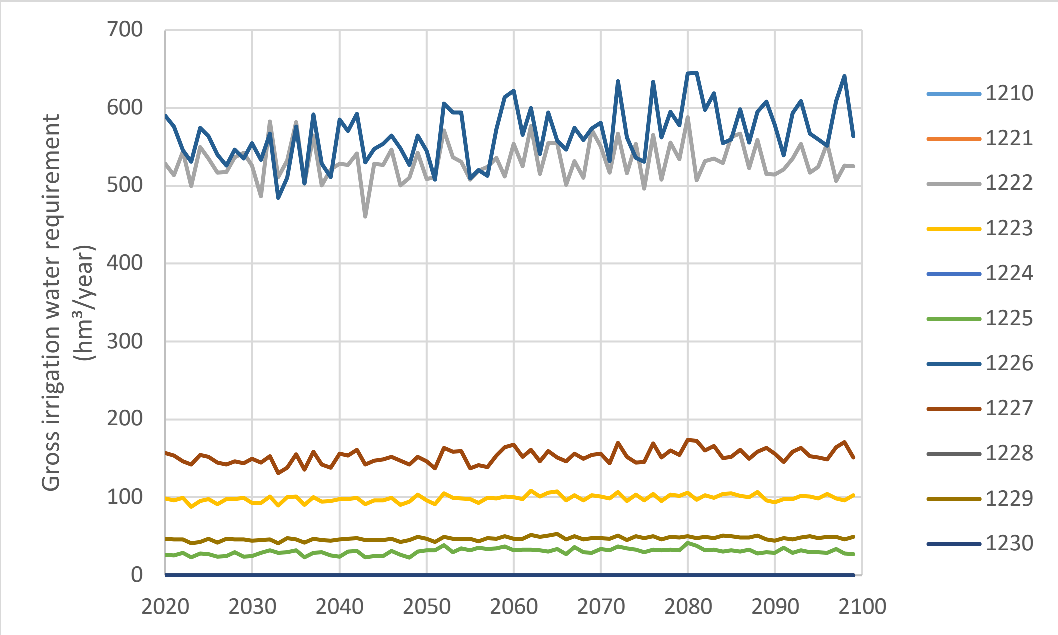

Figure 120 – Gross irrigation requirement for operational sugarcane irrigation schemes per Pfaffstetter level 4 subbasin in the ZRB in hm³/year.

Livestock

In section 2147483647.1.18, food calories and protein derived from livestock products were estimated based on population projections under the SSP2 scenario. To estimate the water requirements to produce these amounts, we assumed that the calorie and protein offtake per animal and the daily water requirement per animal will remain stable under the RCP 4.5 scenario. Under this assumption, water requirement per produced calorie and protein from livestock products will also remain stable in the future. Eventually, water requirements for livestock production per subbasin for the period 2020-2060 were calculated (Figure 122).

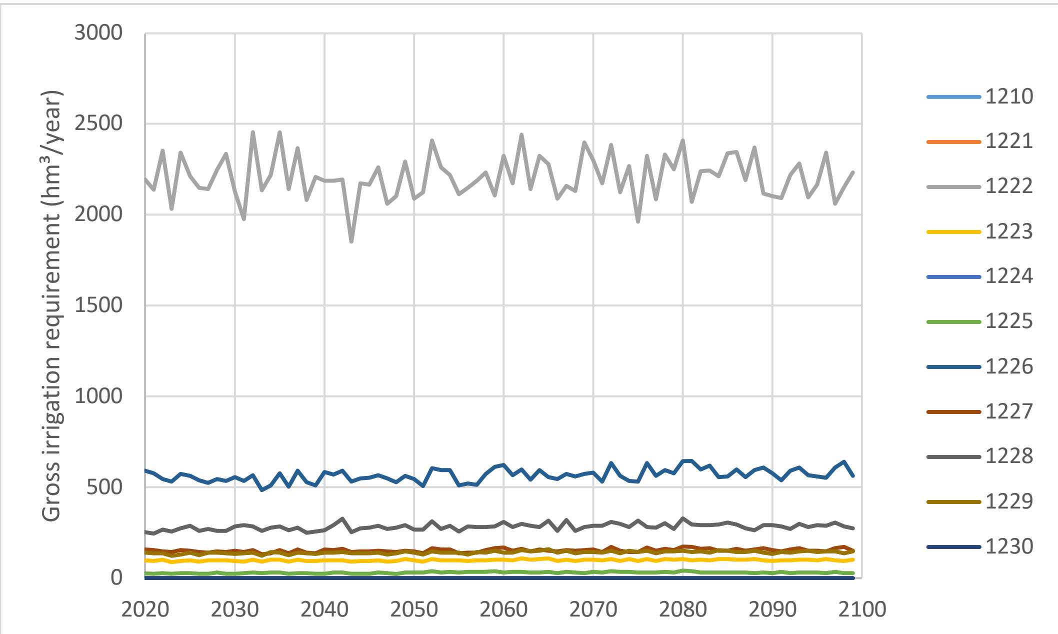

Figure 121 – Gross irrigation requirement for operational and planned sugarcane irrigation schemes per Pfaffstetter level 4 subbasin in the ZRB in hm³/year.

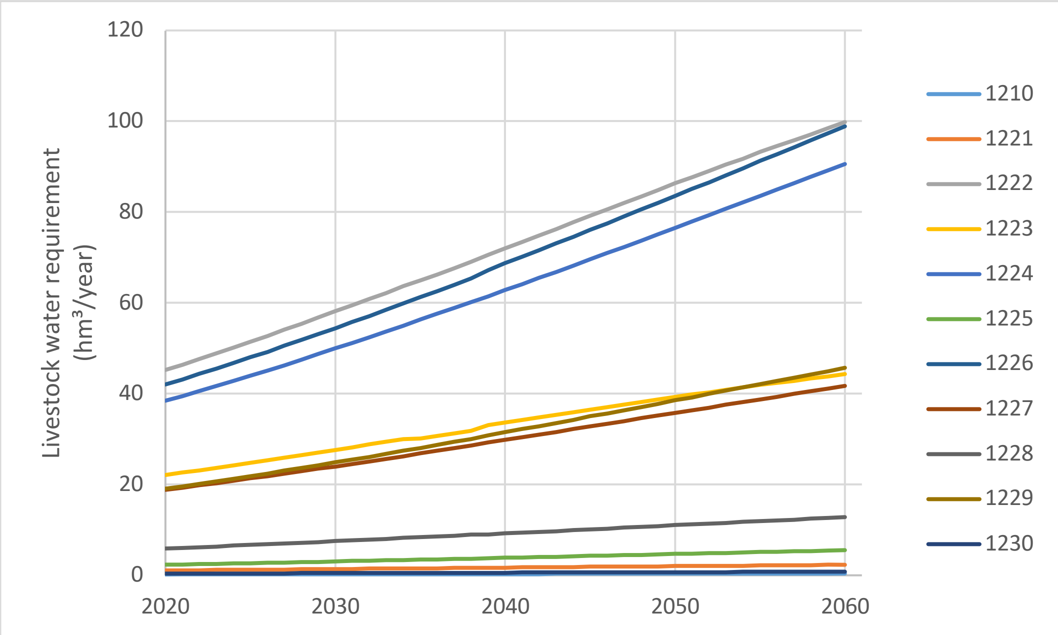

Figure 122 – Annual livestock water requirement in hm³ per year per Pfaffstetter level 4 subbasin in the ZRB.

Compared to irrigated agriculture, annual livestock water requirements are expected to be relatively small (Figure 122). This is especially true when the irrigation water requirements of sugarcane are also taken into account. Since population numbers and total calorie and protein demand estimated for the baseline scenario and here calculated for 2020 are comparable, livestock energy and protein production and thus livestock water requirements in 2020 are also comparable to the baseline livestock water requirements. In all subbasins, livestock water requirements are expected to double by 2060 under the SSP2 scenario as compared to 2020.

5.1.4 Food surplus/deficit at subbasin scale

Food production versus food requirements

By comparing at subbasin scale the yearly amount of calories and proteins available from the combination of harvested crops, livestock and fish products, as derived in section 2147483647.1.18, with the amount of calories and proteins required by private households, we calculated the food deficit or surplus per subbasin in the ZRB.

Average annual food energy and protein requirements were calculated per subbasin in the ZRB (Figures Figure 15 to Figure 17). The absolute food production surplus or deficit was calculated by subtracting the annual food energy and protein requirements of the local population from the annual produced food energy and proteins. A positive value indicates a food production surplus within the subbasin, while a negative value indicates a food production deficit (Figure 123 and Figure 124).

In Figure 123 and Figure 124, the values calculated for 2020 are comparable to the ones calculated for the baseline scenario in D2.1. On the scale of the ZRB, no food energy or protein deficit was calculated for the baseline scenario. Under the RCP 4.5 and SSP2 scenarios, a food energy deficit on basin scale was calculated in terms of calories from 2021 onwards. A food protein deficit was calculated from 2045 onwards. On subbasin scale, a food deficit can already be seen in some subbasins under the baseline scenario. There is furthermore, a general declining trend of produced food energy and proteins relative to food energy and proteins required as population grows. The number of subbasins for which a food deficit is predicted under the RCP 4.5 and SSP2 scenarios is expected to increase in the future. For the subbasins in which a food energy or protein surplus is predicted in the future, this surplus is decreasing. For the subbasins in which there is a food energy or protein deficit, this deficit is increasing.

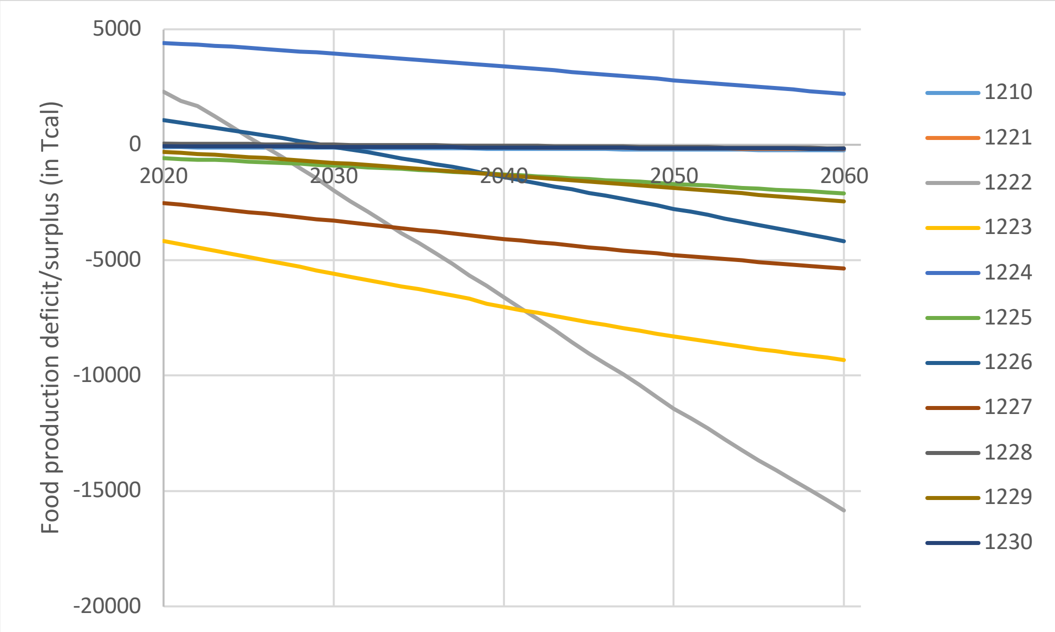

Figure 123 – Food energy production deficit/surplus in terms of teracalories per year per Pfaffstetter level 4 subbasin in the ZRB for the period 2020-2060 under the RCP 4.5 and SSP2 scenarios.

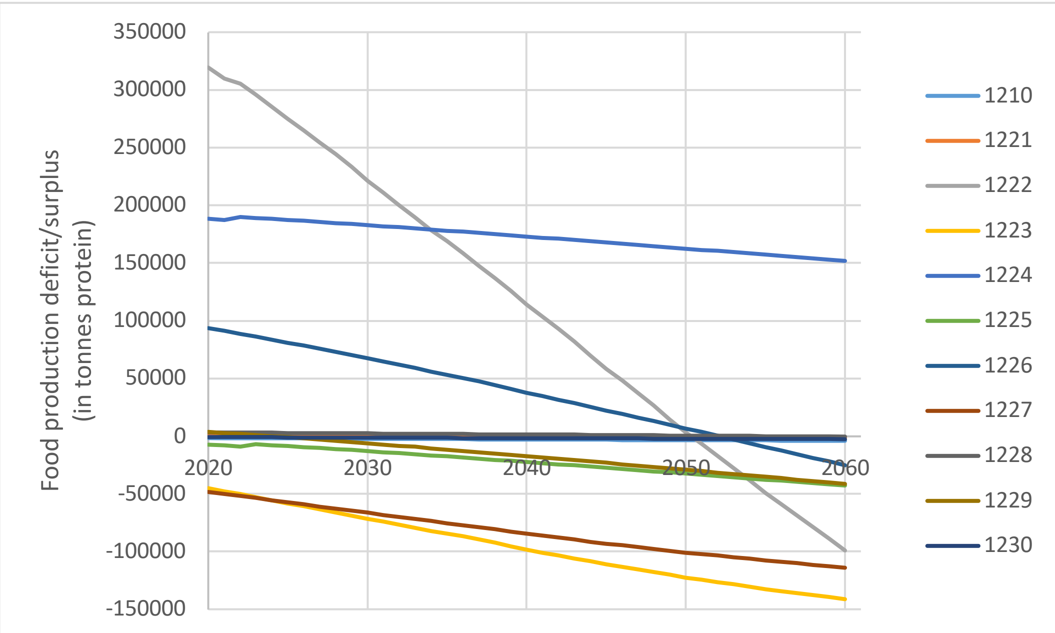

Figure 124 – Food protein production deficit/surplus in terms of tonnes of protein per year per Pfaffstetter level 4 subbasin in the ZRB for the period 2020-2060 under the RCP 4.5 and SSP2 scenarios.

If trading among regions is not considered as an option, achieving a balance in the subbasins characterized by a food energy and/or protein deficit will increase water demand of these regions. The amount of additional water needed depends on the source of food energy and proteins. To estimate the additional water demand, we assumed the additional energy and proteins are produced by irrigated maize. The required tonnes of maize and net irrigation demand were calculated using

AquaCrop and using the same parameters as described in section 2147483647.1.18 (Figure 125). The planting date was considered to be 15 May, at the beginning of the dry season.

To achieve a local balance in the subbasins for which a food energy or protein deficit was predicted, the required gross irrigation water increases in time under the RCP 4.5 and SSP2 scenarios (Figure 125). The additional required water is the largest in subbasins 1229 and 1228, which are located in the west of the ZRB.

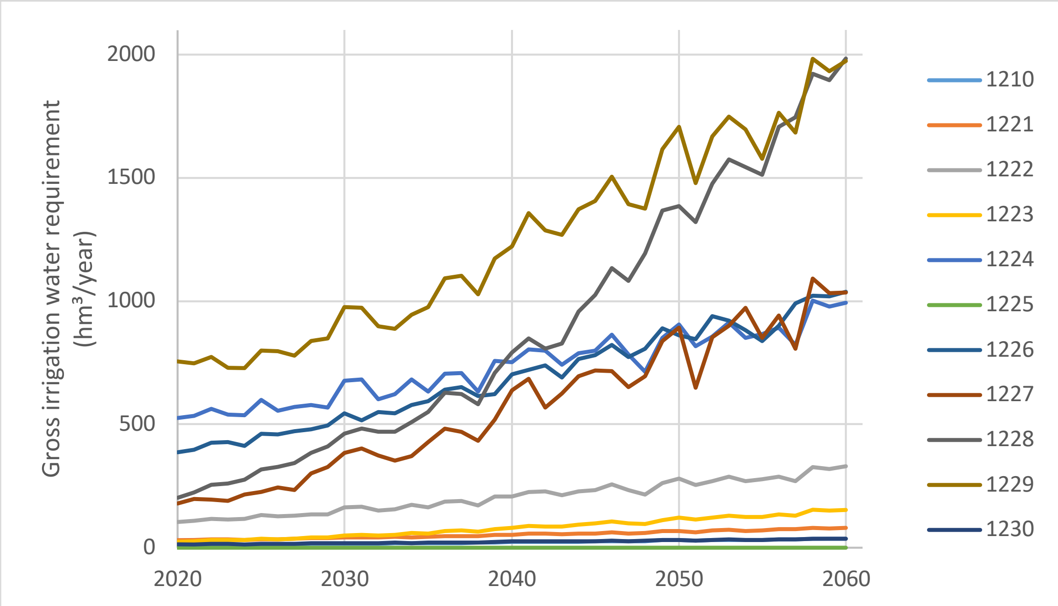

Figure 125 – Gross irrigation water requirement (in hm³/year) needed to eliminate food deficits per year per Pfaffstetter level 4 subbasin in the ZRB for the 2020-2060 period.

5.2 OMO-TURKANA BASIN

In D2.1, we described current crop, livestock and fisheries production in the OTB. In this section, we assess agricultural developments that can be expected in the future. These changes are driven by a number of factors such as population growth and climate change. For simplicity, we will here take into account only one climate change scenario, i.e., RCP 4.5, and one shared SSP, the SSP2. The latter has been further elaborated on in section 2.3.6.

5.2.1 Land used for rainfed and irrigated crop production, land used for livestock production and water bodies used for fisheries

Crops

For crop production, we make a distinction between rainfed and irrigated agriculture. According to the World Bank collection of development indicators, only 0.45% of the total agricultural land in Ethiopia was irrigated in 2011. In Kenya, the share of irrigated agriculture was only 0.04% in 2009 (World Bank, 2019). Given these low numbers, we assumed that all production values assigned to the LUs in D3.3 in the OTB are the result of rainfed agriculture. In D2.1, we converted these values into calories and proteins and considered this the baseline scenario. Here we consider the year 2020 to be identical to the baseline scenario.

We divided the OTB into ten climate zones, according to the ten largest Global yield gap map climate zones (www.yieldgap.org), present in the basin (Figure 126). Climatic homogeneity within these zones was assumed. Within each of the ten climate zones, one point was selected based on the presence of virtual temperature and precipitation stations (Figure 74), and the presence of crop producing LUs around the point. Each of these ten points is assumed to be representative for the corresponding climate zone. We used FAO's AquaCrop to simulate expected yield for a number of crops for each of these ten points. In this way, the evolution of the expected yield as compared to 2020 was assessed for the RCP 4.5 scenario. When expected yield was obtained equal to 0 tonnes/ha this was interpreted as land not suitable for rainfed production of the considered crop in that year.

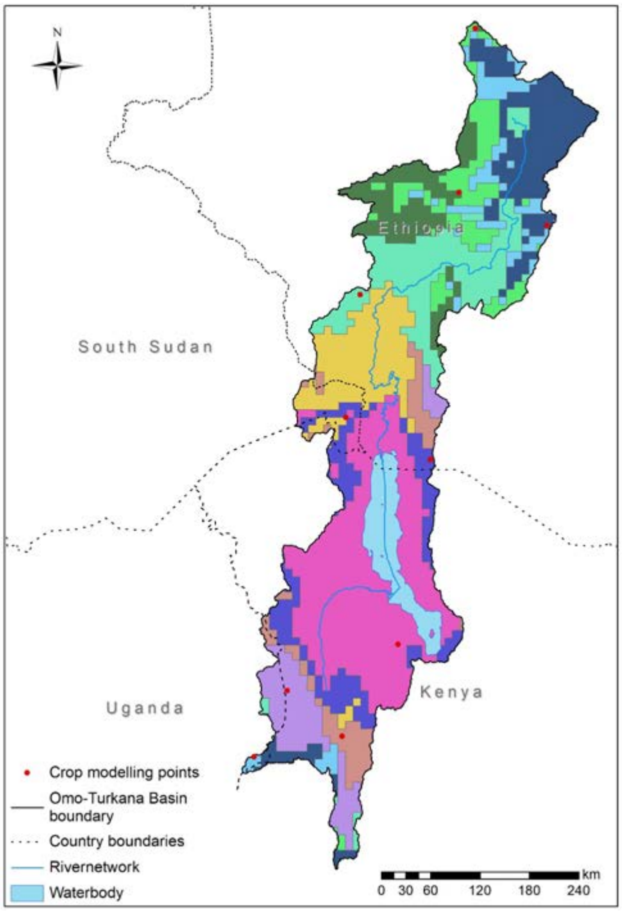

Figure 126 – Ten main climate zones in OTB and corresponding locations for which crop yield was modelled.

Although rainfed agriculture by far dominates in the OTB, irrigated agriculture is expected to become important in terms of water consumption. It was assumed that already operational irrigation schemes identified in D2.1 will remain operational in the future. Further, planned irrigation schemes within the OTB were identified and –if possible– georeferenced by using literature (Woodroofe, 1996; Avery, 2012; Kenya National Irrigation Board, 2016). Information on the planned irrigated area, crop type to be cultivated, and date of commissioning of these schemes were collected. The irrigation schemes already operational and the planned irrigation schemes are mapped in Figure 127. In the Turkana subbasin, 18 future irrigation schemes along the Turkwel and Kerio river were identified. These irrigation schemes are mainly situated on land identified in D3.3 as currently under range grasses and bushes. The irrigation potential in this area is restricted due to the limited water availability and soil salinity (FAO, 2013). Due to the arid character of the area, salt levels sometimes exceed crop salt tolerance. This restricts the expansion of irrigated agriculture in future scenarios.

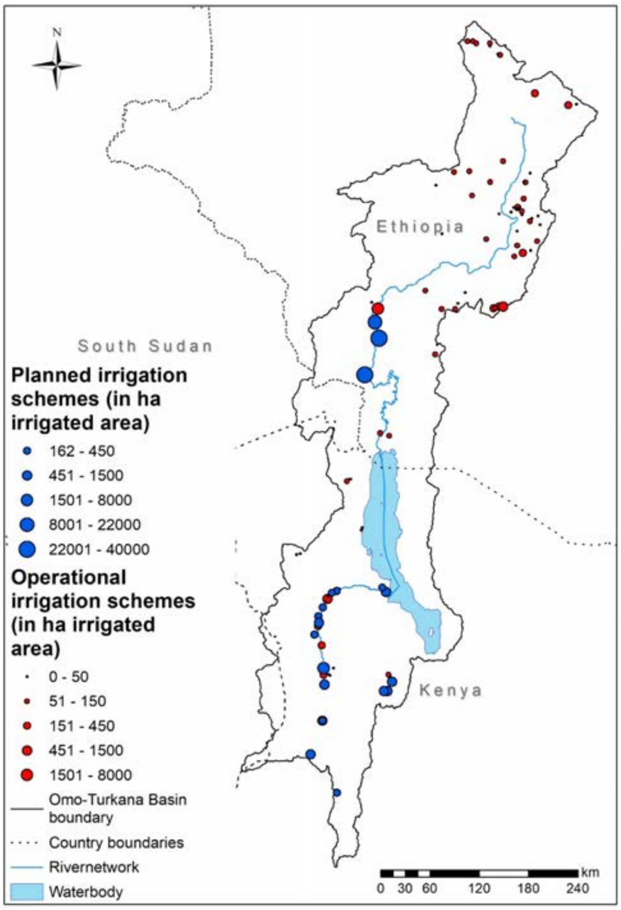

Figure 127 – Operational and planned irrigation schemes in the OTB. The dot size reflects the scheme size.

Besides the planned irrigation projects along the Kerio and Turkwel river, the most notable planned irrigation project in the OTB is the Kuraz sugar estate expansion in Ethiopia. By 2026, the development of three blocks for sugarcane under furrow irrigation is expected, with a maximum area of 100000 ha. The expected irrigated area of the left bank development area is 48000 ha, of the right bank block I it is 22000 ha, and of the right bank block II, which will be situated immediately downstream of the Omo National Park, it is 40000 ha (FDRE Sugar Corporation, 2018). It is expected that these large-scale sugarcane developments will have a significant impact on the water availability locally and in the rest of the basin (Avery, 2012). Therefore, it is important that they are accounted for in future model scenarios. However, since the sugarcane produced in this area will mainly be exported to areas outside of the OTB, we assume its yield will not contribute to providing food (in terms of calories and proteins) to the population living within the basin (FDRE Sugar Corporation, 2018). Therefore, to estimate yields and corresponding irrigation requirements in the OTB, we made a distinction between irrigated sugarcane and irrigation of other crops. The only identified irrigated sugarcane is located at the Kuraz sugar estate.

Livestock

In D2.1, livestock headcounts and production reported in D3.3 were related to current population numbers in order to calculate the proportion of energy and proteins derived from livestock products in the population's diet. Further, the water consumption for livestock was calculated. Here we assumed that livestock numbers will change proportionally with changes in human population numbers under the SSP2 scenario. The exact LUs within the subbasins on which these human population changes will have an impact were however not identified.

Fisheries

In D3.3, Lake Turkana was identified as the major water body for fish catch and aquaculture production in the OTB. The growth of Lake Turkana's fisheries has been historically limited due to a number of socio-economic factors and the fisheries' unpredictability due to the highly variable and climate-sensitive productivity of the lake (Gownaris et al., 2017). The productivity of the lake is highly variable and is correlated with the lake level and its intra- and inter-annual fluctuations, especially when evaporation levels exceed the total inflow of the lake. Drops in water level result in an increased concentration of organic matter and a subsequent drop in fish numbers (Avery, 2012). Since the Omo River acts as the lake's "umbilical cord", any changes in its annual flow will also affect Lake Turkana's water level. The realisation of irrigation schemes for sugarcane in the Omo basin will reduce the water level of Lake Turkana as these irrigation operations are expected to require up to 44% of the Omo River's annual flow (Avery, 2012). The exact impact that these developments will have on fisheries productivity within the lake and on the Omo river is however unknown (Gownaris et al., 2017). Because of the unknown effect of irrigation development and climate change on fish production in the basin, we surmise that future fish catch and production will remain similar to the catch and production in the recent past and that the only changes in fish production are the result of fisheries and aquaculture in newly created reservoirs associated with new dams. The building of dams related to hydropower generation results indeed in the creation of reservoirs which have a potential for fishing and aquaculture. Yields between 56.51 kg ha^{-1} $year^{-1}$ and 301.15 kg ha^{-1} $year^{-1}$ for African reservoirs are reported (Kolding and van Zwieten, 2012). MS16 identified the Koysha dam as the only dam currently under construction in the OTB (see also section 4.5.1). This dam will create a reservoir with an estimated surface area of 119 km² and thus with a fish production potential of 672 and 3584 tonnes per year. An average of 2128 tonnes per year of fish production will be assumed.

5.2.2 Food production from crops, livestock and fisheries

Food production from harvested crops, livestock products, and fish catch and aquaculture were estimated in terms of produced food energy and proteins for the nine subbasins corresponding to the HydroSHEDS[5] subbasins at Pfaffsetter level 5 (Figure 129). In the subsequent figures, each subbasin is identified by a unique code, based on the Pfaffstetter coding system. For livestock products and fish catch and aquaculture, this was done for the period 2020-2100. For harvested crops, this was done for the period for which climatic data was available, i.e. 2020-2089. By comparing the sum of these values per subbasin with the human food requirements within that subbasin, we estimated food surplus or deficit for the period 2020-2089. This is reported in section 5.2.3

Crops

In D3.3, statistics on production of the 38 major crops were disaggregated and assigned to LUs throughout the OTB based on land use type and slope class. Crop production was expressed in tonnes per year. In the case of multiple cropping cycles during one year, per cycle, the production values were summed. Of these 38 major crops, only these crops considered as food crops were retained. This resulted in the selection of the same 36 crops as in D2.1.

The production values of 2020 were considered to be identical to the values calculated in the baseline scenario. To estimate future changes in rainfed crop production of these 36 crops in the OTB, we used FAO's AquaCrop crop growth and yield prediction model to estimate the effect of climatic changes on yield. To do this, for each of the ten crop modelling points (Figure 126), climatic and soil input data had to be retrieved.

[5] https://www.hydrosheds.org

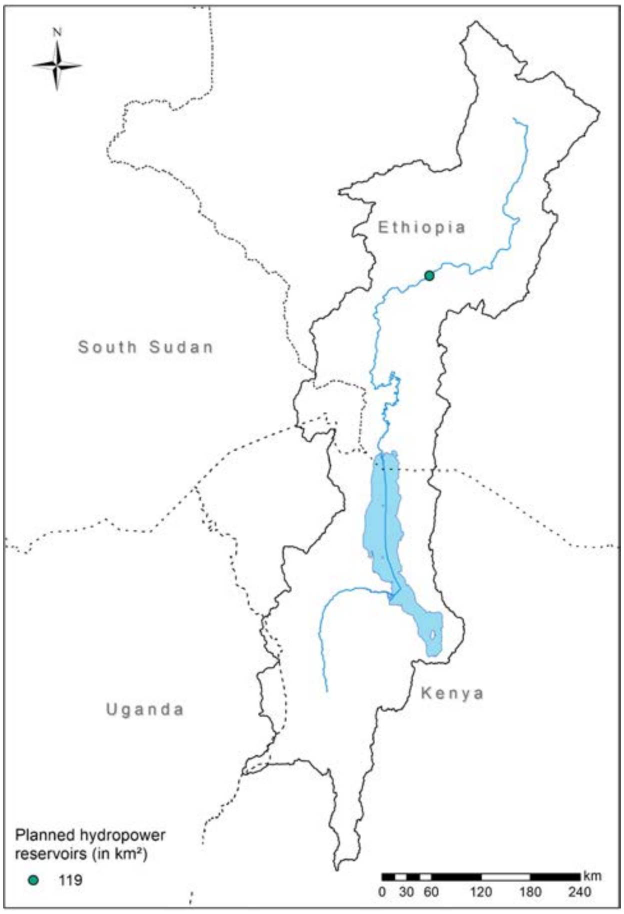

Figure 128 – Planned hydropower reservoirs in the OTB.

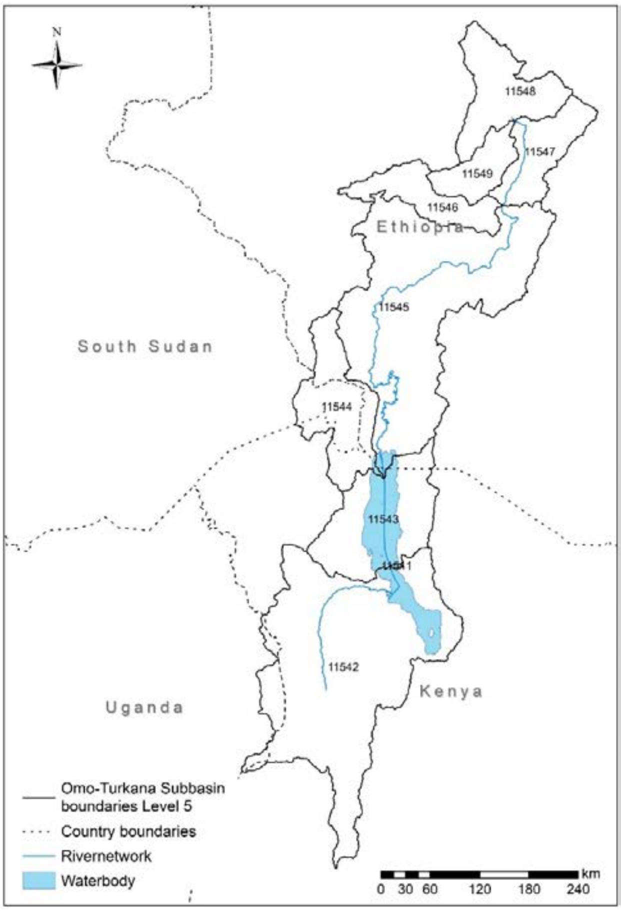

Figure 129 – HydroSHEDS Pfaffstetter level 5 sub-basins of the OTB. The HydroSHEDS subbasin numbers are displayed for each of the nine sub-basins.

