Water Supply and Demand Scenarios for the Zambezi River Basin

Climate Change and Upstream Development Impacts on New Hydropower Projects in the Zambezi Project

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Executive Summary

The "Climate Change and Upstream Development Impacts on New Hydropower Projects in the Zambezi" project is funded by the Climate & Development Knowledge Network (CDKN), a UK Department for International Development (DfID)-funded partnership. The project research consortium is led by University of Cape Town and includes Centre for Energy Environment Engineering Zambia, University of Zambia, University of Eduardo Mondlane (Mozambique), Pöyry Management Consulting, and OneWorld Sustainable Investments.

The objective of the project is to make a "first pass" assessment of how upstream changes in climate and irrigation demand would affect water availability for major downstream Zambezi River Basin hydropower plants. The analysis covers major existing plants (i.e. Kariba, Cahora Bassa and Kafue Gorge Upper), extensions to existing plants (i.e. Kariba North and South bank, Cahora Bass North Bank) and major new plants (i.e. Batoka Gorge, Itezhi-tezhi, Mphanda Nkuwa, Kafue Gorge Lower, and to a lesser extent Boroma and Lupata). This report presents the description of the water modelling and the results of modelling a variety of future scenarios for the basin. An earlier draft of the assumptions and results was discussed at a workshop with Zambezi River Authority (ZRA) and SAPP utilities in October 2013, so this report also draws upon that feedback received in that meeting.

While future climate is subject to scientific uncertainty, the impact of irrigation is a policy uncertainty. This both because the level of irrigation investment is driven by political and economic priorities, but also because the priority given to irrigation demand versus hydropower demand for water is a political decision – and, in this case, an international political one as well, because of the different countries utilising the resources of the Zambezi. The scenarios modelled therefore test the impact of different future climates and levels of irrigation development assuming that hydropower is prioritised over irrigation (i.e. the first six scenarios in Table ES1). Additional scenarios then test the effect of prioritising irrigation over hydropower, while holding climate and absolute water demand levels constant (i.e. the final four scenarios in Table ES1). The purpose of exploring these alternatives is not to arrive at one "right" answer, but to illustrate the implications of different decisions and possible futures.

Table ES1. Specification of future scenarios

	Hydropower development	Irrigation development	Future climate
A. Hydro hist, Irrig hist, Dry	Historical	Historical	Dry
B. Hydro hist, Irrig hist, Wet	Historical	Historical	Wet
C. Hydro BAU, Irrig hist, Dry	Business as Usual	Historical	Dry
D. Hydro BAU, Irrig hist, Wet	Business as Usual	Historical	Wet
E. Hydro BAU, Irrig BAU, Dry	Business as Usual	Business as Usual	Dry
F. Hydro BAU, Irrig BAU, Wet	Business as Usual	Business as Usual	Wet
G. Hydro BAU, Irrig BAU #1, Dry	Business as Usual	BAU with highest demand priority	Dry
H. Hydro BAU, Irrig BAU #1, Wet	Business as Usual	BAU with highest demand priority	Wet
I. Hydro Op, Irrig Op #1, Dry	Optimistic	BAU with highest demand priority	Dry
J. Hydro Op, Irrig Op #1, Wet	Optimistic	BAU with highest demand priority	Wet

As a way of summarising the results of the analyses and figures presented in this chapter, the tables below show two measures of the impacts climate change and upstream irrigation on hydropower generation. The first is the mean annual generation during 2050-2070 as compared to modelled historical production (existing plants) or a stated target (new plants). The second is the share of the years (i.e. between 2010 and 2070) in which annual production is below the target level. This second metric is particularly important, because future climates could be more variable. Given that many of the plants have spare production capacity (i.e. load factors below 70% or even 50% in some cases), there could be scenarios where mean generation does not change but the number of years below target increases significantly. Note also that Table ES2 also shows the share of years below mean generation for the modelled historical period.

Table ES2. Summary results for existing hydropower plants under different climates

	2050-70 mean generation/ modelled historical			% years below modelled historical generation		
Scenario	Kariba	Cahora Bassa	Kafue Upper	Kariba	Cahora Bassa	Kafue Upper
A. Hydro hist irrig hist dry	88%	98%	106%	62%	41%	8%
B. Hydro hist irrig hist wet	100%	107%	108%	20%	8%	7%
Modelled Historical				48%	36%	43%

Table ES3. Summary results for existing hydropower plants with expansions under different climates and irrigation scenarios

	2050-70 mean generation/target*			% years below target* generation		
Scenario	Kariba	Cahora Bassa	Kafue Upper	Kariba	Cahora Bassa	Kafue Upper
C. Hydro BAU irrig hist dry	76%	96%	107%	77%	69%	8%
D. Hydro BAU irrig hist wet	90%	111%	109%	62%	26%	2%
E. Hydro BAU irrig BAU dry	75%	92%	105%	75%	69%	8%
F. Hydro BAU irrig BAU wet	88%	105%	107%	66%	28%	3%
G. Hydro BAU irrig BAU #1 dry	73%	76%	96%	79%	85%	25%
H. Hydro BAU irrig BAU #1 wet	85%	90%	104%	70%	54%	7%

*target is modelled historical generation plus expected generation from expansions at Kariba and Cahora Bassa

Table ES4. Summary results for new hydropower plants under different climates and irrigation scenarios

	2050-70 mean generation (GWh)				% years below target generation			
Scenario	Mphanda Nkuwa	Itezhi-tezhi	Batoka	Kafue Lower	Mphanda Nkuwa	Itezhi -tezhi	Batoka	Kafue Lower
Target*	8600	611	8728	2400				
C. Hydro BAU irrig hist dry	9825	614	7387	3427	14%	23%	84%	2%
D. Hydro BAU irrig hist wet	10823	696	8251	3655	2%	4%	53%	2%
E. Hydro BAU irrig BAU dry	9564	613	7284	3366	14%	23%	80%	2%
F. Hydro BAU irrig BAU wet	10377	699	7725	3559	2%	4%	71%	2%
G. Hydro BAU irrig BAU #1 dry	8319	601	7032	3037	45%	33%	90%	14%
H. Hydro BAU irrig BAU #1 wet	9438	695	7637	3431	8%	12%	73%	4%

*target is from utilities or literature

	2050-70 mean generation (GWh)		% years below target generation	
Scenario	Boroma	Lupata	Boroma	Lupata
Target	1168	4171		
C. Hydro BAU irrig hist dry	1403	4119	0%	52%
D. Hydro BAU irrig hist wet	1420	4473	0%	9%
E. Hydro BAU irrig BAU dry	1399	4019	0%	57%
F. Hydro BAU irrig BAU wet	1419	4316	0%	9%
G. Hydro BAU irrig BAU #1 dry	1283	3416	11%	76%
H. Hydro BAU irrig BAU #1 wet	1385	3883	2%	43%

While future climate is subject to scientific uncertainty, the impact of irrigation is a policy uncertainty. This is both because the level of irrigation investment is driven by political and economic priorities, but also because the priority given to irrigation demand versus hydropower demand for water is a political decision – and, in this case, an international political one as well, because of the different countries utilising the resources of the Zambezi. The initial set of scenarios therefore tested the impact of different future climates and levels of irrigation development assuming that hydropower is prioritised over irrigation. Additional scenarios then tested the effect of prioritising irrigation over hydropower, while holding climate and absolute water demand levels constant. The purpose of exploring these alternatives is not to arrive at one “right” answer, but to illustrate the implications of different decisions and possible futures.

Changes in future climate is an overwhelming driver of future production at almost all hydropower plants. The difference in mean generation under wetting and drying climates is 8-15% for almost all plants (Kafue Gorge Upper and Boroma being the exceptions), and a drying climate generally increases the share of years below target anywhere from 10% to 40%. For Mphanda Nkuwa and Cahora Bassa, however, the impact of upstream irrigation exceeds the impact of alternative climates, particularly when irrigation demands are prioritised over hydropower demand.

Given the constraints of future climate, the expansion of the Kariba appears to be unlikely to reach the planned production levels. Even under a wetting climate, mean generation is around 10% lower than target levels (i.e. historical plus expansions), when new hydropower and irrigation demands are considered. Cahora Bassa, on the other hand, could reach the target for the North Bank expansion under a wetting climate, but would often fall short under a drying climate. Kafue Gorge Upper appears to be the exception, in that future production levels could actually be higher than historical levels under both a drying and wetting climate, which could be in part due to the increased regularity of Itezhi-tezhi releases once hydropower production commences in 2014.

Choosing the appropriate target for future generation for new plants is difficult, because feasibility studies are either under revision or incomplete in many cases. Compared to the values stated by the utilities, however, Batoka Gorge is not able to meet the generation target under any scenario. Itezhi-tezhi, on the other hand, generates more than that stated target of 611 GWh/yr in almost all scenarios and Kafue Gorge Lower levels are well above 2400 GWh/yr. Mphanda Nkuwa can also meet the stated targets under almost all scenarios except when irrigation is prioritised over hydropower in a drying climate. For all new plants, the impact of different climate futures is still highly significant

The impact of irrigation depends not just on the level of demand but, more importantly, on the prioritisation given to agricultural demand over hydropower production. For most plants, including "business as usual" irrigation growth only reduces mean generation by up to 6%, with Cahora Bassa and Batoka Gorge under a wetting climate at the higher end of this range. When irrigation is prioritised over hydropower, the impact on generation is significant across many plants. At Cahora Bassa, average generation drops 20% when irrigation is prioritised. Mphanda Nkuwa losses 13-15% of average generation. This vulnerability at Mphanda Nkuwa reflects the fact that this plant is basically a run-of-river plant, with only a relatively small reservoir. Prioritising irrigation reduces average generation under a drying climate for Lupata, Kafue Gorge Upper and Kafue Gorge Lower by 17%, 11% and 11%, respectively. Lupata is not only a run-of-river plant, but is also downstream to one of the areas with largest irrigation potential – between Mphanda Nkuwa and the confluence with the Shire River. The impacts on Batoka Gorge and Itezhi-tezhi are very limited, given the small amount of irrigation upstream to these plants. Kariba also has a large enough reservoir to cope with the competing sectoral demands, so the prioritisation of irrigation does not result in significant additional losses of generation.

The relatively low consumption of water in the Zambezi River Basin in the past meant that explicit trade-offs across sectors and across countries, while important at a local level, posed less of a challenge for the basin overall. This is very likely to change in the future, as increased demands from all sectors, and major potential changes in climate, and therefore runoff, will require more explicit agreements on how to best utilise a limited resource.

The dramatic potential impacts of climate change on hydropower potential in the Zambezi River Basin point to the need to explicitly consider climate change in both project planning and overall system expansion planning. This is even truer for future plants, where financial viability and loan repayments will depend on the stability of generation and sales revenue. A key next step in this analysis should be to look at not just how climate and development affect individual plants, but how they affect entire national and regional energy systems. This analysis should also use the most recent climate scenario data available, as this field is evolving rapidly. Although there is increasing cooperation in the basin, major decisions on investment and operation are not necessarily coordinated as effectively as possible, and this will be more complex with four or five major new plant in the basin in the coming 10-15 years. Linking the water modelling to an energy system model for the region would allow for more explicit modelling of the energy, water and economic trade-offs, and a deeper understanding of the real costs of a changing climate.

Acknowledgements

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List of Acronyms

CDKN	Climate & Development Knowledge Network
CNRM	Centre for National Weather Research (France)
CORDEX	COordinated Regional Downscaling EXperiment
DNA	National Directorate for Water (Mozambique)
ECHAM	European Centre for medium-mange weather forecasts HAMburg (Germany)
ESCOM	Electricity Supply Corporation (of Malawi)
ETo	Reference evapotranspiration
GCM	Global Climate Model
GPCC	Global Precipitation Climatology Centre
GRDC	Global Runoff Data Center
HCB	Hidroeléctrica Cahora Bassa
HMNK	Hidroeléctrica Mphanda Nkuwa
HPP	Hydropower plant
IFs	International Futures (model)
IPCC	Intergovernmental Panel on Climate Change
MSIOA	(Zambezi) Multi-Sectoral Investment Opportunity Analysis
PRB	Population Reference Bureau
RCM	Regional Climate Model
SAPP	Southern African Power Pool
SEI	Stockholm Environment Institute
WATCH	Water and Global Change (programme)
WEAP	Water Evaluation And Planning (model)
ZAMCOM	Zambezi Basin Commission
ZDSS	Zambezi Decision Support System
ZESCO	Zambia Electricity Supply Corporation (Limited)
ZRA	Zambezi River Authority
ZRB	Zambezi River Basin

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1 Introduction

The “Climate Change and Upstream Development Impacts on New Hydropower Projects in the Zambezi” project is funded by the Climate & Development Knowledge Network (CDKN), a UK Department for International Development (DfID)-funded partnership. The project research consortium is led by University of Cape Town and includes Centre for Energy Environment Engineering Zambia, University of Zambia, University of Eduardo Mondlane (Mozambique), Pöyry Management Consulting, and OneWorld Sustainable Investments. The objective of this research is to make a “first pass” assessment of how upstream changes in climate an irrigation demand would affect water availability for major downstream Zambezi Basin hydropower plants.

After a short introduction to the modelling approach and tool used in Chapter 2, Chapter 3 presents the overall scenario approach to uncertainties in future climate and development pathways. Chapters 4 and 5 present the structure and assumptions used for modelling water supply and demand, respectively, drawing on both scientific literature and extensive engagement with regional stakeholders. These assumptions were reviewed in a stakeholder workshop with ZRA and SAPP utilities. Chapter 6 presents the calibration results to validate the model, following by a detailed presentation of modelling results in Chapter 7 and overall conclusions in Chapter 8.

2 WEAP as a water modelling tool

The methodological tool for this analysis is the Water Evaluation and Planning (WEAP) scenario modelling system, developed by Stockholm Environment Institute (SEI) (D. Yates et al. 2005; Sieber and Purkey 2011). WEAP is a combined hydrological and water allocation model that is widely used internationally (e.g. Mehta et al. 2011; Purkey et al. 2007; D. N. Yates and Miller 2013; Varela-Ortega et al. 2011; Howells et al. 2013; Höllermann, Giertz, and Diekkrüger 2010). There are several different hydrological modelling choices within WEAP (e.g. FAO crop requirements), which can be adapted to the particular needs of the research project. WEAP operates on the basic principle of water balance accounting, and provides an integrated approach to simulating both water supply and demand, with equal attention given to each side of the water balance equation. WEAP is also a database for all water supply and demand parameters, as well as a forecasting tool simulating water demand, supply, flows, storage, and pollution.

WEAP uses an intuitive graphical interface to show a schematic of the water system including all of the supply sources (e.g. rivers, groundwater, and reservoirs); withdrawal, transmission and wastewater treatment facilities; ecosystem requirements, water demands and pollution generation. The graphic interface prompts the user, catches errors and also provides on-screen guidance. Each of these components then has a corresponding data sheet with fixed parameters as well time series parameters. Expandable data structures allow the model to evolve during the course of a project, or be modified afterward as more detailed data becomes available.

One of the reasons for choosing WEAP is its power to present scenarios for water and supply and demand that are relatively easy for policy makers to understand. All of the parameters and results can be shown in scenario format, and choices on water allocation are explicit in each scenario, so that policy makers can see the implications of those decision.

Finally, WEAP has a recently completed built-in interface to SEI's Long-Range Energy Alternatives Planning (LEAP) modelling system. This means that the two models together provide a dynamic tool to analyse the implications of climate change and increased irrigation demands not only on hydropower production from individual facilities, but also for the energy system as whole, which is the goal of this overall research project.