ETo was calculated by using the temperature-based Penman-Monteith equation (Allen et al., 1998). This is a simplified version of the standard Penman-Monteith equation using only daily minimum and maximum temperature as input variables. Average daily temperature was obtained by identifying the nearest neighbouring virtual temperature stations for which RCP 4.5 simulation output was available from chapter 3. Monthly average temperature ranges were derived from the WorldClim version 2 mean monthly minimum and maximum temperatures (www.worldclim.org). These ranges were used to estimate daily minimum and maximum temperatures from daily average temperatures. This was done by respectively subtracting and adding half of the temperature range to the average daily temperature values. Elevation of the location of the virtual temperature stations, used to derive Atmospheric pressure, was derived from the 90m resolution Shuttle Radar Topography Mission (SRTM)-Digital Elevation Model (https://earthexplorer.usgs.gov/). Daily precipitation values at the location of the ten points were obtained by identifying the nearest neighbouring virtual precipitation station. This resulted in time series of daily minimum and maximum temperature, ETo, and precipitation at ten locations in the OTB.

Soil input data required by AquaCrop were retrieved from the SoilGrids-database for the 250 meter cells within a buffer of 10 km around the crop modelling points after which the median value was computed (www.soilgrids.com). The soil characteristics for up to seven layers, that were selected from SoilGrids, based on the soil input data required by AquaCrop, are:

- Soil organic carbon content in ‰ (g kg^{-1});
- Sand and clay content (weight %);
- Bulk density (kg m^{-3}) of the fine earth fraction (< 2 mm).

Soil organic carbon content was converted into soil organic matter content by using a conversion factor of 1.72. Soil hydraulic characteristics were estimated by the pedo-transfer functions proposed by Saxton et al. (2006). These functions estimate water content at permanent wilting point (PWP), at field capacity (FC) and at saturation (SAT), and saturated hydraulic conductivity (K_{sat}) from soil granulometric fractions, organic matter content and bulk density. Values of soil granulometric fractions and organic matter content used in the pedo-transfer functions are the median values calculated per buffer zone around the crop modelling points.

The time series of climatic variables and the soil hydraulic variables were then used to model growth and yield of rain-fed maize and teff by means of AquaCrop for the rainy seasons within the period 2020-2089, with linked simulation runs. Due to the lack of basin-wide validation data, the crop parameters could not be calibrated. Therefore the simulations were done by using the default crop parameters available in AquaCrop. The planting date of both crops was assumed to be 1 April, at the beginning of the wet season. This resulted in time series of seasonal maize and teff yield estimates. These yield values were then used to calculate average changes in estimated yield for each of the ten climate zones compared to yield values modelled in 2020. These estimated average changes were used to assess the expected changes between 2021 and 2089 in yield and production values of 36 crops identified in D3.3, under the RCP 4.5 scenario. Crop production in 2020 was considered to be identical to crop production calculated under the baseline scenario. These estimated average changes were used to assess the expected changes between 2021 and 2089 in yield values compared to the yield values simulated for 2020 of the 36 crops identified in D3.3, under the RCP 4.5 climate change scenario. Crop production in 2020 was considered to be the same as in the baseline scenario. Production values for 2021-2089 were estimated by changing the baseline production values proportional to the simulated average changes in yield.

These projected production values were summed per subbasin and converted into the amount of calories (Figure 130) and proteins (Figure 131) based on energy and nutrient coefficients for the considered crops as derived from FAO (2001) and USDA (2018). These conversion values can be found in Table 11 and correspond to the ones used in D2.1.

In Figure 130 and Figure 131, it can be seen that when the area under rainfed crop production remains constant, crop production energy and proteins remains fairly stable under the RCP 4.5 scenario. In some subbasins, produced food energy and proteins are estimated to go slightly up (e.g., subbasins 11545 and 11546), while in others, produced food energy and proteins are expected to go slightly down (e.g., subbasins 11548 and 11549).

To estimate yield and irrigation requirements of irrigation schemes within the OTB with a crop other than sugarcane, AquaCrop was used to model maize yield and corresponding net irrigation requirement in the ten crop modelling points. The net irrigation requirements were determined in such a way that the root zone depletion did not drop below 30% of the readily available soil-water in the root zone. The modelled yield and irrigation water requirements per crop modelling point were assigned to all irrigation schemes within the corresponding climate zone (Figure 126). Since the crop production data collected in D3.3 and used in D2.1 are from both rainfed and irrigated crop production, modelled yield and production values and thus energy and protein production values from existing irrigation schemes are assumed to be already accounted for in Figure 130 and Figure 131. For the planned irrigation schemes and the schemes already under construction, modelled yield values were multiplied with planned irrigated areas and converted into energy in terms of calories (Figure 132) and into proteins (Figure 133) by using the conversion values from Table 11.

In Figure 133 and Figure 134 it can be seen that irrigated maize yield and thus produced food energy and proteins for the planned irrigation schemes in the OTB are expected to go down in the future under the RCP4.5 scenario. Therefore, to obtain the same amount of food energy and proteins from irrigated agriculture, more land and thus irrigation water should be used in order to keep food energy and protein output constant over time.

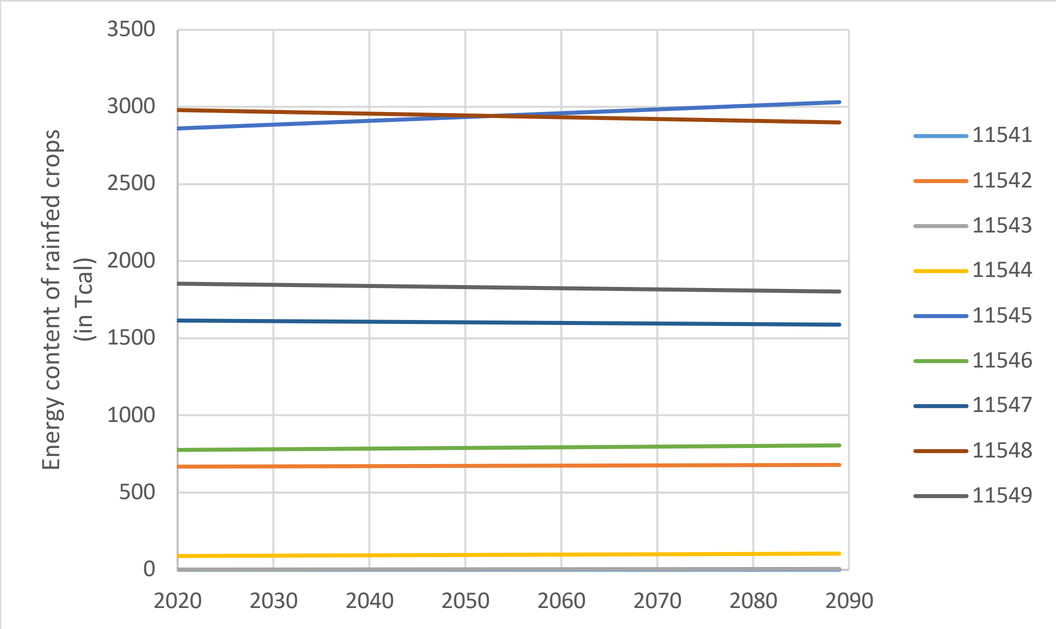

Figure 130 – Predicted energy content of harvested rainfed crops in terms of teracalories per year per Pfaffstetter level 5 subbasin in the OTB under RCP 4.5.

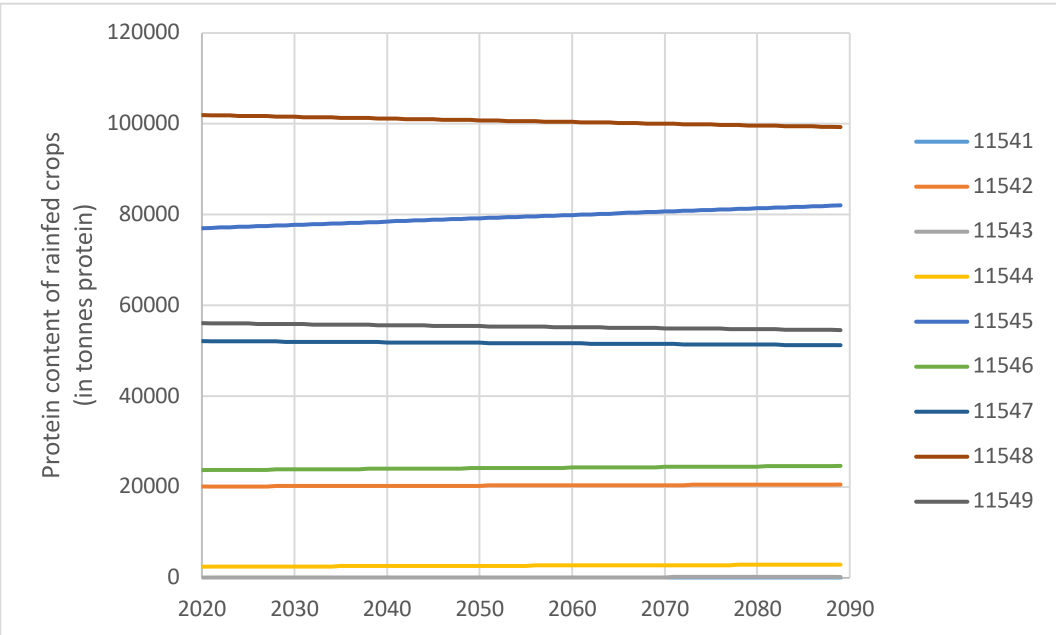

Figure 131 – Predicted protein content of harvested rainfed crops in terms of tonnes of protein per year per Pfaffstetter level 5 subbasin in the OTB under RCP 4.5.

Table 11 – Energy content (kcal) and protein content (grams) per 100g retail weight of the 36 crops considered for OTB (from FAO (2001) and USDA (2018)).

Crop	Energy content [kcal/100g]	Protein content [g/100g]	Crop	Energy content [kcal/100g]	Protein content [g/100g]
Avocado	119	1.5	Mango	45	0.4
Banana	60	0.7	Millet	340	9.7
Barley	332	11	Neug	483	17.35
Beans	341	22.1	Oats	385	13
Cabbage	19	1	Onion	31	1.1
Cassava	109	0.9	Orange	34	0.7
Chickpeas	358	20.1	Papaya	26	0.4
Eth. cabbage	19	1	Potato	67	1.6
Fababeans	88	7.92	Red haricots	337	22.53
Fieldpeas	31	1.1	Red pepper	26	0.99
Garlic	332	11	Sorghum	343	10.1
Grasspeas	31	1.1	Sugarcane	30	0.2
Green pepper	20	0.86	Sweet potato	92	0.7
Groundnuts	567	25.7	Taro	86	1.5
Kale	35	2.92	Teff	367	13.3
Lentils	346	24.2	Tomato	17	0.8
Linseed	498	18	Wheat	334	12.2
Maize	356	9.5	Yam	101	1.3

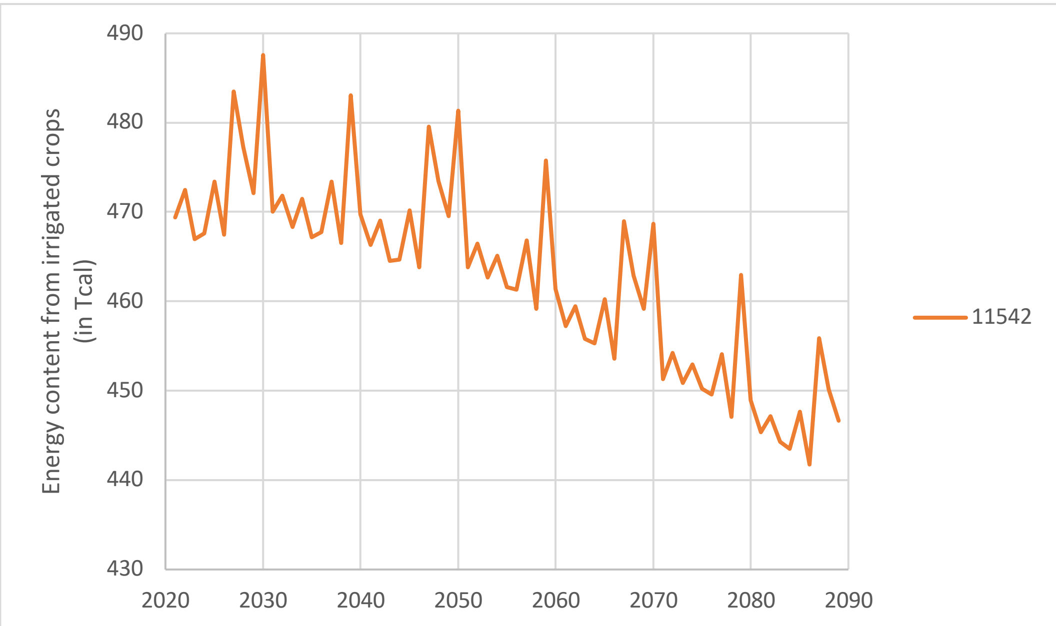

Figure 132 – Predicted energy content of harvested crops under planned irrigation in terms of teracalories per year for subbasin Pfaffstetter level 5 subbasin 11542 in the OTB under RCP 4.5.

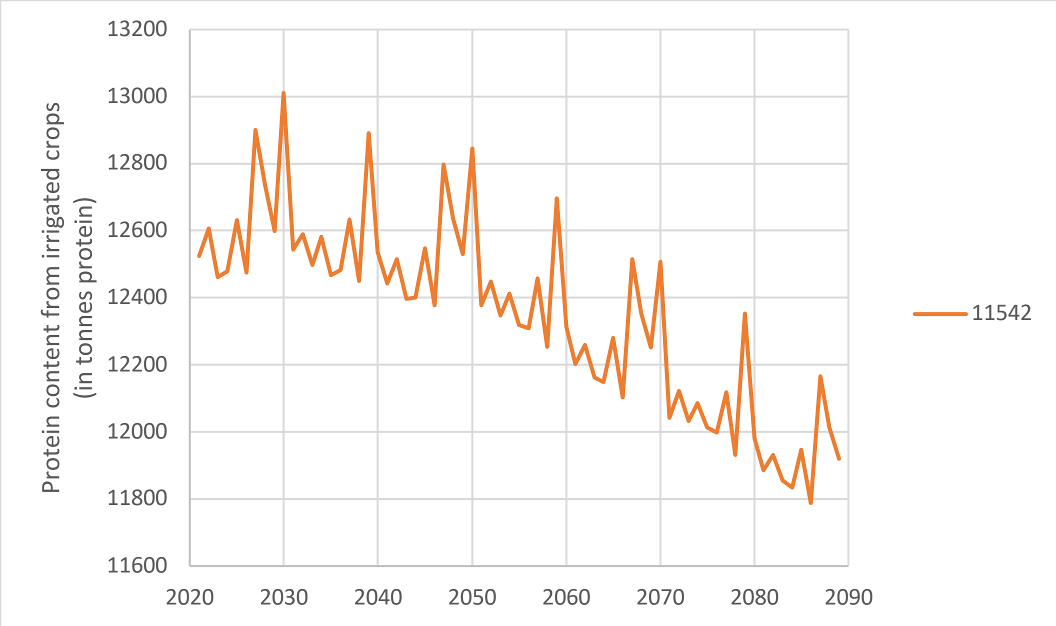

Figure 133 – Predicted protein content of harvested crops under planned irrigation in terms of tonnes of protein per year for Pfaffstetter level 5 subbasin 1154 in the OTB under RCP 4.5.

Livestock

In D2.1, statistics on livestock collected in D3.3 were related to current population numbers in the subbasins and the water consumption for livestock was calculated. By assuming that the relative contribution of livestock products to the total amount of calories and proteins in the diet, as calculated from the baseline scenario, will remain stable in the future, estimations of total calories and proteins derived from livestock products could be calculated for the SSP2 scenario and the 2020-2099 time period based on population projections (Figure 134 and Figure 135). Since population numbers and food energy and protein demands per subbasin in 2020 are similar to the baseline scenario, energy and proteins derived from livestock products in 2020 are also similar compared to the baseline scenario.

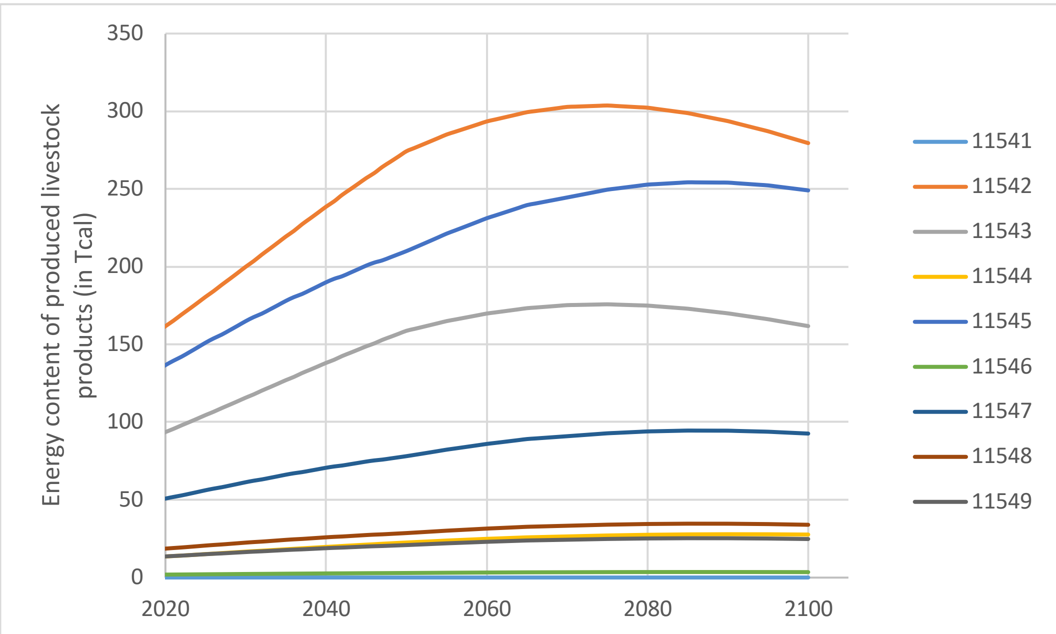

Figure 134 – Predicted energy content of livestock products in terms of teracalories per year per Pfaffstetter level 5 subbasin in the OTB under the SSP2 scenario.

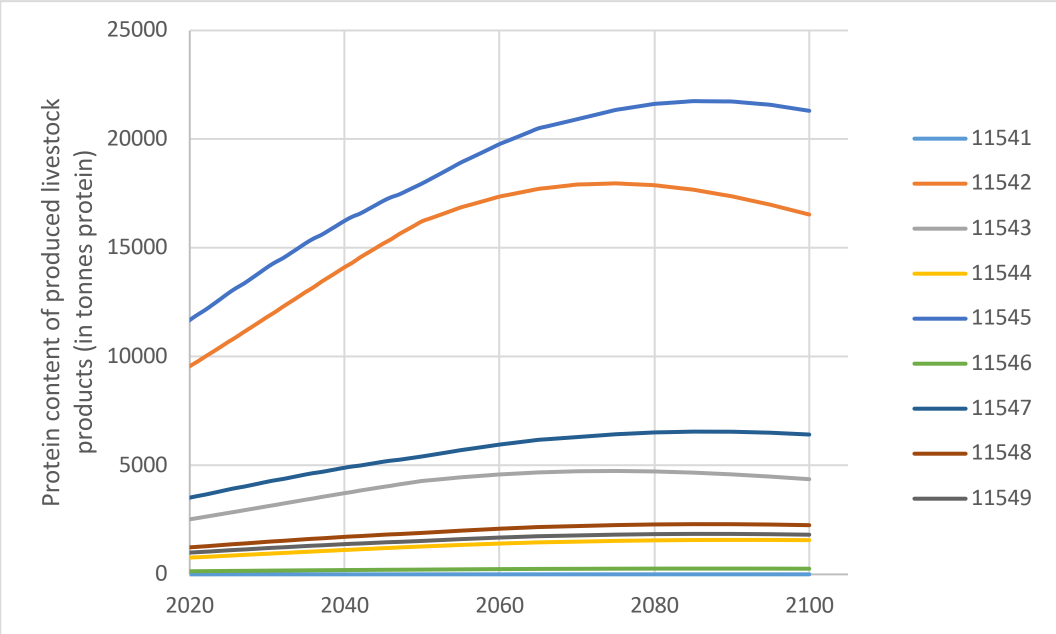

Figure 135 – Predicted protein content of livestock products in terms of tonnes of protein per year per Pfaffstetter level 5 subbasin in the OTB under the SSP2 scenario.

In Figure 134 and Figure 135, the values for 2020 are comparable to the ones calculated for the baseline scenario. Under the assumption that livestock production values follow the same trend as population numbers, we can see that these variables are expected to increase in the future under the SSP2 scenario. In subbasin 11545, in the lower Omo valley, and 11542, in the most southern part of the OTB, calories, and proteins derived from livestock products and thus livestock numbers will need to go up significantly to keep up with the expected demographic changes under the SSP2 scenario. In the other subbasins, the expected changes are less pronounced.

Fisheries

We assumed that fish catch and production in the existing water bodies will remain stable in the future and that the only changes in fish production compared to the baseline scenario will happen in new reservoirs associated with new hydropower plants (Figure 128). Therefore, the predicted production values from the planned hydropower basin were added to the current annual fish catch and production values and converted into amounts of calories (Figure 136) and proteins (Figure 137) based on the nutrient content of fresh fish as derived from FAO (2001). It was assumed that all fish caught and produced is pelagic fish. The energy and protein content is presented in Table 10.

Fish energy and protein production is mainly concentrated in the Lower Omo valley in Ethiopia (subbasin 11545) and in the Kenyan part of the OTB (subbasin 11542 and 11543), containing the major share of Lake Turkana. The new hydropower plant, located in subbasin 11545, is expected to have a great impact from 2022 onwards on calories and protein derived from fish within that subbasin (Figure 136 and Figure 137).

Crops, livestock and fisheries combined

For each of the nine subbasins in the OTB, the sum of the total annual agricultural output in terms of amount of calories (Figure 138) and proteins (Figure 139) was calculated by adding the amounts of calories (respectively proteins) coming from harvested crops, livestock products and fish catch and production.

If the year 2020 is considered to be comparable as the baseline scenario, it can be seen from Figure 139 and Figure 140 that the total energy and protein content derived from agricultural products is not expected to change significantly under the RCP4.5 and SSP2 scenarios compared to the baseline scenario described in D2.1. The increase of produced food energy and proteins in sub-basin 11545 can be explained by both the relatively high increase in predicted population and thus energy and proteins derived from livestock products, and by the increased productivity of rainfed agriculture in the subbasin. The increase of produced food energy and proteins in subbasin 11542 from 2020 to 2021 can mainly be explained by the planned irrigation schemes in the subbasin.

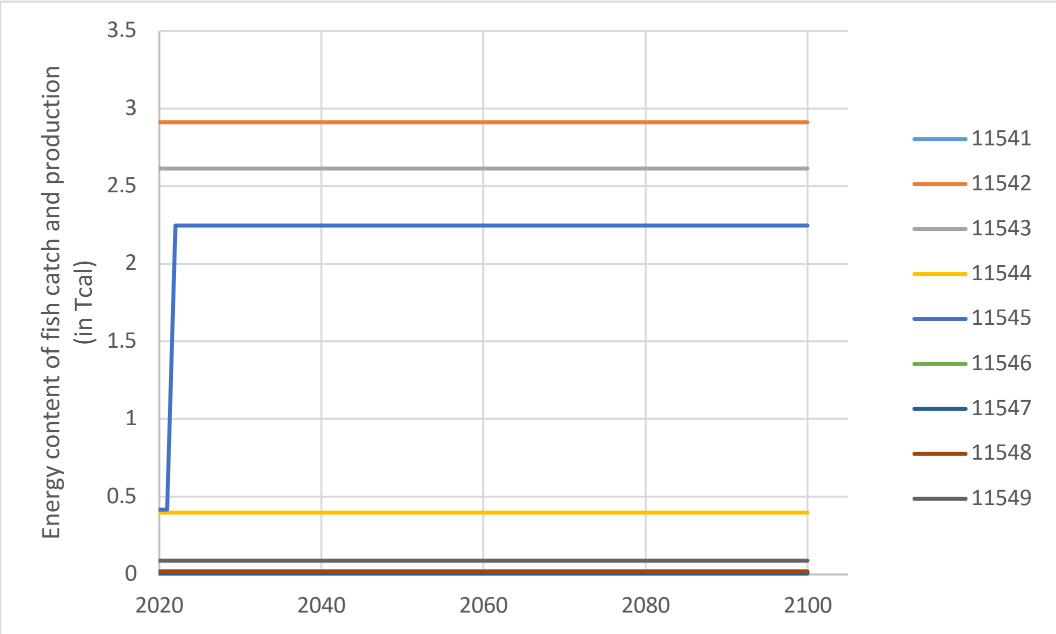

Figure 136 – Predicted energy content of fish caught and produced in OTB in terms of Teracalories per year per Pfaffstetter level 5 subbasin.

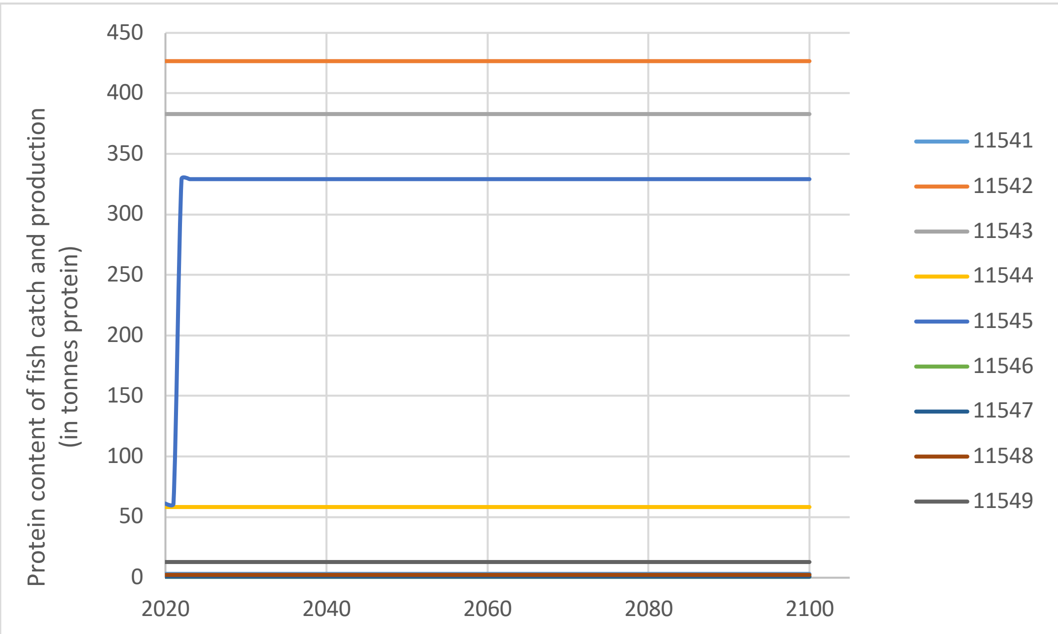

Figure 137 – Predicted protein content of fish caught and produced in OTB in terms of tonnes of protein per year per Pfaffstetter level 5 subbasin.

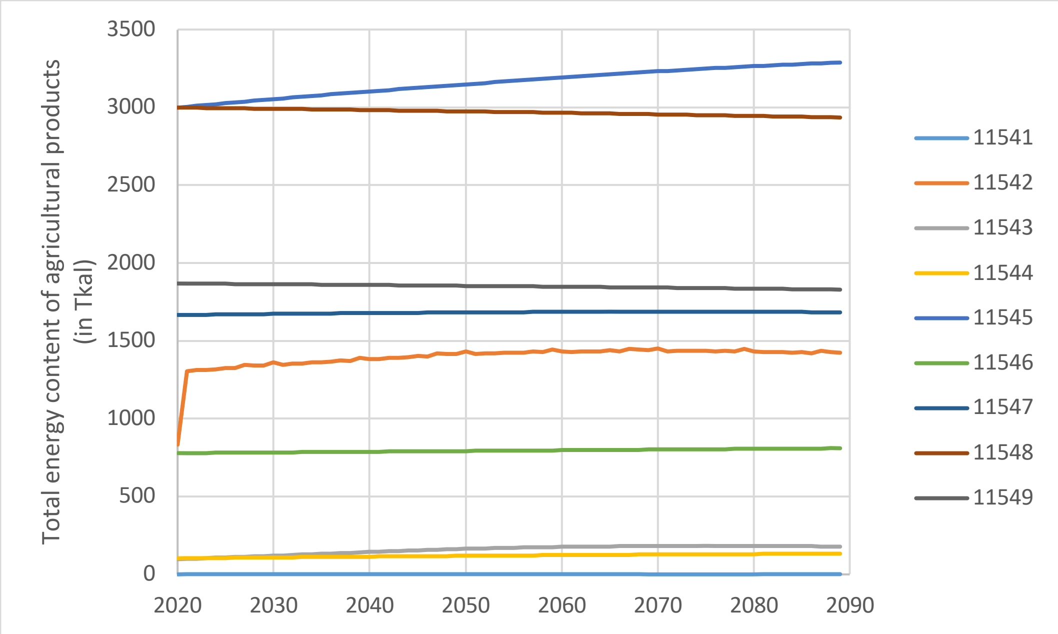

Figure 138 – Total estimated energy content of agricultural products in terms of teracalories per year per Pfaffstetter level 5 subbasin in the OTB for the period 2020-2089 under the RCP4.5 and SSP2 scenarios.

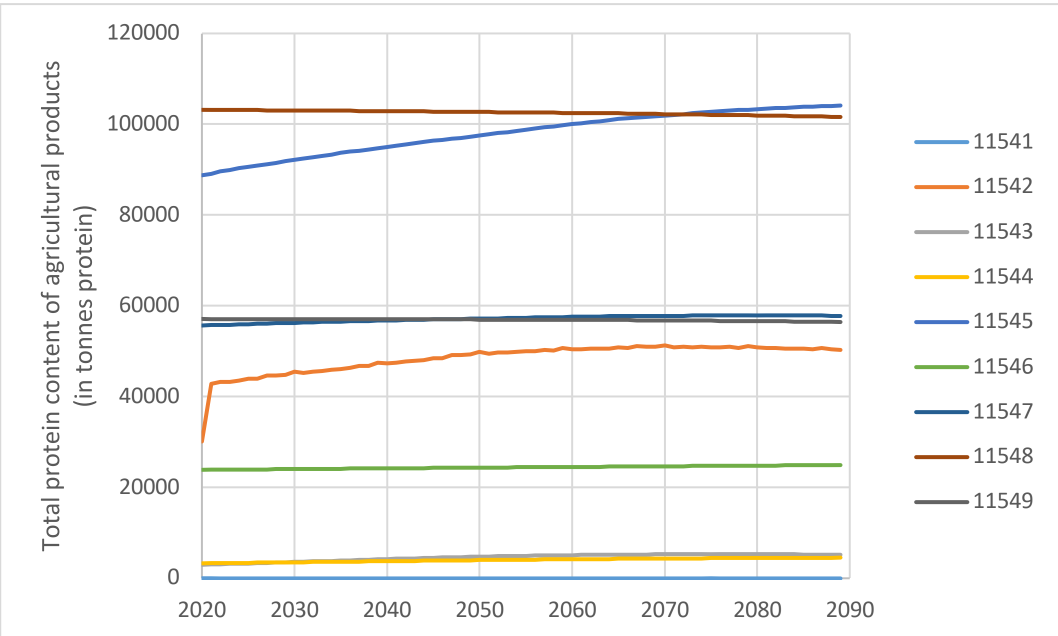

Figure 139 – Total estimated protein content of agricultural products in terms of tonnes of protein per year per Pfaffstetter level 5 subbasin in the OTB for the period 2020-2089 under the RCP4.5 and SSP2 scenarios.

5.2.3 Water use associated with irrigated crop production and livestock production

Crops

Although a proper assessment of crop water consumption by agriculture will be provided through modelling results to be reported in D3.5, in this section, we carried out a first attempt to estimate water requirements for irrigated agriculture between 2020 and 2089 under the RCP 4.5 scenario. In section 0, we described how AquaCrop was used to predict changes in yield of maize under the

RCP 4.5 scenario for both rain-fed and irrigated crop production. A similar approach was used for OTB.

To estimate net irrigation requirements, a distinction was made between irrigated land under sugarcane and land irrigated for different crops.

To estimate water consumption (and yield) of irrigated sugarcane in the Kuraz sugar estate, we derived time series of temperature and precipitation data at the location of the estate based on the time series corresponding to the available virtual temperature and precipitation station using inverse distance weighting. The current and predicted agricultural areas of the estate were multiplied with the net irrigation requirement calculated by AquaCrop. The planting date was considered to be 1 January. Gross irrigation water requirement was estimated by assuming an irrigation efficiency of 45%, based on field and conveyance efficiencies derived for local agricultural practices from Brower and Heibloem (1986) (Figure 140).

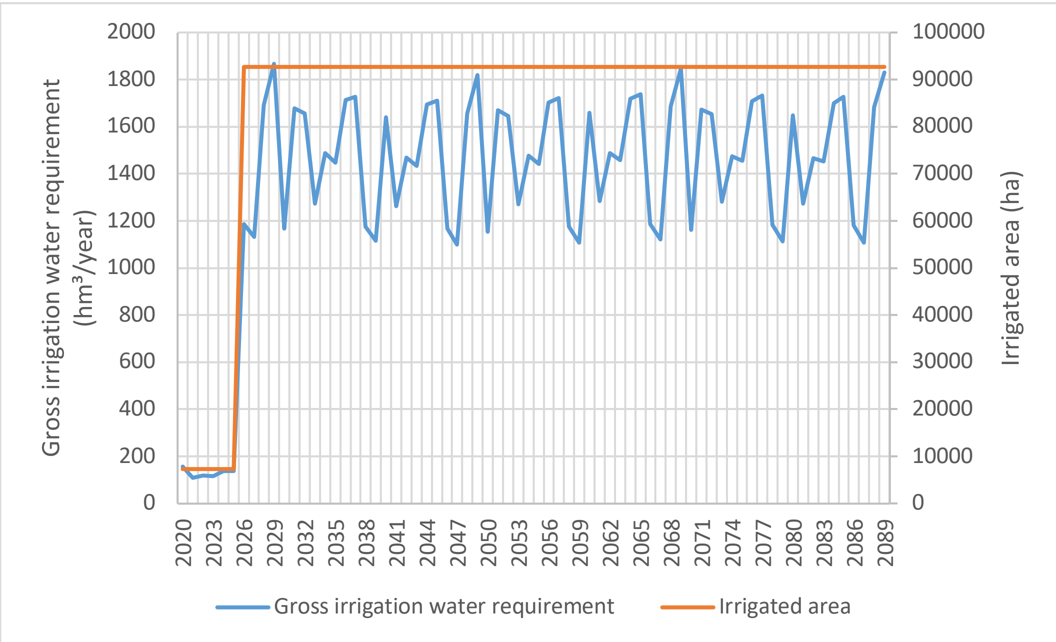

Figure 140 – Gross irrigation water requirement for the Kuraz sugar estate in hm^3/year.

For current and planned irrigation schemes other than the Kuraz sugar development, net irrigation water requirement was estimated by multiplying the reported areas under irrigation with the net irrigation requirement calculated by AquaCrop for irrigated maize (Figure 141). Gross irrigation water requirement was calculated by assuming again an irrigation efficiency of 45%. Maize was selected because it has been identified as the crop with the highest production values in the OTB. With the exception of the Kuraz sugar estate, maize was reported as one of or the only crop on the planned irrigation schemes for which the intended crop could be identified. Therefore, it is assumed maize will remain important as an irrigated crop in the OTB in the future.

Figure 141 shows that when the planned irrigation schemes in subbasin 11542, the most southern part of the OTB, are implemented, gross irrigation water requirement goes up significantly. In Figure 127, it can be seen that these schemes are mainly situated along the Turkwel river. Since less than 2% of riverine water flowing into Lake Turkana is contributed by the Turkwell river, it is expected that unlike the implementation of the Kuraz sugar estate, the implementation of these irrigation schemes will not have a significant impact on the lake levels. The significance of the irrigation water requirement of the Kuraz scheme can be seen in Figure 142, which shows that gross irrigation water requirements go up around 6 times in subbasin 11545 after 2025, after which the full 100000 ha of sugarcane irrigation is expected to be implemented.

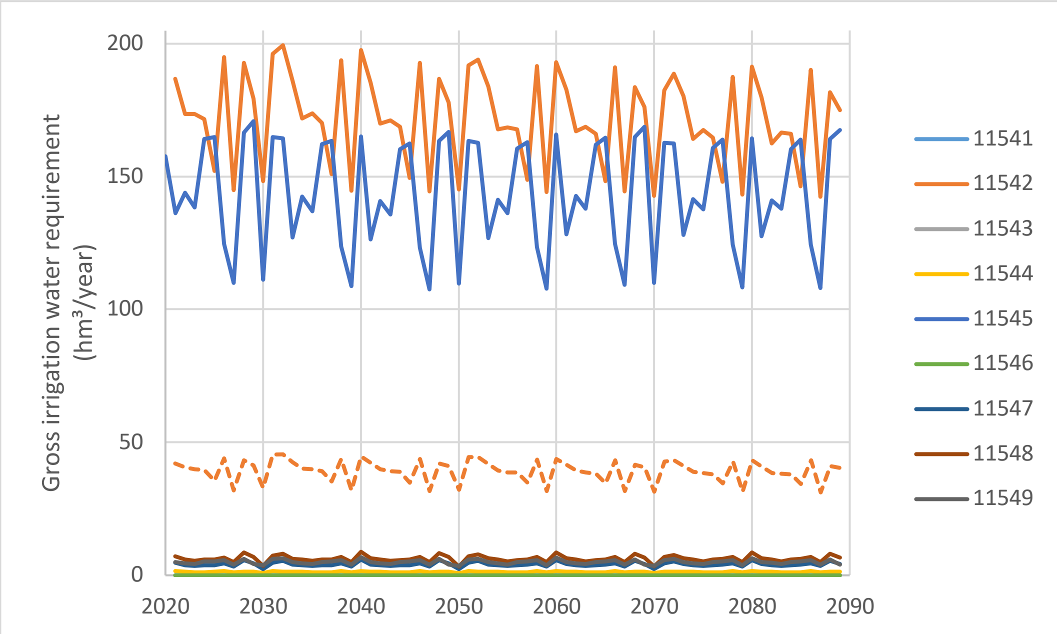

Figure 141 – Gross irrigation water requirement for current and planned irrigation schemes (without the Kuraz sugar estate) per Pfaffstetter level 5 subbasin in the OTB in hm³/year. Dashed lines represent gross irrigation water requirement for existing irrigation schemes. Solid lines represent gross irrigation requirement for existing and planned irrigation schemes combined.

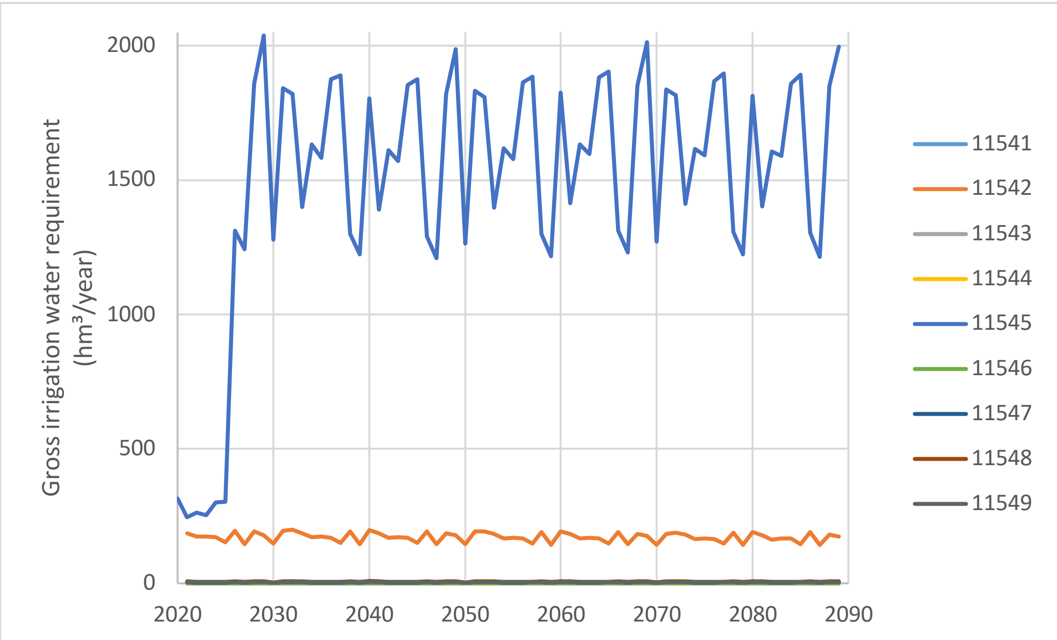

Figure 142 – Gross irrigation water requirement for current and planned irrigation schemes, including the Kuraz sugar estate, per Pfaffstetter level 5 subbasin in the OTB in hm³/year.

Livestock

In section 5.2.2, food energy and proteins derived from livestock products were estimated based on population projections under the SSP2 scenario. To estimate the water requirements to produce this quantities, we assumed that calorie and protein offtake per animal and daily water requirement per animal will remain stable under the RCP 4.5 scenario. Under this assumption, water requirement per produced calorie and protein livestock product will also remain stable in the future. Eventually water requirements for livestock per subbasin in the OTB for the period 2020-2100 was calculated (Figure 143).

Water consumption for livestock production is highest in subbasin 11545 situated in the Lower Omo Valley, and in subbasin 11542 situated in the most southern part of the OTB, around the Turkwel and Kerio Rivers. Before the implementation of the Kuraz sugar estate, water requirements for livestock production are expected to be higher than those estimated for irrigated agriculture (Figure 142 and Figure 143). After 2025, when water requirements of irrigated agriculture in the OTB are expected to significantly increase due to the Kuraz sugar estate, water requirements of irrigated agriculture exceed these of livestock production.

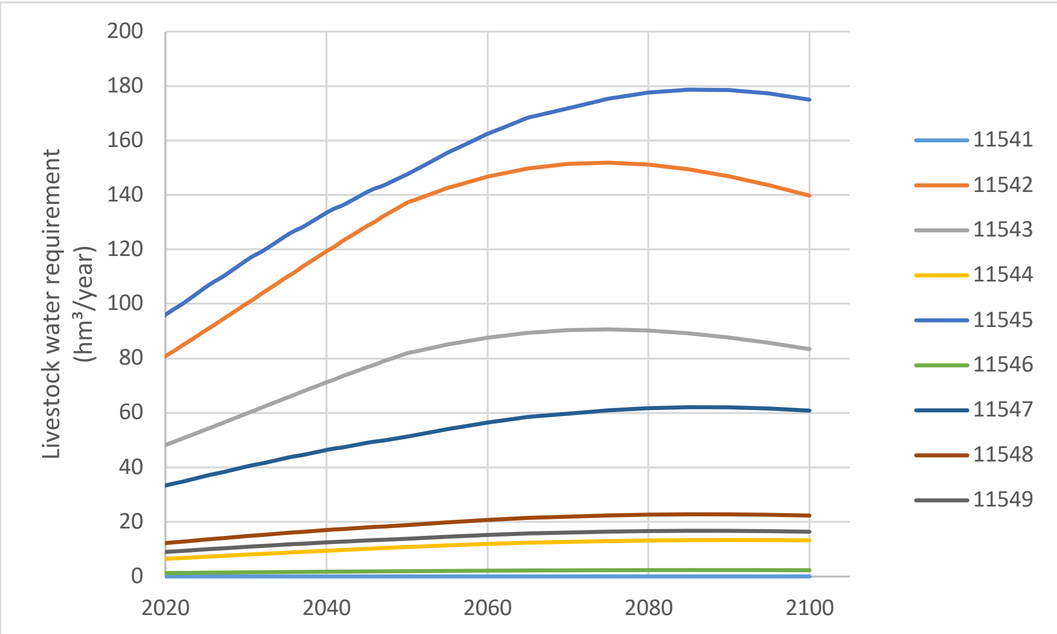

Figure 143 – Annual livestock water requirement in hm³/year per Pfaffstetter level 5 subbasin in the OTB.

5.2.4 Food surplus/deficit at subbasin scale

Food production versus food requirements

By comparing at subbasin scale the yearly amount of calories and proteins available from the combination of harvested crops (with the exception of sugarcane produced in the Kuraz sugar estate), livestock and fish products, as derived in section 5.2.2, with the amount of calories and proteins required by private households, we calculated the food deficit or surplus per subbasin in the OTB.

Average annual food requirements in terms of calories and proteins were calculated per subbasin in the OTB (Figures Figure 38 to Figure 40). The absolute food production surplus or deficit was calculated by subtracting the annual food requirements (in terms of calories and protein) by the local population from the annual produced food energy and proteins. A positive value indicates a food production surplus within the subbasin, while a negative value indicates a food production deficit (Figure 144 and Figure 145).

On basin scale, no food energy or protein deficit was calculated for the baseline scenario. Under the RCP 4.5 and SSP2 scenarios, a food energy deficit on basin scale was calculated in terms of calories from 2040 onwards. A food protein deficit was calculated from 2058 onwards. On subbasin scale, a food deficit can already be seen in some subbasins under the baseline scenario. There is furthermore, as in the ZRB, a general declining trend of produced food energy and proteins relative to food energy and proteins required as population grows. The number of subbasins for which a food deficit is predicted under the RCP 4.5 and SSP2 scenarios is expected to increase in the future. For the subbasins in which a food energy or protein surplus is predicted in the future, this surplus is decreasing. For the subbasins in which there is a food energy or protein deficit, this deficit is increasing.

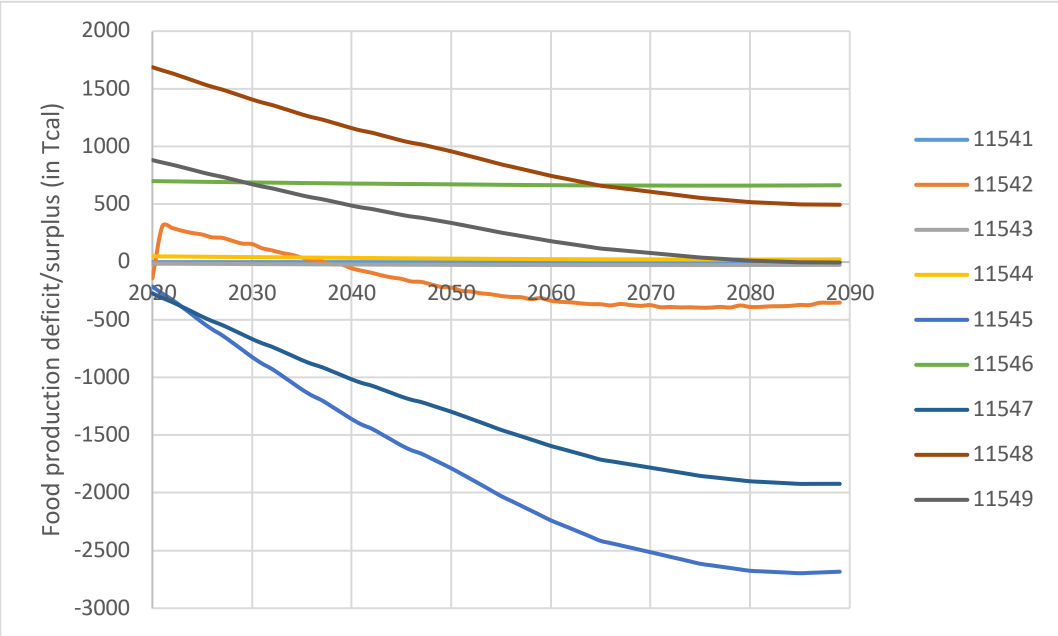

Figure 144 – Food production deficit/surplus (in teracalories per year) per Pfaffstetter level 5 subbasin in the OTB.

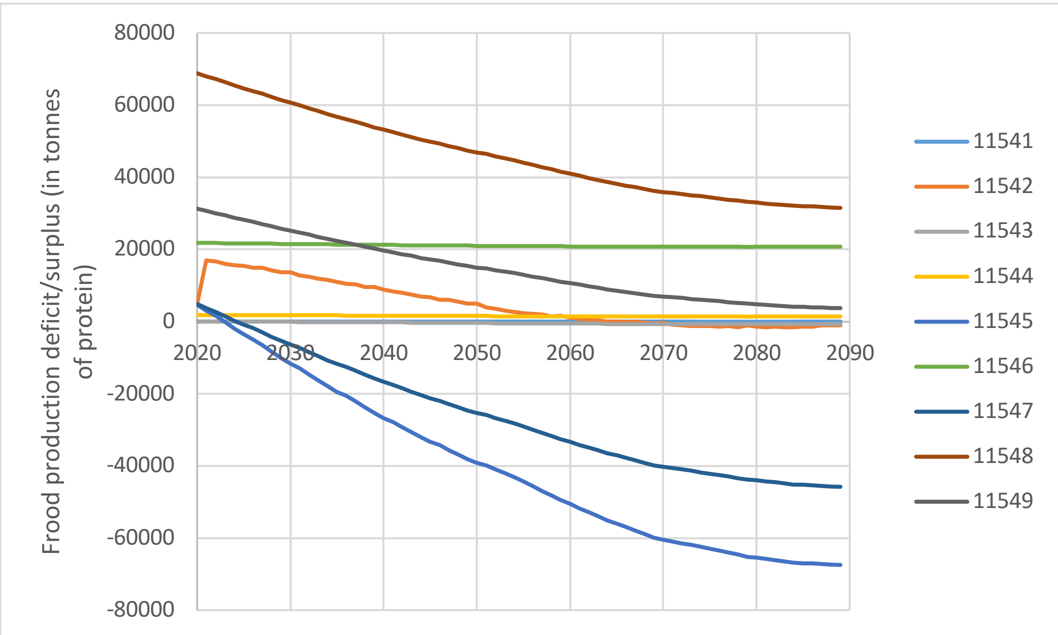

Figure 145 – Food production deficit/surplus (in tonnes of protein per year) per Pfaffstetter level 5 subbasin in the OTB.

If trading among regions is not considered as an option, achieving a balance in the subbasins characterized by a food energy and/or protein deficit will increase water demand of these regions. The amount of additional water needed depends on the source of food energy and proteins. To estimate the additional water demand, we assumed the additional energy and proteins are produced by irrigated maize. The required tonnes of maize and net irrigation demand were calculated using AquaCrop and using the same parameters as described in section 0 (Figure 146). The planting date was considered to be 1 December, at the beginning of the dry season.

To achieve a local balance in the subbasins for which a food energy or protein deficit was predicted, the additional required water is –by far– largest in subbasins 11545 and 11547.

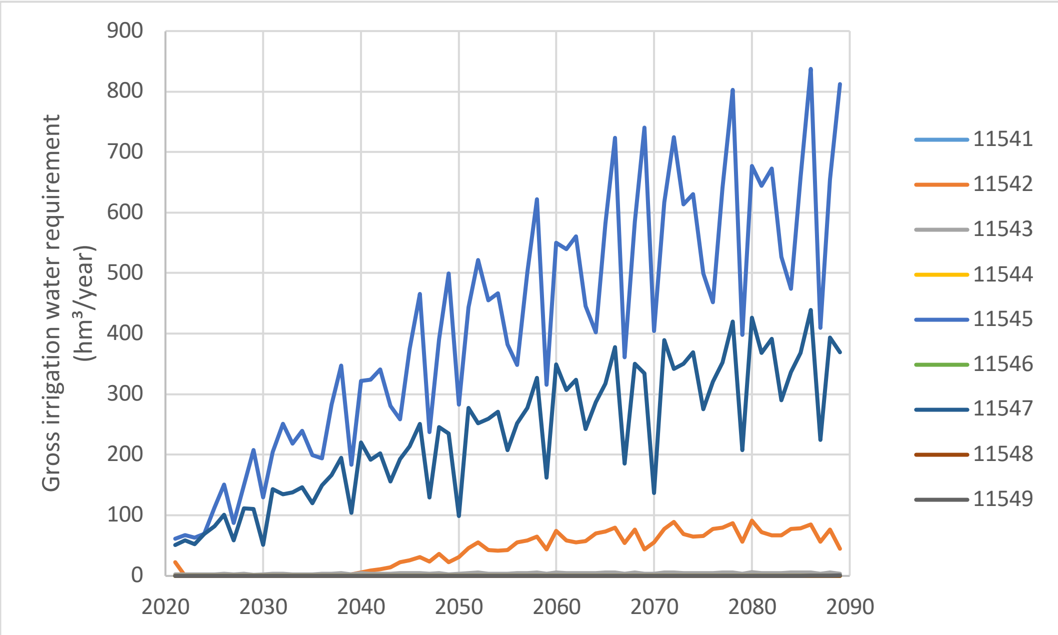

Figure 146 – Gross irrigation water requirement (in hm³/year) to eliminate food deficits per Pfaffstetter level 5 subbasin in the OTB for the 2020-2089-period.

6. ENVIRONMENT

In this chapter we consider the most likely management measures to maintain and expand the use and benefits from Ecosystem services in the two case study basins, the ZRB (section 6.1) and the OTB (section 6.2).

6.1 ZAMBEZI RIVER BASIN

6.1.1 Ecosystem management scenarios

In deliverable D3.4, we reported a range of potential and necessary ecosystem management scenarios, including reservoir release strategies, flood management, maintaining in-stream connectivity, sediment management, dam removal, forest and land cover management and protected areas. To avoid replication, we here focus only on those management scenarios that are most likely to happen or already exist in some form.

Establishment of protected areas

Deliverable D2.1 presented existing protected areas and key biodiversity areas. The main challenge for the future will be to maintain and improve conservation within these areas. Given the current political agenda, new protected areas such as national parks are not likely to be established in the near future. Most changes are expected in terms of regional integration of adjacent protected areas as a means of landscape-wide conservation across national boundaries. One documented example for this are Transfrontier Conservation Areas (TFCA). Initially called “Peace Parks”, the concept of transboundary conservation has been pioneered in Southern Africa and provides a positive example, how conservation across borders can be shaped by integrative measures (Ali, 2007). Building an identity for an entire region or watershed can attract tourists but also provide incentives to decision makers and local populations to engage in constructive solutions to complex conservation issues. The oldest, most established and also largest TFCA is in the Kavango-Zambezi region, spanning across parts of five countries (Figure 147). Other TFCA for which the treaty has already been signed, is in the border region of Zambia and Malawi. Three others are still in the conceptual phase (Table 12).

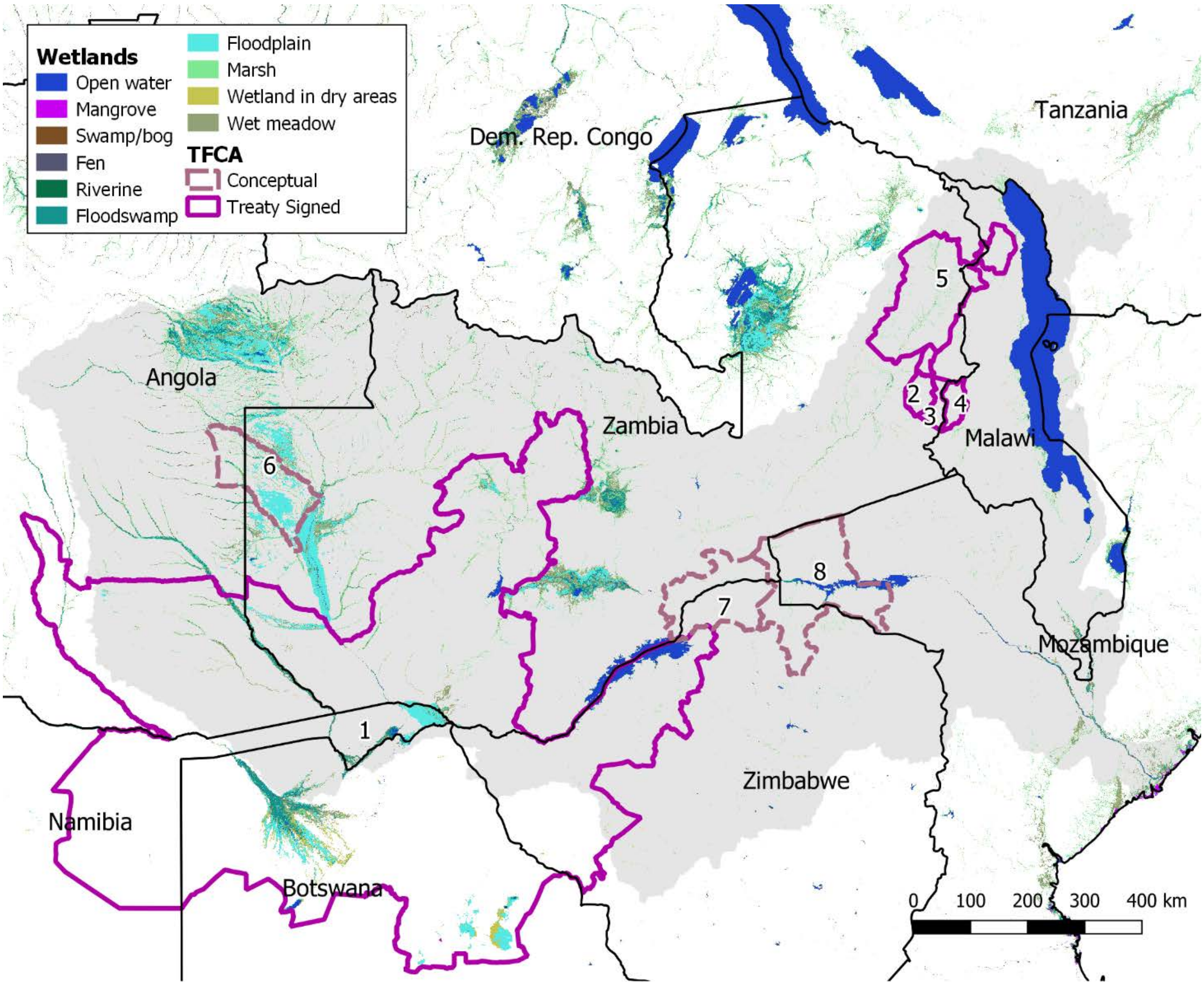

Figure 147 – Location of Transfrontier conservation areas and wetlands in the Zambezi basin (see Table 12 for description).

Environmental flow releases

At Zambezi basin level, no concerted strategic plan for wetland management and planned environmental flows exists (pers. comm. Evans Kaseke, ZAMCOM). ZAMCOM has entered into an MOU with WWF on environmental policy. Therefore, whatever work has been done in, for example, the Kafue Basin can be replicated in other catchments within the Zambezi. So far, WWF (Kahinda and Kapangaziwiri, 2012) has identified four key areas that are most vulnerable to changes in flow: Lower Kafue/ Kafue flats, Lower Zambezi/ Zambezi Delta, Upper Zambezi (Barotse and Kabompo) and Luangwa. Both the Luangwa and the Upper Zambezi river are still largely free-flowing and water resource management at dams is not necessary as yet. However, land-use change such as deforestation as well as climate change are affecting water availability and catchment dynamics (see deliverable D3.4).

Table 12 – Transfrontier Conservation Areas with major characteristics and implementation status (Peace Parks Foundation, 2017)

ID	Name	Type	Status	Area (km^2)	Countries involved
1	Kavango Zambezi TFCA	TFCA	Treaty Signed	516,407	Zambia, Angola, Namibia, Botswana, Zimbabwe
2	Kasungu Lukusuzi TFCA	TFCA	Treaty Signed	2,700	Zambia, Malawi
3	Kasungu Lukusuzi TFCA	Corridor Linkage	Treaty Signed	3,197	Zambia, Malawi
4	Kasungu Lukusuzi TFCA	TFCA	Treaty Signed	2,464	Zambia, Malawi
5	Nyika-North Luangwa TFCA	TFCA	Treaty Signed	26,926	Zambia, Malawi
6	Liuwa Plains-Mussuma TFCA	TFCA	Conceptual	16,289	Zambia, Angola
7	Lower Zambezi-Mana Pools TFCA	TFCRA	Conceptual	17,789	Zambia, Zimbabwe
8	Zimbabwe Mozambique Zambia Transfrontier Conservation and Resource Area	TFCA	Conceptual	29,860	Zimbabwe, Mozambique, Zambia

The lower Kafue/Kafue Flats

Itezhi-Tezhi dam on the Kafue River is the only dam in the Zambezi basin that has explicitly incorporated environmental flows into its' design. This dam was constructed to be 15% bigger than necessary for its main purpose, power generation. This allowed dam operators to store additional water and simulate the natural downstream flood regime to maintain flooded grasslands for cattle grazing and wildlife. The extent to which this practice has been successful remains an open question, but the intent of the original design is noteworthy. Given its' pioneering role, the Kafue river can serve as a model for the consideration of environmental flow measures at other dams.

Yet, the operation rules of Itezhi-Tezhi have changed frequently since construction in 1977 and the impacts on the Kafue flats ecosystems have been severe (Beilfuss and Davies, 1999; Mumba and Thompson, 2005). Suggested by WWF, improved operating rules are in place since 2007. It is, however, questionable how these will be maintained since the new hydropower plant at Itezhi-Tezhi became operational in 2016 (WWF, 2017).