3 Scenario approach

Given long time frame (i.e. 2010 - 2070) of analysis, and the scientific and political uncertainties within the Zambezi River Basin, this research utilises a scenario approach for the development and climate inputs to the modelling. The first dimension of uncertainty is socio-economic development futures, which includes not only possible GDP and population growth, which influences water use, but also the level of investment in irrigation and hydropower. The second dimension is climate, which includes two possible futures that describe the range of projections by downscaled climate model data for the Zambezi River Basin. In particular, these alternative futures cover both decreases and increases in mean precipitation, as these are both plausible under IPCC scenarios. In addition, scenarios with historical development levels and alternative climate futures show the impact of climate change on its own, without any new demands from new hydropower plant or irrigation developments. The scenarios are the combination of the climate and development futures, as shown conceptually in Table 1 . A more detailed description of the scenarios is found in Chapter 7.

Table 1. Conceptual framework for water scenario analysis

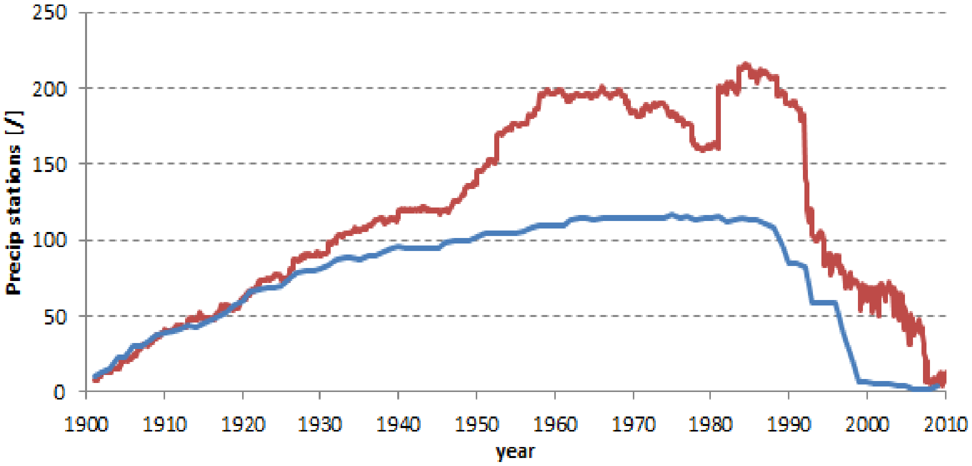
		Climate futures	
		"Dry" (e.g. limited drying in many sub-basin)	"Wet" (e.g. moderate wetting in many sub-basins.)
	Historical Development	Shows effect of change in climate without any new HPP plants or irrigation	Shows effect of change in climate without any new HPP plants or irrigation
Development Futures	Business as Usual (e.g. moderate growth)	??	No major constraint on hydropower production, irrigation or electricity trade
	Optimistic (e.g. higher GDP growth and investment)	Highest likelihood for conflict of water use rights and compromise of hydropower investments	??

To understand how the climate and development futures may affect hydropower plants, the analysis presented in 7 proceeds step-by-step through the following questions:

- How will future climate impact existing hydropower plants?
- How will the commissioning of new hydropower plants affect the operation and performance of existing plants?
- How will the new hydropower plants perform under different climate futures?
- What additional impact will increased irrigation demand have on the performance of existing and new hydropower plants?
- To what extent does the speed of implementation for hydropower and irrigation affect the results?

Because climate change only occurs over multiple decades, the timeframe for the analysis is up to 2070. Historical data from the 1960s to the present are used to populate the model, with the key water and climate data being from 1961-1990, because this period has the highest number of reporting weather stations, particularly in the Global Precipitation Climatology Centre (GPCC) dataset (see Figure 1).

Figure 1. Number of reporting precipitation stations in GPCC (red line) and CRU (blue line) datasets for the Zambezi River Basin



Source: Kling et al. (Submitted)

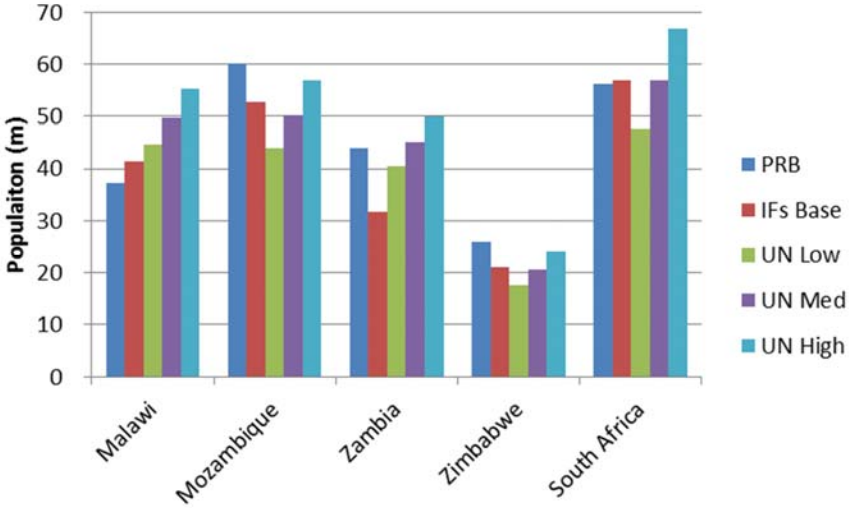
3.1 Development futures

The context for the demand and supply models across the water and electricity sectors is the future economic and social development of the Zambezi River Basin countries. Because both water and electricity demand are driven by inter-linked demographic and economic trends across countries, assessing future risks requires a consistent set of assumptions about the economic and social development of the region. While these assumptions can be compared with other data on GDP or population projections in the literature, taking possibly conflicting assumptions from different sources would not provide a realistic scenario for the future. The International Futures (IFs) modelling system is “a large-scale, long-term, integrated global modelling system. It represents demographic, economic, energy, agricultural, socio-political, and environmental subsystems for 183 countries interacting in the global system” (Hughes 2010; Hughes et al. 2009). As Chapman (2012) reports, “IFs uses a general equilibrium structure for its 6-sector economic module. IFs is useful for modelling stocks and flows of elements such as goods and services, money, human well-being, environmental conditions, materials status, and knowledge. IFs also has functions for many non-market socio-economic interactions.” IFs has a standard embedded scenario known as the Base Case that has been developed using extensive data from United Nations and other official international and peer-reviewed sources. The “Base Case” contains mid-range projections using standard international data, and essentially simulates a continuation of status quo trends. It is a “scenario portraying a reasonable dynamic evolution of current patterns and trends”, or a central tendency scenario (Hughes et al. 2009). The “African Renaissance” scenario (see Cilliers, Hughes, and Moyer 2011) is more optimistic, with greater investment in development, increased international trade, improved productivity across almost all sectors, and increased foreign direct investment in Africa. The result of these changes is to accelerate economic and social development and reduce population growth. This scenario was selected to represent a plausible evolution of the region’s economic trajectory given recent changes in government that favour more open economies and the attraction of inward investment.

For population growth, Figure 2 shows the IFs base case projection alongside the United Nations projections (UNDESA 2011) and those of the Population Reference Bureau (PRB)(PRB 2013). The four countries with the largest share of Zambezi

River water supply and demand are shown, plus South Africa as the largest source of electricity supply and demand in the region. The PRB projections are shown because they are cited in the SADC “Integrated Water Resources Management Strategy for the Zambezi River Basin” (Euroconsult and Mott MacDonald 2007 p. 47), which is also referenced in the World Bank Zambezi Multi-Sectoral Investment Opportunity Analysis (MSIOA) study (World Bank 2010a). The IFs projections are well within the band of UN projections for Mozambique, Zimbabwe and South Africa, but are lower than the UN projections for Malawi and Zambia. For Malawi, the PRB projections are also considerably lower than those of the UN as well.

Figure 2. Population projections for 2050 for key countries



Sources: Hughes (2010), UNDESA (2011), PRB (2013)

The most important distinction in the development futures, however, is the degree to which irrigation and hydropower investments are realised. For hydropower, the scenarios include different timeframes for constructing the potential hydropower plants, with one scenario being based on the current SAPP generation expansion plan (see Table 2), which is generally considered quite optimistic. These are explored in the sub-section below. For irrigation, the difference in the development scenarios will be the year in which the “identified irrigation projects” and “high level potential irrigation”, as defined in the MSIOA study, will be reached (see Table 2).

Table 2. Summary of development futures

	"Business as Usual"	"Optimistic"
Population	IFs "Base Case" projections	IFs "African Renaissance" projections
GDP	IFs "Base Case" projections	IFs "African Renaissance" projections
Hydropower Investment	5-10 year delay in commissioning of most plants	As per SAPP plan and other stated commissioning dates
Irrigation Investment	Identified projects reached in 2030; High level potential reached in 2060	Identified projects reached in 2020; High level potential reached in 2040

3.1.1 Population

For the water model, only urban population projections are used, because rural domestic water demand is very small compared to other major demands (e.g. irrigation). Urban demand growth rates are estimated from national growth rates. Although there may be some shifts in urban-rural migration patterns over this period, this magnitude and even direction of these shifts is unclear for many countries, so national growth rates are used as the most reasonable proxy. As discussed above, the Optimistic future is based on higher economic and social development, which results in lower population growth. To illustrate these differences, Table 3 shows the projected populations of selected urban centres under these two scenarios.

Table 3. Selected urban population (millions) in each development future

	Development Future	
Urban population	Business As Usual	Optimistic
Harare		
2020	2,311,169	2,220,407
2050	3,337,321	2,719,407
Lusaka		
2020	2,295,054	2,179,387
2050	4,399,510	3,427,593
Lilongwe		
2020	1,090,121	1,012,212
2050	2,290,376	1,591,316

3.1.2 Irrigation investment

The MSIOA addressed irrigation expansion with two different irrigation projections (roughly in 2025): one based on "identified projects" in national plans and the other on "high level" irrigation potential (i.e. closer to maximum theoretical potential). The advantage of using the same future irrigation projections is that the MSIOA study contains detailed analysis of irrigation area by sub-basin and crop for each future. Again, given long time frame for this study, the question is more *when* these levels of irrigation will be reached, rather than *whether* they will be reached. Table 24 below shows the years where each level of irrigation expansion is reached in the two different development futures modelled in this study.

Table 4. Irrigation expansion in each development future

Irrigation area target	Development Future Business as Usual	Optimistic
Year when "identified projects" have been realised	2030	2020
Year when "high level" irrigation potential has been realised	2060	2040

3.1.3 Hydropower investment

In terms of hydropower investment, the "optimistic" development future is the most recent version of the SAPP expansion plan. This specifies when different new hydropower plants, or plant extensions, are due for commissioning. This is considered optimistic, because many of these hydropower plants have been under development for decades but still face financial and technical barriers. The "business as usual" future is therefore a delay of 5-10 years in implementing the plants in the SAPP expansion plan. Similarly, for plants not currently included in the SAPP plan, the development futures have a shorter and longer timeframe for commissioning. Dates for key new plants are shown in Table 5 below.

Table 5. Hydropower expansion in each development future

Plant	Year of commissioning in each development future Business as Usual	Optimistic
Cahora Bassa North	2022	2017
Mphanda Nkuwa	2022	2017
Kariba South Extension	2018	2015
Kariba North Extension	2014	2013
Kafue Gorge Lower	2022	2017
Itezhi-tezhi	2014	2014
Boroma	2025	2020
Lupata	2025	2020
Devil's Gorge	2028	2018
Batoka Gorge	2022	2018

3.2 Climate futures

For the climate futures, two criteria are important for this study. First, the climate futures should illustrate both possible overall wetting and drying trends in the Zambezi River Basin. Second, where possible, these futures should use similar data as the major studies already undertaken in the Basin and/or already undertaken by the team. This is to reduce the time required for pre-processing data, but also to build on the stakeholder engagement that already occurred for previous studies – particularly the two by the project teams[1]. A significant advantage of the downscaled-GCM WATCH dataset used in the current Pöyry study is that no further

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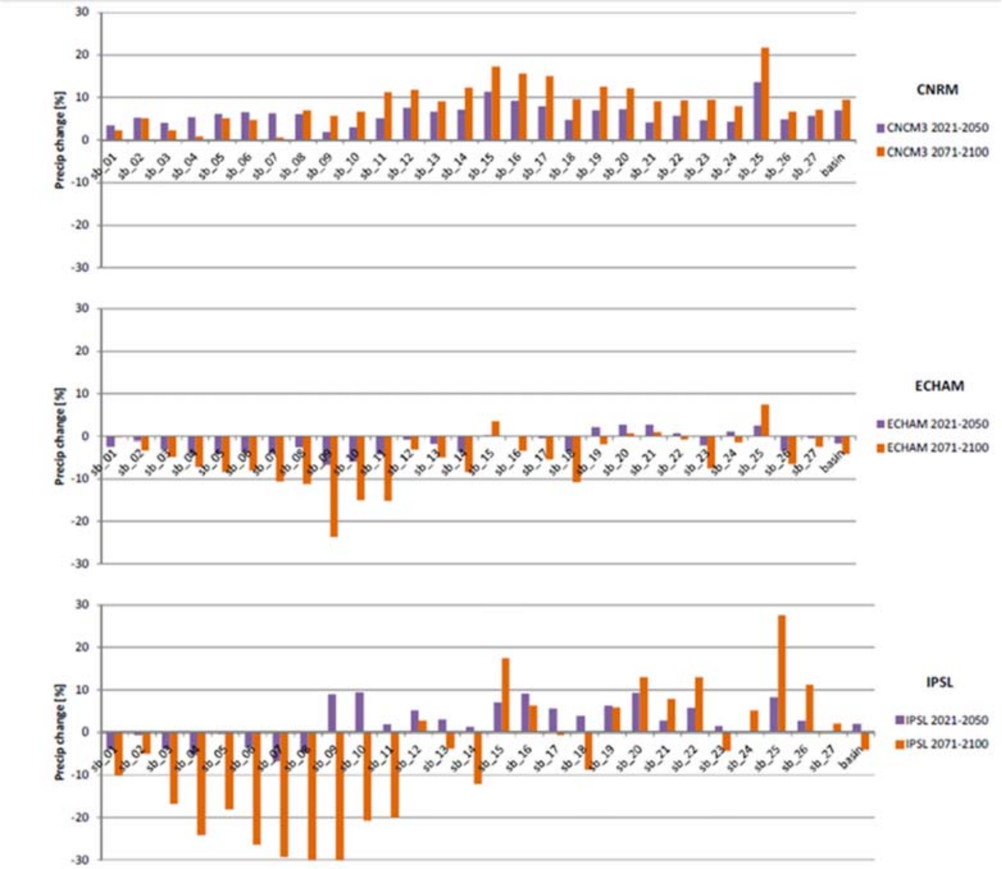
[1] The study led by CEEEZ is reported in Yamba et al. (2011). The study by Poyry Energy Vienna on a Zambezi Decision Support System (DSS) is reported in Kling et al. (Submitted)

bias correction is required. The WATCH (Water and Global Change)[2] climate dataset includes the statistically downscaled results of several different GCMs, which span the range of wetting to drying in the ZRB (see Figure 3). For this reason, the CNRM[3] results are used to represent the “wetting” scenario, while the ECHAM[4] results are used for the “drying” scenario. The sub-basins shown in the figure are the same as in the WEAP model, moving roughly from upstream to downstream in the basin.

Figure 3. Change in annual precipitation (compared to 1961-90 mean) of different sub-basins projected by the GCMs of WATCH.



Source: (Kling and Preishuber 2012)

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[2] The Integrated Project Water and Global Change (WATCH, 2007-2011), funded under the EU FP6, brought together the hydrological, water resources and climate communities to analyse, quantified an predicted the components of the current and future global water cycles and related water resources states; evaluated their uncertainties and clarified the overall vulnerability of global water resources related to the main societal and economic sectors (http://www.eu-watch.org/)

[3] CNRM-CM3 global coupled system is the third version of the ocean-atmosphere model initially developed at CERFACS (Toulouse, France), then regularly updated at Center National Weather Research (CNRM, METEO-FRANCE, Toulouse) (http://www.cnrm.meteo.fr/scenario2004/references_eng.html)

[4] ECHAM is a comprehensive general circulation model of the atmosphere from the Max Plank Institute for Meteorology. The ECHAM GCM has its original roots in global forecast models developed at ECMWF. This model has been modified for climate research, and its development continued to the current cycle ECHAM5. http://www.mpimet.mpg.de/en/wissenschaft/modelle/echam.html)

4 Water supply model

4.1 Hydrological features

The supply model includes all of the major rivers in the Zambezi River Basin, as well as existing and planned reservoirs that include hydropower production (see Figure 4). The level of detail for the river definitions are the same as those in the ZDSS and more detailed than the MSIOA study, as discussed in later sections.