For future operation of environmental flows the following guidelines have been proposed that are largely applicable also for other dams (King and Brown, 2014):

- Timing of flooding: Earlier in wet years, later in dry years to give more time for flood dependent ecological processes
- Duration of flooding: At least one month to prevent shrub encroachment into grasslands
- Volume of flood release: Flexible, depending on actual rainfall, ranging from 215 to 820 m3 s-1
- Rate of change of flood release: Following the natural flood hydrograph, avoiding sharp rises and falls to allow people, livestock and wildlife to leave
- Extent of flooded area: Variable between wet and dry years
- More dynamic flow releases are especially important if under climate change weather phenomena become more extreme

The Kafue flats are a special case because not only inflows are controlled by a dam but also outflows (at Kafue gorge dam). Here, it would be necessary to release larger amounts of water also during the dry season to drain permanently inundated areas in the flats such as Chunga Lagoon in Lochinvar National Park that were previously grasslands(Figure 148). Overall, more water should be stored at Itezhi Tezhi and less at Kafue gorge (King and Brown, 2014).

The Lower Zambezi/Zambezi Delta

Flows arriving at the Zambezi Delta in Mozambique are largely controlled by Cahora Bassa (CB) dam. For CB, there are no determinations or enforcements for environmental flow releases in place or planned (pers. comm. D. Juizo.). In the past, before the Caia bridge was built (commissioned around 2009), HCB, who run the hydropower plant at CB would be asked to guarantee releases of water to ensure safe navigation of the ferry linking the two margins of the Zambezi Caia-Chemba. Since the bridge has been finalized, there are no external considerations in the operation of the dam regarding low flows. In terms of floods, HCB is required to coordinate with the regional water administration in managing the releases of water from the Dam to ensure there are no aggravated scenarios resulting from a combination of peak flows entering the Zambezi from downstream tributaries (pers. comm. D. Juizo.). Practically, environmental flow releases have to come from the capacity of Cahora Bassa dam, as the upstream Kariba dam is not constructed in a way that would allow major controlled releases as long as the lake is not full (Beilfuss and Davies, 1999). It has to be noted that releasing water in an environmental flow regime does not reinstall natural conditions. Especially the sediment trapped behind upstream dams is lacking in the delta and has been made responsible for extensive dieback of mangrove forests among many other negative effects (Beilfuss and Davies, 1999).

Figure 148 – Release of water at the Kafue gorge dam in Zambia (image by ATEC 3D)

The scientific literature evaluates water requirements for different purposes in the Zambezi Delta (Beilfuss and Brown, 2010). The tested scenarios range from 1350 to 10,000 m^3s^{-1}, released over periods ranging from 2 to 8 weeks. For each scenario, the reduction of hydropower production at CB is calculated and trade-offs and benefits for the following land uses and ecosystem properties are discussed: Commercial agriculture, estuarine ecology and coastal fisheries, livestock, water-birds, invasive species control, groundwater recharge (water supply), in-channel navigation, small-scale agriculture, freshwater fisheries, large mammals, floodplain vegetation, water quality and natural resources availability.

Reinstatement of annual floods

The environmental flow scenario for the delta that is most likely to happen is the reinstatement of moderate annual floods. The majority of users in the delta would benefit from some form of annual floods, for example through recession agriculture, grazing grounds, groundwater recharge and general wetland productivity. Only those concerned about in-channel navigation and commercial agriculture were neutral regarding flood releases. The ideal scenario for most ecosystem services would be releases during 8 weeks in December and January that amount to 10,000 m^3s^{-1} discharge in the delta. A balance between the interests of all stakeholders (including hydropower production) could be achieved by (in the order of preference: (1) 4500 m^3s^{-1} of discharge in the delta during 2 weeks in December (2) 4500 m^3s^{-1} during 2 weeks in February or (3) 7000 m^3s^{-1} during two weeks in December. The slight preference for December is due to the interests and timings of hydropower. (Beilfuss and Brown, 2010)

Reductions in dry-season low-flows

From a biodiversity conservation perspective, it would be useful to reduce flows in the dry-season in order to reinstall a more natural regime (e.g. for Mangrove regeneration and to provide breeding habitat on sandbanks). Yet, other interests would be negatively affected and such measures might only be realistic during particularly dry years (every 3-5 years, (Beilfuss and Brown, 2010)).

1:5-year return ‘extreme’ flood

Extreme floods that occur only once or twice per decade are important for the functioning of large-scale ecological processes. Yet, the risk of such floods for example as a danger to human life are high (Beilfuss and Brown, 2010). Given that many more people have settled down in the delta area since the dams have been build more than 50 years ago, it will be politically difficult to realize such extreme flooding events.

Effects of climate change

Climate predictions for Zambia forecast increased temperatures and reduced rainfall. Combined, this will result in a 13% reduction of water availability by 2100 (Hamududu and Ngoma, 2018). This will aggravate the competition for water and increase the need for environmental flow measures to compensate for lack of water in wetlands.

6.1.2 Floating invasive vegetation as indicators for flow-related ecosystem changes

D3.4 described the various ecosystem services that depend on steamflow and will be influenced by predicted changes in the Zambezi river basin with climate change and industrial development. Given the complexity of the ecological system and sparse data availability, it is impossible to predict how all different ecosystem services will develop in the future.

We focused on invasive floating vegetation as one indicator that depends on both water quality and streamflow and at the same time negatively affects hydropower production. Dams serve both as traps for floating vegetation and provide improved habitat conditions for plants such as invasive water hyacinths (*Eichhornia crassipes*) by slowing down flow speed. We used the floating vegetation coverage of the Kafue gorge reservoirs as a gauge for water quality in the overall Kafue river catchment. We processed the full archive of LANDSAT images in Google Earth Engine to follow the development of floating vegetation cover from 1990 to 2018 (see examples in Figure 149). We linked these observations with rainfall and flow observations from Itezhi-Tezhi dam above and Kafue Gorge dam below the reservoir.

The time series from the Kafue gorge show long-term dynamics in floating vegetation coverage that can be associated with changes in the flow regime. During the 1990s, peak releases from both

Itezhi-Tezhi and Kafue gorge did not follow particular patterns both in terms of timing and amount (King and Brown, 2014). This coincided with continuous dense coverage of invasive floating vegetation. The first large flood release occurred in 2001, followed by more regular intervals from 2007 onwards (King and Brown, 2014). The first major release of water and not the extensive plant removal campaigns that happened during the 1990s (https://allafrica.com/stories/199710160051.html) ended the dominance of floating vegetation that only picked up again since 2011 (Figure 150).

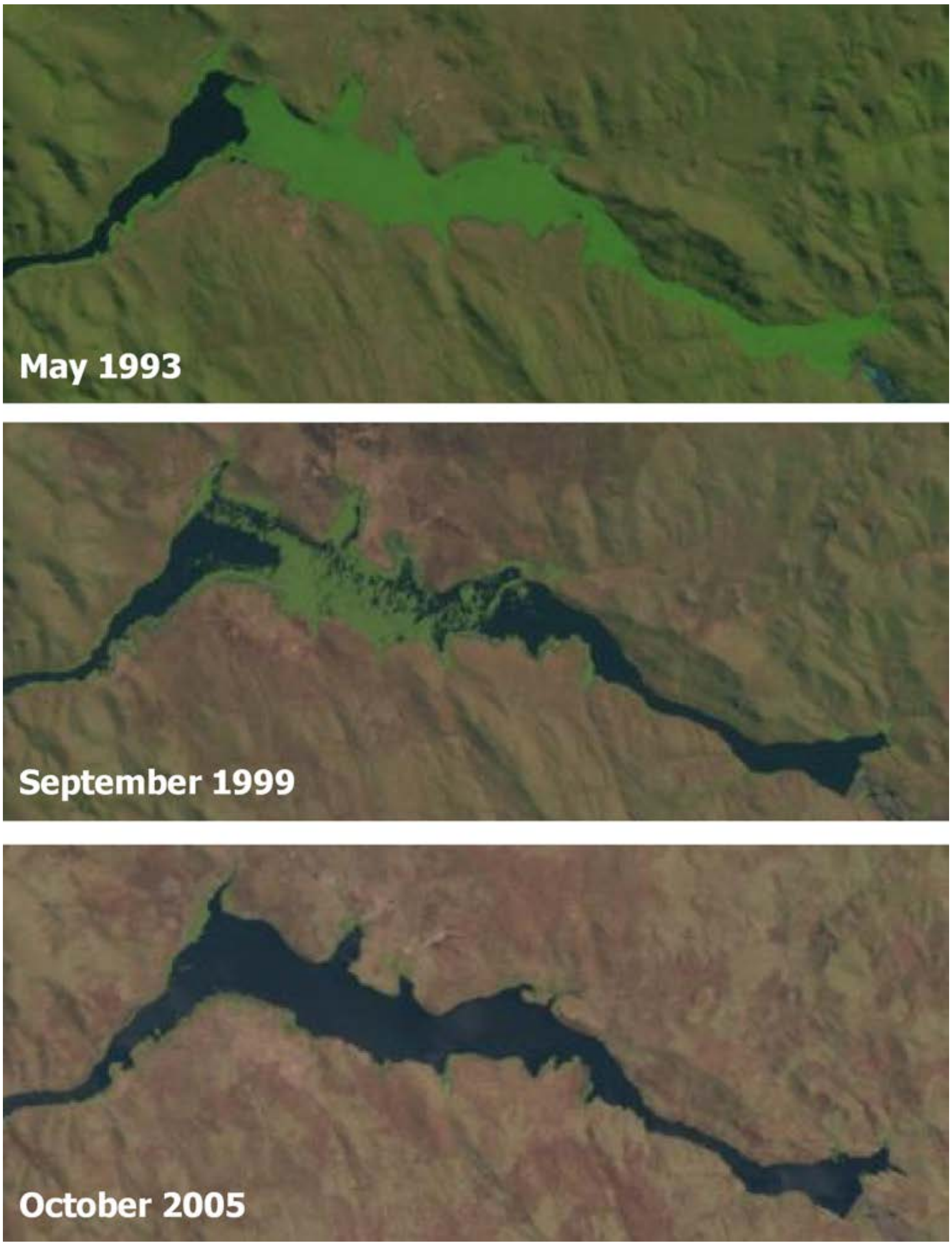

Figure 149 – Example of LANDSAT images of the Kafue gorge showing floating vegetation coverage.

The timing is key for environmental flow releases. As shown in deliverable D3.4, the Kafue flats were not flooded throughout the 1990s due to a misalignment of the dam releases and the natural flow peaks. This changed only after 2000, helping to reduce floating vegetation invasions. Floating vegetation coverage undergoes pronounced seasonal cycles. The peak occurrence of floating vegetation follows after the rainy season and ends once the flood gates are opened at the downstream dam (Figure 150). During times of flood, floating vegetation drifts into the floodplains, where gets stranded. It can thus serve as a potential vector to transport nutrients from the water to the land during periods of high flows, floods and strong winds (Figure 151). We suggest that future environmental flow regimes should use the potential to control invasive species.

We predict that under climate change, the occurrence of floating vegetation invasions might increase due to higher temperatures and warmer winters. Additional dam constructions will favour such invasions as they create a novel ecosystem by slowing down the flow speed of a river. Also nutrient loads can be high in reservoirs due to decomposing vegetation in the flooded areas. Yet, while the mass-growth of floating vegetation is boosted by nutrients, it is also limited by their availability. Long term invasions require continuous input of nutrients such as from urban areas with untreated wastewater. Increasing development of sewage plants will potentially reduce nutrient availability.

The massive problems with floating vegetation in the 1990's led to concerted eradication campaigns. A combination of mechanical, chemical and biological weed control measures has been implemented since then (Chola, 2001). Yet, as our data shows, dominance has picked up again recently, leading to a statement of the Zambian president on the urgency of the issue (https://www.znbc.co.zm/lungu-quizzes-lusambo-over-kafue-weed/). In the context of the DAFNE project, we were the first to show that floating vegetation in the Kafue and Zambezi rivers is not anymore mostly comprised of water hyacinth. Instead, the Amazon Frogbit (*Limnobium laevigatum*), which is another exotic floating species, has become very dominant (http://www.kafuerivertrust.org/amazon-frogbit-invades-the-kafue-flats/).

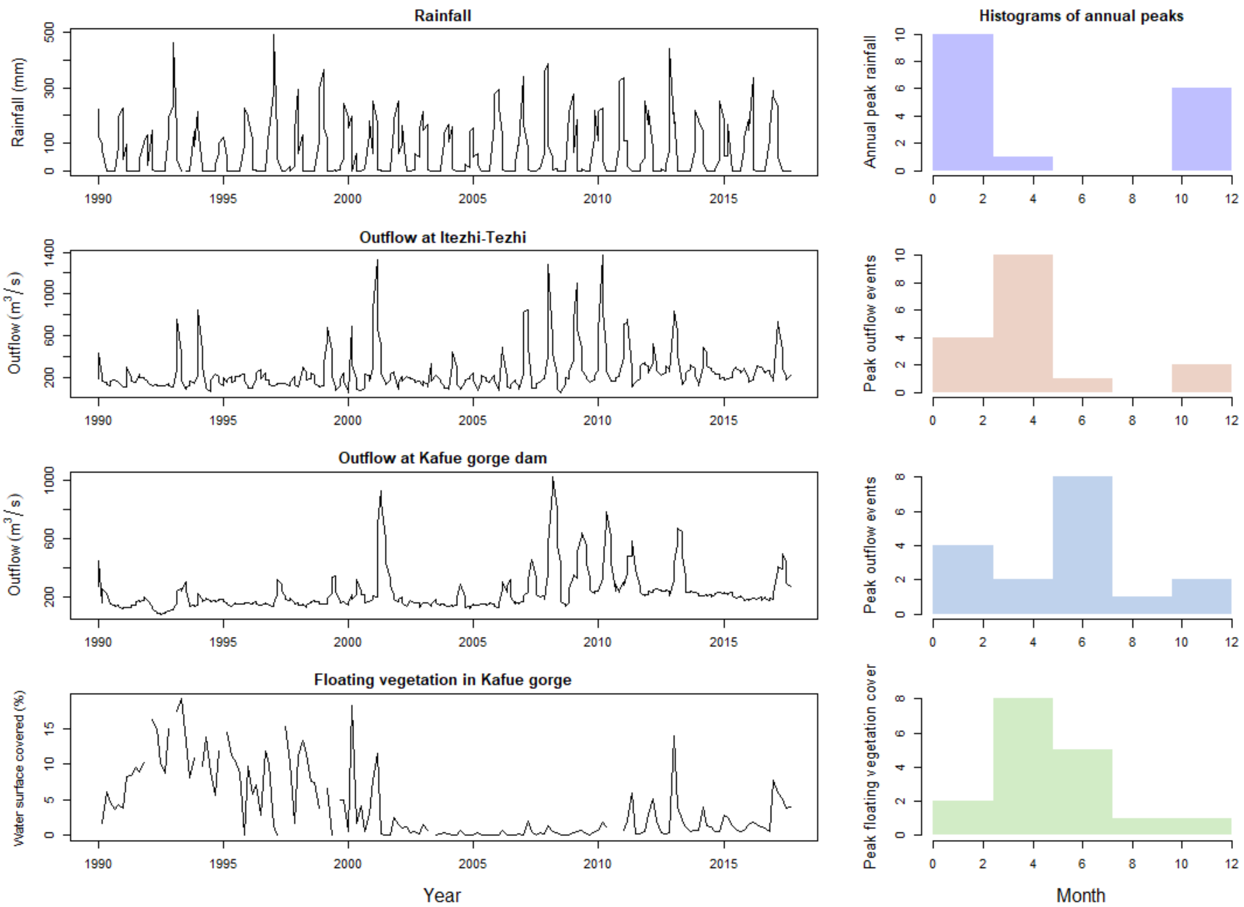

Figure 150 – Time series and peak histograms for rainfall and outflow at Itezhi Tezhi and Kafue gorge dams (ZESCO station data) and percentage of floating vegetation coverage in the Kafue gorge reservoir (LANDSAT time series processed in Google Earth Engine).

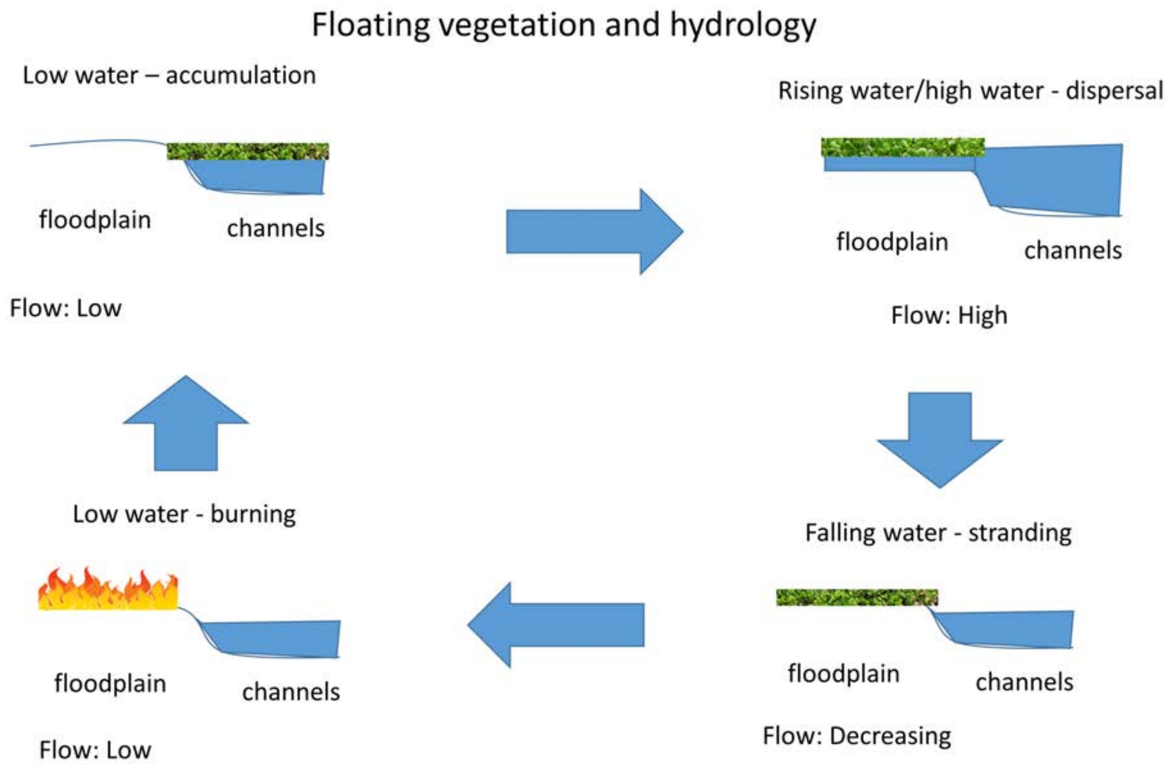

Figure 151 – Conceptual diagram of the seasonal cycle of water hyacinths in the Kafue river system

Our long-term observations show that the effect of plant removal interventions is limited in time and extent, as long as sufficient nutrients and stagnant water are available. Even biological control mechanisms are in vain, if one invasive species gets replaced by another that occupies the same niche. If nutrient inputs cannot be reduced, flow management through controlled flooding and dam releases might be the most effective way in controlling the spatial extent of floating vegetation coverage. For the Zambezi Delta, the flushing of stagnant waterways through a major release of water from Cahora Bassa has resulted in a 10-20% reduction in cover of invasive floating vegetation (Beilfuss and Davies, 1999).

6.2 OMO-TURKANA BASIN

6.2.1 Ecosystem management scenarios

Protected area management

It is unknown what the governmental strategies for conservation in the OTB are. The World Database of protected areas (UNEP-WCMC and IUCN, 2018) shows a relatively dense coverage of protected areas, largely covering the key conservation areas described in deliverable D2.1, but it is unclear how far they are implemented (Figure 152). Instead, evidence from satellite imagery shows that for example the Kuraz sugar development is taking place within both the Omo National Park and the Tama Wildlife Reserve (Figure 153). In this case a degazettement or a shift of the boundaries must have happened, which is not yet reflected in the internationally available World Database of Protected areas. The Environmental Impact Assessment report (EIA) for the Kuraz Sugar Development Project (Ejigayehu Global Trading and Development Consultancy PLC, 2017) mentions that Omo National Park will be impacted by the sugar plantations but does not provide any details, how this will affect the official delineation of national park borders and how the impacts will be mitigated.

The most notable recent addition to the set of protected areas in the upper catchment is the Kafa UNESCO MAB Biosphere Reserve (Dresen, 2015) aiming to link sustainable food production, tourism and conservation across the landscape. Management and conservation of shared water resources and ecosystems in the Omo-Turkana catchment require a political and legal framework that goes beyond national interests and crosses borders. Past conservation measures in the region such as the instalment of national parks have included evictions and resettlement (Turton, 2011), which often led to alienation of local populations, despite the shared interests of maintaining ecosystem services.

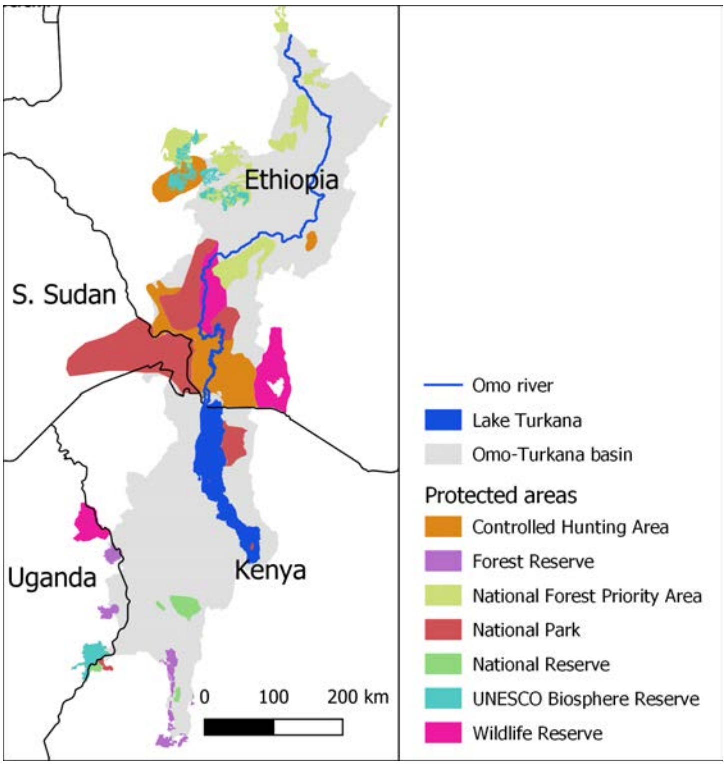

Figure 152 – Overview of different types of protected areas in the OTB (UNEP-WCMC and IUCN, 2018)

Environmental flow releases

The Omo River is a major lifeline that brings water and nutrients to the extremely dry lower Omo valley and Lake Turkana in Kenya. Local communities depend on seasonal floods to enrich the floodplains where cattle graze and people cultivate their fields. Therefore, the Environmental Impact Assessment of the Gibe III dam proposes annual environmental flow releases to mimic natural flood patterns (Sogreah, 2010).

The stated target value is to reach 1600 m^3s^{-1} as a peak annual discharge at the inflow to Lake Turkana. Different scenarios are evaluated to reach this target (Sogreah, 2010): Releases between 1200 and 1400 m^3s^{-1} for 10 days during peak flows in the rainy season. This would require the release of about 500 through the spillgates. Yet, this approach has been criticized as too short to achieve the same benefits as natural floods and as too costly for hydropower. It is unclear, which of these management scenarios has been endorsed by Ethiopian decision-makers.

Floods can be both a blessing and a curse. Environmental flows should ideally range from high to low, to get maximum benefits. Yet, the impacts of extremes—floods and droughts—are also associated with hazard and risks for people. Consequently, there is a potential dilemma: If a free-flowing river causes death and destruction, it is a natural disaster. If a flood released from a dam does the same, somebody is responsible for it. Living and working in flood plains has always been a risk: in 2006 flash floods devastated large areas of the lower Omo valley, causing many deaths (https://www.independent.co.uk/news/world/africa/floods-threaten-tribes-in-ethiopias-omo-valley-

412376.html). At the same time the benefits of floods are often unquantified and largely unrecognized. Therefore, dam managers may, quite understandably, hesitate to release high environmental flows (that is, controlled floods), as they do not want to risk being accused of threatening lives and properties downstream. What's more, as more and more people settle on floodplains, in part because flooding is reduced by dams, the need to prevent destructive floods grows.

Once humans dam a river, decision making about flood releases gets very complex. Only a direct link with stakeholders can help dam operators adjust flows to the actual needs and location of the people living below the dam. Flood warning systems are essential. In remote regions, such as the Lower Omo Valley, where it would be difficult to warn all potentially affected people in time, it is important that the timing of the flood is reliable and aligns with the natural pattern of seasonal flooding depending on amounts of rainfall, so that people are prepared.

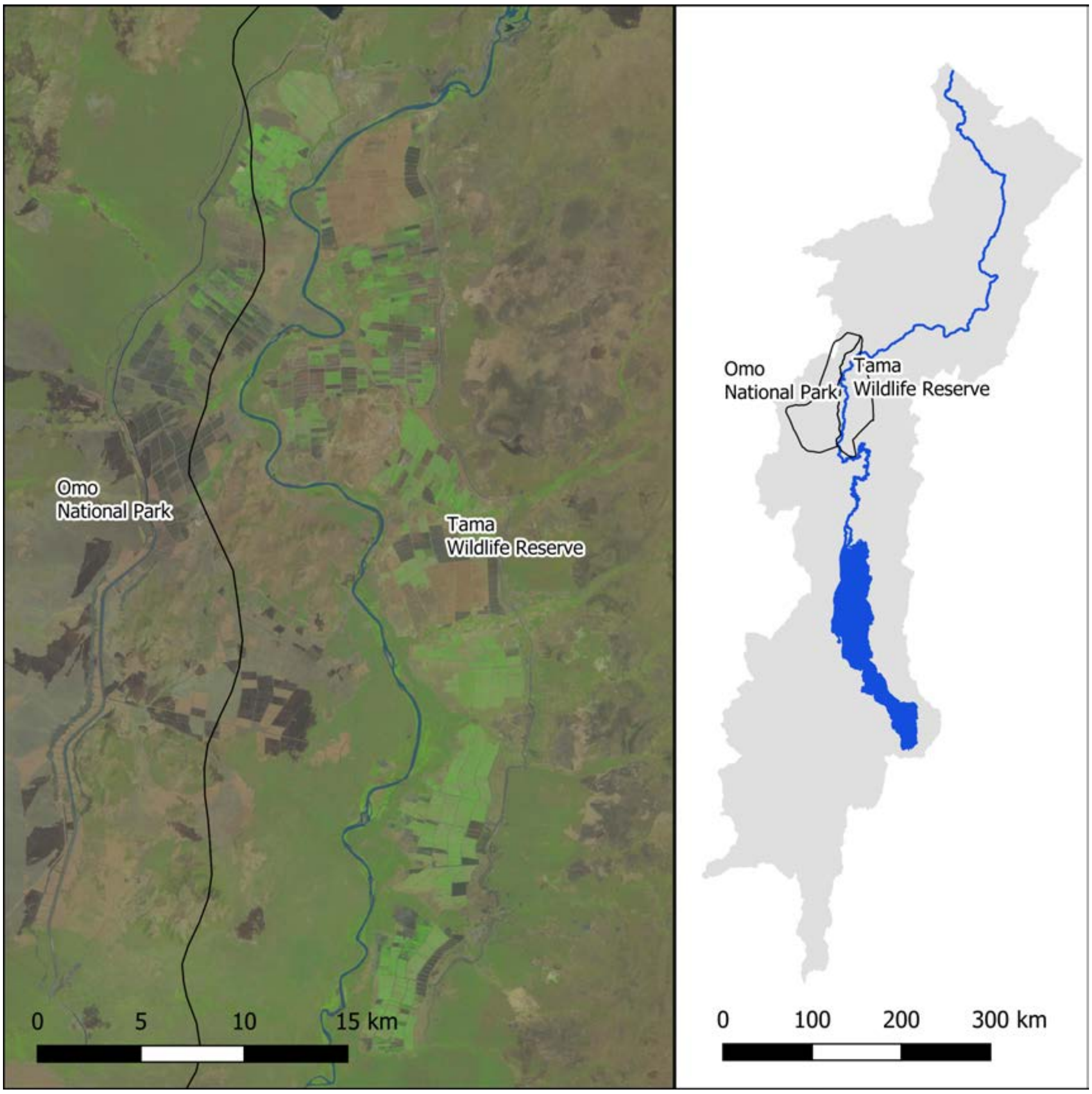

Figure 153 – State of the Kuraz sugar development area (rectangular patterns) as seen on a LANDSAT image taken on 30/01/2019 and the overlap with two protected areas (UNEP-WCMC and IUCN, 2018).

Schemes to maintain flood recession agriculture

Alternative suggestions instead of environmental flows are focused on maintaining flood recession agriculture. One plan was to build a weir above the inflow to lake Turkana to be able to simulate floodings in the lower Omo (Sogreah, 2010). Yet, this doesn't take into account the requirements for regular peak inflows into Lake Turkana which are of high importance for fisheries (Gownaris et al., 2015).

Field observations have shown that the Ethiopian government is providing pumps to farmers who previously practiced flood recession agriculture and are now potentially affected by reduced flooding dynamics due to Gibe III dam. Pumps can replace the lack of water in the floodplains, however, the amounts of sediment that a pump transports is probably much less than during a natural flood. This will result in reduced amounts of available nutrients in the floodplains. Additionally, also natural vegetation provides important services to local communities (see section 6.2.2) and the water demand of the overall vegetation cannot be replaced with pumps. The availability of pumped water has the potential to fundamentally change the way people live in that region as they will be able to grow crops throughout the year and could theoretically give up their nomadic lifestyles.

6.2.2 Leaf area index as indicator for water-related ecosystem changes

As described in deliverable D3.4, rivers and lakes in the OTB provide a large variety of ecosystem services from local to global importance. Given the data scarcity in the region, it is impossible to predict for all of them, how they are going to develop in the future.

We chose Leaf Area Index (LAI) as the one indicator that is detectable through remote sensing and that captures the widest range of ecosystem services. Leaf area index derived from remote sensing is an established indicator for vegetation dynamics and forest biomass and has been successfully used in alluvial forests (Tillack et al., 2014). We measured LAI in 10-day intervals based on PROBA-V satellite imagery across the OTB (processed by VISTA). The basin shows strong regional patterns in LAI that can largely be explained with rainfall, following the same seasonality (Figure 154).

Green vegetation measured through LAI represents the primary source of goods and services across Africa (Ribeiro et al., 2008). Especially in the desert regions in the Lower Omo Valley and around Lake Turkana, humans depend largely on livestock grazing, small-scale agriculture and use of forest products. While in the rainy season grass as a feed for livestock is available everywhere, during the dry season the riparian zones of the Omo river provide the “last resort” for local communities to find and grow food (Turton, 1977). With increasing extremes in precipitation patterns under climate change, droughts are expected to occur more frequently in the future and people will depend more on the availability of remaining green vegetation along the river.

We estimated the importance of water availability from the Omo river for riparian vegetation - independent from rainfall. To do this, we compared average LAI measurements across multiple ring buffers around the Lower Omo River (Figure 155). We then compared the LAI within the nearest buffer of 500 m with the ones that are further away and linked those results with rainfall and the modelled streamflow (Figure 156 A, B, C). The seasonal variability of LAI in all buffers is closely linked with rainfall. Yet, areas closer to the river have overall higher values than those further away. We interpret this difference between the curves as the effect of the river. To isolate this effect, we built new curves from the difference between the inner and the outer buffers. The result shows the varying effect of river water availability over time (Figure 156 D). Notably, the effect of the river has been decreasing during the observation period between 2014 and 2019. This can be associated with the reduced water availability due to the filling of the Gibe III reservoir. An expected reduction in streamflow due to large-scale irrigation projects will lead to a reduction in riparian productivity and provision of ecosystem services to local communities.

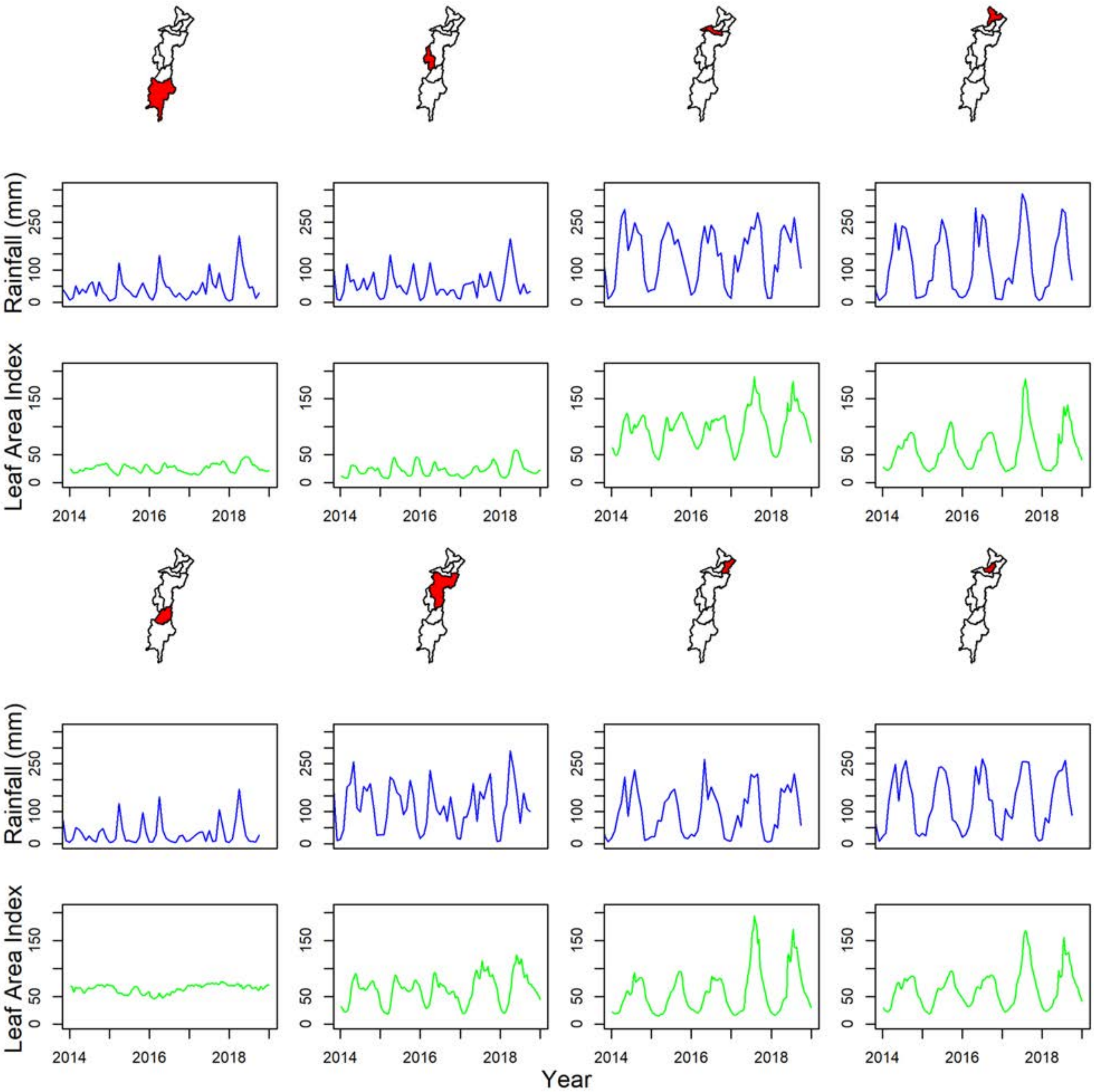

Figure 154 – Sub-basins of the OTB (indicated in red) with time series for rainfall (blue) and Leaf area index (LAI, green).

6.3 CONCLUDING REMARKS

Predicting the responses of ecosystems to human interventions in the future is an extremely complex task. The only thing certain is that dams by default induce severe changes to land and water systems (Rufin et al., 2019) and it is impossible to reverse such changes. Environmental flow regimes are a vehicle to mitigate certain effects of dams and the closer they are to the natural flow regime, the better. That means, they have to be dynamic in the provision of low flows, high flows total amounts and timing and even the rates of change. For both basins, plans for environmental flows are on the table. The example of the Zambezi Delta shows that it is extremely difficult to implement flood releases retrospectively as land uses and settlement patterns change and after a few years, previously flooded areas cannot be flooded anymore without threatening people and their property. Even if the exact procedures and amounts of flows are not fully known, it is advisable to start with flow releases immediately after the start of dam construction. Continuous monitoring needs to be an essential part of such programs in order to better understand resulting processes and adjust flow releases accordingly.

Both climate change and economic development will increase the future competition for water. Wetlands will suffer from the consequences, in addition to ongoing pressures from changes in land-use. In the face of this prediction, even more efforts will be required for wetland preservation as they are important as buffers in the hydrological cycle as well as sinks for organic carbon and therefore have a key role in counteracting the effects of the increase in atmospheric CO_2 causing climate change (Junk et al., 2013).

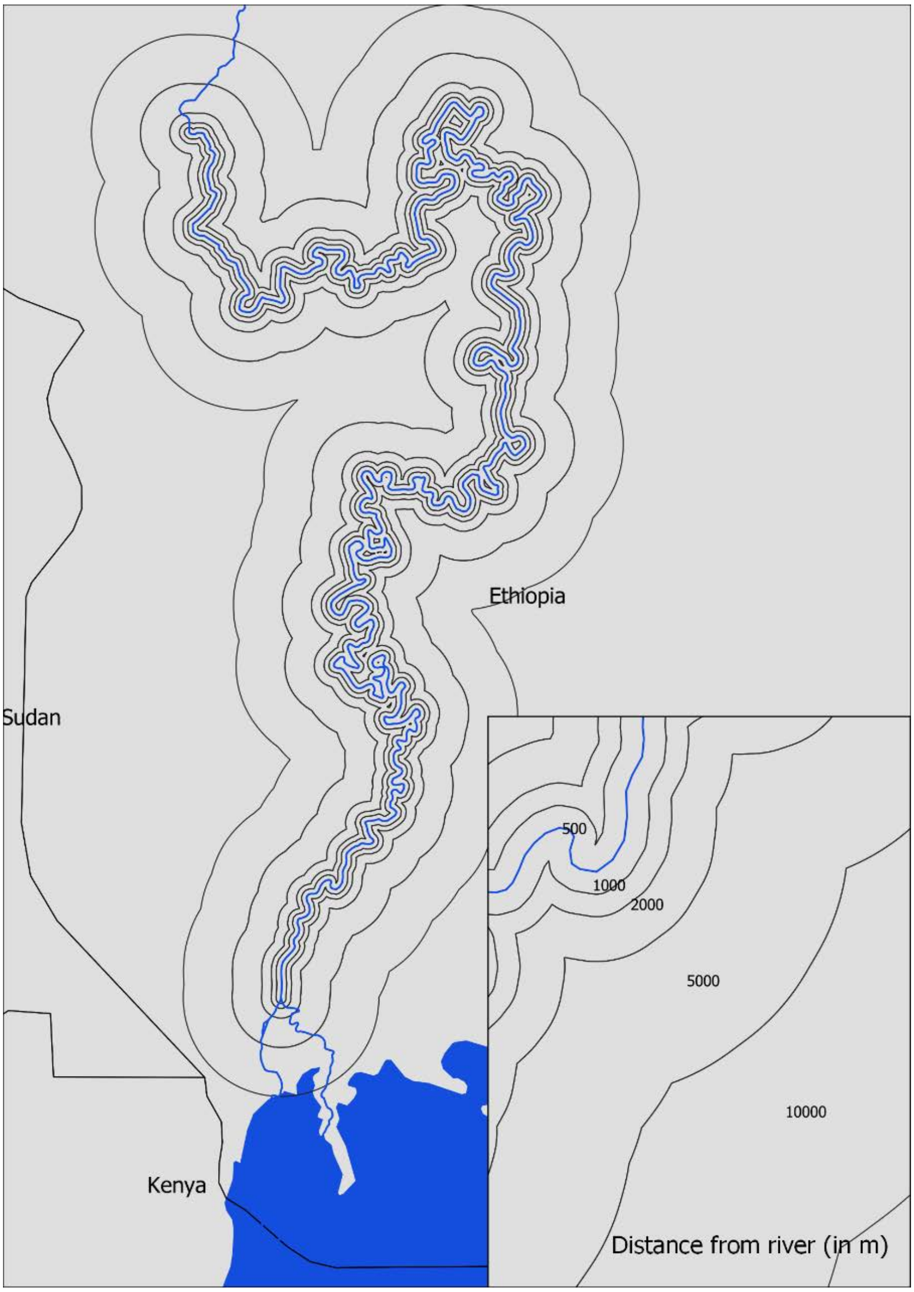

Figure 155 – Buffers in varying distance around the Lower Omo River.

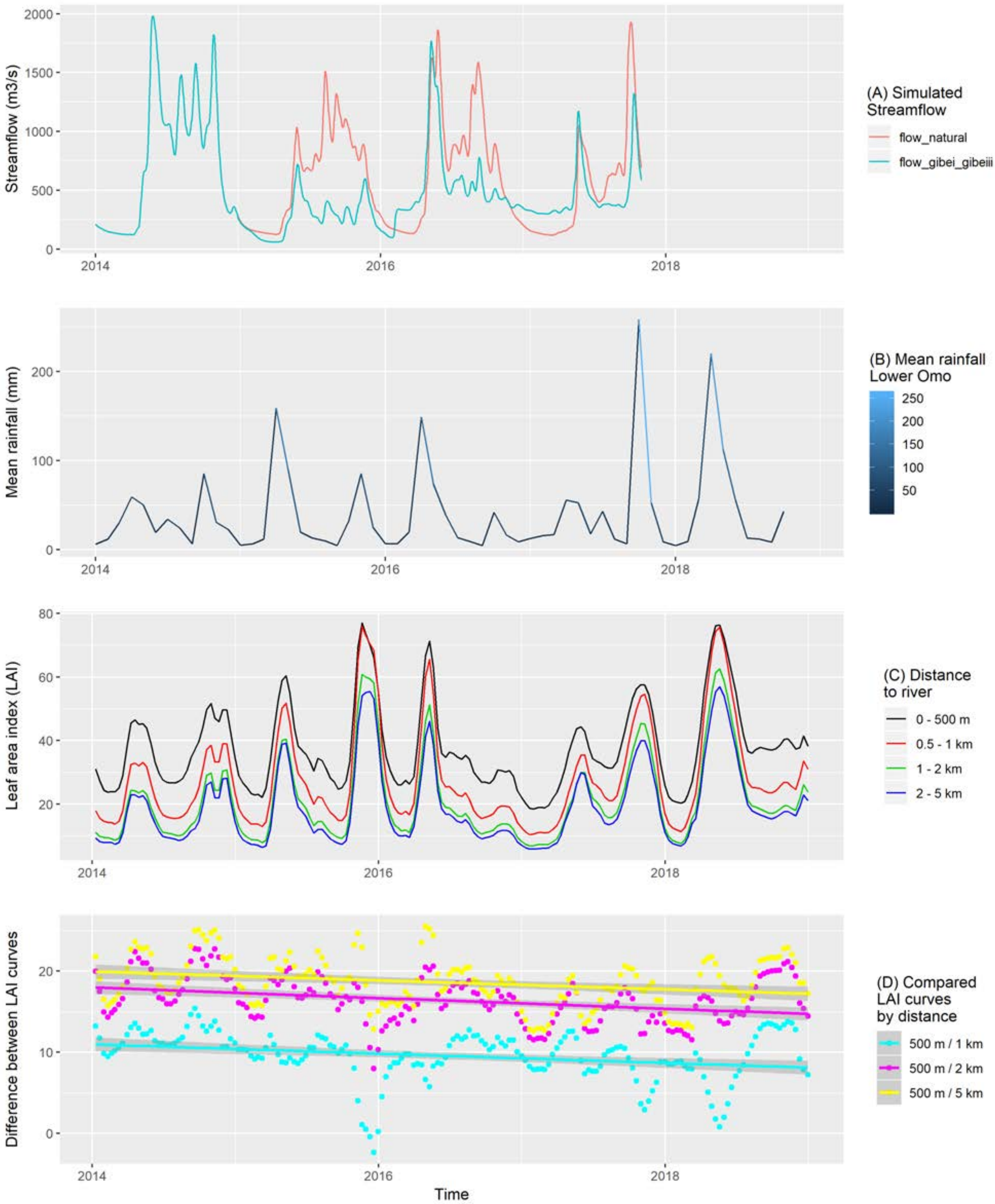

Figure 156 – Comparison between time series of streamflow, rainfall and leaf area index in the Lower Omo region. (A) Simulated daily streamflow from the DAFNE Topkapi model; (B) Mean monthly rainfall with 5 km distance of the Lower Omo from the CHIRPS dataset (Funk et al., 2014); (C) Weekly Leaf Area Index (LAI) from PROBA-V imagery averaged across buffers with indicated distances (Figure 155); (D) Difference between the curves in (C), comparing the black curve with the two other curves (with regression line).

7. INSTITUTIONAL FRAMEWORK OF WATER GOVERNANCE

Full analysis of the scope and application of the key legal principles relating to the OTB and ZRB are provided in Milestones 4 and 57 (Yihdego and Hawkins 2017, Yihdego and Hawkins 2018), as well as within Deliverable 4.4 (Yihdego and Gibson, 2018). Therefore, while a brief outline of the legal principles relevant to the OTB and ZRB will be provided here for clarity, emphasis will be placed on some of the key drivers which could influence governance frameworks, as well as potential pathways for future reform.[6]

7.1 KEY LEGAL PRINCIPLES AND RULES AS DRIVERS

The principal agreement covering the governance of international freshwater resources is the Convention on the Law of Non-Navigational Uses of International Watercourses (UNWC).[7] The agreement is formed of both substantive and procedural obligations. The key substantive principles provided within the UNWC are:

a) Equitable and reasonable use (Article 5)
b) The obligation to prevent significant harm to other watercourse states (Article 7)
c) The protection and preservation of ecosystems (Article 20)
d) The prevention, reduction and control of pollution (Article 21) and
e) The general duty to cooperate on the basis of sovereign equality, territorial integrity, mutual benefit and good faith (Article 8).

One of the key provisions which links water governance to other issues within the WEF nexus is Article 6 of the UNWC, which provides a list of factors which should be taken into consideration when determining equitable and reasonable utilisation (Article 5). These factors link to the future drivers being considered within the DAFNE project, such as population, social and economic needs, existing and potential use and conservation and protection of the watercourse. The list of factors provided within Article 6 is, however, non-exhaustive and their consideration may vary on a case-by-case basis. An illustration of the factors which may be taken into consideration is provided in Figure 157. The factors given in Article 6 are of pivotal importance for the DAFNE project and the development of water governance frameworks which are able to consider and carefully balance the trade-offs within each of the respective riparian states. Cooperation is also vital for the implementation of Article 6, as it is necessary for decision makers to have a complete picture of each of the factors across each of the basin states and agree on an equitable share of water resources.

The duty to prevent significant harm, contained in Article 7 of the UNWC, is the second most notable rule of international water law. The principle states that 'watercourse states shall, in utilising an international watercourse in their territories, take all appropriate measures to prevent the causing of significant harm to other watercourse states'. The definition of harm under the rule is has been understood to include both water and non-water related interests.[8] Therefore, it is vital to ensure that any new or planned uses of a watercourse take this principle into consideration.

In addition to the substantive rules, a number of key procedural rules exist within the UNWC, including the general obligation to exchange information and detailed notification and consultation requirements (Articles 11-19). Planned measures are generally understood as intended projects or programmes which 'may have significant adverse effect on other watercourse States'.[9] Significant emphasis is also placed on institutional mechanisms for cooperation, as detailed within Article 8(2):

> 'In determining the manner of such cooperation, watercourse States may consider the establishment of joint mechanisms or commissions, as deemed necessary by them, to facilitate cooperation on relevant

[6] Analysis of national level law and policies will also not be included within this chapter, details regarding such frameworks can also be found in Milestones 4 and 57 and Deliverable 4.4.

[7] UN Convention on the Non-navigational Uses of International Watercourses (UNWC) (36 ILM 700; signed 21 May 1997; in force 17 August 2014). Hereinafter UNWC.

[8] Owen McIntyre, "Benefit-sharing and upstream/downstream cooperation for ecological protection of transboundary waters: opportunities for China as an upstream state" Water International (2015) 41 (1) 54

[9] UNWC, Article 12

measures and procedures in light of experience gained through cooperation in existing joint mechanisms and commissions in various regions.'

The importance of joint or shared mechanisms for cooperation will be considered in subsequent sections.

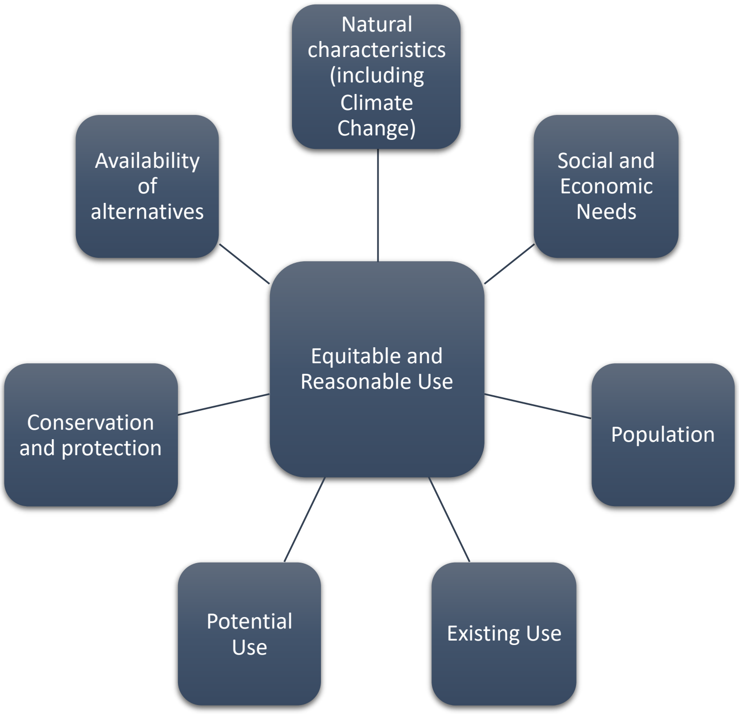

Figure 157 – Factors to be taken into consideration

Within the ZRB, only Namibia has ratified the UNWC. However, the majority of provisions within the UNWC are replicated within the SADC Revised Protocol on Shared Watercourses (SADC-PC) which has been ratified by all ZRB states, except Zimbabwe and Angola, who have signed the agreement. Neither Ethiopia or Kenya have ratified the UNWC, however both states have demonstrated support for the key principles established within the agreement, thorough other frameworks, as will be discussed later. Most notably, the main substantive principles and rules of international water law enshrined in the UNWC are considered as reflections of customary international law, hence, applicable to all riparian states in the world. Given that the UNWC is a framework Convention, however, a successful and effective watercourse governance requires a specific agreement that suit a particular river basin.

7.2 LAW AND GOVERNANCE IN THE ZAMBEZI BASIN

7.2.1 Overview of Basin Frameworks

Underpinning the governance of the ZRB is the SADC-PC, which, as stated, largely replicates the provisions contained within the UNWC. In some cases, the SADC-PC goes further than the UNWC, for instance, Article 3(8)(a)(ii) adds environmental needs of the watercourse states to the list of factors which should be considered in the utilisation of shared watercourses. This is important, as it extends beyond watercourse states, making the environment a legal actor, and recognising environmental needs. In addition to the SADC-PC, the SADC has adopted several policies for the management and development of regional water resources. The 2005 Regional Water Policy for the SADC (SADC, 2005) was developed in order to further the implementation of the SADC-PC. In 2006, the Regional Water Strategy was formed to provide a framework for implementing the SADC-PC and the Policy. The SADC has also produced a number of guidelines for transboundary cooperation, including the 2010 SADC Guidelines for Strengthening River Basin Organisations (SADC, 2010), the 2012 Regional Infrastructure Development Master Water Sector Plan (SADC, 2012) which guides the implementation of-cross border infrastructure projects. The most recent, Regional Strategic Action Plan for Integrated Water Resources Development was approved in 2014 (SADC, 2015) and presents a number of targets for the region.

A long history of cooperation exists within the ZRB.[10] As detailed within Deliverable 4.4, the main legal frameworks for the ZRB are:

- 1987 Agreement between Zambia and Zimbabwe Concerning the Utilisation of the Zambezi River (ZRA, 1987) (Zambia and Zimbabwe)
- 1987 Agreement on the action plan for the environmentally sound management of the Common Zambezi River System (ZACPLAN, 1987) (Signed by Botswana, Mozambique, Tanzania, Zambia and Zimbabwe)
- 2004 Agreement on the Establishment of the Zambezi Watercourse Commission (ZAMCOM, 2004) (Ratified by all except Malawi, which has signed)

ZAMCOM has also put in place a number of additional procedures and rules contained within various agreements. For instance, the Rules and Procedures for Sharing Information and Data,[11]and the 2017 Procedures for Notification of Planned Measures.[12] ZAMCOM is also in the process of finalising the development of the Strategic Plan for the Zambezi Watercourse (ZSP) which is expected to be in place by early 2019. The ZSP is aims to enhance cooperation among the ZRB states to bring joint benefits of energy and food security, amongst others.[13]

7.2.2 Strengths and Weaknesses

As stated, the ZRB has in place a number of comprehensive legal frameworks. The SADC-PC effectively puts in place the key legal principles of international water law at a regional level. However, what is less clear, is the extent to which these principles are consistently implemented at a national level. It is also not clear whether the procedural rules and agreements put in place are strictly adhered to in terms of implementation. As stated by the SADC itself ‘There is no effective link between the SADC Secretariat, the SADC National Committees and relevant key stakeholders who are supposed to oversee and effectively implement SADC activities and programmes at national level’.[14] There has been reluctance among the Zambezi States to take a regional perspective towards energy generation projects, with the majority of such arrangements continuing to operate bilaterally. The aim is that once countries have reached a stage of adequate energy generating capacity in order to fulfil domestic need, that the Southern African Power Pool (SAPP) could be used in order to trade energy. Regional cooperation is also needed with regard to agriculture in order to provide greater stability in situations of drought, which could be put in place through trade in virtual water with regards to irrigation. Both the SAPP and virtual water will be discussed in subsequent sections. Further, the key drivers of change which are likely to take place within the ZRB are not widely acknowledged within the frameworks. The likely impact of population growth and climate change upon the ZRB will necessitate even more flexible frameworks which take into consideration the changing dynamics across the basin.

[10] Early agreements were formed in the imperial era and largely focused on the demarcation of national boundaries, put in place by colonial governments, while agreements which came slightly later were largely bilateral. These agreements are nonetheless important to acknowledge the history of cooperation within the basin. For a full analysis of all of the agreements formed within the ZRB, *see* Jonathan, L., P. Zebediah, S. Vladimir & S. Davison. 2017. The Zambezi River Basin: Water and sustainable development. Taylor and Francis.

[11] Zambezi Water Course Commission, Rules and Procedures for Sharing of Data and Information Related to the Management and Development of the Zambezi Watercourse, adopted by the ZAMCOM Council on 25th February 2016, effective 26th of March 2016

[12] ZAMCOM, “Procedures for Notification of Planned Measures” (Zambezi Watercourse Commission, adopted by the ZAMCOM Council on 23rd February 2017

[13] See, ZAMCOM, Strategic Plan for the Zambezi Watercourse http://www.zambezicommission.org/sites/default/files/publication_downloads/zsp.pdf Global Water Partnership, “Enhancing Cooperation through the Strategic Plan for The Zambezi Watercourse”, 12th July 2018 https://www.gwp.org/en/GWP-SouthernAfrica/About-GWP-SAF/more/News/enhancing-cooperation-throughthe-strategic-plan-for-the-zambezi-watercourse/

[14] SADC, Desk Assessment of the Regional Indicative Strategic Development Plan 2005-2010, available at https://www.sadc.int/files/4413/5292/8372/Regional_Indicative_Strategic_Development_Plan_Desk_Assessment.pdf

7.3 LAW AND GOVERNANCE IN THE OMO-TURKANA BASIN

7.3.1 Overview of Basin Frameworks

As stated in Milestone 57 (Yihdego and Hawkins, 2018), neither Kenya nor Ethiopia have ratified the UNWC, meaning that the convention does not bind these states. However, as previously stated, the UNWC's substantive key principles are frequently regarded as codifying customary international law and are replicated in other global instruments relevant to transboundary freshwater.[15] The OTB does not have the same comprehensive regional agreements as have been developed in the ZRB. However, the East African region is progressively moving towards the formation of similar arrangements. For example, the progression of the frameworks formed under the Intergovernmental Authority on Development (IGAD) are likely to be of significant importance. In 2012, the IGAD Inland Water Resources Management Programme (INWRMP) was developed after water scarcity was linked to conflicts within the region. This programme subsequently led to the formation of a Regional Water Resources Policy in 2015 which provides general guiding principles which are drawn from international water law. The policy also puts in place provision for a number of regional and national workshops to ensure stakeholder participation. IGAD is also currently in the process of finalising a Regional Water Resources Protocol. On the basis of the current draft, the Protocol will aim to:

> '(a) to promote and facilitate the establishment of agreements on, and institutional arrangements for, the management of international river basins and transboundary aquifers and aquifer systems; (b) to promote the harmonization of policies and legislation on the use, development, protection, conservation and management of international river basins and transboundary aquifers and aquifer systems, and of the resources related thereto, and; (c) to promote research, technology development and capacity building so as to facilitate the use, development, protection, conservation and management of inter- national river basins and transboundary aquifers and aquifer systems, and of the resources related thereto.'[16]

Many of the provisions are expected to be taken from the UNWC and from the Nile Basin Cooperative Framework.[17]

7.3.2 Strengths and Weaknesses

The agreements in place within the OTB are not as elaborate as those of the ZRB. However, positive developments are being made, particularly with regard to the creation of regional frameworks through the IGAD, as well as power sharing agreements within the OTB. The main weakness is the lack of a basin level institutional mechanism for joint and cooperative management of the shared watercourse, although Kenya and Ethiopia have close socio-economic ties and cooperation including on water-related benefit sharing endeavours. However, it is possible that the creation of a permanent framework could be built from the IGAD Water Protocol, once it is in place. It is therefore possible that lessons regarding the formation and implementation of a cooperative framework within the ZRB could be drawn on within the OTB.

7.4 DRIVERS OF CHANGE

While the formation of legal frameworks including key legal principles and their implementation through effective institutional mechanisms are vital for the good governance of shared watercourses, those frameworks must also be adaptive to change. Within both the ZRB and the OTB, climate change and population growth will likely impact water availability and change water use in the future.

[15] For instance, the 1992 United Nations Economic Commission for Europe Convention on the Protection and Use of Transboundary Watercourses and International Laws (UNECE Water Convention).

[16] Marcella Nanni, "Water Challenges in the IGAD region: towards new legal frameworks for cooperation", Water International (2016) 41(4) 635-651

[17] ibid.

7.4.1 Climate Change

As stated by Verschuuren, 'the impacts of climate change on freshwater systems are so vast that they are almost impossible to grasp', according to IPCC predictions, current practices of water management are unlikely to be enough to reduce the impacts of climate change on the reliability of water supply, health, energy, flood risk and aquatic ecosystems.[18] Decreasing water levels and increasing demand have the potential to upset the current framework of equitable and reasonable use, causing tension among states. Therefore, new strategies for governance must be formed, which take into consideration the future drivers and potential scenarios of change within shared river basins.

The establishment of joint bodies or similar cooperative management institutions are vital to ensure the implementation of such measures. This should be linked to integrated river basin planning which allows continuous monitoring of changes within the river basin and the allocation of water between users. The UNECE Convention adopted the Guidance on Water and Adaptation to Climate Change in 2009[19], providing detailed guidelines for adaptation measures. These guidelines will be discussed further in subsequent sections in relation to future recommendations. In addition to flood prevention and mitigation, such plans must also cover the possibility of water scarcity and droughts, putting in place appropriate measures relating to altering dam operations, adaptation schemes and water storage.

With regards to the Zambezi River Basin (ZRB), the natural variability of the river is impacted by a number of large dams, in particular the Cahora Bassa and Kariba, as well as the Itezhi-Tezhi and Kafue Gorge on the Kafue tributary. Existing and planned hydropower operations, as well as expanded irrigation, also dominate the discourse of the Omo-Turkana Basin (OTB). [20] While future climate predictions are largely estimations, the vulnerability of hydropower to climate change has been widely discussed within the literature.[21] In addition, climate risks have been stated as high within the ZRB; in 2001 the Intergovernmental Panel on Climate Change (IPCC) categorised the Zambezi as the river basin exhibiting the 'worst' potential effects of climate change among 11 major African basins, due to increasing temperatures and decreasing rainfall.[22] It is therefore likely that hydropower operations will have to change over time, with evolving weather patterns. In relation to governance, this means that rigid agreements will be difficult to implement. Instead, what should be put in place are cooperative frameworks which are able to be adaptive to change. Within the OTB, it is also likely that traditional pastoralist communities within the basin will be impacted by changing climatic patterns. As such, within the formation of a river basin plan for the OTB, due regard should be given to the changes which could occur, ensuring that potential alternative options are given to key stakeholders, such as indigenous communities.

7.4.2 Population Growth

Changes in natural resources often result in increased mobility, it is therefore vital that any governance frameworks for the management of shared resources take into consideration the possibility of migration and therefore redistributed use of water resources, in addition to population growth.[23] Increasing demand from population growth is an important factor within both the ZRB and OTB.[24]Within the SADC region, the population living in urban areas has increased from 33% to

[18] Jonathan Verschuuren, Climate change adaptation and water law, in J. M. Verschuuren (Ed.), Research Handbook on Climate Change Adaptation Law, 250-272

[19] UNECE Guidance on Water and Adaptation to Climate Change (2009) ECE/MP.WAT/30

[20] Enyew BD and Ronald Hutjis, 'Climate Change Impact and Adaptation in the South Omo Zone' Journal of Geology and Geophysics (2015) 4 (3)

[21] Xiao Zhang et al., 'Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development, Renewable Energy (2018) 116 827-834

[22] Richard Beilfuss. A Risky Climate for Southern African Hydro: Assessing Hydrological Risks And Consequences For Zambezi River Basin Dams. *International Rivers (September)*. 2012;1–5. See also Luxon Nhamo et al. 'The Water-Energy-Food Nexus: Climate Risks and Opportunities in Southern Africa' Water (2018) 10

[23] ibid.