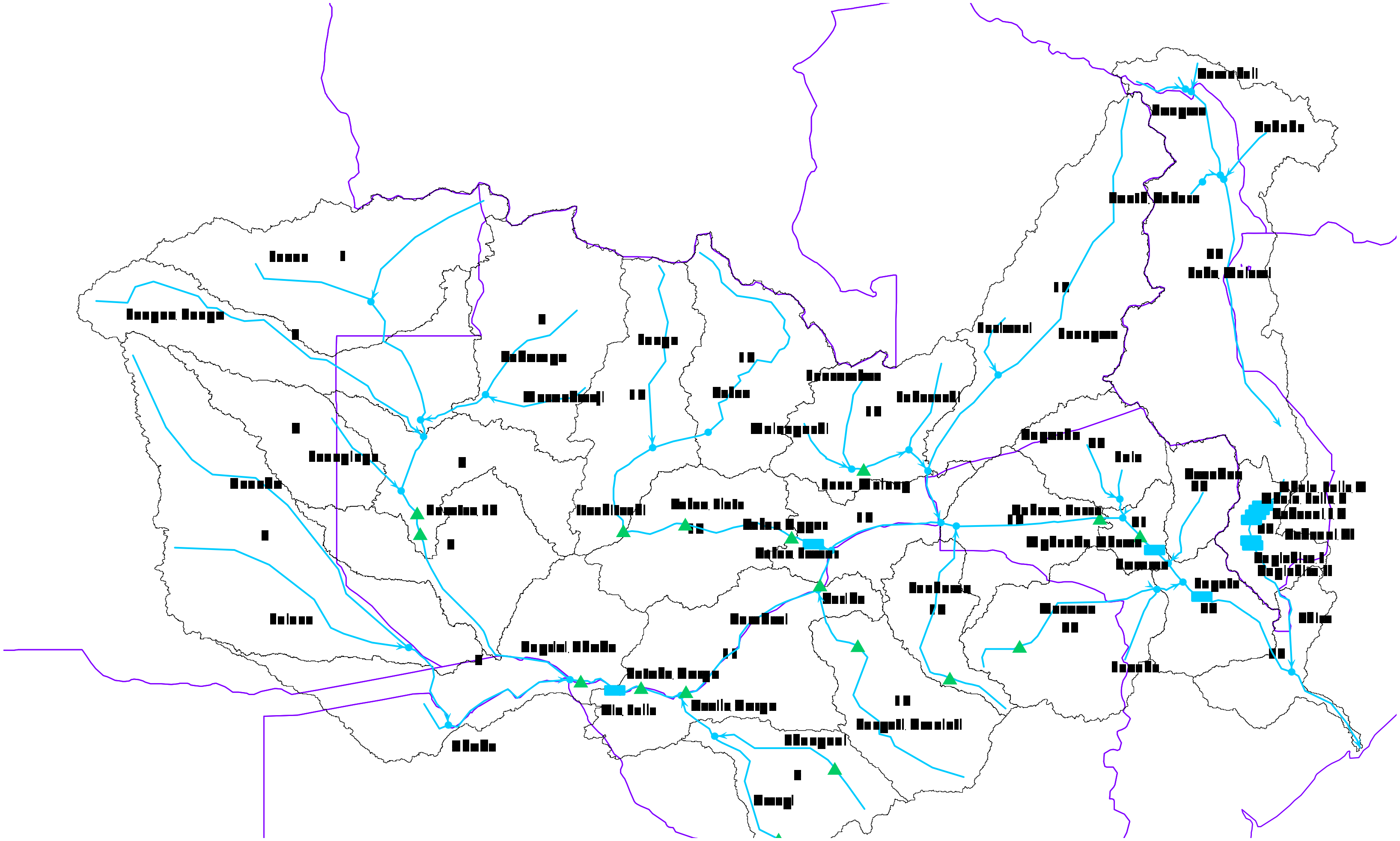
The Lake Malawi system is modelled separately from the Shire River, with calibrated outflows from the outlet of the lake from the ZDSS used as the headflows of the Shire River. The reason for this is the complexity of the Lake Malawi system, the steep gradient in precipitation along the length of the lake, and the fact the focus of this study is on major Zambezi River downstream hydropower plants, not upstream catchments. In fact, the objective of the study is to focus on downstream plants on the Zambezi River, which are not affected at all by the Shire River, because there are no hydropower plants below the confluence of the Shire and the Zambezi. However, for the sake of presenting a complete picture of the entire river basin, the Lake Malawi system is still included in this study, albeit at a coarser level of detail.

While groundwater is also important in some areas of the ZRB, the source of the groundwater is still rainfall (i.e., it is not “fossil groundwater”). Because the timing of groundwater replenishment and use is not the focus of this study, all of the rainfall-runoff flows are treated as surface water.

4.2 Sub-basin boundaries and catchments

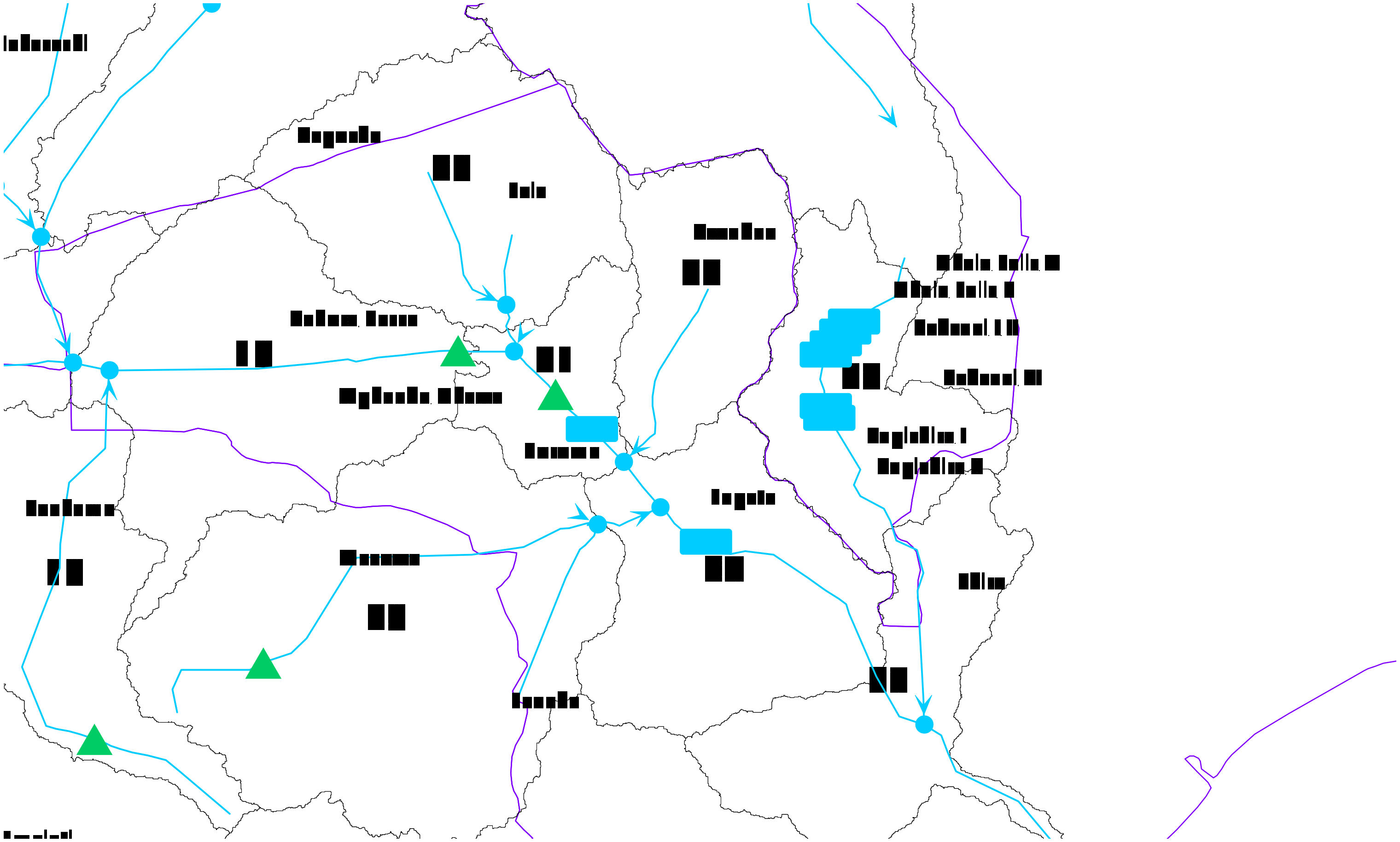
The sub-basin boundaries correspond to the ZDSS, with additional sub-divisions for runoff inflows and irrigation catchment areas to take into consideration the placement of new hydropower plants within a given sub-basin. The 27 main sub-basins used (see Figure 4) are more detailed than the 13 sub-basins used in the MSIOA study.

Figure 4. Schematic of rivers, reservoirs and run-of-river hydropower plants



Note: Natural and man-made reservoirs are green triangles. Run of river hydropower plants are blue rectangles. Only modelled hydropower plants are shown. Green triangles without labels represent the aggregation of multiple small irrigation storage reservoirs.

Figure 5. Detail of lower Zambezi and Shire River hydropower plants



Note: Natural and man-made reservoirs are green triangles. Run of river hydropower plants are blue rectangles.

Although the WEAP model contains almost all of the plants mentioned in the literature on the Zambezi River Basin, not all of these are modelled in detail, both because of the limitations of data availability and the negligible impact of many plants on major downstream hydropower investments. Having the plants in the model, however, allows for future development and expansion of the analysis in particular sub-basins, where more data is made available or where stakeholders have strong interest. The plants included in the modelling are discussed in more detail in section 5.2.

Because of limitations in the spatial resolution of the hydrology modelling (See next section) some smaller hydropower plants and their catchment areas were combined into larger catchments. Examples include the following:

- The Lunsemfwa and Mulungushi Rivers in Zambia are combined into one catchment area, and the two existing power plants on those rivers treated as a combined plant.
- The three future potential plants on the Revubue River mentioned in the earlier Euroconsult Mott McDonald (2007) study are combined into one catchment area.
- The two future potential plants on the Luia and Capoche Rivers mentioned in the earlier Euroconsult Mott McDonald (2007) study are also combined into one catchment area.

In addition, some of the small plants were not modelled, both because of lack of data and their negligible impact on downstream activities. These include Wovwe in Malawi (5MW) and Lusiwasi in Zambia (12MW).

4.3 Hydrology and runoff inputs

While WEAP has several built-in hydrological models, a fully calibrated hydrology dataset for all of the sub-basins is available through the recently completed Zambezi Decision Support System (ZDSS) developed by Pöyry Energy for the Mozambique National Institute for Disaster Management (INGC)[5]. This model and dataset are in the public domain, and are flexible enough to allow extraction of surface inflows at any point in the river network. The underlying precipitation and temperature data can also be similarly extracted. The ZDSS has been calibrated against stream flow gauge data for all of the key sub-basins and reservoirs in the Zambezi. An example of the calibration of the ZDSS at key points on the Zambezi is shown in Figure 6 and as reporting in Kling et al. (Submitted). This runoff data provides surface inflow inputs to the rivers in the WEAP model, net of any evapotranspiration from vegetation (irrigated agriculture or natural vegetation).

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[5] Freely available at http://zdss.ingc.gov.mz/

Figure 6. Simulated and observed monthly flow rates at key gauging stations on the Zambezi from the ZDSS, 1960-1992

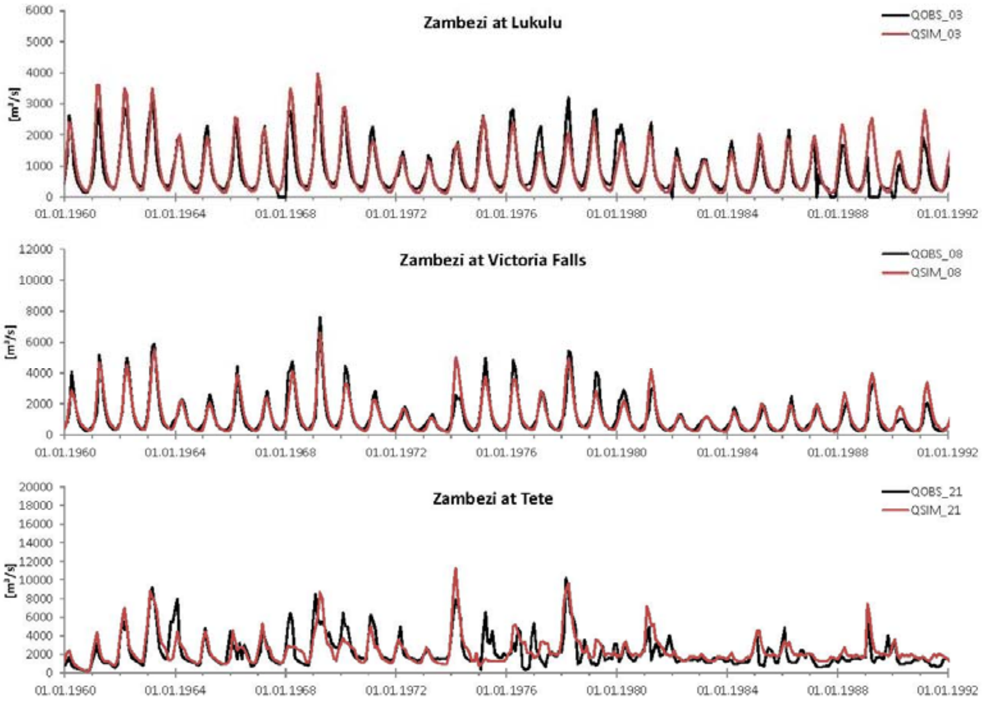

Figure 66: Simulated (red) and observed (black) monthly hydrographs at key locations along the Zambezi.

Source: (Kling and Preishuber 2012; Kling, Stanzel, and Preishuber Submitted)

The only adjustment necessary to the ZDSS surface inflow is related to runoff from irrigated areas. This means that the runoff estimates already include any excess precipitation from irrigated land (i.e. when rainfall exceeds the demand from crops and the ability of the soil to absorb the moisture). The irrigation demand calculations in WEAP, however, also assume that runoff may occur from irrigated land area if the precipitation is in excess of the “effective precipitation” level. This could lead to some double counting in sub-basins where irrigation land is a significant share of total land area. For those sub-basins (see sub-basins 11, 24, 26 and 27 in Table 6), the ZDSS runoff inputs are reduced by the share of irrigated land to total sub-basin area, so that the runoff calculations for irrigated areas are calculated in WEAP. The share of irrigated land in those sub-basins increases over time, reaching the “current + identified projects” level in 2020 or 2030 and “total” (i.e. including high level potential as well) by 2040 or 2060, depending on the scenario. Note that this adjustment is much less important for sub-basins 26 and 27, because there are no hydropower plants downstream of the surface inflow points.[6]

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[6] This adjustment is affected in WEAP using a Key Assumption for “runoff adjustment”, interpolating the values for 1960 (zero), 2000 (current), 2025 (current + identified) and 2050 (2025 + high level). The surface inflow data from the ZDSS is then multiplied by (1 – runoff adjustment).