[24] For details regarding population growth see Deliverable 4.3, pg. 20 and 21

40% in the last decade.[25]Forecasts of population growth in Ethiopia estimate the population doubling before 2035.[26] Significant portions of the population in both the ZRB and OTB continue to live in conditions of relative poverty and energy insecurity and the demographic structure of both basins is fragmented. It is therefore essential that future population projections, including urbanisation, change in livelihoods, and therefore potential changes in water use, are taken into consideration in the planning of basin level governance frameworks.

While there are many methods of adaptive management on shared watercourses, benefit sharing has been utilised within both the ZRB and the OTB, to different extents. The inclusion of benefit sharing within cooperative frameworks can allow states greater flexibility to adapt to future drivers of change by extending the benefits from the watercourse beyond quantified water availability.

7.4.3 Benefit Sharing & Virtual Water

Benefit sharing can be used as a mechanism to share water related benefits, as well as to eliminate, mitigate or compensate for the actual or potential harm to a state, as a practical implementation of the 'no harm' rule. The theory behind benefit sharing is that the optimal economic, social and environmental benefits are derived from water use within the basin. The key point with regards to benefit sharing is not that the flow of water or ecosystem functions must be shared *per se* but rather the benefits which arise from their use. This may take the form of compensation which can be given in many forms including cash payments, capacity building and training, frameworks or allowances relating to land rights, technology transfer, reduced cost energy or other ecosystem services as appropriate within the specific river basin context. Benefit sharing can therefore operate a cost-benefit paradigm and contribute towards the reduction of poverty, empowerment of local groups, contribute towards food and energy security and work towards the overall creation of a WEF nexus approach.

Benefit Sharing can also be linked to the concept of virtual water sharing. The idea of trading in virtual water is the exchange of trading in goods which have 'embedded water'. The concept goes slightly beyond both benefit sharing and the WEF nexus approach, as it can also include industrial items and services. Unlike benefit sharing, which traditionally operates at a basin scale, virtual water can operate regionally or even globally.

A history of benefit sharing exists within the ZRB, particularly with relation to power sharing agreements as illustrated by the ZRA, which states that all energy produced from the Kariba Dam should be shared equally (Article 23). Power sharing agreements are also in place with relation to the OTB (although the content is at present unknown) and positive views towards benefit sharing have also been illustrated by Ethiopia with regards to hydropower in the Nile Basin.[27]

At a regional level, the SAPP was established through an intergovernmental Memorandum of Understanding, signed in August 1995.[28] The mandate of SAPP is to provide non-binding regional masterplans to guide electricity generation and transmission infrastructure delivery, but with countries retaining the right to development and implement their own national plans. The mandate of the SAPP is guided by the SADC Protocol on Energy which was signed in 1996. A revised intergovernmental memorandum of understanding (IGMOU) was also signed in 2006 in order to allow new members to join. It makes clear that regional cooperation should be enhanced. As it currently stands there is no clear policy to interconnect the SADC-PC with the Energy Protocol. It is possible that this cooperative energy framework could also be linked to water governance strategies, and

[25] Barbara Schreiner, 'Mechanisms to Influence Water Allocations on a Regional or National Basis' in Annal Entholzner and Charles Reeve (Eds.) 'Building Climate Resilience through Virtual Water and Nexus Thinking in the Southern African Development Community', Springer 2016

[26] Federal Democratic Republic of Ethiopia, Ethiopian Electric Power, Koysha Hydroelectric Project, Environmental and Social Management Plan, March 2017

[27] See Rawia Tawfik, "The Grand Ethiopian Renaissance Dam: a benefit sharing project in the Eastern Nile? Water International (2016) 41(4) 574-592

[28] The SAPP is governed by five agreements, *see* SAPP Governance http://www.sapp.co.zw/sapp-governance

approached from the perspective of benefit sharing, however there do not appear to be any plans to do so at present. [29]

Overall, despite the formation of such progressive plans, the same progress in implementation is not present. Improvements still need to be made in terms of working towards the optimisation of resources to increase productivity. Projections of future drivers demonstrate the need for increasingly integrated regional strategies and plans, however, as countries each maintain the right to develop and implementation national plans, the issue of political sovereignty over resources remains strong.

7.5 RECOMMENDATIONS AND FUTURE PATHWAYS FOR GOVERNANCE

As stated within the UNECE Guidance Note on Water and Adaptation to Climate Change, what is essential for 'good governance' is for there to be effective coordination between government and society, society and science, and government and science.[30] This model supports participatory governance at all levels. However, in order to be effective, the institutional structures underpinning such interactions must be comprehensive, coordinated and transparent in the sharing of data and knowledge. The pathways discussed below build upon those developed within the Water Governance Model in Deliverable 4.4. It should be noted that the 'pathways' detailed below are not alternative possibilities, they detail a number of paths which will assist in the formation of a good water governance framework.

Pathway 1: Strengthened Implementation of Key Principles of Water Governance

Key principles need to be more strongly incorporated within the national frameworks of both the ZRB and OTB (*see* Deliverable 4.4) in order to improve coherence between national, regional and international level frameworks. However, this must be done in a manner which continues to allow for sufficient flexibility in order to adapt to projected or unforeseen change. As detailed within the UNECE Guidelines, the following recommendations should be incorporated into water governance frameworks, in order to ensure that future drivers, such as climate change and population growth, can be appropriately managed.

- Transboundary agreements, or the regulations which implement them, should be able to allow for variations in water availability.
- In the negotiation of basin and riparian agreements, historical, current, future and possible extremes should be considered.
- Special provisions should be included in order to adapt to special circumstances, such as severe droughts. Such provisions can be balanced by the inclusion of a 'compensation' mechanism, once the special circumstance is no longer in effective. For instance, water allocations could be reduced during a drought period, but greater allocations made following the droughts end. Compensation mechanisms can also extend beyond the water sector, tying in with the potential for virtual water trading or benefit sharing arrangements.
- Mechanisms for the prioritisation of water use under drought conditions should also be included.
- It is also possible to include annual periodic reviews of water allocation arrangements to ensure that new circumstances are continuously taken into consideration.

Traditionally 'fixed' legal frameworks and institutional arrangements should therefore move progressively towards more flexible and adaptive systems. However, in doing so, the basic principles of international water law should continue to serve as the foundation for such frameworks, in order to ensure a degree of consistency.

[29] For discussion regarding Climate Change and the SAPP, see Randall Spalding-Fecher et al. 'Climate Change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wise impacts and policy implications' Energy Policy (2017) 103 84-97

[30] UNECE Guidance on Water and Adaptation to Climate Change (2009) ECE/MP.WAT/30

Pathway 2: Creation/Implementation of Comprehensive Institutional Mechanisms for Joint Management of Shared Watercourses

As detailed within Deliverable 4.4, a number of good practice principles were created under the UNECE Convention which can be utilised in the formation of joint mechanisms.[31]While joint mechanisms do exist within the ZRB, there is little emphasis on adaptive capacity at a basin level. It is also essential that in the formation of cooperative frameworks, the adaptive capacity of each basin state is taken into consideration. Adaptive governance must also work towards horizontal integration, moving away from traditionally siloed approaches, in harmony with goal of a WEF nexus approach. Vertical integration is equally important, ensuring that decentralised governance structures operate effectively, and that approaches are participatory to local level.

In the Zambezi, the WEF nexus was identified in the Regional Strategic Action Plan (RSAP IV). The action plan recognises the role of the nexus in adapting to the future drivers within the basin, such as population growth and climate variability and change. However, one of the key limitations within both the ZRB and the OTB is the lack of reliable data. In order to be able to establish cooperative frameworks which will be needed for the effective governance of the region going forward, the accuracy of data and the mechanisms through which it is shared must be improved. The capacity of each institution involved within the water, energy and food sectors should be clarified in order to ensure effective interaction can be established. It is only through clear definition of responsibilities and roles that institutional gaps can be identified. This also includes the involvement of all levels of governance, from national to local level.

Pathway 3: Integration with Sustainable Development Goals

While transboundary water governance through a nexus approach is relevant to a number of the Sustainable Developments Goals (SDGs), as detailed within Deliverable 4.4, transboundary water cooperation is particularly critical to achieving SDG 6. Indicator 6.5.2 focuses specifically on transboundary water cooperation, highlighting the urgency of the need to face growing water challenges in a cooperative manner. The indicator measures the proportion of transboundary basin area (river, lake or aquifer) within a country which has an operational arrangement for water cooperation in place. This could take the form of a bilateral or multilateral treaty, an agreement, a convention or any other form of framework which provides for cooperation within a transboundary basin. For the arrangement to be considered operational, there must be: i) a joint body or mechanism in place; ii) at least annual meetings between riparian states; iii) a joint or coordinated water management plan or joint objectives; and iv) at least annual exchanges of data and information. Therefore, it is not enough for a framework or agreement to be in place, it must be possible to demonstrate that it is operational. While SDG 6.5.2 is a positive indicator for measuring some aspects of global water governance, it must also be noted that the indicator does not measure any informal arrangements for water governance. It also does not measure the extent to which such operational arrangements actually contribute to positive outcomes such as reduced conflict or improved water quality. The first report regarding indicator 6.5.2 was published in August 2018.[32] Of the countries within the ZRB, Malawi, Mozambique and Tanzania did not report, while the remaining ZRB countries demonstrated a high percentage of transboundary basins/sub-basins of rivers and lakes covered by operational arrangements. In the OTB, only Kenya reported with a percentage of 35.9.

While it is known that there are at least some operational arrangements in place within all of the ZRB states, the lack of reporting suggests potential constraints in capacity or finance. With regards to the OTB, the relatively low percentage reported by Kenya suggests a need for a greater number or higher level of operation of transboundary arrangements. The creation of a joint framework for the OTB could therefore assist with contributing to the implementation of SDG 6.5.2 for both Kenya and Ethiopia. As previously stated, the differing reporting capacities of states should also be taken into consideration in the formation of joint arrangements and frameworks.

[31] UNECE, Principles for Effective Joint Bodies for Transboundary Water Cooperation under the Convention on the Protection and Use of Transboundary Watercourses and International Lakes, ECE/MP.WAT/50, New York and Geneva (2018)

[32] UN Water, Progress on Transboundary Water Cooperation: Global Baseline for SDG Indicator 6.5.2, 2018

Table 13 – Source: Progress on Transboundary Water Cooperation: Global Baseline for SDG Indicator 6.5.2, UN Water, 2018

Country	Rivers & Lakes Component (%)
Angola	100.0
Botswana	100.0
Malawi	-
Mozambique	-
Namibia	100.0
Tanzania	-
Zambia	76.8
Zimbabwe	76.2
Ethiopia	-
Kenya	35.9

8. SUMMARY OF SCENARIOS AND CONCLUDING REMARKS

The content of this deliverable describes the scenarios that form the basis for the modelling of the WEF Nexus that will be carried out in WP3. Scenarios are combinations of climate change, water, electricity and food demand for each sector (with appropriate co-variation based on viable SSP and RCP combinations for the basins). Climate change scenarios are selected on the basis of time horizon and RCP. The modelling planning session led finally to the combination scenarios listed in Table 14. These will be co-ordinated with the pathways identified in deliverable D5.1. Water, electricity and food demand scenarios will need to be harmonised with the envisaged structural action alternatives (e.g.: a high electricity demand makes sense only for alternatives that foresee the construction of new hydropower systems or the development of alternative electricity production – e.g. wind and/or solar based). In this report, however, a detailed description of the scenario has been detailed, for sake of brevity and clarity, only with respect to the Shared Socioeconomic Pathway (SSP) 2, which represents a middle of the road scenario (see section 2.2.6 and 2.3.6) and is, as of today, often assumed as the most plausible scenario for the next few decades, and with respect to the Representative Concentration Pathway 4.5, which also represents a middle of the road climate scenario corresponding to emissions, technology and population developments that are consistent with the SSP2. The use of these two scenarios will allow investigating the practical implications of connecting a wide variety of sub-models to simulate the WEF nexus in great detail. The resulting integrated modelling approach will be later used also for the simulation of the remaining scenarios listed in Table 14.

Table 14 – Summary of future scenarios as combination of RCPs, SSPs, time horizon, number of ensemble members and pathways to be considered in the WEF Nexus modelling of WP3.

Basin	RCP	SSP	Horizon	Ensemble	# Pathways	
					Structural	*Non Structural*
ZRB / OTB	4.5	1	2060	30	5	10
	4.5	2	2060	30	5	10
	4.5	5	2060	30	5	10
OTB	4.5	2	2100	30	3	5
	4.5	5	2100	30	3	5
	8.5	2	2100	30	3	5
	8.5	5	2100	30	3	5

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APPENDIX 1 – HYDROPOWER PLANT DATA

1.1 POWER PLANTS UNDER CONSTRUCTION

1.1.1 Kafue Gorge Lower - Zambia

Plant Data

General data		**Notes**	**Source**
Country	Zambia		
River	Kafue		
Operator	ZESCO		
Status	CON	To be fully commis-sioned in 2019	Cervigni et al. (2015)
Closure	2019		Cervigni et al. (2015)
Type	Reservoir		
Operating Targets	Hydropower Production		“Kafue Gorge Lower (KGL) Power Station, Zambia” (2015)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Av-erage Altitude [m asl]	1000-1200	Average altitude	African Development Bank Group (2013)
Reservoir data			
Reservoir Area [km2]	0.28		Tilmant et al. (2012)
Reservoir Length [km]	0.378		“Kafue Gorge Lower (KGL) Power Station, Zambia” (2015)
Crest Elevation [m asl]	586		Stenek et al., 2011
Max Depth (Dam Height [m])	62		Tilmant et al. (2012)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	0.0022		Tilmant et al. (2012)
Dead Storage [km3]			
Minimum Operating Level [m asl]	530		The World Bank (2010)
Maximum Operating Level [m asl]	582		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Available		The World Bank (2010)
Level-Surface Curve	Available		The World Bank (2010)

Dam data			
Dam Type	Concrete-face rock fill		"Kafue Gorge Lower (KGL) Power Station, Zambia" (2015)
Number of Spillways	3		Stenek et al. (2011)
Type of Spillways	Radial gates	Radial gated crest according to Tilmant et al. (2012)	Stenek et al. (2011)
Spillway Sill Elevation [m asl]	582		Stenek et al. (2011)
Spillway Capacity [km3/yr]	124.85	164 km3/yr according to Tilmant et al. (2012)	Stenek et al. (2011)
Number of Emergency Spillways	n.a.		
Type of Emergency Spillways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Capacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	560		Tilmant et al. (2012)
Power plant characteristics			
Installed Capacity [MW]	750		Basson (2010)
Number of Turbines	5	Francis turbines	Basson (2010)
Max Power per Turbine [MW]	150		Basson (2010)
Max Discharge per Turbine [m3/s]	97.4	88.3 m3/s according to Tilmant et al. (2012)	Basson (2010)
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capacity [m3/s]	n.a.		
Max Hydraulic Head [m]	182.7		Basson (2010)
Mean Hydraulic Head [m]	173.3		Basson (2010)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	88		Stenek et al. (2011)
KEN	n.a.		
Mean Annual Production [GWh/yr]	n.a.		

Intake Rating Curve	n.a.		
Tailwater Rating Curve	Available		Cervigni et al. (2015)
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	2143.3		Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35		Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62		Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

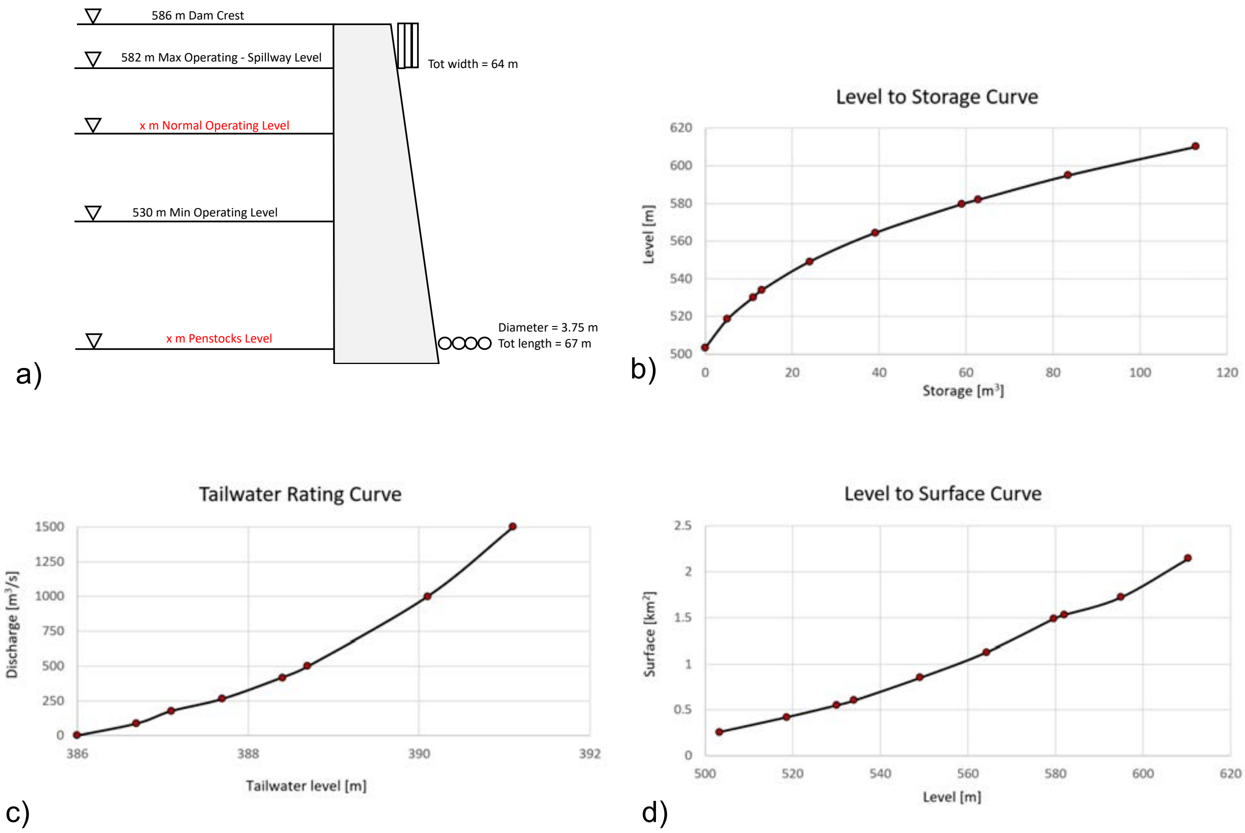

Figure 158 – Kafue Gorge Lower dam feature elevations (panel a) and hydropower plant curves (panel b,c,d). In particular, Panel a shows the existence of 4 penstocks, whose dimensions are 3.75 m diameter each and 67 m length in total.

9.1 PLANNED POWER PLANTS

1.1.2 Ndevu Gorge - Zambia

Plant Data

General data		**Notes**	**Source**
Country	Zambia		
River	Luangwa		
Operator			
Status	Planned		Conlen et al. (2017)
Closure	2022		Construction Intelligent Center (2018)
Type	Reservoir		Conlen et al. (2017)
Operating Targets	Hydropower production		Conlen et al. (2017)
Catchment data			
Catchment Area (natural + diversions) [km2]	92.492	Calculated from watershed analysis	Conlen et al. (2017)
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	1.027	Average altitude	Mr. Chanda (LHPC)
Reservoir data			
Reservoir Area [km2]	1510	At fully supply level of 505 m asl	Conlen et al. (2017)
Reservoir Length [km]	165		Lusaka Times (2017)
Crest Elevation [m asl]	n.a.	17-m high second dam to be built to prevent the primary dam wall to be bypassed according to Conlen et al. (2017)	
Max Depth (Dam Height [m])	n.a.		
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	n.a.		
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	n.a.		
Maximum Operating Level [m asl]	505		Conlen et al. (2017)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		

Level-Surface Curve	n.a.		
Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		
Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	235-240		Lusaka Times (2017)
Number of Turbines	n.a.		
Max Power per Turbine [MW]	n.a.		
Max Discharge per Tur-bine [m3/s]	n.a.		
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	n.a.		
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	n.a.		
KEN	n.a.		
Mean Annual Production [GWh/yr]	n.a.		
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		

Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	n.a.		
Fixed Cost [USD/kW]	n.a.		
Variable Cost [USD/MWh]	n.a.		
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

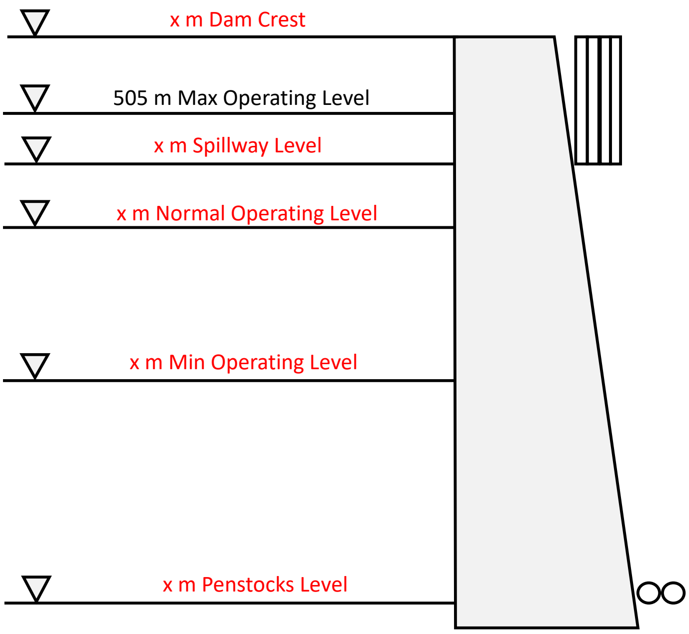

Figure 159 – Ndevu Gorge dam feature elevations.

1.1.3 Muchinga - Zambia

Plant Data

General data		**Notes**	**Source**
Country	Zambia		
River	Mkushi/Lunsemfwa	The Mkushi Dam will be located on the Mkushi River, approximately 6 km upstream of the confluence between Lunsemfwa and Mkushi River. The Muchinga hydropower station will be located on the Lunsemfwa river, approximately 35 km downstream of the existing Mita Hills Dam and 25 km downstream of the existing Lunsemfwa hydropower station. Water will be transferred from Mkushi Dam to Muchinga hydropower station through a planned headrace tunnel	
Operator	Muchinga Power Company Limited (MPC)	MPC is a joint venture between LHPC, Agua Imara AS (formerly known as SN Power Africa) and eleQtra (infraCo) Ltd.	
Status	Planned		ERM (2013A)
Closure	n.a.		
Type	Reservoir		ERM (2013A)
Operating Targets	Hydropower production	The planned hydropower scheme will be operated to maintain as high reservoir level as possible (to maintain the generating head) but low enough to provide sufficient storage to minimize spillage	ERM (2013A)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [m3/s]	9.17		ERM (2013A)
Maximum, Minimum, Average Altitude [m asl]	1027		LHPC (Mr. Chanda)
Reservoir data			

Reservoir Area [km2]	5		ERM (2013A)
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	995		ERM (2013A)
Max Depth (Dam Height [m])	85-90		ERM (2013A)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	70		ERM (2013A)
Dead Storage [km3]	13		ERM (2013A)
Minimum Operating Level [m asl]	960		ERM (2013A)
Maximum Operating Level [m asl]	995		ERM (2013A)
Normal Operating Level [m asl]	990-995		ERM (2013A)
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		
Level-Surface Curve	n.a.		
Dam data			
Dam Type	Not yet decided. Either a rockfilled dam or arch-gravity concrete dam		ERM (2013A)
Number of Spillways	n.a.		
Type of Spillways	Overflow type on the dam crest		ERM (2013A)
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spillways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Capacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		

Medium Outlet Rating Curve	n.a.			
Number of Bottom Outlets	n.a.			
Type of Bottom Outlets	n.a.			
Bottom Outlet Elevation [m asl]	n.a.			
Bottom Outlet Rating Curve	n.a.			
Intake Elevation [m asl]	n.a.			
Power plant characteristics				
	A	**B (if multiple sub-plants)**		
Installed Capacity [MW]	240-330			ERM (2013A)
Number of Turbines	3		Francis turbines	ERM (2013A)
Max Power per Turbine [MW]	80-110			ERM (2013A)
Max Discharge per Turbine [m3/s]	n.a.			
Min Discharge per Turbine [m3/s]	n.a.			
Turbine Penstock Capacity [m3/s]	n.a.			
Max Hydraulic Head [m]	n.a.			
Mean Hydraulic Head [m]	488			ERM (2013A)
Turbine Outlet Elevation [m asl]	n.a.			
Turbine Efficiency [%]	n.a.			
KEN	n.a.			
Mean Annual Production [GWh/yr]	1100			ERM (2013A)
Intake Rating Curve	n.a.			
Tailwater Rating Curve	n.a.			
Rule Curve	n.a.			
Turbines Efficiency - Releases Curve	n.a.			
Costs				
Capital Cost [USD/kW]	n.a.			
Fixed Cost [USD/kW]	n.a.			
Variable Cost [USD/MWh]	n.a.			

Operational constraints				
Release Constraints [m3/s]	n.a.			
Level Constraints [m]	n.a.			
Other Constraints	n.a.			

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

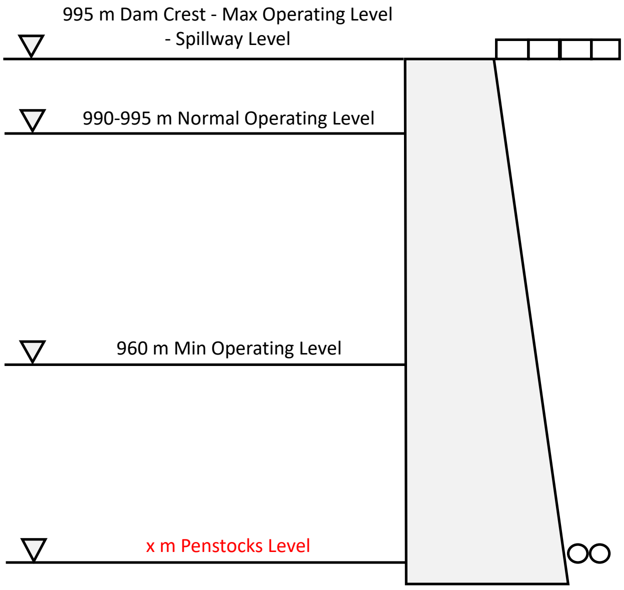

Figure 160 – Muchinga dam feature elevations.

1.1.4 Mulungushi - Zambia

Plant Data

General data		Notes	Source
Country	Zambia		
River	Mulungushi		
Operator	Lunsemfwa Hydropower (LHPC)		
Status	Planned	Replacement of the existing Mulungushi hydropower station. The existing Mulungushi Dam will still be used, i.e. no additional impoundment is necessary	ERM (2013B)
Closure	n.a.		
Type	Reservoir		ERM (2013B)
Operating Targets	Hydropower production		ERM (2013B)
Catchment data			
Catchment Area (natural + diversions) [km2]	4371		LHPC (Mr. Chanda)
Average Inflow [m3/s]	14.19		LHPC (Mr. Chanda)
Maximum, Minimum, Average Altitude [m asl]	1027		LHPC (Mr. Chanda)
Reservoir data			
Reservoir Area [km2]	n.a.		
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	1071.6		ERM (2013B)
Max Depth (Dam Height [m])	46		ERM (2013B)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	256		ERM (2013B)
Dead Storage [km3]			
Minimum Operating Level [m asl]	1052.7		ERM (2013B)
Maximum Operating Level [m asl]	1068.3		ERM (2013B)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		
Level-Surface Curve	n.a.		
Dam data			

Dam Type	Zoned rockfill, concrete faced dam			ERM (2013B)
Number of Spillways	40			ERM (2013B)
Type of Spillways	Gates			ERM (2013B)
Spillway Sill Elevation [m asl]	1066.4			ERM (2013B)
Spillway Capacity [km3/yr]	200			ERM (2013B)
Number of Emergency Spillways	n.a.			
Type of Emergency Spillways	n.a.			
Emergency Spillway Sill Elevation [m asl]	n.a.			
Emergency Spillway Capacity [km3/yr]	n.a.			
Spillway Rating Curve	n.a.			
Medium Outlet Elevation [m asl]	n.a.			
Medium Outlet Rating Curve	n.a.			
Number of Bottom Outlets	n.a.			
Type of Bottom Outlets	n.a.			
Bottom Outlet Elevation [m asl]	n.a.			
Bottom Outlet Rating Curve	n.a.			
Intake Elevation [m asl]	n.a.			
Power plant characteristics				
	A	**B (if multiple sub-plants)**		
Installed Capacity [MW]	80-100			ERM (2013B)
Number of Turbines	1	1	Francis turbines	ERM (2013B)
Max Power per Turbine [MW]	40-50	40-50		ERM (2013B)
Max Discharge per Turbine [m3/s]	n.a.	n.a.		
Min Discharge per Turbine [m3/s]	n.a.	n.a.		
Turbine Penstock Capacity [m3/s]	n.a.	n.a.		
Max Hydraulic Head [m]	n.a.	n.a.		
Mean Hydraulic Head [m]	n.a.	n.a.		
Turbine Outlet Elevation [m asl]	n.a.	n.a.		
Turbine Efficiency [%]	n.a.	n.a.		

KEN	n.a.	n.a.		
Mean Annual Production [GWh/yr]	349			ERM (2013B)
Intake Rating Curve	n.a.	n.a.		
Tailwater Rating Curve	n.a.	n.a.		
Rule Curve	n.a.	n.a.		
Turbines Efficiency - Releases Curve	n.a.	n.a.		
Costs				
Capital Cost [USD/kW]	n.a.	n.a.		
Fixed Cost [USD/kW]	n.a.	n.a.		
Variable Cost [USD/MWh]	n.a.	n.a.		
Operational constraints				
Release Constraints [m3/s]	n.a.			
Level Constraints [m]	n.a.			
Other Constraints	n.a.			

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

Data	**From**	**To**	**Frequency**	**Source**
Inflow to the Reservoir [m3/s]	1997	date	daily	LHPC
Reservoir Level (or Storage) [m] (or [km3])	n.a.	n.a.		
Total Release [m3/s]	n.a.	n.a.		
Turbinated Flow [m3/s]	n.a.	n.a.		
Reservoir Spill [m3/s]	n.a.	n.a.		
Hydropower Production [GWh]	n.a.	n.a.		
Precipitation on reservoir [mm]	1922	date	daily	LHPC
Temperature on reservoir [°C]	2013	date	daily	LHPC
Evaporation [mm]	n.a.	n.a.		
Other Meteorological Variables	n.a.	n.a.		