Table 6. Irrigated area versus sub-basin size

		Irrigated Areas (ha)					Irrigation share of total (%)	
Sub-basin	Name	Current	Identi-fied	High level	Total	Subbasin area (km2)	Total	Current + Identified
1	Chavuma Mission	2,500	5,000	10,000	17,500	79,821	0.22%	0.09%
2	Kabompo	350	6,300	10,000	16,650	66,459	0.25%	0.10%
3	Lukulu	1,000	500	10,000	11,500	66,345	0.17%	0.02%
4	Luanginga	750	5,000	10,000	15,750	32,989	0.48%	0.17%
6	Senanga	200	7,008	10,000	17,208	46,329	0.37%	0.16%
7	Katima Mulilo	620	300	15,000	15,920	113,501	0.14%	0.01%
8	Kwando	1,575	13,346	12,300	27,221	71,014	0.38%	0.21%
9	Gwaai	1,300	566	0	1,866	39,117	0.05%	0.05%
10	Sanyati	21,600	5,203	0	26,803	45,340	0.59%	0.59%
11	Kariba	3,711	98,637	430,000	532,348	73,107	7.28%	1.40%
12,13	Mswebi & Itezhi-tezhi	4,177	6,000	0	10,177	106,569	0.10%	0.10%
14	Kafue Gorge	35,021	6,650	25,000	66,671	46,167	1.44%	0.90%
15	Upper Luangwa	1,000	1,479	0	2,479	96,838	0.03%	0.03%
16	Lower Luangwa	9,100	4,651	25,000	38,751	45,209	0.86%	0.30%
17	Middle Zambezi	1,960	6,823	0	8,783	33,223	0.26%	0.26%
18	Panhane	22,085	7,521	0	29,606	24,404	1.21%	1.21%
19	Cahora Bassa	10	0	100,000	100,010	35,036	2.85%	0.00%
20	Luia	0	0	0	0	28,698	0.00%	0.00%
21	Luia	10	150	0	160	28,698	0.01%	0.01%
22	Revubue	0	0	0	0	16,262	0.00%	0.00%
23	Luenha	12,713	11,661	0	24,374	53,581	0.45%	0.45%
24	Mutarara	315	11,000	100,000	111,315	26,166	4.25%	0.43%
25	Liwonde	25,391	23,887	50,000	99,278	132,277	0.75%	0.37%
26	Chiromo	17,025	35,625	300,001	352,651	19,259	18.31%	2.73%
27	Delta	6,998	77,055	100,000	184,053	22,246	8.27%	3.78%

While this project uses the runoff data from the ZDSS, WEAP is used for the water balance model. The runoff data is input as surface inflows at various points along the river network, corresponding to the catchments areas from which the runoff estimates are derived. The advantage of using runoff data and simulations from the ZDSS is that it is a well calibrated model that has been tested against actual historical flow gauges, and allows calculation of inflows at any point in the river system. WEAP is used for all demand calculations and for water balance modelling and allocation, which is the main value added of this project (in addition to linking WEAP to the energy modelling system). The ZDSS also provides projected runoff under the future climate scenarios discussed earlier.

Table 7 shows the list of surface inflow points and describes their location and which sub-basins they represent. The sub-basin numbers from the ZDSS and the World Bank MSIOA are given for clarity. The rationale for the selection of surface inflow points is to ensure that flows above each hydropower plant (existing and potential) and irrigation abstraction point are in the correct order so that the combined impact of upstream abstractions and flows on each hydropower plant can be analysed. This means that, for example, if there is more than one hydropower plant in a sub-basin, two inflow points may be necessary – one above and one below the hydropower plant. The inflow points are shown in the model schematic as gauges (as a placeholder only – they do not represent actual gauges, but this is the only icon available in WEAP for this).

Table 7. Surface inflow points in river network

upstream surface inflow point	World Bank (WB) sub-basin name	WB sub-basin	ZDSS Sub-basin	Inflow description
SI1	Upper Zambezi	12	1	All of SB1
SI2	Kabompo	13	2	All of SB2
SI3a	Lungue Bungo	11	3	Lungue Bungo within SB3
SI3b		11	3	Additional Zambezi and Kabompo inflows within SB3
SI4	Luanginga	10	4	All of SB4
SI5	Barotse	9	5	Additional Zambezi inflows within SB5
SI6		9	6	Additional Zambezi inflows within SB6
SI7	Cuando / Chobe	8	7	All inflows in SB7 (Cuando and Luiana)
SI8a		8	8	Additional Zambezi/Chobe inflows to Caprivi Floodplain
SI8b		8	8	Additional Zambezi inflows down to Victoria Falls
SI13	Kafue	7	12,13	SB12 and 13 above Itezhi-tezhi
SI14a		7	14	Kafue inflows between Itezhi-tezhi and Kafue Flats
SI14b		7	14	Kafue inflows between Kafue Flats and Kafue Gorge
SI9	Kariba	6	9	All inflows in SB9 (Shangani and Gwayi)
SI10		6	10	All inflows in SB10 (Sanyati-Umniati)
SI11a		6	11	All Zambezi inflows from Vic Falls to Gwayi River inflow
SI11b		6	11	All Zambezi inflows from Gwai River to Kariba Dam (incl into reservoir)
SI15	Luangwa	5	15	All of SB15
SI16a		5	16	Lunsemfwa and Mulungushi rivers up to their confluence
SI16b		5	16	All of SB16 inflows except above confluence of Lunsemfwa and Mulungishi
SI17	Mupata	4	17	All inflows to Zambezi between Kariba and Chogwe guaging station plus inflows to Kafue between Kafue Gorge and joining the Zambezi

upstream surface inflow point	World Bank (WB) sub-basin name	WB sub-basin	ZDSS Sub-basin	Inflow description
SI18a	Tete	2	18	Lake Manyame and upstream Hunyani River
SI18b		2	18	All of Hunyani/Panhane River flows below Lake Manyame
SI19		2	19	All inflows to Zambezi bewteen Chongwe and Cahora Bassa HPP
SI20		2	20	SB20 - Luia and Capoche rivers
SI21		2	21	Inflows to Zambezi between Cahora Bassa and Mphanda Nkuwa
SI24a		2	24	Additional Zambezi inflows bewteen Mphanda Nkuwa and Lupata
SI24b		2	24	Additional Zambezi inflows between Lupata and Chemba
SI23		2	23	All of Luenya and Mazowe in SB23
SI22		2	22	All of SB22 (Revubue River)
SI25a	Lake Malawi / Shire	3	25	Inflows to Rumakali above Rumakali HPP
SI25b			25	Inflows to Ruhuhu above Masigira HPP
SI25c			25	Inflows to Songwe above Songwe HPP
SI25d			25	Inflows to North Rumphi above North Rumphi HPP
SI25e			25	Inflows to South Rukuru above Lower Fufu HPP
SI25f			25	All inflows to Lake Malawi
SI25g		3	25	Net **outflow** from Lake Malawi, from ZDSS
SI26		3	26	All inflows from Lake Malawi to end of SB26
SI27	Zambezi Delta	1	27	inflows in SB27 and below Chemba HPP in SB24

4.4 Wetlands

There are three key wetlands areas within the ZRB: Barotse, Kafue Flats, and Chobe-Caprivi. These are modelled in WEAP as reservoirs, to ensure that evaporation from wetlands is captured, and, in some cases, with an additional "virtual reservoir" to delay the peak in the hydrograph. A similar analysis was conducted in the ZDSS, and so the modelling draws upon these results as well.

For Kafue Flats, the relationship between discharge and storage volume is taken from the ZDSS, which analysed observed trends in releases over time. These and the other characteristics used for Kafue Flats are shown in Table 8. Because WEAP does not have the capability to calculate releases from instantaneous storage, the expression used for discharge requirements from the natural reservoir is linked to the storage levels in the previous two time steps, using a linear equation derived from the data in the table[7]. In addition, research has shown that water takes up to 90 days to travel between Itezhi-tezhi reservoir and Kafue Gorge, through the Kafue Flats, so a shift in the hydrograph is expected.

Table 8. Hydrological assumptions for Kafue Flats wetlands

Volume (mcm)	15	77	303	989	2143	3616	5285	7094	8039	9006	9498
Elevation (m amsl)	976	977	978	979	980	981	982	983	983.5	984	984.25
Area (km^2)	30	114	405	950	1340	1586	1745	1865	1915	1955	1975
Release (cms)	2	11	42	137	298	502	734	985	1117	1251	1319

Source: Beilfuss (2001), Table 4-3, except for release, which is from ZDSS model

For the Barotse Flood Plain, a different approach is used, because of the importance of the observed shift in the hydrograph, such that the peak moves from March to April. Two reservoirs are used in the model. The first has the shape and size of the Barotse as reported in the literature. To ensure that this reservoir fills during the wet season (i.e. instead of the water simply passing through), the reservoir filling priority is set higher than downstream demands. This means that WEAP will allocate water to filling the reservoir even when there are downstream hydropower and irrigation demands. This simulates what happens in the natural setting, where the flood plain expands dramatically in size during the wet season, and this is not affected by the large downstream hydropower plants. The second reservoir is large enough to hold two months of peak flow, and discharges an amount in each time period equal to the inflows in the previous time period. In this way, it shifts the hydrograph by exactly one month, so that peak flows are in April, while the first reservoir attenuates the difference between peak and low flows.

The Chobe-Caprivi wetlands are modelled using the reservoir shape from the literature as shown in Table 9, sourced from the ZDSS.

Table 9. Hydrological assumptions for Chobe-Caprivi wetlands

Volume (mcm)	0	180	720
Area (km^2)	0	10	2000
Elevation (m amsl)	1000	1018	1018.3

Source: ZDSS model

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[7] Release = 0.5*(PrevTSValue(Supply and Resources\River\Kafue\Reservoirs\Kafue Flats:Storage Volume[m^3])/10^6)*.1389+0.5*(PrevTSValue(Supply and Resources\River\Kafue\Reservoirs\Kafue Flats:Storage Volume[m^3],2)/10^6)*.1389)

To improve the simulations of natural reservoirs, buffering assumptions were also included in the modelling (see section 6.1). A “buffer zone” is the reservoir volume at which there is a limit placed on monthly releases, to ensure that the reservoir is not drawn down too fast. The “buffer coefficient” is the percentage of the remaining buffer zone that can be released in the next time period. The buffer zones are specified relative to the desirable top level of the reservoir (“Top of Conservation), which may vary over the year where there is a Design Flood Rule Curve in place.

Table 10. Buffering assumptions for natural reservoirs

Reservoir	Buffer Zone (% of storage capacity)	Buffer Coefficient (%)
Barotse (both reservoirs)	75	10
Chobe-Caprivi	75	10

4.5 Abstraction points

The irrigation abstraction points in the model are show as irrigated catchments, with a transmission link from the relevant water source and a return flow for any unused runoff or excess rainfall. This list of abstraction points, and their relationship to previous research under the MSIOA study, is shown in Table 23.

5 Demand model

As shown in Table 11 below, reservoir evaporation is the largest current source of demand on available runoff, at 16%. The second largest source is irrigated agriculture at 1.4%. Urban demand follows at 0.17%, which is small but has been included because of the possible significant increase in urban populations in the ZRB. The focus on the demand analysis is therefore hydropower demand/reservoir evaporation, irrigated agriculture, and urban demand.

Table 11. Demand sources and share of runoff for Zambezi River Basin

	(Mm3)	(%)
Available run off	103,224	100.00
Hydropower (evaporation)	16,989	16.46
Irrigated agriculture	1,478	1.43
Urban domestic consumption	175	0.17
Rural domestic consumption	24	0.02
Industrial consumption	25	0.02
Mining	120	0.12
Environmental/flood releases*	1,202	1.16
Livestock	113	0.11
Total water demand	20,126	19.49

*from Itezh-tezhi only, released for downstream ecosystems so not available for agriculture or hydropower from Itezhi-tezhi
Source: Euroconsult & Mott MacDonald (2007), Table 4.10

5.1 Reservoir evaporation

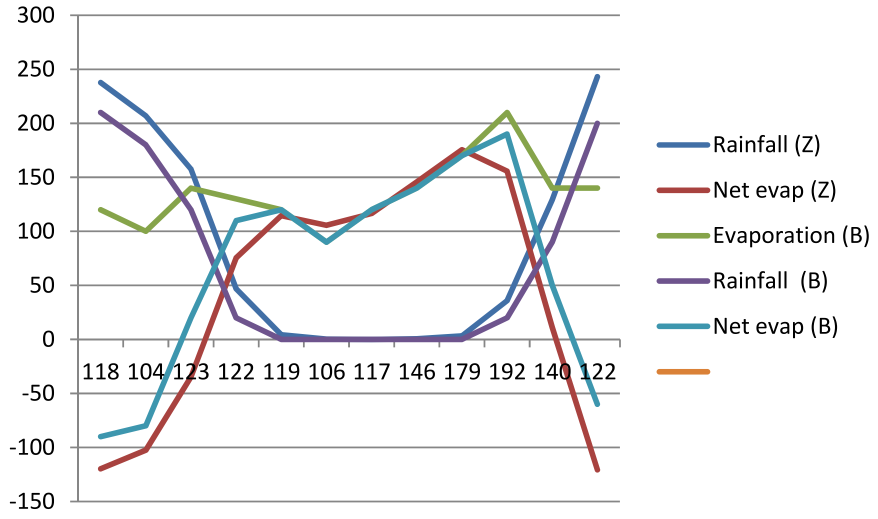
The operators of the major reservoirs – particularly Lake Kariba, Lake Cahora Bassa and Itezhi-tezhi - have historical data on rainfall and evaporation, although these data are often estimated from a fairly small number of stations and need to be corrected for the difference in conditions between standard Pan Evaporation tests and evaporation from a reservoir surface (e.g. relative humidity, wind speed) (Allen et al. 1998). The ZDSS provides monthly evaporation and rainfall data by sub-basin, which has been used for the reservoirs in those sub-basins. This is a finer resolution of climate data than the MSIOA study sub-basins (i.e. 13 vs 26 sub-basins in this study). Table 12 shows historical (1960-1990) monthly evaporation and rainfall in sub-basin 13, which contains the Itezhi-tezhi reservoir. This data is similar to that used by Beilfuss and dos Santos (2001), as shown in Figure 7.

Table 12. Historical annual average evaporation, rainfall and net evaporation from Itezhi-tezhi (mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Evaporation	118	104	123	122	119	106	117	146	179	192	140	122
Rainfall	238	207	158	47	4	0	0	1	3	36	129	243
Net Evaporation	-120	-103	-35	75	114	106	117	146	176	156	11	-121

Note: data is for entire sub-basin 13.
Source: ZDSS

Figure 7. Evaporation, rainfall and net evaporation at Itezhi-tezhi (mm)



Note: Z=from ZDSS, B=from Beilfuss and dos Santos (2001)

The data for Lake Kariba and Cahora Bassa are shown in Table 13 and Table 14. For Lake Kariba, the reservoir with by far the most surface area, the average net evaporation data from the ZDSS and the data presented in Beilfuss and dos Santos (2001) are within 2%. For the other reservoirs, however, such as Cahora Bassa and Itezhi-tezhi parameters are considerably lower than those reported in Beilfuss and dos Santos (2001). The reason for this is that the Bielfuss paper uses a pan evaporation correction factor of 0.9, while the ZDSS uses much lower values. Typical pan correction factors range from 0.35- 0.85 (Allen et al. 1998), and the ZDSS aligns with the lower values based on local conditions.