Power plant curves

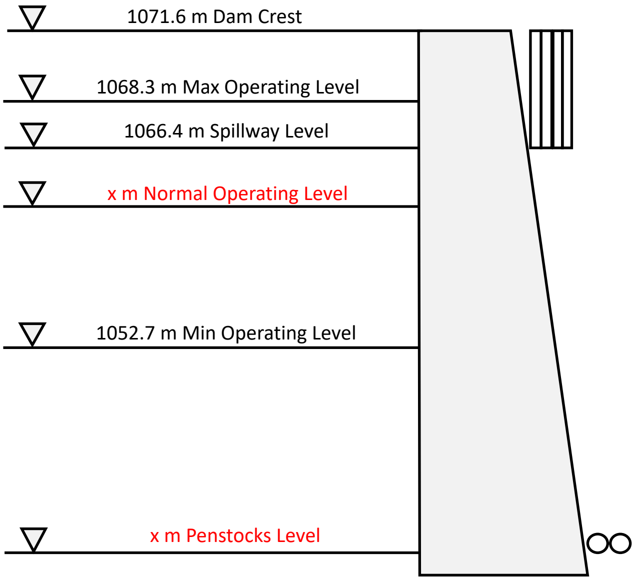

Figure 161 – Mulungushi dam feature elevations.

1.1.5 Devil's Gorge – Zambia/Zimbabwe

Plant Data

General data		**Notes**	**Source**
Country	Zambia/Zimbabwe		
River	Zambezi		
Operator	ZESCO/ZPC		
Status	PLN	The scheme is actually not being developed but has been reserved as one of potential sites for future development according to ZRA (2018). It lacks financial viability according to the World Bank (2010)	Cervigni et al. (2015)
Closure	2019	2028 according to Spalding-Fecher et al. (2016)	Cervigni et al. (2015)
Type	Reservoir		Cervigni et al. (2015)
Operating Targets	Hydropower production		ZRA (2018)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	975	Average altitude going from 650 m asl in the north to 1300 m asl in the south	Balon et al. (2012)
Reservoir data			
Reservoir Area [km2]	750	762 according to SADC (2007)	Beilfuss and Dos Santos (2001)
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	n.a.		
Max Depth (Dam Height [m])	n.a.		
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	1219		
Live Storage [km3]	33		Beilfuss and Dos Santos (2001)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	n.a.		
Maximum Operating Level [m asl]	595		SADC (2007)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		

Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		
Level-Surface Curve	n.a.		
Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		
Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	1240	1200 (600 MW in Zambia and 600 MW in Zimbabwe) ac-cording to the World Bank (2010)	Cervigni et al. (2015)
Number of Turbines	n.a.		
Max Power per Turbine [MW]	620		ZRA (2018)
Max Discharge per Tur-bine [m3/s]	n.a.	1515 m3/s in total according to ZRA (2018)	
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	110		SADC (2007)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	0.88		ZRA (2018)
KEN	n.a.		

Mean Annual Production [GWh/yr]	5604		ZRA (2018)
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	2679.20		Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35		Cervigni et al. (2015)
Variable Cost [USD/MWh]	0.45		Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

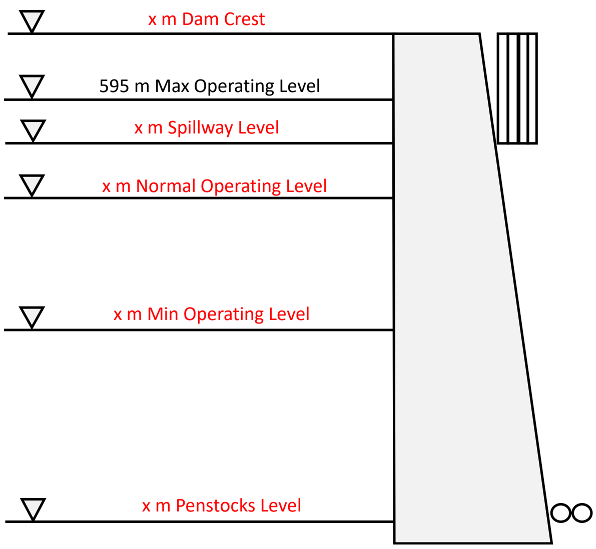

Figure 162 – Devil's Gorge dam feature elevations.

1.1.6 Mpata Gorge – Zambia/Zimbabwe

Plant Data

General data		**Notes**	**Source**
Country	Zambia/Zimbabwe		
River	Zambezi		
Operator	ZESCO/ZPC		
Status	PLN	The scheme is currently not being developed but has been reserved as one of potential sites for future development according to ZRA (2018). It is not feasible wrt environmental priorities as it would at times flood Mana Pools, a UNESCO World Heritage site, according to the World Bank (2010)	Cervigni et al. (2015)
Closure	2023		SADC (2012)
Type	Reservoir		The World Bank (2010)
Operating Targets	Hydropower Generation		Cervigni et al. (2015)
Catchment data			
Catchment Area (natural + diversions) [km2]	840,000		Beilfuss and Dos Santos (2001)
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	800	Average altitude	SADC (2007)
Reservoir data			
Reservoir Area [km2]	1230	At maximum operating level	ZRA (2018)
Reservoir Length [km]	480		ZRA (2018)
Crest Elevation [m asl]	384		ZRA (2018)
Max Depth (Dam Height [m])	78		ZRA (2018)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	2380		SADC (2007)
Live Storage [km3]	19,8		ZRA (2018)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	n.a.		
Maximum Operating Level [m asl]	381		ZRA (2018)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		

Level-Surface Curve	n.a.		
Dam data			
Dam Type	Double curvature concrete arch dam abutting onto a concrete gravity wing on the right bank		ZRA (2018)
Number of Spillways	1	12 gates according to ZRA (2018)	ZRA (2018)
Type of Spillways	Central overflow spillway controlled by radial gates		ZRA (2018)
Spillway Sill Elevation [m asl]	381		ZRA (2018)
Spillway Capacity [km3/yr]	454		ZRA (2018)
Number of Emergency Spillways	n.a.		
Type of Emergency Spillways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Capacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	1200		ZRA (2018)
Number of Turbines	8		ZRA (2018)
Max Power per Turbine [MW]	150		ZRA (2018)
Max Discharge per Turbine [m3/s]	n.a.		
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capacity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	55		ZRA (2018)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	0.88		ZRA (2018)
KEN	n.a.		

Mean Annual Production [GWh/yr]	7570		ZRA (2018)
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	2679.20		Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35		Cervigni et al. (2015)
Variable Cost [USD/MWh]	0.45		Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

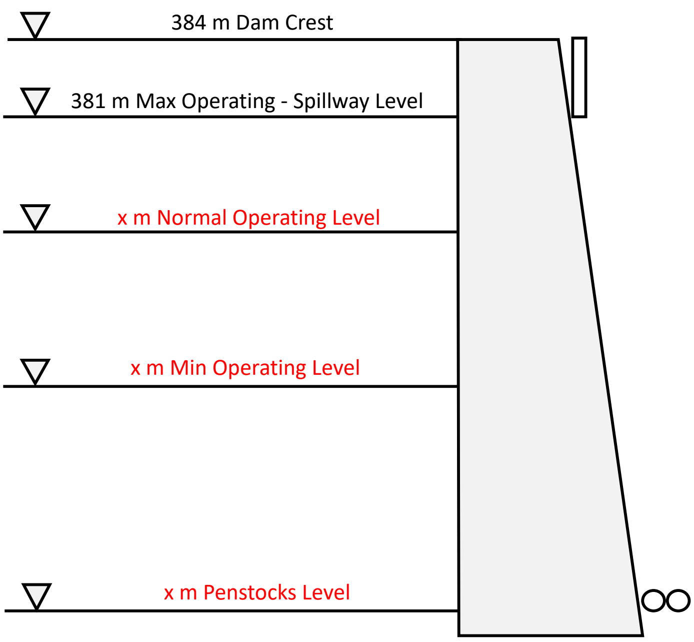

Figure 163 – Mpata Gorge dam feature elevations.

1.1.7 Batoka Gorge – Zambia/Zimbabwe

Plant Data

The two hydropower stations in Zambia and Zimbabwe both presents the same characteristics, thus they are aggregated into one plant in the table below.

General data		**Notes**	**Source**
Country	Zambia/Zimbabwe		
River	Zambezi		
Operator	ZESCO/ZPC		
Status	PLN	To be fully commissioned in 2024 according to ERM (2014b)	Cervigni et al. (2015)
Closure	2024		ERM (2014b)
Type	Reservoir/Run-of-River		Zambezi River Authority (2015)
Operating Targets	Allow more efficient use of the storage in Lake Kariba	Hydropower production is a minor operating target	Zambezi River Authority (2015)
Catchment data			
Catchment Area (natural + diversions) [km2]	508,000		Tumbare (2005)
Average Inflow [km3/yr]	33.74		Zambezi River Authority (2015)
Maximum, Minimum, Average Altitude [m asl]	975	Average altitude going from 650 m asl in the north to 1300 m asl in the south	Balon et al. (2012)
RESERVOIR DATA			
Reservoir Area [km2]	23	25.6 km2 according to Tumbare (2005)	Zambezi River Authority (2015)
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	766		Zambezi River Authority (2015)
Max Depth (Dam Height [m])	181		Zambezi River Authority (2015)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	n.a.		
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	746		The World Bank (2010)
Maximum Operating Level [m asl]	762		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		

Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Available		The World Bank (2010)
Level-Surface Curve	Available		The World Bank (2010)
Dam data			
Dam Type	Roller Compacted Concrete gravity arch		Zambezi River Authority (2015)
Number of Spillways	1	Located in Zimbabwe according to ERM (2014b)	Zambezi River Authority (2015)
Type of Spillways	Crest overflow with 7 radial gates		Tumbare (2005)
Spillway Sill Elevation [m asl]	743.5		Zambezi River Authority (2015)
Spillway Capacity [km3/yr]	630.7		The World Bank (2010)
Number of Emergency Spillways	n.a.		
Type of Emergency Spillways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Capacity [km3/yr]	n.a.		
Spillway Rating Curve	Available		The World Bank (2010)
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	1600	2x800 MW	Tumbare (2005)
Number of Turbines	8	2x4 Francis turbines	ERM (2014b)
Max Power per Turbine [MW]	200		Tumbare (2005)
Max Discharge per Turbine [m3/s]	138.82		The World Bank (2010)
Min Discharge per Turbine [m3/s]	n.a.		

Turbine Penstock Capacity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	166.56		The World Bank (2010)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	86		Tumbare (2005)
KEN	n.a.		
Mean Annual Production [GWh/yr]	n.a.		
Intake Rating Curve	n.a.		
Tailwater Rating Curve	Available		Cervigni et al. (2015)
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	2,679.2		Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35		Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62		Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

Data	From	To	Frequency	Source
Inflow to the Reservoir [m3/s]	01/10/1958	05/02/2010	Daily	ADAPT Database (Matos et al., 2015)
Reservoir Level (or Storage) [m] (or [km3])	n.a.	n.a.		
Total Release [m3/s]	n.a.	n.a.		
Turbinated Flow [m3/s]	n.a.	n.a.		
Reservoir Spill [m3/s]	n.a.	n.a.		
Hydropower Production [GWh]	n.a.	n.a.		
Precipitation on reservoir [mm]	n.a.	n.a.		
Temperature on reservoir [°C]	n.a.	n.a.		

Evaporation [mm]	n.a.	n.a.		
Other Meteorological Variables	n.a.	n.a.		

Power plant curves

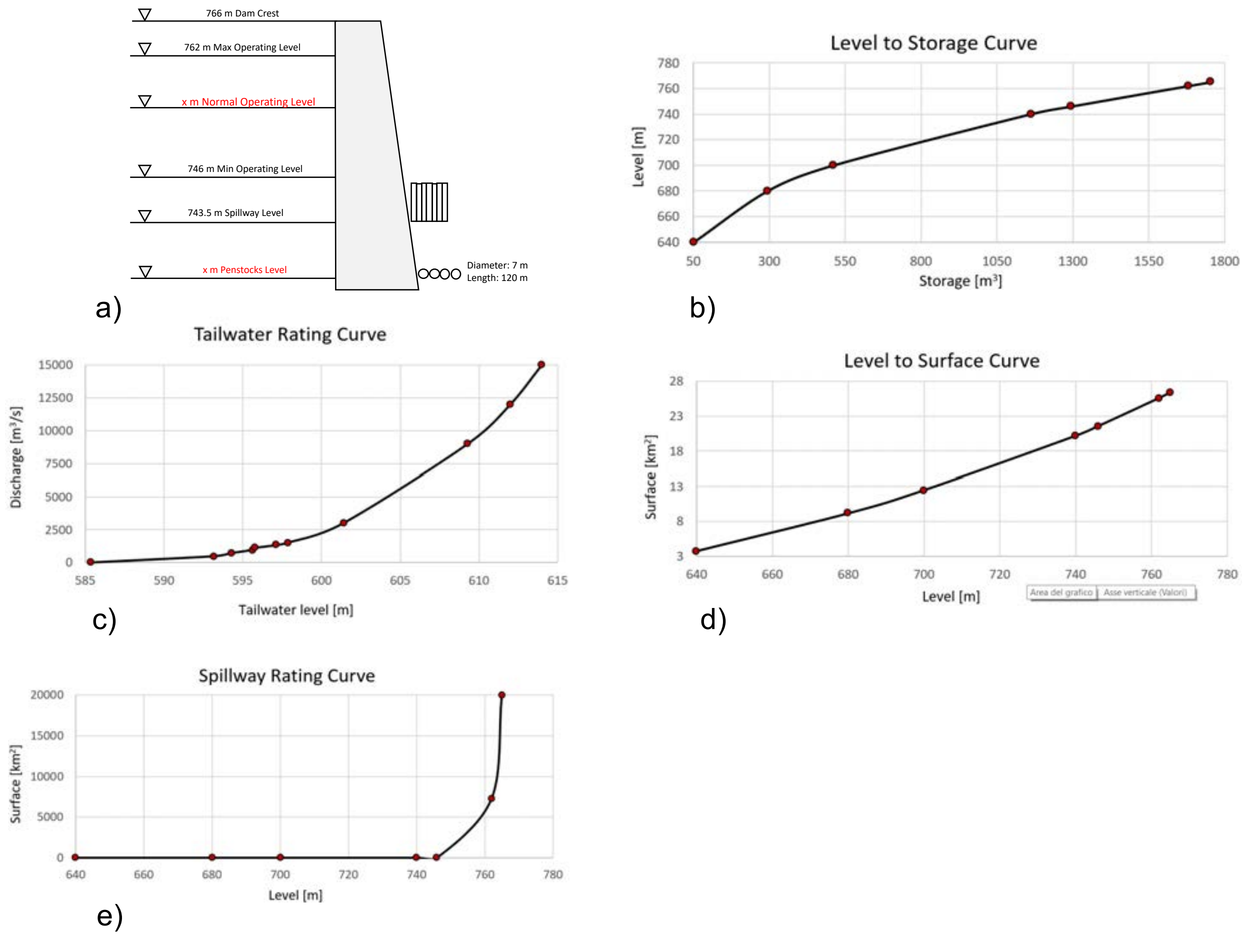

Figure 164 – Batoka Gorge dam feature elevations (panel a) and hydropower plant curves (panel b,c,d,e). In particular, Panel a shows the existence of four penstocks, whose dimensions are 7 m diameter and 120 m length each.

1.1.8 Mphanda Nkuwa – Mozambique

Plant Data

General data		Notes	Source
Country	Mozambique		
River	Zambezi		
Operator	EDM		
Status	PLN	To be fully commissioned by 2017	Cervigni et al. (2015)
Closure	n.a.	Latest project stage recorded as of 2016 is the transaction support and financial close (PIDA, 2017)	
Type	Reservoir	To be operated as run-of-the-river. If the installed capacity is upgraded, it will operate in midmerit/peaking mode	The World Bank (2010)
Operating Targets	Hydropower Production	The electricity produced will be mainly exported (IRN, 2006)	The World Bank (2010)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	800	Average altitude	SADC (2007)
Reservoir data			
Reservoir Area [km2]	100		The World Bank (2010)
Reservoir Length [km]	0.7		COBA et al. (2009)
Crest Elevation [m asl]	n.a.		
Max Depth (Dam Height [m])	0.1		COBA et al. (2009)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	0.13		Beilfuss et al. (2001)
Live Storage [km3]	2.3		Beilfuss et al. (2001)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	n.a.		
Maximum Operating Level [m asl]	207		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		
Level-Surface Curve	n.a.		

Dam data			
Dam Type	Concrete gravity		COBA et al. (2009)
Number of Spillways	1	Equipped with 13 radial crest gates	SADC (2011)
Type of Spillways	Crest overflow with 13 radial gates		SADC (2011)
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	977.6		SADC (2011)
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	1,300	4x325MW It is possible to upgrade the installed capacity up to 2,275 MW in the future by extend-ing the north bank power sta-tion or building an under-ground powerhouse on the south bank (Beilfuss, 2012)	The World Bank (2010)
Number of Turbines	4	Located adjacent to the dam on the left bank	The World Bank (2010)
Max Power per Turbine [MW]	325		The World Bank (2010)
Max Discharge per Tur-bine [m3/s]	n.a.	2,200 m3/s in total according to SADC (2011)	
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		

Mean Hydraulic Head [m]	67		Spalding-Fecher et al. (2014)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	89		The World Bank (2010)
KEN	n.a.		
Mean Annual Production [GWh/yr]	8,600		Spalding-Fecher et al. (2014)
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	1,648.2		Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35		Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62		Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

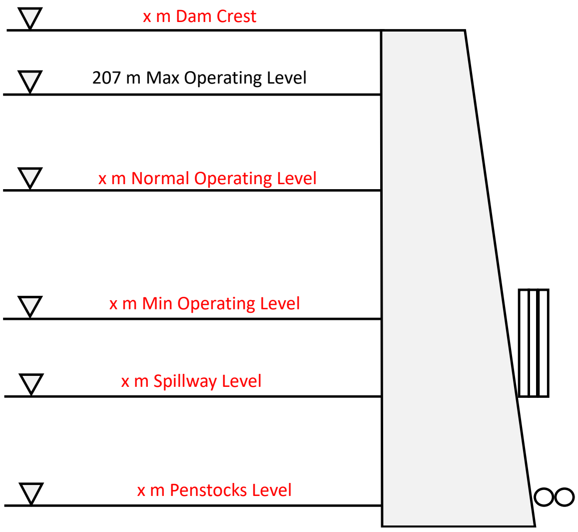

Figure 165 – Mphanda Nkuwa dam feature elevations.

1.1.9 Boroma – Mozambique

Plant Data

General data		Notes	Source
Country	Mozambique		
River	Zambezi		
Operator	EDM		
Status	PLN		The World Bank (2010)
Closure	2025		Spalding-Fecher et al. (2016)
Type	Reservoir		The World Bank (2010)
Operating Targets	Regulation of fluctuating downstream river flows	Needed if only Mphanda Nkuwa will be developed to its full potential. It is currently considered economically unfeasible according to Beilfuss and Dos Santos (2001)	The World Bank (2010)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	800	Average altitude	SADC (2007)
Reservoir data			
Reservoir Area [km2]	30	Calculated on fully supply level	SADC (2007)
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	n.a.		
Max Depth (Dam Height [m])	n.a.		
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	65		SADC (2007)
Live Storage [km3]	n.a.		
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	132		Stanzel and Kling (2014)
Maximum Operating Level [m asl]	142		Stanzel and Kling (2014)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		

Level-Surface Curve	n.a.		
Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		
Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	444	400 according to Stanzel and Kling (2014)	The World Bank (2010)
Number of Turbines	n.a.		
Max Power per Turbine [MW]	n.a.		
Max Discharge per Tur-bine [m3/s]	n.a.	2665 according to Stanzel and Kling (2014)	
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	17		Stanzel and Kling (2014)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	0,9		Stanzel and Kling (2014)
KEN	n.a.		
Mean Annual Production [GWh/yr]	3.240		SADC (2007)
Intake Rating Curve	n.a.		

Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	n.a.		
Fixed Cost [USD/kW]	n.a.		
Variable Cost [USD/MWh]	n.a.		
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

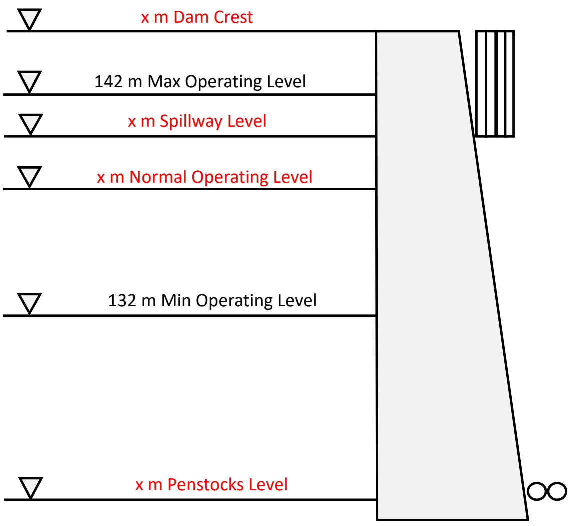

Figure 166 – Boroma dam feature elevations.

1.1.10 Lupata – Mozambique

Plant Data

General data		**Notes**	**Source**
Country	Mozambique		
River	Zambezi		
Operator	EDM		
Status	PLN		The World Bank (2010)
Closure	2025		Spalding-Fecher et al. (2016)
Type	n.a.		
Operating Targets	n.a.		
Catchment data			
Catchment Area (natural + diversions) [mln km2]	1		Stanzel and Kling (2014)
Average Inflow [m3/s]	2800	Average over the 1961-1990 period	Stanzel and Kling (2014)
Maximum, Minimum, Average Altitude [m asl]	800	Average altitude	SADC (2007)
Reservoir data			
Reservoir Area [km2]	n.a.		
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	n.a.		
Max Depth (Dam Height [m])	n.a.		
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	n.a.		
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	115		Stanzel and Kling (2014)
Maximum Operating Level [m asl]	125		Stanzel and Kling (2014)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	n.a.		
Level-Surface Curve	n.a.		

Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		
Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill El-evation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	654		The World Bank (2010)
Number of Turbines	n.a.		
Max Power per Turbine [MW]	n.a.		
Max Discharge per Turbine [m3/s]	n.a.	2743 m3/s in total according to Stanzel and Kling (2014)	
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capacity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	27		SADC (2007)
Turbine Outlet Elevation [m asl]	n.a.		

Turbine Efficiency [%]	0,9		Stanzel and Kling (2014)
KEN	n.a.		
Mean Annual Production [GWh/yr]	4.171		SADC (2007)
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	n.a.		
Fixed Cost [USD/kW]	n.a.		
Variable Cost [USD/MWh]	n.a.		
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

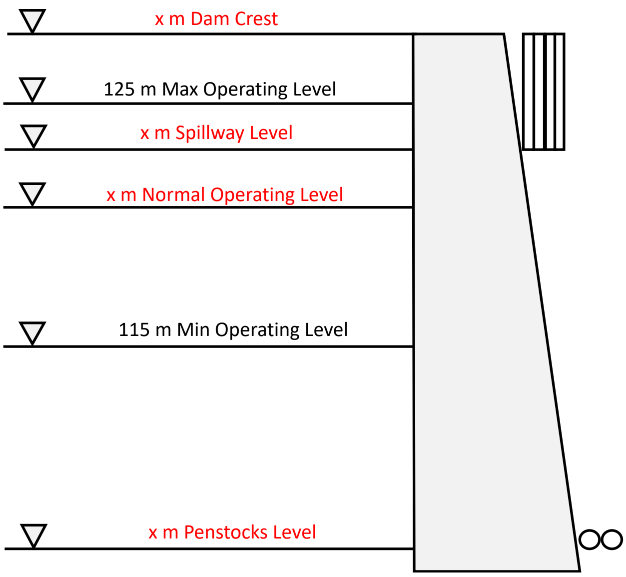

Figure 167 – Lupata dam feature elevations.

1.1.11 Lower Fufu – Malawi

Plant Data

General data		**Notes**	**Source**
Country	Malawi		
River	South Rukuru		
Operator	ESCOM		
Status	PLN	To be fully commissioned by 2024	The World Bank (2010)
Closure	2024		The World Bank (2010)
Type	Run-of-the-river		The World Bank (2010)
Operating Targets	Hydropower Produc-tion		Cervigni et al. (2015)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Av-erage Altitude [m asl]	n.a.		
Reservoir data			
Reservoir Area [km2]			
Reservoir Length [km]			
Crest Elevation [m asl]			
Max Depth (Dam Height [m])			
Average Depth [m]			
Average Inflow [km3/yr]			
Average Net Reservoir Evaporation [mm]			
Live Storage [km3]			
Dead Storage [km3]			
Minimum Operating Level [m asl]			
Maximum Operating Level [m asl]			
Normal Operating Level [m asl]			
Storage to Flow Volume Ratio			
Mean Residence Time [yr]			
Level-Storage Curve			
Level-Surface Curve			
Dam data			
Dam Type			
Number of Spillways			
Type of Spillways			

Spillway Sill Elevation [m asl]			
Spillway Capacity [km3/yr]			
Number of Emergency Spillways			
Type of Emergency Spill-ways			
Emergency Spillway Sill Elevation [m asl]			
Emergency Spillway Ca-pacity [km3/yr]			
Spillway Rating Curve			
Medium Outlet Elevation [m asl]			
Medium Outlet Rating Curve			
Number of Bottom Outlets			
Type of Bottom Outlets			
Bottom Outlet Elevation [m asl]			
Bottom Outlet Rating Curve			
Intake Elevation [m asl]			
Power plant characteristics			
Installed Capacity [MW]	90	100 MW according to JICA (2014)	Cervigni et al. (2015)
Number of Turbines	2		Cervigni et al. (2015)
Max Power per Turbine [MW]	45		Cervigni et al. (2015)
Max Discharge per Tur-bine [m3/s]	n.a.	30 m3/s in total according to Cervigni et al. (2015); 40 m3/s in total according to JICA (2014)	
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	336		Cervigni et al. (2015)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	n.a.		
KEN	n.a.		
Mean Annual Production [GWh/yr]	n.a.		
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Re-leases Curve	n.a.		

Costs			
Capital Cost [USD/kW]	1,511		Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35		Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62		Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

None

1.1.12 Songwe – Malawi

The Songwe I reservoir is presented below.

Songwe I - Plant Data

General data		**Notes**	**Source**
Country	Malawi		
River	Songwe		
Operator	ESCOM		
Status	PLN	To be fully commissioned by 2024	Cervigni et al. (2015)
Closure	2024		Cervigni et al. (2015)
Type	Reservoir		The World Bank (2010)
Operating Targets	Flood Control and Hydropower Production	They are operated primarily for flood mitigation	The World Bank (2010)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	n.a.		
Reservoir data			
Reservoir Area [km2]	30	At fully supply level (1,255 m asl)	The World Bank (2010)
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	1,265		The World Bank (2010)
Max Depth (Dam Height [m])	65		The World Bank (2010)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	0.25		Ministry of Energy and Minerals (2013)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	1,230		Ministry of Energy and Minerals (2013)
Maximum Operating Level [m asl]	1,255		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Available		The World Bank (2010)

Level-Surface Curve	Available		The World Bank (2010)
Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		
Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	34		The World Bank (2010)
Number of Turbines	3		The World Bank (2010)
Max Power per Turbine [MW]	11.3		The World Bank (2010)
Max Discharge per Tur-bine [m3/s]	47		The World Bank (2010)
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	89.625		The World Bank (2010)
Mean Hydraulic Head [m]	71.1		The World Bank (2010)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	87	Reservoir operated for flood control	The World Bank (2010)
KEN	n.a.		

Mean Annual Production [GWh/yr]	120		African Development Bank (2010)
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	Available		The World Bank (2010)
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	1,339.6	It refers to the three Songwe plants together	Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35	It refers to the three Songwe plants together	Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62	It refers to the three Songwe plants together	Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Songwe I - Available Time-series

None

Songwe I - Power plant curves

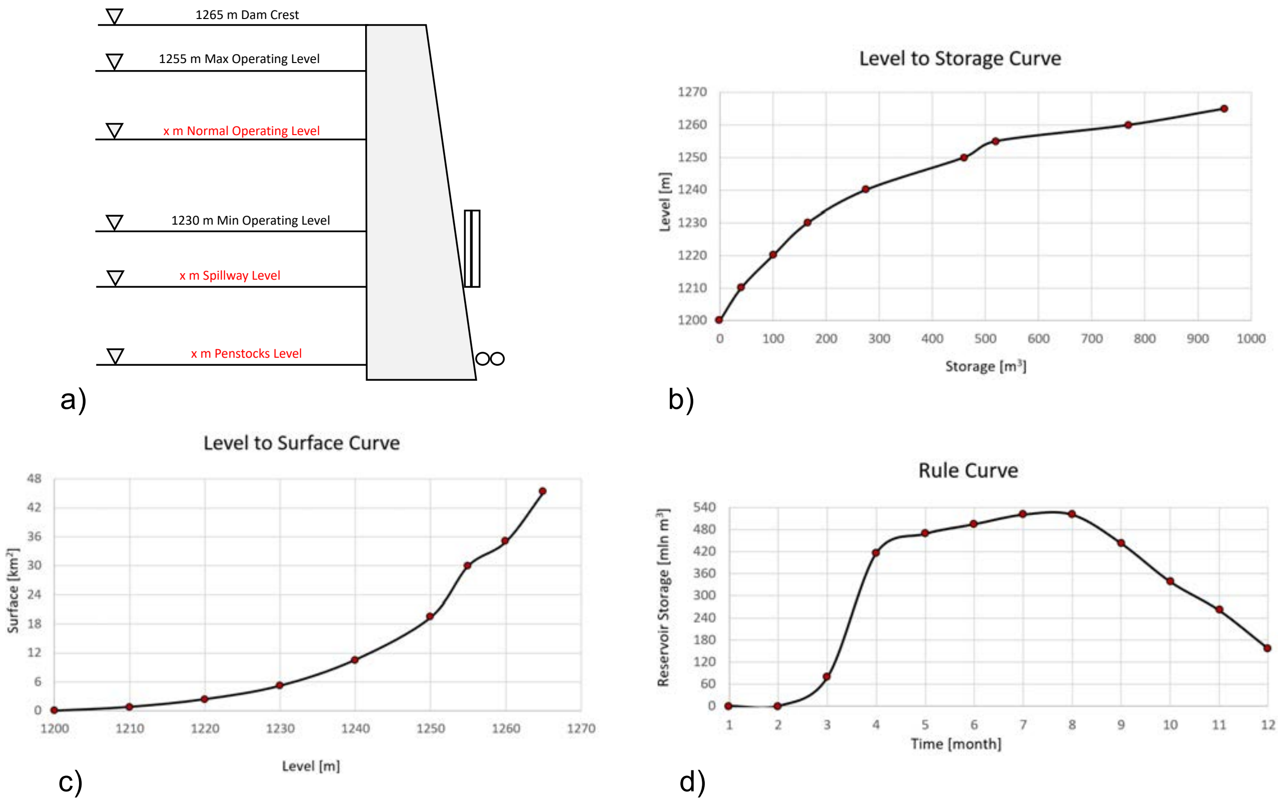

Figure 168 – Songwe I dam feature elevations (panel a) and hydropower plant curves (panel b,c,d).

The Songwe II reservoir is presented below.