Table 13. Historical annual average evaporation, rainfall and net evaporation from Lake Kariba (mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Evaporation	135	117	137	128	117	100	109	142	182	211	164	144
Rainfall	173	160	89	30	4	1	0	0	2	19	67	163
Net Evaporation	-38	-43	48	98	113	99	109	142	180	191	98	-20

Note: data is for entire sub-basin 11.
Source: aggregated from monthly data in ZDSS

Table 14. Historical annual average evaporation, rainfall and net evaporation from Cahora Bassa (mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Evaporation	123	110	122	112	101	85	93	119	150	182	155	140
Rainfall	216	195	113	29	5	2	2	1	1	11	58	202
Net Evaporation	-93	-84	8	83	96	82	91	118	149	172	96	-62

Note: data is for entire sub-basin 19.
Source: aggregated from monthly data in ZDSS

Table 15. Historical annual average evaporation, rainfall and net evaporation from Kafue Gorge (mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Evaporation	129	114	134	134	130	116	127	160	196	210	153	134
Rainfall	202	175	86	26	4	0	0	0	2	19	89	211
Net Evaporation	-73	-62	48	108	126	116	127	160	194	191	64	-77

Note: data is for entire sub-basin 14.
Source: aggregated from monthly data in ZDSS

For the natural reservoirs of Kafue Flats, Barotse floodplains, and the Chobe-Caprivi wetlands, evaporation could also lead to significant water losses. The Lake Malawi evaporative losses are already taken into consideration in the discharge data from the lake used as an input to the WEAP model, but for the other natural reservoirs evaporation data is shown in Table 16 and Table 17. Kafue Flats uses the same data as Kafue Gorge reservoir.

Table 16. Historical annual average evaporation, rainfall and net evaporation from Barotse floodplain (mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Evaporation	125	112	124	130	133	121	136	165	192	186	137	123
Rainfall	206	183	131	41	3	0	0	1	3	33	112	197
Net Evaporation	-81	-72	-7	88	129	120	136	165	189	153	25	-73

Note: data is for entire sub-basin 5.
Source: aggregated from monthly data in ZDSS

Table 17. Historical annual average evaporation, rainfall and net evaporation from Chobe-Caprivi floodplain (mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Evaporation	125	112	124	130	133	121	136	165	192	186	137	123
Rainfall	206	183	131	41	3	0	0	1	3	33	112	197
Net Evaporation	-81	-72	-7	88	129	120	136	165	189	153	25	-73

Note: data is for entire sub-basin 8.
Source: aggregated from monthly data in ZDSS

The sensitivity of evaporation to changes in mean temperature is the same as the sensitivity of reference evapotranspiration. Reservoir evaporation can be calculated using the same basic equations used for evapotranspiration (Kling, Stanzel, and Preishuber Submitted) but modified for the non-typical surface of the reservoir and the potential for heat transfer with the water body (e.g. as presented in Allen et al. 1998). The relative change in reservoir evaporation due to increasing temperatures is the same as for potential evapotranspiration. As explained in chapter 5.3, one degree Celsius increase in temperature leads to a 2.5% increase in evapotranspiration, and therefore evaporation as well.

Applying the temperature projections from the two climate futures in the relevant sub-basin for each reservoir provides the basis for calculating future evaporation. This combined with future precipitation in each climate future yields future net evaporation.

5.2 Hydropower demand

5.2.1 *Historical data*

The WEAP model utilises required energy production and the characteristics of each reservoir or run-of-river plant to determine the flows necessary for meeting specified hydropower demand. The actual production then depends not only upon water availability, but also other demands upstream and downstream. If more water must pass through the dam than is necessary to produce the required energy demand (e.g. to comply with the Design Flood Rule Curve or to meet a high priority downstream demand), then WEAP pushes this water through the turbines, up to the specified maximum turbine flow. If the maximum turbine flow is reached, the water is discharged through spillway gates up to the specified maximum hydraulic flow.

For the historical time period, the simulation uses actual monthly hydropower production (see Table 18), generation efficiency, and head height (fixed or variable depending on the plant type) to determine the flows going through the turbines. For plants with reservoirs, the volume-elevation curve is also used, and for the largest plants the modelling includes the tailwater rating curves and Design Flood Rule Curves (see Annex A for detail). DFRCs are used for Kariba (ZRA 2013; SADC 2011), Cahora Bassa (ZDSS analysis of recent operations at HCB), and Itezhi-tezhi (Beilfuss and Brown 2010). The existing hydropower plants in the basin are shown in Table 20 below.

Table 18. Historical generation annual and monthly data availability

Dam/Plant Name	Commission Year	Average Annual only	Annual Data	Monthly Data	Sources	
					Annual	Monthly
Cahora Bassa	1976-77		1977-2012	2004-2013	HCB	HCB
Kafue Gorge Upper	1968		1993-2012	1993-2012	ZESCO	ZESCO
Kariba South	1958		1990-2009		IEA	IEA
Kariba North Bank	1959		1993-2012	1993-2012	ZESCO	ZESCO
Victoria Falls	1972		1993-2012	1993-2012	ZESCO	ZESCO
Mulungushi	1955	✓				
Lunsemfwa	1944	✓				
Nkula Falls A	1966			2005-2012		ESCOM
Nkula Falls B	1981			2005-2012		ESCOM
Tedzani I & II	1977			2005-2012		ESCOM
Tedzani III	1995			2005-2012		ESCOM
Kapichira I	2000			2005-2012		ESCOM

For Cahora Bassa, the average turbine discharge from October 1998 (when plant was fully back on line after reconstruction) and April 2007 (last data from Mozambique National Water Directorate) was 1310 cms, which would mean the tailwater elevation was approximately 202 m amsl (see Annex A for rating curve). Over the same period, the mean reservoir elevation was 322 m amsl, so the net head was 120m. This corresponds to a generation efficiency of 95.6% (see Annex A for relationship between net head and efficiency). Similarly, for Itezhi-tezhi, the tailwater elevation is estimated from an average net head of 40m (Euroconsult and Mott MacDonald 2007) and the average reservoir surface elevation between 1977 and 2002 of 1025.8m amsl (Walimwipi 2012).

For generation efficiency for the other plants, all plants in Zambia are assigned the same value as Kariba and Kafue Upper (88%) given in Beilfuss (2001). All new plants in Mozambique are assigned the same efficiency as that of Mphanda Nkuwa (94%), as given in HMNK (2012). For plants in Malawi and Tanzania, a benchmark efficiency of 90% is used to represent a typical hydropower plant (USBR 2005).

For technical availability (i.e. net of planned and unplanned outages), where this is not specified by the utility, 93% is used, based on the SAPP Pool Plan Study (Nexant 2007). Plant-specific availability was only available for Cahora Bassa (96%) and Mphanda Nkuwa (91%).

Note that both plants on Lake Kariba are treated as one reservoir hydropower plant, with combined energy demand for Kariba South and Kariba North, for modelling practical reasons.

Maximum hydraulic flow (turbines and spillway) is only specified for Lake Kariba (9515 cms) (Beilfuss and Brown 2010) and Cahora Bassa (16,250 cms)(Beilfuss and dos Santos 2001).

Maximum turbine flow is a key parameter in WEAP, and must be specified for the model to allow electricity generation. Turbine flow should correspond to the rated capacity of the plant, taking into consideration the net head, efficiency and availability of the plant. In some cases the reported maximum turbine flow had to be adjusted to match the stated capacity of the plant. For example, Cahora Bassa has a rated output of 2075 MW and reported maximum turbine flow of 2250 cms. With an efficiency of 96% and availability of 96%, however, this would produce 2300 MW at the average net head of 116m. Because WEAP will always direct streamflow to turbines first, the maximum turbine flow must be adjusted downward to 2000 cms to ensure that the model does not yield higher generation than the rated capacity.

Other maximum turbine flows are defined for Kariba (1794 cms), Victoria Falls (117 cms)(MEWD 2010), Kafue Upper (252 cms) (Beilfuss and dos Santos 2001), Nkula Falls A&B (246 cms) (World Bank 2010a), Tedzani I, II & III (276 cms) (World Bank 2010a), and Kapichira I (134 cms)(ESCOM 2013a).[8]

As the catchment area of a hydropower plant decreases, so the certainty of the climate and runoff projections also decreases, because of the relatively low density of reporting weather stations in much of the Zambezi River Basin. For this reason, small stations such as Lusiwasi (12MW) and Wovwe (5MW) are not included in the modelling. In addition, the Lunsemfwa (18MW) and Mulungushi (20MW) plants are combined in one "virtual plant" with the larger reservoir and catchment area, to reduce the uncertainty in runoff projections.

For all existing hydropower plants, monthly historical generation was requested from the relevant utilities, but this was not always available, or was sometimes only available for specific years. Table 18 shows the cases where annual or monthly data was available, and for what years. For plants with no annual or monthly data, the average annual production data was used, as per Table 20.

As with natural reservoirs, buffering parameters (see section 4.4 for explanation) are also specified for the existing man-made reservoirs, as shown in Table 19.

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[8] Because WEAP requires a non-zero maximum turbine flow to allow water to flow through the turbines, for plants without maximum turbine flow specified in the literature, a dummy value of 1000 was used.

Table 19. Buffering assumptions for existing reservoirs

Plant*	Buffer Zone (% of storage capacity)	Buffer Coefficient (%)
Cahora Bassa	58	6
Kafue Gorge Upper	75	10
Kariba	62	6/2 (>2000)**

*Calibration for Itezhi-tezhi was most accurate without buffering, so these are not included for this reservoir

**After 2000, the buffering coefficient for Kariba is reduced to 2%, because of the vulnerability of drying climate and irrigation demand leading to excessive reservoir draw down loss of net head for power production.

Table 20. Existing hydropower plants in the Zambezi River Basin

Dam/Plant Name	Country	River	Installed capacity	Commis-sion	Average annual generation	Reservoir Active Storage	Surface area when full	Reservoir elevation when full	Average Head
			MW	year	GWh	M m3	km2	m amsl	m
Cahora Bassa	Mozambique	Zambezi	2,075	1976-77	14,729	51,704	2,665	326	116
Kafue Gorge Upper	Zambia	Kafue	990	1968	5,160	785	805	976.6	394
Kariba South	Zimbabwe	Zambezi	750	1958	3.584	64,798	5,577	488.5	95
Kariba North Bank	Zambia	Zambezi	720	1959	2,859	64,798	5,577	488.5	95
Victoria Falls	Zambia	Zambezi	108	1972	612	N/A	N/A	N/A	112.7
Mulungushi	Zambia	Mulungushi	20	1955	80		31		325
Lunsemfwa	Zambia	Lunsemfwa	18	1944	131		45		380
Itezhi-tezhi Reservoir	Zambia	Kafue	N/A	1977	N/A	4,925	374	1,029.5	40
Nkula Falls A	Malawi	Shire	24	1966	161	N/A	N/A	N/A	52
Nkula Falls B	Malawi	Shire	100	1981	575	N/A	N/A	N/A	57
Tedzani I & II	Malawi	Shire	40	1977	276	N/A	N/A	N/A	37
Tedzani III	Malawi	Shire	53	1995	312	N/A	N/A	N/A	42
Kapichira I	Malawi	Shire	64	2000	427	N/A	N/A	N/A	54

Note: commission date is for turbines.

Sources: (HCB 2013; ZESCO 2013; ESCOM 2013b; Euroconsult and Mott MacDonald 2007; Burian et al. 2012; Beilfuss and dos Santos 2001; Beilfuss 2001; Beilfuss and Brown 2010; MEWD 2010)

5.2.2 Future demand – planned HPP

Table 22 shows the planned and potential additional hydropower plants in the basin. As with historical plants, these inputs are used to determine the flow requirements at each location. However, less data is available on most of these plants. In some cases (see table), plants were only reported with their potential capacity in the literature and so could not be included, because this is not sufficient to calculate flow requirements. Where generation efficiency and availability was not specified, the same assumptions as for existing plants were used (see previous section).

Maximum turbine flow was not reported for many of the proposed plants, or the reported values in the literature were too low to yield the projected capacity. For example, the reported maximum flow at Mphanda Nkuwa is 662 cms (HMNK 2012), but 2730 cms would be required to produce the rated output of 1500 MW.[9] The reported maximum flow to Itezhi-tezhi of 306 cms (MEWD 2010) is sufficient to deliver the rated output of 108 MW.

For Kariba North, 455 cms would be sufficient to produce 360 MW output. Because this expansion will be used in peaking mode, the expected load factor is very low, however (12%). For the Kariba South expansion, 425 cms is needed for the 300 MW capacity rating. Batoka Gorge is estimated at 1220 cms maximum turbine flow based on the installed generation capacity, net head, efficiency and availability.

The buffering assumptions for the new reservoirs are shown in Table 21. Note that Mupata Gorge is not included, because, according to ZRA, this project would negatively affect Victoria Falls and so is very unlikely to be commissioned. Itezhi-tezhi maintains the same operating rules as currently.

Table 21. Buffering assumptions for new reservoirs

Plant	Buffer Zone (% of storage capacity)	Buffer Coefficient (%)
Batoka Gorge	75	10
Mphanda Nkuwa	75	10
Devil's Gorge	75	10

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[9] The reported value may be for a single turbine

Table 22. Future planned and potential hydropower plants in the Zambezi River Basin

Plant Name	**Country**	**River**	**Owner**	**Installed capacity**	**Annual generation**	**Reservoir capacity**	**Surface area when full**	**Reservoir elevation when full**	**Average Head**
				MW	GWh	M m3	km2	m amsl	m
Cahora Bassa North	Mozambique	Zambezi	HCB	1245	2835	existing	0	0	116
Mphanda Nkuwa	Mozambique	Zambezi	Mozambique	1500	8600	2324	97	207	67
Batoka Gorge	Zam/Zim	Zambezi	ZRA	1600	8728	1680	25.6	762	166
Itezhi-Tezhi	Zambia	Kafue	ZESCO/TATA	120	611	existing	0	0	80
Devil's Gorge	Zam/Zim	Zambezi	ZRA	1240	5604	31200	710	592	103.5
Kariba South Ext	Zimbabwe	Zambezi	ZESA	300	1183	existing	0	0	95
Kariba North Ext	Zambia	Zambezi	ZESCO	360	380	existing	0	0	95
Kafue Gorge Lower	Zambia	Kafue	ZESCO	750	2400	N/A	0	0	186
Boroma	Mozambique	Zambezi	EdM	160	1168	N/A	0	N/A	17
Lupata	Mozambique	Zambezi	EdM	550	4171	N/A	0	N/A	27
Kapichira II	Malawi	Shire	ESCOM	64	469	N/A	2	N/A	54
Kabompo Gorge	*Zambia*	*Kabompo*	*CEC*	*34*	*176*	*289*	*28*	*0*	*160*
Lunsemfwa Ext	*Zambia*	*Lunsemfwa*	*LHPC*	*55*	*462*	*existing*	*0*	*0*	*113*
Ancuaze-Sinjal	*Mozambique*	*Zambezi*	*EdM*	*330*	*2230*	*N/A*	*0*	*N/A*	*13*
Ancuaze-Sinjal	*Mozambique*	*Zambezi*	*EdM*	*600*	*4460*	*N/A*	*0*	*N/A*	*27*
Chemba	*Mozambique*	*Zambezi*	*EdM*	*1040*	*8760*	*20080*	*1400*	*98*	*43*
5.9	*Mozambique*	*Revubue*	*EdM*	*110*	*310*	*N/A*	*0*	*N/A*	*155*
Masigira	*Tanzania*	*Ruhuhu South*	*TANESCO*	*118*	*630*	*N/A*	*N/A*	*N/A*	*238*
Lower Fufu	*Malawi*	*Rukuru*	*ESCOM*	*90*	*570*	*N/A*	*N/A*	*N/A*	*336*
Kholombidzo	*Malawi*	*Shire*	*ESCOM*	*100*		*N/A*	*N/A*	*N/A*	*0*
Nachimbeya	*Malawi*	*Shire*	*ESCOM*			*N/A*	*N/A*	*N/A*	*0*
Mpatamanga	*Malawi*	*Shire*	*ESCOM*	*310*		*N/A*	*N/A*	*N/A*	*0*
5.8	*Mozambique*	*Revubue*	*EdM*	*36*	*155*	*0*	*0*	*0*	*71*

Plant Name	**Country**	**River**	**Owner**	**Installed capacity**	**Annual generation**	**Reservoir capacity**	**Surface area when full**	**Reservoir elevation when full**	**Average Head**
				MW	GWh	M m3	km2	m amsl	m
Mkushi	*Zambia*	*Mkushi*	*LHPC*	*65*	*223*	*0*	*0*	*0*	*357*
Upper Fufu	*Malawi*	*S Rukuru*	*0*	*70-145*		*0*	*0*	*0*	*0*
Henga Valley	*Malawi*	*S Rukuru*	*0*	*20-40*		*0*	*0*	*0*	*0*
5.13	*Mozambique*	*Revubue*	*EdM*	*85*	*380*	*0*	*0*	*0*	*99*
7.6	*Mozambique*	*Luia*	*EdM*	*267*	*600*	*0*	*0*	*0*	*90*
7.11	*Mozambique*	*Capoche*	*EdM*	*60*	*250*	*0*	*0*	*0*	*88*
Ruo	*Mozambique*	*Ruo/Shire*	*EdM*	*100*		*0*	*0*	*0*	*0*
Rumakali	*Tanzania*	*Rumakali*	*TANESCO*	*222*	*1320*	*N/A*	*N/A*	*N/A*	*0*

Note: Plants in *italics* are not included in model due insufficient data.