Songwe II - Plant Data

General data		**Notes**	**Source**
Country	Malawi		
River	Songwe		
Operator	ESCOM		
Status	PLN	To be fully commissioned by 2024	Cervigni et al. (2015)
Closure	2024		Cervigni et al. (2015)
Type	Reservoir		The World Bank (2010)
Operating Targets	Flood Control and Hydropower Production	They are operated primarily for flood mitigation	The World Bank (2010)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	n.a.		
Reservoir data			
Reservoir Area [km2]	16	At fully supply level (1,150 m asl)	The World Bank (2010)
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	1,160		The World Bank (2010)
Max Depth (Dam Height [m])	120		The World Bank (2010)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	0.36		Ministry of Energy and Minerals (2013)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	1,110		Ministry of Energy and Minerals (2013)
Maximum Operating Level [m asl]	1,150		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Available		The World Bank (2010)
Level-Surface Curve	Available		The World Bank (2010)

Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		
Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	157		The World Bank (2010)
Number of Turbines	3		The World Bank (2010)
Max Power per Turbine [MW]	52.3		The World Bank (2010)
Max Discharge per Tur-bine [m3/s]	57		The World Bank (2010)
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	322.75		The World Bank (2010)
Mean Hydraulic Head [m]	258.2		The World Bank (2010)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	87	Reservoir operated for flood control	The World Bank (2010)
KEN	n.a.		
Mean Annual Production [GWh/yr]	630		African Devel-opment Bank (2010)

Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	Available		The World Bank (2010)
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	1,339.6	It refers to the three Songwe plants together	Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35	It refers to the three Songwe plants together	Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62	It refers to the three Songwe plants together	Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Songwe II - Available Time-series

None

Songwe II - Power plant curves

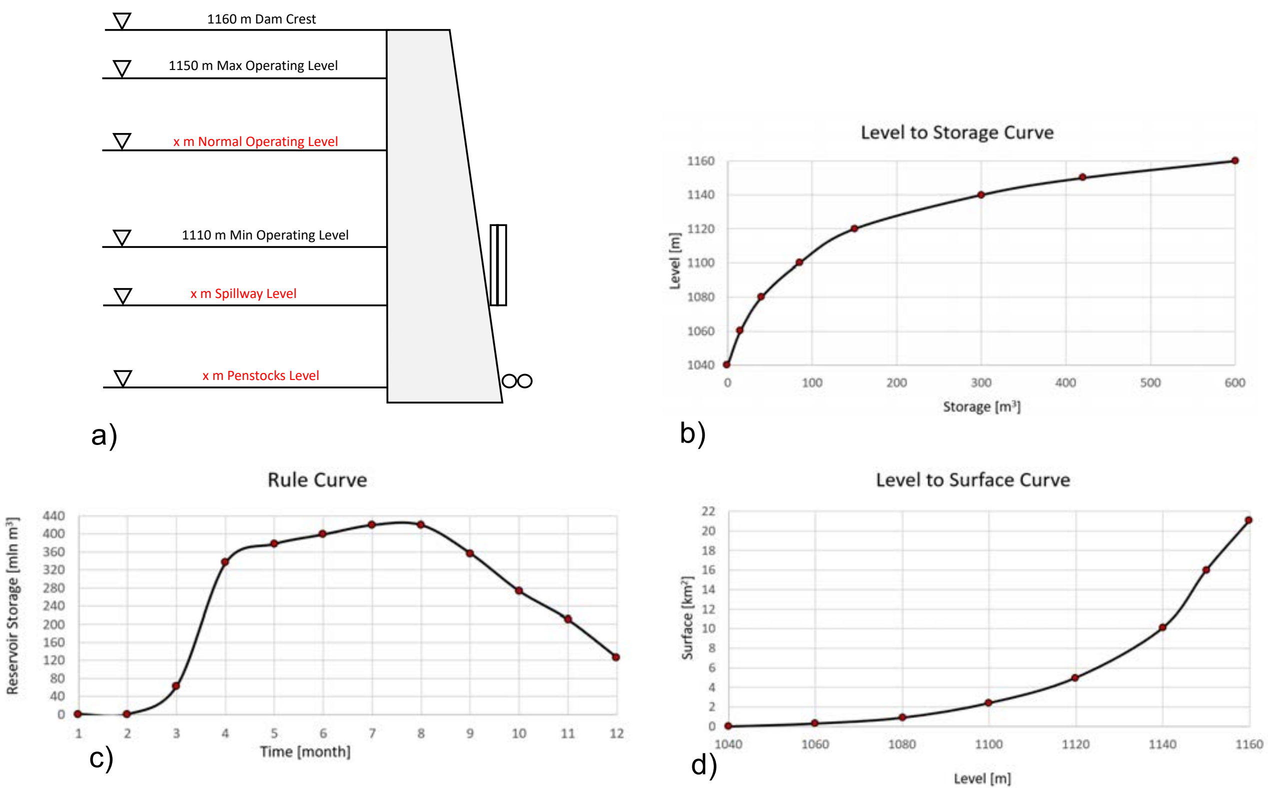

Figure 169 – Songwe II dam feature elevations (panel a) and hydropower plant curves (panel b,c,d).

The Songwe III reservoir is presented below.

Songwe III - Plant Data

General data		**Notes**	**Source**
Country	Malawi		
River	Songwe		
Operator	ESCOM		
Status	PLN	To be fully commissioned by 2024	Cervigni et al. (2015)
Closure	2024		Cervigni et al. (2015)
Type	Reservoir		The World Bank (2010)
Operating Targets	Flood Control and Hydropower Production	They are operated primarily for flood mitigation	The World Bank (2010)
Catchment data			
Catchment Area (natural + diversions) [km2]	3,559		MITC (2016)
Average Inflow [km3/yr]	1.2		MITC (2016)
Maximum, Minimum, Average Altitude [m asl]	n.a.		
Reservoir data			
Reservoir Area [km2]	11.1	At fully supply level (790 m asl)	The World Bank (2010)
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	n.a.		
Max Depth (Dam Height [m])	n.a.		
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	0.26		Ministry of Energy and Minerals (2013)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	700		Ministry of Energy and Minerals (2013)
Maximum Operating Level [m asl]	790		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Available		The World Bank (2010)
Level-Surface Curve	Available		The World Bank (2010)

Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		
Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	149		The World Bank (2010)
Number of Turbines	3		The World Bank (2010)
Max Power per Turbine [MW]	49.7		The World Bank (2010)
Max Discharge per Tur-bine [m3/s]	68		The World Bank (2010)
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	261.25		The World Bank (2010)
Mean Hydraulic Head [m]	209		The World Bank (2010)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	87	Reservoir operated for flood control	The World Bank (2010)
KEN	n.a.		
Mean Annual Production [GWh/yr]	630		African Devel-opment Bank (2010)

Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	Available		The World Bank (2010)
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	1,339.6	It refers to the three Songwe plants together	Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35	It refers to the three Songwe plants together	Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62	It refers to the three Songwe plants together	Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Songwe III - Available Time-series

None

Songwe III - Power plant curves

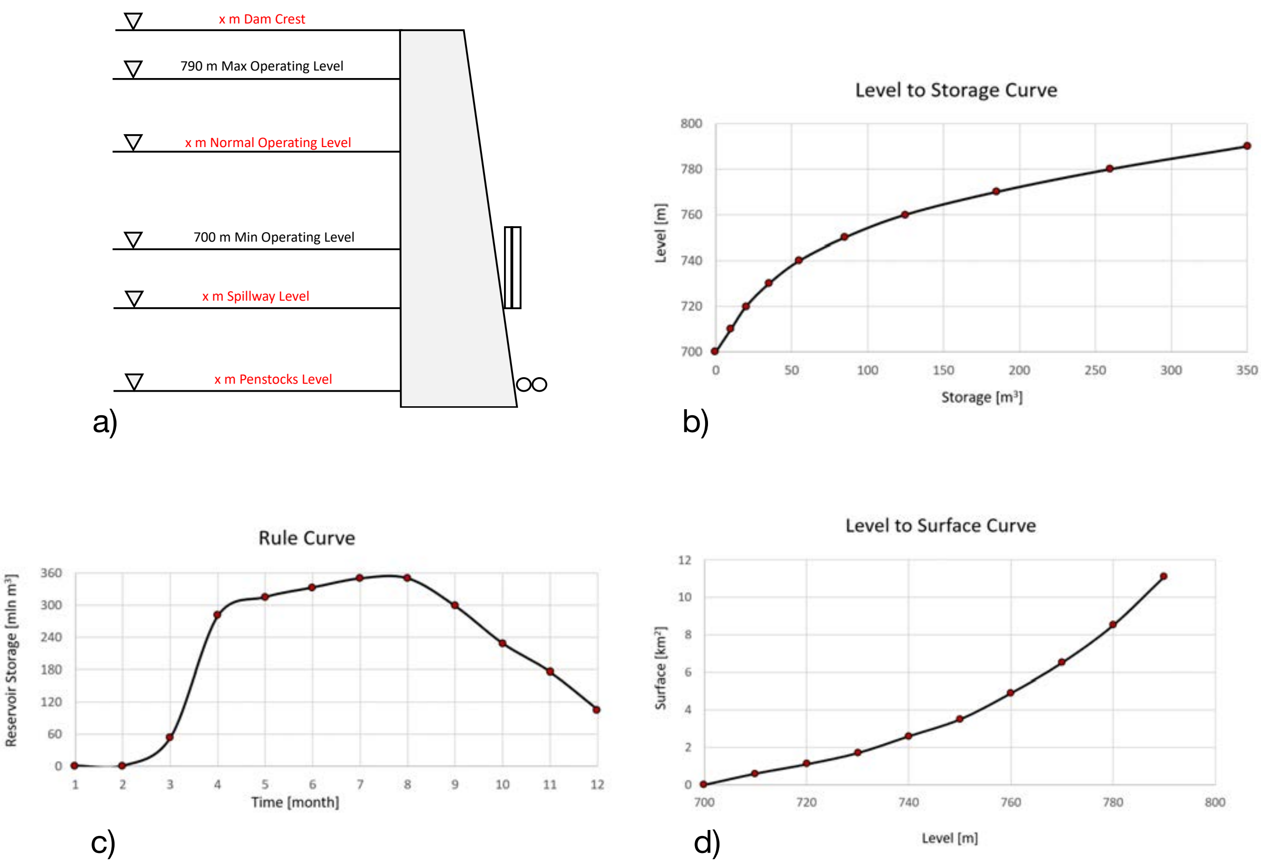

Figure 170 – Songwe III dam feature elevations (panel a) and hydropower plant curves (panel b,c,d).

1.1.13 Kholombidzo – Malawi

Plant Data

General data		**Notes**	**Source**
Country	Malawi		
River	Kholombizo		
Operator	ESCOM		
Status	PLN		The World Bank (2010)
Closure	2025		The World Bank (2010)
Type	Pondage		The World Bank (2010)
Operating Targets	Hydropower Production		Cervigni et al. (2015)
Catchment data			
Catchment Area (natural + diversions) [km2]	n.a.		
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	n.a.		
Reservoir data			
Reservoir Area [km2]	n.a.		
Reservoir Length [km]	n.a.		
Crest Elevation [m asl]	n.a.		
Max Depth (Dam Height [m])	n.a.		
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	0.46		The World Bank (2010)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	471		The World Bank (2010)
Maximum Operating Level [m asl]	475		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Available		The World Bank (2010)
Level-Surface Curve	Available		The World Bank (2010)
Dam data			
Dam Type	n.a.		
Number of Spillways	n.a.		

Type of Spillways	n.a.		
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	n.a.		
Number of Emergency Spillways	n.a.		
Type of Emergency Spill-ways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Ca-pacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	240		The World Bank (2010)
Number of Turbines	4		The World Bank (2010)
Max Power per Turbine [MW]	60		The World Bank (2010)
Max Discharge per Tur-bine [m3/s]	93		The World Bank (2010)
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capac-ity [m3/s]	n.a.		
Max Hydraulic Head [m]	n.a.		
Mean Hydraulic Head [m]	72		The World Bank (2010)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	n.a.		
KEN	n.a.		
Mean Annual Production [GWh/yr]	n.a.		
Intake Rating Curve	Available		The World Bank (2010)
Tailwater Rating Curve	Available		The World Bank (2010)
Rule Curve	n.a.		

Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	n.a.		
Fixed Cost [USD/kW]	n.a.		
Variable Cost [USD/MWh]	n.a.		
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-Series

None

Power plant curves

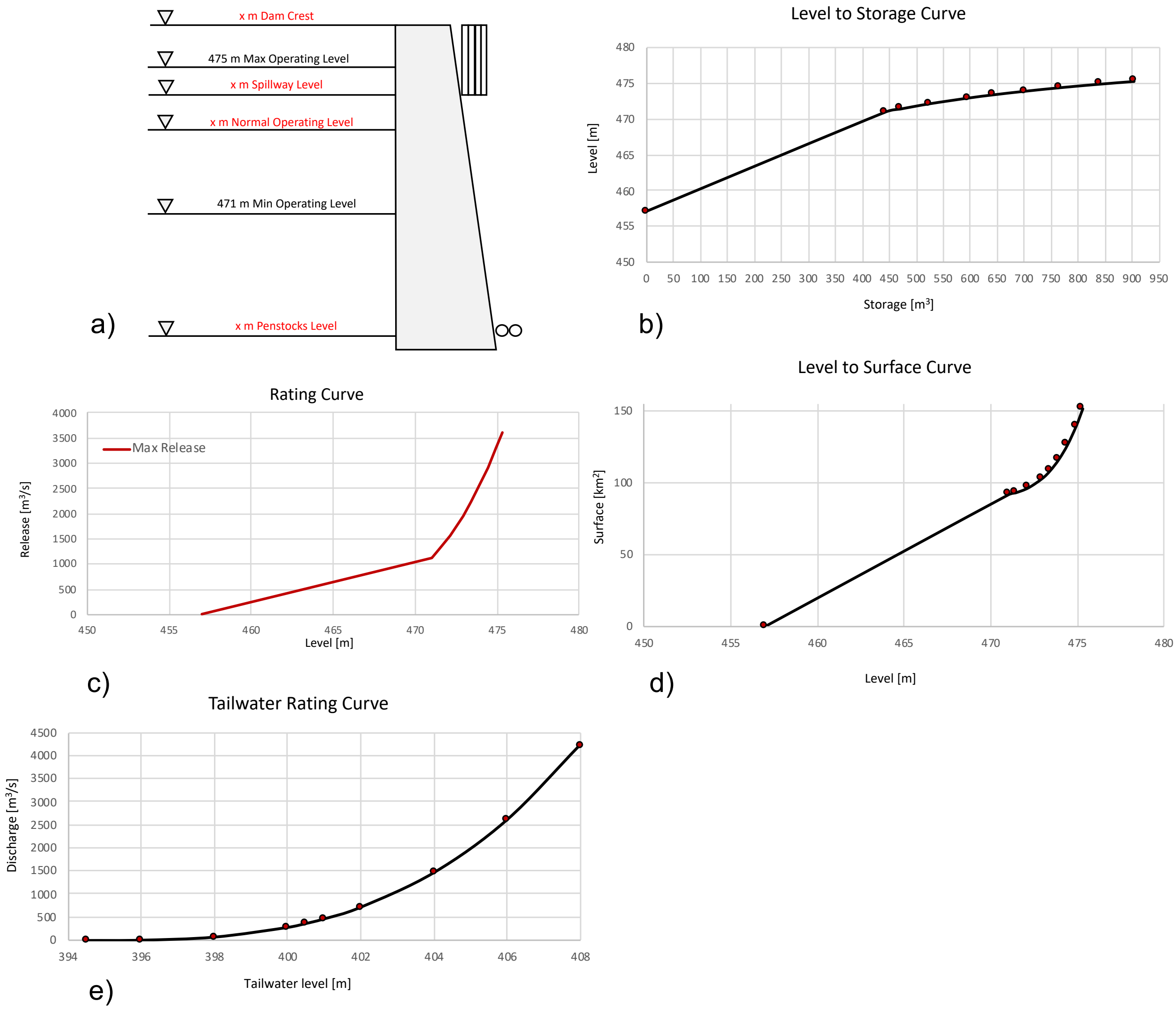

Figure 171 – Kholombidzo dam feature elevations (panel a) and hydropower plant curves (panel b,c,d,e).

1.1.14 Rumakali - Tanzania

Plant Data

General data		**Notes**	**Source**
Country	Tanzania		
River	Rumakali		
Operator	TANESCO		
Status	PLN	To be fully commissioned by 2019	Cervigni et al. (2015)
Closure	2019		Cervigni et al. (2015)
Type	Reservoir		The World Bank (2010)
Operating Targets	Hydropower Production		SMEC (2013)
Catchment data			
Catchment Area (natural + diversions) [km2]	717	The Rumakali Project is supposed to exploit five catchments, namely Rumakali (406 km2); Nyithule + basin 2220 North (113 km2); Kikugu (139 km2); Rumbira (46 km2) and basin 2220 North	SMEC (2013)
Average Inflow [km3/yr]	0.716	Total annual flow from all the five catchments	SMEC (2013)
Maximum, Minimum, Average Altitude [m asl]	n.a.		
Reservoir data			
Reservoir Area [km2]	13.2	At fully supply level (2,055 m asl)	The World Bank (2010)
Reservoir Length [km]	0.8		Studio Pietrangeli (2012)
Crest Elevation [m asl]	n.a.		
Max Depth (Dam Height [m])	93		Studio Pietrangeli (2012)
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm]	n.a.		
Live Storage [km3]	0.256		Ministry of Energy and Minerals (2013)
Dead Storage [km3]	n.a.		
Minimum Operating Level [m asl]	2,025		The World Bank (2010)
Maximum Operating Level [m asl]	2,055		The World Bank (2010)
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		

Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Available		The World Bank (2010)
Level-Surface Curve	Available		The World Bank (2010)
Dam data			
Dam Type	Rockfill dam		Studio Pietrangeli (2012)
Number of Spillways	1		Studio Pietrangeli (2012)
Type of Spillways	Freeflow spillway		Studio Pietrangeli (2012)
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [km3/yr]	11.04		Studio Pietrangeli (2012)
Number of Emergency Spillways	n.a.		
Type of Emergency Spillways	n.a.		
Emergency Spillway Sill Elevation [m asl]	n.a.		
Emergency Spillway Capacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	520	Upgraded from 222 MW	Ministry of Energy and Minerals (2013)
Number of Turbines	4	Pelton turbines	Studio Pietrangeli (2012)
Max Power per Turbine [MW]	130		Studio Pietrangeli (2012)
Max Discharge per Turbine [m3/s]	n.a.	41 m3/s in total	Studio Pietrangeli (2012)
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capacity [m3/s]	n.a.		

Max Hydraulic Head [m]	1,295		Ministry of Energy and Minerals (2013)
Mean Hydraulic Head [m]	1,281.5		The World Bank (2010)
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	90		The World Bank (2010)
KEN	n.a.		
Mean Annual Production [GWh/yr]	n.a.		
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [USD/kW]	2,492.7		Cervigni et al. (2015)
Fixed Cost [USD/kW]	9.35		Cervigni et al. (2015)
Variable Cost [USD/MWh]	1.62		Cervigni et al. (2015)
Operational constraints			
Release Constraints [m3/s]	n.a.		
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

CON=Under Construction; HC=Historic Capacity (i.e. Existing); PLN=Planned Capacity

Available Time-series

None

Power plant curves

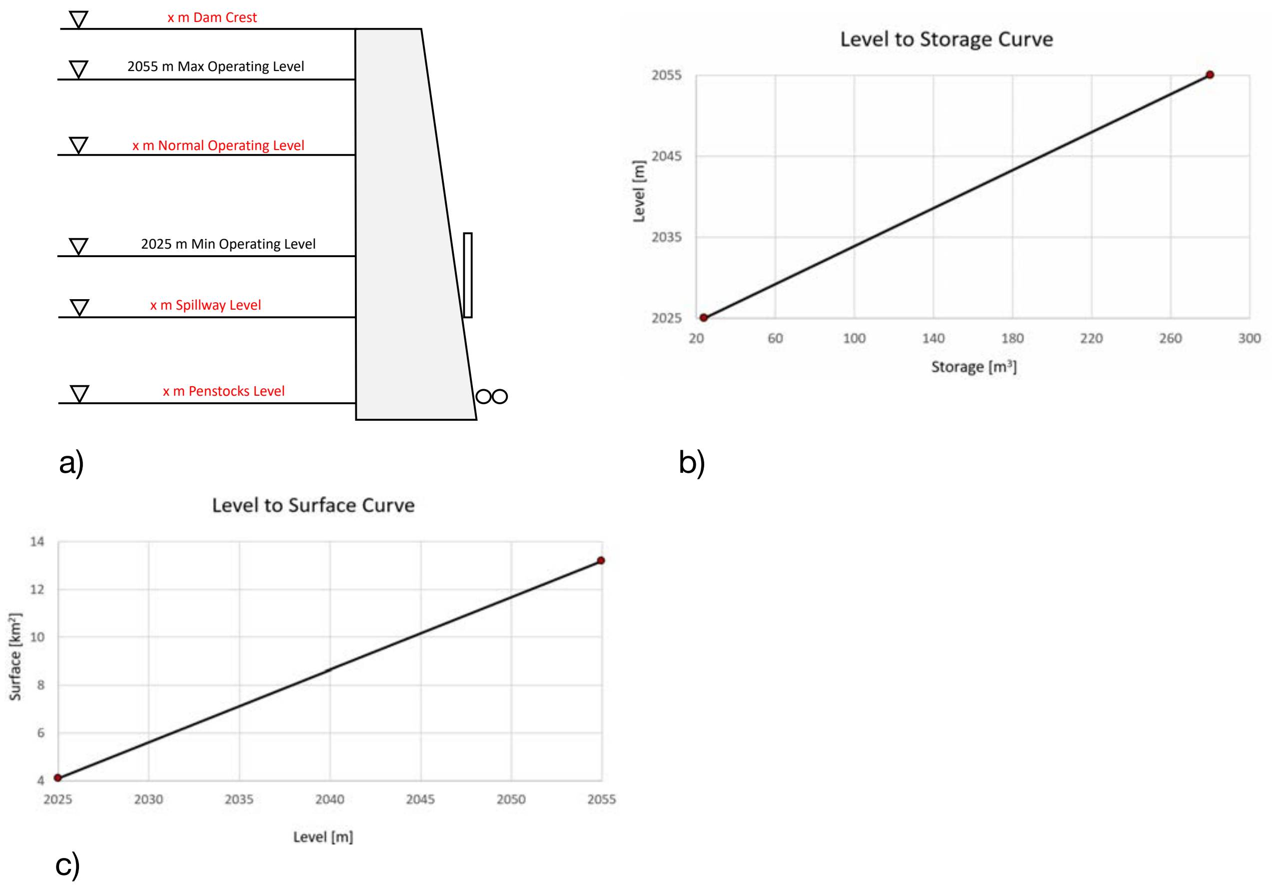

Figure 172 – Rumakali dam feature elevations (panel a) and hydropower plant curves (panel b,c).

1.1.15 Koysha Dam - Ethiopia

Plant data

General data		**Notes**	**Source**
Country	Ethiopia		Salini Impregilo, 2017
River	Omo		Salini Impregilo, 2017
Operator	EEPCo		Salini Impregilo, 2017
Status	In construction		Salini Impregilo, 2017
Closure	-		
Type	Reservoir		Salini Impregilo, 2017
Operating Targets	Hydropower Production and irrigation		Salini Impregilo, 2017
Catchment data			
Catchment Area (natural + diversions) [km2]	44325		Woldemariam et al., 2016
Average Inflow [km3/yr]	n.a.		
Maximum, Minimum, Average Altitude [m asl]	n.a.		
Reservoir data			
Reservoir Area [km2]	119		Woldemariam et al., 2016
Reservoir Length [km]	129		Woldemariam et al., 2016
Crest Elevation [m asl]	680		Woldemariam et al., 2016
Max Depth (Dam Height [m])	178.5		Woldemariam et al., 2016
Average Depth [m]	n.a.		
Average Net Reservoir Evaporation [mm/year]	1100		Woldemariam et al., 2016
Live Storage [km3]	5240		Woldemariam et al., 2016
Dead Storage [km3]	760		Woldemariam et al., 2016
Minimum Operating Level [m asl]	616		Woldemariam et al., 2016
Maximum Operating Level [m asl]	680		Woldemariam et al., 2016
Normal Operating Level [m asl]	n.a.		
Storage to Flow Volume Ratio	n.a.		
Mean Residence Time [yr]	n.a.		
Level-Storage Curve	Curve Available	Retrieved from DEM	
Level-Surface Curve	Curve Available	Retrieved from DEM	
Dam data			
Dam Type	Roller compacted concrete (RCC) dam		Salini Impregilo, 2017
Number of Spillways	n.a.		
Type of Spillways	gated		Woldemariam et al., 2016
Spillway Sill Elevation [m asl]	n.a.		
Spillway Capacity [m3/s]	13100		Woldemariam et al., 2016

Number of Emergency Spill-ways	n.a.		
Type of Emergency Spillways	n.a.		
Emergency Spillway Sill Ele-vation [m asl]	n.a.		
Emergency Spillway Capacity [km3/yr]	n.a.		
Spillway Rating Curve	n.a.		
Medium Outlet Elevation [m asl]	n.a.		
Medium Outlet Rating Curve	n.a.		
Number of Bottom Outlets	n.a.		
Type of Bottom Outlets	n.a.		
Bottom Outlet Elevation [m asl]	n.a.		
Bottom Outlet Rating Curve	n.a.		
Intake Elevation [m asl]	n.a.		
Power plant characteristics			
Installed Capacity [MW]	2160		Salini Impregilo, 2017
Number of Turbines	8 Francis		Salini Impregilo, 2017
Max Power per Turbine [MW]	270		Woldemariam et al., 2016
Max Discharge per Turbine [m3/s]	192		Woldemariam et al., 2016
Min Discharge per Turbine [m3/s]	n.a.		
Turbine Penstock Capacity [km3/yr]	n.a.		
Max Hydraulic Head [m]	158		Woldemariam et al., 2016
Mean Hydraulic Head [m]	150		Woldemariam et al., 2016
Turbine Outlet Elevation [m asl]	n.a.		
Turbine Efficiency [%]	n.a.		
KEN	n.a.		
Mean Annual Production [GWh/yr]	6450		Salini Impregilo, 2017
Intake Rating Curve	n.a.		
Tailwater Rating Curve	n.a.		
Rule Curve	n.a.		
Turbines Efficiency - Releases Curve	n.a.		
Costs			
Capital Cost [$]	2.5 Bilion		Salini Impregilo, 2017
Fixed Cost [$/kW]	n.a.		
Variable Cost [$/MWh]	n.a.		
Operational constraints			

Release Constraints [m3/s]	25	Minimum environ-mental flow	Woldemariam et al., 2016
	1000 - 1200	Flood pulse	Woldemariam et al., 2016
Level Constraints [m]	n.a.		
Other Constraints	n.a.		

Available Time Series

Data	**From**	**To**	**Frequency**	**Source**
Inflow to the Reservoir [m3/s]	1999	2017	daily	Topkapi ETH simulations
Reservoir Level (or Storage) [m] (or [km3])	n.a.	n.a.		
Total Release [m3/s]	n.a.	n.a.		
Turbinated Flow [m3/s]	n.a.	n.a.		
Reservoir Spill [m3/s]	n.a.	n.a.		
Hydropower Production [GWh]	n.a.	n.a.		
Precipitation on reservoir [mm]	n.a.	n.a.		
Temperature on reservoir [°C]	n.a.	n.a.		
Evaporation [mm]	n.a.	n.a.		
Other Meteorological Variables	n.a.	n.a.		

**Note: the listed time series were simulated via Topkapi model in ETH. No observed time series is available for the reservoir*

Power Plant Curves

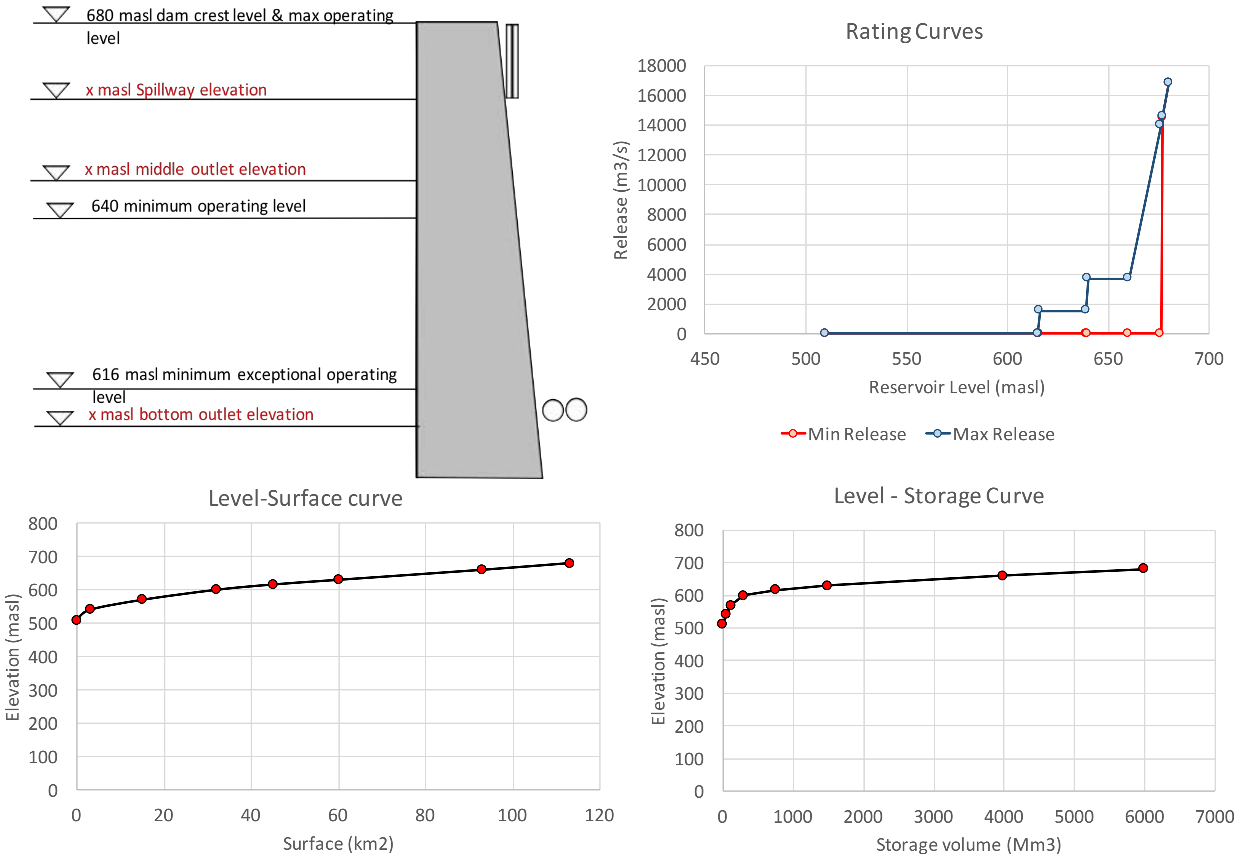

Figure 173 – Koysha dam feature elevations (panel a) and hydropower plant curves (panel b,c).