Sources: (HCB 2013; ZESCO 2013; ESCOM 2013b; Euroconsult and Mott MacDonald 2007; Beilfuss and dos Santos 2001; Beilfuss 2001; MEWD 2010; ZRA 2013; Nexant 2007)

The timing of the investments is explained earlier in section 3.1.2. Given that the objective of this study was to assess impacts on major downstream plants, most of the analysis focuses on Cahora Bassa North, Mphanda Nkuwa, expansion of Kariba, Batoka Gorge. Kafue Gorge Lower was also a focus due to its importance for Zambia. Boroma and Lupata are also considered briefly.

5.3 Irrigation demand

Irrigation demand for water is a function of acreage, crop type, growing cycles (and their corresponding crop coefficients), reference evapotranspiration, and effective precipitation within the irrigated area. Using the “irrigation only” demand model in WEAP, the model first calculates the crop requirements and determines whether effective precipitation is sufficient. If it is not, water will be abstracted from the river via the transmission link, taking into consideration the efficiency of the irrigation system. Any rainfall that is above the effective precipitation level, or rainfall in months when there is no crop demand, becomes runoff. This runoff was discussed in section 4.3.

The location of the **irrigation abstraction points** in the river network is specified to reflect the approximate location of major projects and/or potential development areas. These locations have been established based on geographic data provided in the MSIOA and ZDSS, and are presented in Table 23 below.

Table 23. Irrigation abstraction points relative to sub-basin definitions

World Bank (WB) sub-basin	WB sub-basin	Sub-basin ZDSS	Abstraction Point (WB)	IA Point	IA point description
Upper Zambezi	12	1	I.12.01	IA1	All irrigation in SB1
Kabompo	13	2	I.13.01	IA2	All irrigation in SB2
Lungue Bungo	11	3	I.11.01	IA3	All irrigation in SB3
Luanginga	10	4	I.10.01	IA4	All irrigation in SB4
Barotse	9	6	I.09.01	IA6	All irrigation in SB6
Cuando / Chobe	8	7	I.08.01-3	IA7	Cuando before entering Namibia
Kariba	6	8	I.06.01-4	IA8	Chobe-Cuando above Zambezi
Kafue	7	12,13	I.07.01	IA13	Above Itezhi-tezhi
	7	14	I.07.02		no irrigation planed – not used
	7	14	I.07.03	IA14	Below Kafue Flats, above Kafue Gorge HPP
Kariba	6	9	I.06.09	IA9	All irrigation in SB9
	6	10	I.06.10	IA10	Sanyati river before Kariba
	6	11	I.06.05-6		no irrigation planed –not used
	6	11	I.06.07-8	IA11a	Between Batoka Gorge and Devils Gorge (both sides)
	6	11	I.06.11-12	IA11b	Bottom of Kariba Reservoir
Luangwa	5	15	I.05.02	IA15	all of SB15
	5	16	I.05.01	IA16	SB16, all below HPPs
Mupata	4	17	I.07.04		no irrigation planed – not used
		17	I.07.05	IA17a	between Kafue Lower and Zambezi

		17	I.05.03-4		no irrigation planed – not used between confluence of Kafue and Chongwe gauging station
		17	I.04.01-2	IA17b	
Tete	2	18	I 02.01	IA18	All of SB18
		19	I.02.02	IA19	from Cahora Bassa Reservoir
		21	I.02.03	IA21	between Cahora Bassa and Mphanda Nkuwa
		24	I.02.04	IA24	All of SB24
		23	I.02.05-06	IA23	All of SB23
Lake Malawi/ Shire	3	25	I.03.04-12	IA25	All irrigation in SB25
		26	I.03.01-3	IA26	All irrigation between Lake Malawi and confluence with Zambezi
Zambezi Delta	1	27		IA27	All irrigation in SB27

Acreage and **crop type** is provided by detailed tables in Volume 4 of the World Bank Zambezi Multi-Sectoral Investment Opportunity Analysis (MSIOA) study (World Bank 2010a). This study provides current area, area of identified irrigation projects (e.g. short to medium term) and high level irrigation potential (e.g. long term) (see Annex B for detail). The development futures differ by the year when each level of irrigation area will be achieved, as shown in Table 24.

Table 24. Irrigation expansion in each development future

Development Future	A	B
Year when “identified projects” have been realised	2030	2020
Year when “high level” irrigation potential has been realised	2060	2040

Note that the MSIOA study provides acreage for dry season, wet season and perennial crops, but the actual equipped area is less than the sum of these three areas since some land is used for both dry and wet season crops. Unfortunately, there is no simple correspondence between which crops are planted on the same land throughout the year, with several different wet season crops being planted in one dry season crop area. This presents a problem for the WEAP model, since the model assumes that the precipitation in a particular sub-basin falls year round on every hectare with a crop designated. In other words, 1 hectare of winter wheat is assumed to receive rainfall throughout the year, even though that hectare may also be included under the area of summer wheat. This could lead to double counting of rainfall and an overestimate of runoff from irrigated areas (i.e. because the winter wheat area would appear to have significant runoff in the summer, even though in reality that rainfall might be completely used by evapotranspiration from summer crops on the same land). Of course this is not a problem for perennial crops, nor is it a major problem for wet season crops (i.e. because when there is no crop in the field there is also almost no rainfall, from May to Oct). The problem is with dry season crops, [in those sub-basins where irrigated area could become a significant share of total land area]. The solution to this in WEAP is to “turn off” the precipitation on dry season crop area during the summer months, by making precipitation a function of crop stage. In other words, when the crop coefficient (Kc) is zero, this means there is no crop in the field. During the months when Kc is zero (generally October to April for dry season crops), the precipitation inputs for that area are set to zero, so that this precipitation is recorded instead under the area designated for wet season irrigated crops. This correction is only necessary in sub-basins where irrigated area is a significant share of total land area (i.e. sub-basins 11, 24, 26 and 27).

Crop coefficients are also sourced from the MSIOA study, which provides decadal (e.g. 10 days) estimates of crop coefficients for all of the relevant crops. These are converted to monthly coefficients for the WEAP model.

Table 25. Crop coefficients by month

Monthly mean	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Winter wheat	0.00	0.00	0.00	0.00	0.33	0.68	1.14	1.00	0.40	0.00	0.00	0.00
Summer Maize	1.06	1.01	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.71
Winter Maize	0.00	0.00	0.00	0.00	0.45	0.71	1.06	1.01	0.46	0.00	0.00	0.00
Summer Rice	1.13	1.19	1.20	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.05
Winter Rice	1.13	1.19	1.20	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.05
Sugarcane	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Vegetables	0.00	0.00	0.00	0.70	0.86	1.07	1.10	1.10	1.10	0.68	0.10	0.00
Soybeans	0.96	1.15	0.93	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.46
Beans	0.00	0.00	0.00	0.00	0.13	0.59	1.09	0.88	0.12	0.00	0.00	0.00
Tea	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.98	1.00
Coffee	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Summer cotton	0.90	1.15	0.98	0.65	0.11	0.00	0.00	0.00	0.00	0.00	0.27	0.53
Winter cotton	0.00	0.00	0.00	0.00	0.27	0.53	0.90	1.15	0.98	0.65	0.11	0.00
Tobacco	1.20	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.85
Banana	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Citrus	0.73	0.70	0.67	0.65	0.65	0.65	0.75	0.75	0.75	0.75	0.75	0.75
Pasture	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Other (tomatoes)	0.00	0.00	0.00	0.70	0.86	1.07	1.10	1.10	1.10	0.68	0.10	0.00
Sorghum	0.76	1.05	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44

Source: (World Bank 2010a, Table A3.3)

Reference evapotranspiration (ETo) varies by sub-basin and is related to local climate parameters. For the historical data series and two climate futures, monthly ETo is extracted from the ZDSS for each sub-basin. The historical averages are shown in Table 26.

Table 26. Monthly ETo for selected sub-basins

Sub-Basins	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	118	105	117	122	125	114	128	156	181	176	129	117
2	114	102	113	118	121	111	124	151	176	171	125	113
3	114	102	114	118	121	110	124	151	175	170	125	113
4	121	109	121	126	129	117	132	161	187	181	133	120
5	125	112	124	130	133	121	136	165	192	186	137	123
6	134	119	134	129	121	105	117	149	184	194	156	141

Source: ZDSS Model

For the future scenarios, ETo is adjusted for projected temperatures in each climate scenario as explained in Box 1.

Box 1. Evapotranspiration and future climate

Long-term mean monthly potential evapotranspiration (mPET) data were obtained from the CLIMWAT data set of FAO for 30 stations in the region. The Penman-Monteith method was used in the CROPWAT model of FAO to calculate the sensitivity of mPET to changes in temperature. Thus, time-series of monthly potential evapotranspiration (PET) were obtained with the following simple equation:

$$PET_t = mPET_i \cdot (\Delta T_t \cdot F + 1) \qquad \text{Eq. 1}$$

where PET_t is the monthly potential evapotranspiration of time-step t in [mm], $mPET_i$ is the long-term mean monthly potential evapotranspiration of the month i in [mm], ΔT_t is the temperature difference between the current time-step t and the long-term mean monthly temperature of month i in [°C], and F is an empirical factor obtained from sensitivity tests with Penman-Monteith method and specified as 0.025 in [mm/(mm.°C)].

The equation above shows that for an increase in temperature by +1°C there is an increase in PET by +2.5%. In the sensitivity analysis we found only insignificant differences in this factor between stations and months.

Effective precipitation differs from actual precipitation, because in high rainfall periods some water runs off before it can be utilised by vegetation. According to the research behind the MSIOA study, any rainfall above 150mm/month will be lost to surface runoff, so the actual monthly precipitation is capped at 150mm/month to yield effective precipitation.

Irrigation efficiency depends on the mode of irrigation. Gravity fed schemes are 39% efficient, while pivot/sprinkler systems are 50% efficient (World Bank 2010a, Table A3.6). The MSIOA study notes that the Kafue and Luangwa sub-basins widely use pressurised irrigation, but for the other sub-basins there is either evidence of a large share of gravity fed schemes or no information at all on the shares. The model therefore uses pressurised irrigation efficiency for Kafue (sub-basins 12, 13 and 14) and Luangwa (sub-basin 15) and gravity-fed scheme efficiency for other areas.

5.4 Urban demand

Urban demand is driven entirely by population growth. The current per capita consumption is taken from the Rapid Assessment Final Report for the Integrated Water Resources Management Strategy for the Zambezi River Basin study (Euroconsult and Mott MacDonald 2007, 37), as 70 litres per day in urban areas and 20 litres per day in rural areas. Given the fact that urban demand is already a very small percentage of runoff in the basin, only the largest urban centres are considered: Lusaka, Harare, Bulawayo, Lilongwe, Blantyre, Copperbelt (Ndola and Kitwe) and Livingstone-Victoria Falls area.

The water source of each major urban centre was identified, as well as the discharge location, because these are not always in the same sub-basin. For Lusaka, the water abstraction is from the Kafue River before the Kafue Gorge Upper power hydropower station. The discharge, however, is into the Luangwa River basin. Harare uses Lake Manyame catchment.[10] For Bulawayo, current water supplies are from dams outside the Zambezi River Basin (e.g. Ncema, Inyankuni, Inciza, Umzingwane). Bulawayo has experienced chronic water shortages, however, and had to severely ration water during recent drought years[11]. The Matabeleland Zambezi Water Trust Project (MZWTP) has been proposed to draw water from the Zambezi River to alleviate Bulawayo's water shortages, although this project has seen numerous delays due to political and economic challenges in Zimbabwe.[12] The government of Zimbabwe announced in July 2012 that China had committed $1.2 billion to this project, and that the 400km pipeline and associated dams would be complete within 3 years.[13] For this reason, Bulawayo water demand is only included in the WEAP model from 2015, and then drawing from the Zambezi River at Lake Kariba.

5.5 Inter-basin transfers

While a number of inter-basin transfers have been mentioned in the literature, none is at an advanced stage of feasibility study, nor is there any political agreement on these. The MSIOA includes a scenario that considered a proposed scheme for abstracting water from the Chobe-Zambezi area for the Dikgatlhong reservoir in Botswana (in connection with the North-South Carrier Water Project), which would remove 25.7 cms or 810 mcm per year. This would be the second phase of the proposed Pandamatanga agricultural abstraction transfer, which would draw up to 16 cms from the same area, before the pipeline is extended all the way to Botswana's North-South Carrier (WRC 2010). Flows at Kasane, however, are only below 108 cms in only 1.3% of the months between 1960 and 1990, so this withdrawal is unlikely to have major downstream impacts. These smaller scale transfer have been noted, but have not been included in the modelling.

5.6 Demand Priorities

While water has not been a major constraint in most historical years, future demands could grow rapidly and, as discussed earlier, considerably drier climate patterns are possible. This means that the model must include clear priorities on which demands to prioritise in case of a shortfall, or, rather, the order in which to fill those priorities. In WEAP this is specified by setting demand priorities for reservoir filling, hydropower generation, irrigation demand and urban demand – with 1 being the highest and 99 being the lowest. Because urban demand is very small compared to all other demands and is likely to be prioritised for political reasons, urban demand is set at 5 in all scenarios. For the main hydropower analysis scenarios, hydropower priorities are set higher than irrigation, with irrigation demand having a priority of 20.

For the Barotse floodplain, as discussed in section 4.4, the reservoir filling priorities must be higher than downstream demands to ensure that the model simulates the annual flooding (rather than drawing all the water downstream for hydropower

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[10] http://www.waterworld.com/news/2012/10/11/harare-water-woes-no-solution-in-sight-75-years-later.html
[11] http://allafrica.com/stories/201208310055.html
[12] http://www.newsday.co.zw/2012/10/02/bulawayo-water-woes-a-crisis-of-leadership/
[13] http://www.newzimbabwe.com/news-8476-China+funds+$1,2bn+Zambezi+Water+Project/news.aspx

production). For this reason, the Barotse reservoir, as well as the “virtual reservoir” below it both have a demand priority of 5.

The hydropower plants start with a priority of 10 for generation in the main analysis, and these are then adjusted according to different downstream and upstream priorities. Within the different hydropower plants, the question is to what extent these reservoirs can be drawn down to meet downstream hydropower demand when local hydropower demand is already met (and any Design Flood Rule Curve requirements are met). For example, Kariba might have already produced 700 GWh in a month, but there is still downstream demand for hydropower generation in that month that has not yet been met. If the reservoir filling priority for Kariba is the same as the downstream plant’s hydropower generation, then the reservoir could be drawn down to some extent to meet these competing demands, which could leave the reservoir vulnerable during the dry season. For Itezhi-tezhi, the priority of operation is to serve the Kafue Gorge Upper (and, in the future, Lower) plants with consistent flows for generation, and this would be a higher priority than releasing more water to flow downstream to Cahora Bassa. For this reason, Itezhi-tezhi reservoir filling priority is set at the hydropower priority less three (“HP-3”). The relative adjustment is used so that the entire hydropower generation system can be given a different set of priorities relative to irrigation and urban demand. For water to be released for power generation at Itezhi-tezhi, the priority must be higher than reservoir filling, so this is set at “HP-4”. A similar situation applies at Kariba, in that, although the Joint Operating Technical Committee (JOTC) does coordinate the operation of Kariba and Cahora Bassa, it is unlikely that the Kariba reservoir would be drawn down solely to supply water for Cahora Bassa, if all other local generation and flood control demands had been met. The same applies to Cahora Bassa versus the further downstream plants. The priorities are summarised below.

Table 27. Individual hydropower plant demand priorities relative to the overall hydropower demand priority

	Generation	Reservoir Filling
Itezhi-tezhi	HP-6	HP-5
Kafue Gorge Upper	HP-6	HP-5
Batoka Gorge	HP-4	HP-3
Devil’s Gorge	HP-2	HP-1
Kariba	HP-2	HP-1
Cahora Bassa	HP	HP+1
Mphanda Nkuwa	HP+2	HP+1
Boroma & Lupata	HP+3	N/A

Note: HP=overall hydropower priority specified for a given scenario

6 Model calibration

Because the WEAP model is using runoff data that has already been calibrated in the ZDSS, all that is necessary is to calibrate the modelling of the operation and evaporation from reservoirs (including wetlands as natural reservoirs) and to check that downstream flows are still accurately modelled when historical irrigation and urban demand are included. In addition, irrigation demand is also compared with published studies to check the crop demand model.

6.1 Natural reservoirs

Calibration of discharges from natural reservoirs was done by comparing downstream gage data with modelled discharges.

In addition to visual calibration of the model results, which WEAP facilitates from the graphical reporting formats available, several statistics were calculated: correlation, bias ratio, variability ratio and a modified KGE statistic (Gupta et al. 2009; Kling and Preishuber 2012). The KGE statistic combines correlation, bias ratio and variability ratio, so that the model calibration balances the temporality of flows with the mean volumes and variability, rather than only focusing on one of these issues.

For Kafue Flats, the Nyimba gauge is in the middle of the Flats, so would not be appropriate. The only gauge between the Flats and Kafue Gorge Upper HPP is Kasaka. However, this gauge is affected by the backwater from Kafue Gorge Upper after the plant was in full operation in the late 1960s. For this reason, the Kasaka gauge is used only from January 1961 to December 1970 for the calibration. As Figure 8 shows, there is a close correlation between the modelled results and observed gauge readings. The statistical results are reported in Table 28. The shift in the hydrograph shown in Figure 9 shows how significantly these large wetlands both attenuate the upstream flows and shift the peak flows, which is consistent with the findings in other modelling studies in the Zambezi, as discussed earlier.

Figure 8. Observed versus modelled flows at Kasaka (1961-1970)

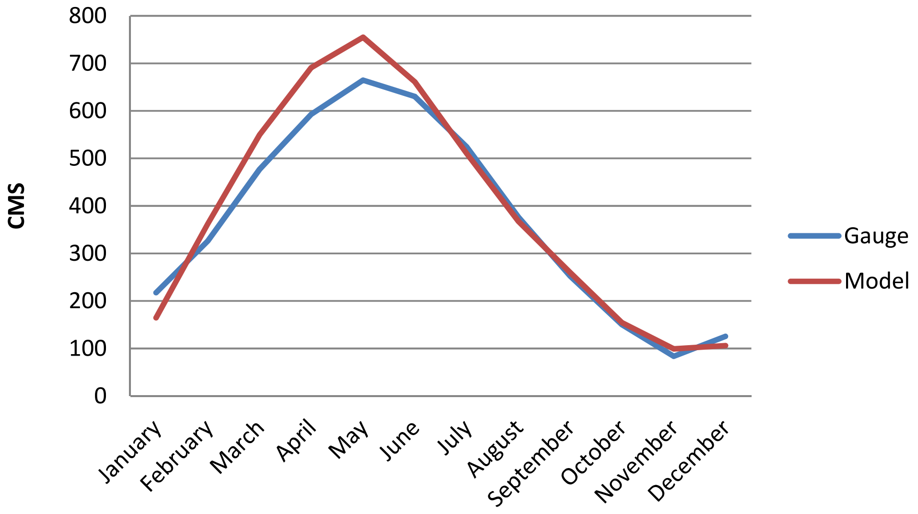
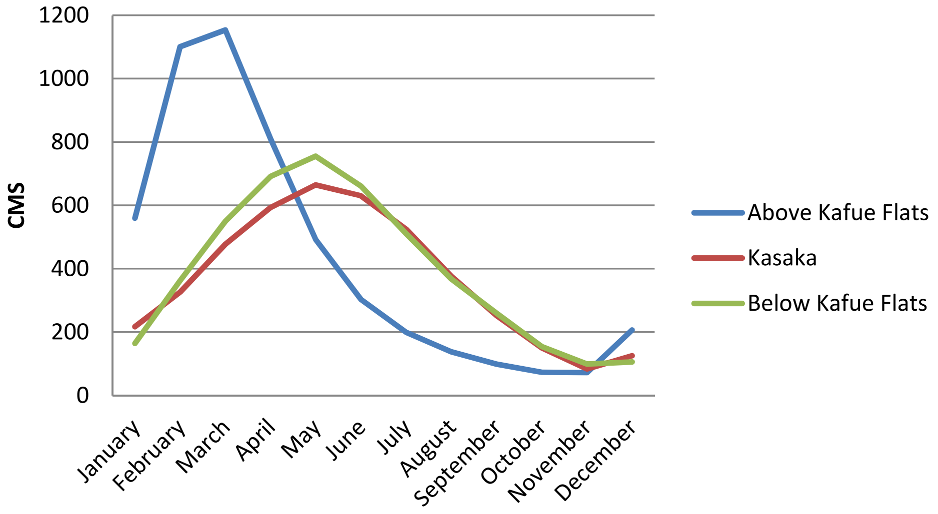
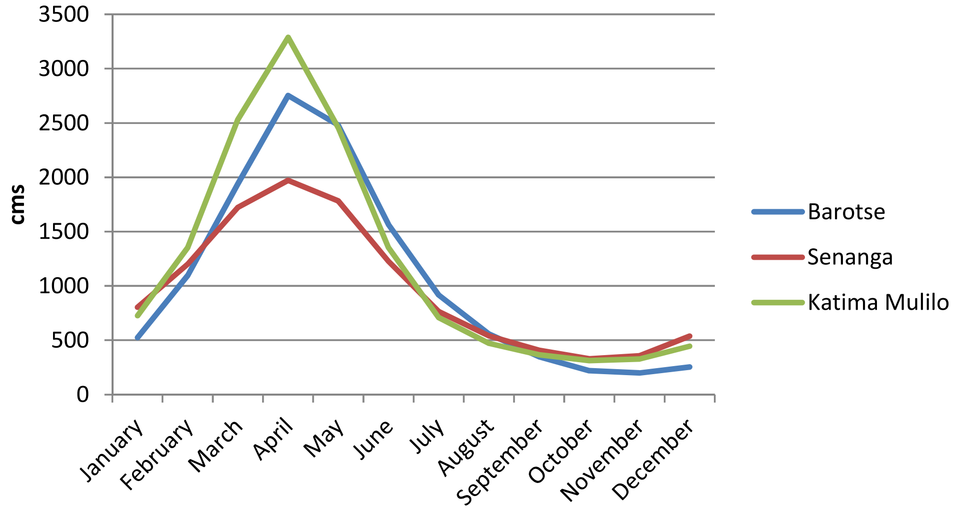


Figure 9. Average monthly flows above and below Kafue Flats (1961-70)



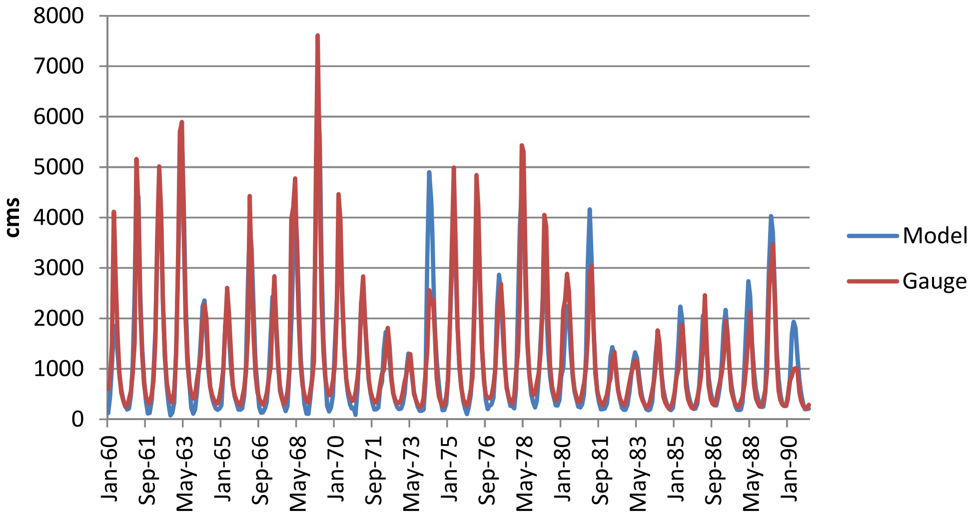
For Barotse, the challenge is that that ZDSS research showed that Senanga tends to under-report peak flows while Katima Mulilo tends to over-report them. For this reason, the Senanga and Katima Mulilo records are only used to identify the peak flow periods. As Figure 10 below shows, the modelled flows follow the hydrographs for the two gauges very closely, even though magnitude of flows is different, as expected.

Figure 10. Comparison of hydrograph of modelled Barotse flood plain with Senanga and Katima Mulilo gauges



The best calibration for Barotse and the Chobe-Caprivi wetlands as well, is at the Victoria Falls gauge. The modelled flows versus gauge are shown in Figure 11, demonstrating the good calibration of the model at this point. The calibration statistics are reported in Table 28.

Figure 11. Observed versus modelled flows at Victoria Falls

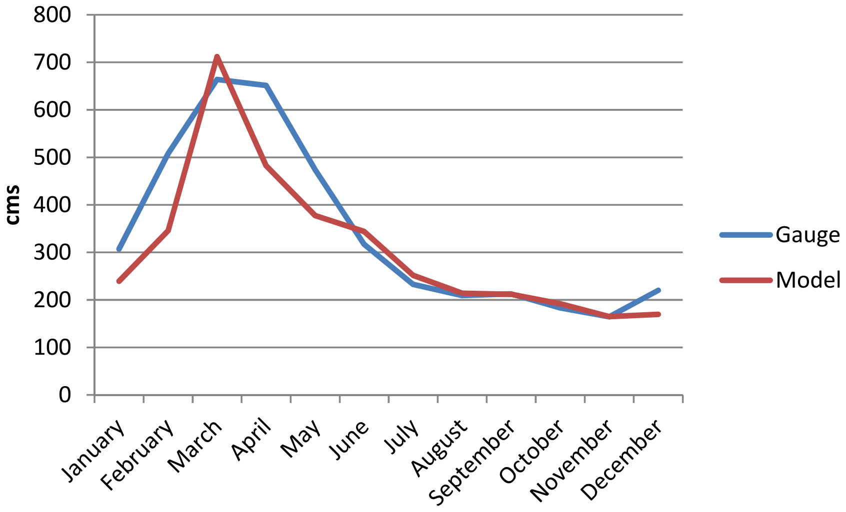


6.2 Man-made reservoirs

For man-made reservoirs, calibration may be based on observed versus modelled reservoir volume or on discharges. As with natural reservoirs, the KGE statistic is used, as well as its statistical components.

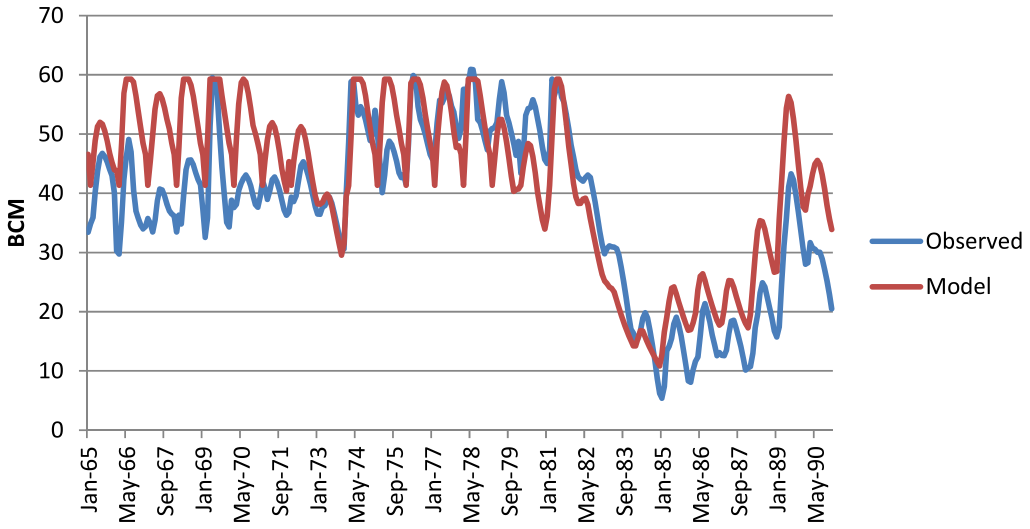
For Itezhi-tezhi, the gauge data from GRDC for the outflow point of the reservoir is used, and this is confirmed by data from ZESCO. The calibration period starts in 1977, when the reservoir was commissioned, and ends in 1990. Note that the Itezhi-tezhi modelled flows were calculated with and without the Design Flood Rule Curve assumptions given in Beilfuss (2001), and the calibration statistics with the DFRC showed that this assumption more closely matched the observed data.

Figure 12. Observed versus modelled discharge at Itezhi-tezhi (1977-1990)



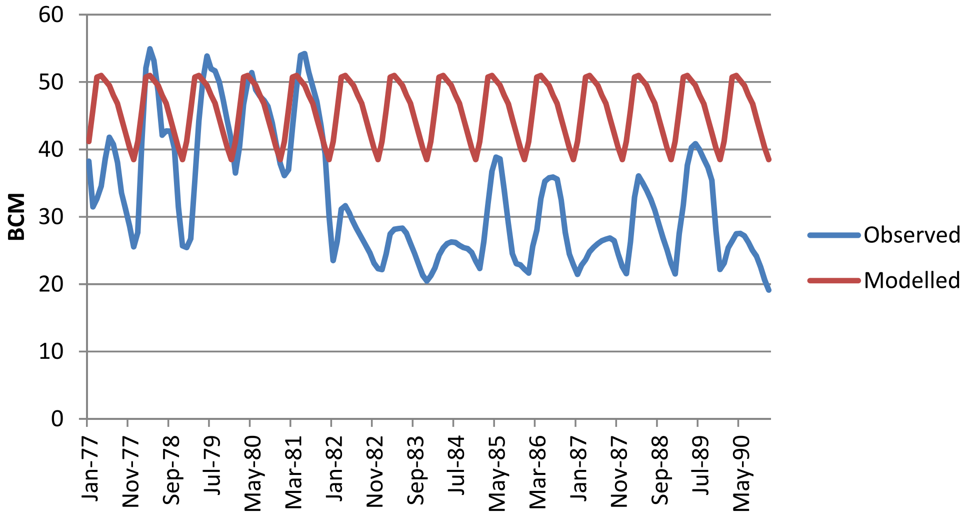
For Lake Kariba, modelled reservoir levels (volume) are also well correlated with observed volume, even during the very dry period of 1983 to 1988, as shown in Figure 13.

Figure 13. Observed versus modelled volume at Lake Kariba



Similarly, for Cahora Bassa, modelled volume is compared with observed volume provided by the Mozambique National Directorate for Water (DNA). The difficulty with Cahora Bassa, however, is the during the period from 1983 to 1997 when the transmission lines to South Africa were out of commission, the reservoir did not follow normal operating rules. During this period the reservoir was drawn down even though there sufficient inflow to maintain higher levels. In addition, operation was erratic during the earlier years after commissioning. For these reasons, a formal calibration is not feasible for Cahora Bassa. Figure 14 does show, however, the model correctly implements the specified Design Flood Rule Curve for Cahora Bassa.

Figure 14. Observed versus modelled volume at Cahora Bassa



Kafue Gorge Upper has only a small holding reservoir, so the calibration is conducted with modelled discharge versus gauge data.

Figure 15. Observed versus modelled discharge at Kafue Gorge Upper hydropower plant

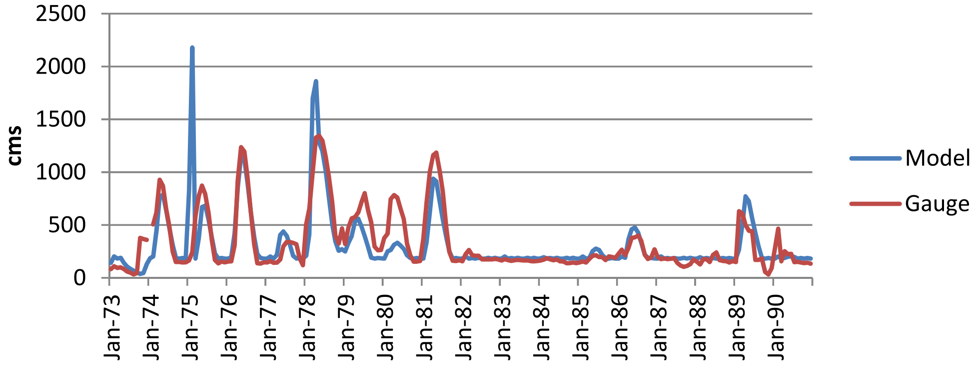


Table 28. Summary reservoir calibration statistics

Reservoir	Gauge	Period	Correlation	Ratio of Mean	Ratio of Variation	KGE
Kafue Flats	Kasaka	'61-'90	0.877	1.057	0.961	0.859
Baroste & Chobe-Caprivi	Vic Falls ZRA	‘61-90	0.932	0.975	0.999	0.928
Itezhi-tezhi	Itezhi-tezhi	'77-'90	0.793	0.900	1.035	0.767
Kariba	Kariba ZRA*	’65-90	0.848	1.12	.878	0.772
Kafue Gorge Upper	Kafue Gorge Upper	’73-‘90	0.746	0.951	1.064	0.733

*calibration to reservoir volume, instead of monthly discharge

6.3 Irrigation demand

Table 29 shows the calculated irrigation demand in the WEAP model versus the estimated abstractions from the World Bank (2010b) MSIOA study. The WEAP sub-basin data are aggregated to the sub-basins from the MSIOA for comparison. The total abstraction demand is virtually the same, and all of the major basins are within 10-20%. This is a good fit considering the large uncertainties in irrigation system efficiencies, which are included the abstraction requirement estimates of both studies.

Table 29. Calculated abstraction requirements for irrigation compared to the MSIOA study

Sub-basin names and numbers			Total Abstraction (MCM)		
World Bank		WEAP	World Bank	WEAP	WEAP/ WB
Upper Zambezi	12	1	37.6	40.2	107%
Kabompo	13	2	4.8	5.6	116%
Lungue Bungo	11	3	15.7	16.6	106%
Luanginga	10	4	14.2	14.1	99%
Barotse	9	6	3.5	3.6	104%
Cuando / Chobe	8	7	10.1	10.8	107%
Kariba	6	8,9,10,11	649.2	528.4	81%
Kafue	7	12,13,14	626.0	727.8	116%
Luangwa	5	15,16	120.5	170.7	142%
Mupata	4	17	308.6	296.6	96%
Tete	2	18,19,20, 21,23,24	669.0	612.6	92%
Lake Malawi / Shire	3	25,26	648.6	717.3	111%
Zambezi Delta	1	27	127.0	143.2	113%
Total			3234.8	3287.4	102%

7 Results

After specifying the scenarios that were analysed using the WEAP model for the Zambezi River Basin, this section presents the results of the modelling in successive steps to answer the series of questions presented in Chapter 3:

- How will future climate impact existing hydropower plants?
- How will the commissioning of new hydropower plants affect the operation and performance of existing plants?
- How will the new hydropower plants perform under different climate futures?
- What additional impact will increased irrigation demand have on the performance of existing and new hydropower plants?
- To what extent does the speed of implementation for hydropower and irrigation affect the results?

To answer each of these questions, the actual performance of the plants must be compared to a “target” for hydropower generation. These targets, explained in more detail in the following sections, are derived from a combination of modelled historical generation and utility assumptions about future projects.

7.1 Scenarios

The scenarios presented in the results are different combinations of climate futures and development futures (see Table 30). In addition, the changes in irrigation and hydropower development are also considered separately, to understand the relative impact of additional downstream hydropower demand (e.g. on Kariba) versus the impact of increased irrigation demand. The definitions of “business as usual” and “optimistic” for hydropower and irrigation development are explained in section 3.1. Hydropower production for the existing plants is compared with modelled generation in the historical period (1960-1990), to eliminate any bias in the comparisons with future scenarios.

Table 30. Specification of future scenarios

		Hydropower development	Irrigation development	Future climate
A	Hydro hist, Irrig hist, Dry	Historical	Historical	Dry
B	Hydro hist, Irrig hist, Wet	Historical	Historical	Wet
C	Hydro BAU, Irrig hist, Dry	Business as Usual	Historical	Dry
D	Hydro BAU, Irrig hist, Wet	Business as Usual	Historical	Wet
E	Hydro BAU, Irrig BAU, Dry	Business as Usual	Business as Usual	Dry
F	Hydro BAU, Irrig BAU, Wet	Business as Usual	Business as Usual	Wet
G	H BAU I BAU #1 Dry	Business as Usual	BAU with highest demand priority	Dry
H	H BAU I BAU #1 Wet	Business as Usual	BAU with highest demand priority	Wet
I	H Op I Op #1 Dry	Optimistic	Optimistic with highest demand priority	Dry
J	H Op I Op #1 Wet	Optimistic	Optimistic with highest demand priority	Wet

7.2 How will future climate impact existing hydropower plants?

This section considers how the three major existing hydropower plants – Kariba, Cahora Bassa and Kafue Gorge Upper – would be affected by different climate futures, without any changes in irrigation demand or any new hydropower plants in the Basin. As shown in section 6.1, while the model results are highly correlated with historical measurements, there is still some bias. To eliminate this bias in interpreting the results of the future simulations, it is important to compare future generation with modelled historical generation rather than actual generation. For example, average annual generation for Kariba from 1960-1990 was approximately 5750 GWh/yr (Tumbare 2000). More recent average generation from 1993 to 2012 was 6934 GWh/yr[14]. Modelled generation from 1960 to 1990 is 6759 GWh/yr, so this is the basis of comparison with future scenarios.

Figure 16 below shows that climate has a dramatic effect on hydropower production at Kariba. Kariba production would below the modelled historical generation level the majority of years (62%) in a drying climate and a significant share of years (20%) even under a wetting climate. Mean generation under a wetting climate would only match historical levels, while for a drying climate it would be 12% lower (see summary Table 31 in section 7.7 for mean values).

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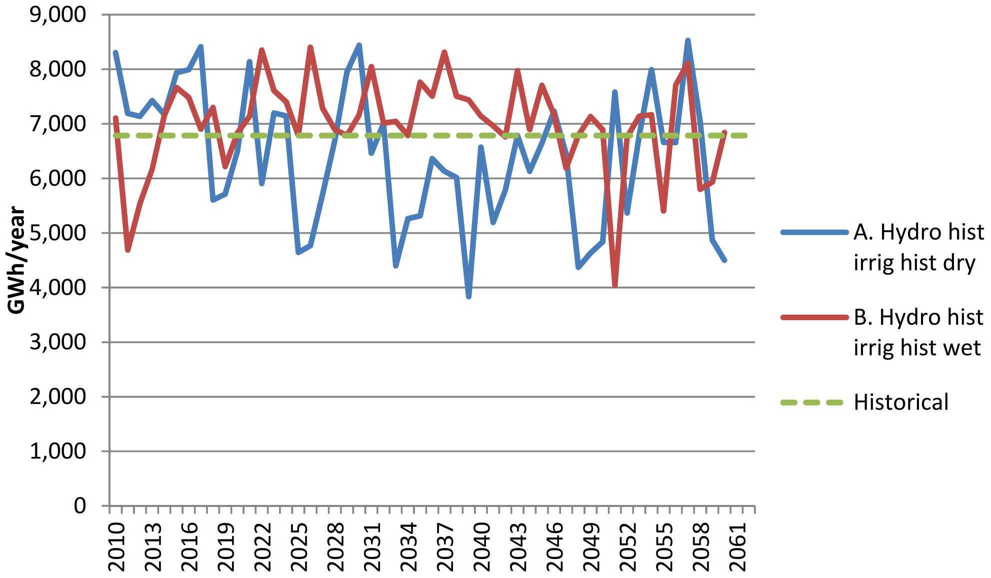
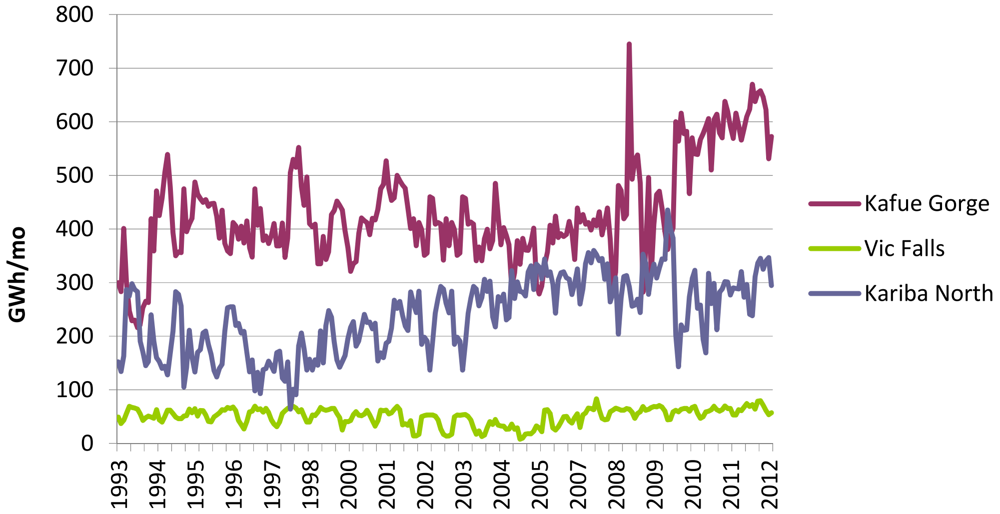
[14] Kariba North generation is from ZESCO, while Kariba South is total hydropower generation for Zimbabwe as reported by IEA (2011)

Figure 16. Future annual generation at Kariba without new hydropower or irrigation



It is important to remember that actual historical production is also highly variable. Figure 17 shows historical monthly generation at Kariba North, Kafue Gorge Upper and Victoria Falls, which all vary according to season and between years.

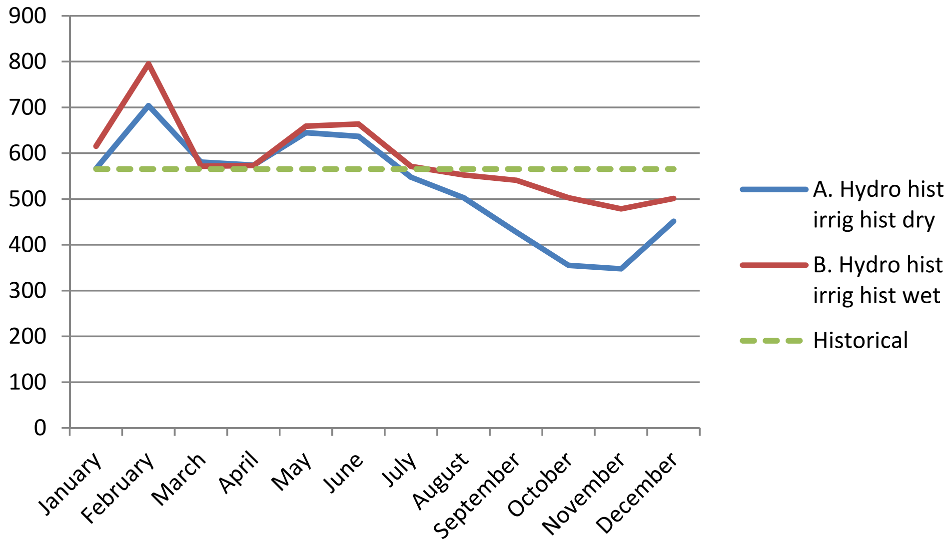
Figure 17. Historical monthly generation (1993-2012) at ZESCO hydropower plants



Source: ZESCO

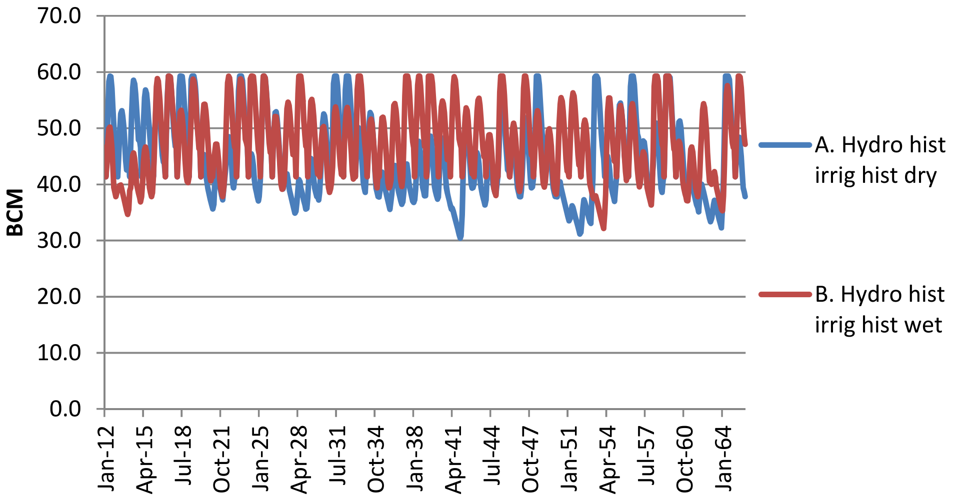
In terms of monthly generation, Figure 18 shows that the decline in generation in a drier climate is across all of the low flow months of August to December. The higher generation in February is from lowering the lake level as per the Design Flood Rule Curve. The model assumes this additional outflow will pass through the turbines as long as the flow is less than the maximum turbine flow (which is the case at Kariba).

Figure 18. Future monthly generation at Kariba without new hydropower or irrigation



The reservoir levels generally follow the Design Flood Rule Curve for the wetting climate, but for the drying climate will drop below 40 BCM (Figure 19). The buffering coefficients presented earlier in prevent the rapid draw down of the reservoir once it drops below 40 BCM, to maintain the head for the hydropower turbines.

Figure 19. Future reservoir volume at Kariba without new hydropower or irrigation



For Cahora Bassa, modelled historical generation during the calibration period is 17,114 GWh/year. This is about 10% higher than the current target stated by HCB of 15,500 GWh/year. For purposes of comparison with future scenarios, it is therefore important to use the modelled historical generation, to accurately show the percentage change in generation. While projected mean generation would be slightly above and below the historical mean in wetting and drying climates, respectively, under a drying climate annual generation would be below historical levels in more than 40% of future years (Figure 20).

Monthly generation is also generally above historical levels in a wetting climate (Figure 21) but slight below under a drying climate. Reservoir levels are maintained at the level maintained by the Design Flood Rule Curve except during severe drought years in the drying climate (Figure 22).

Figure 20. Future annual generation at Cahora Bassa without new hydropower or irrigation

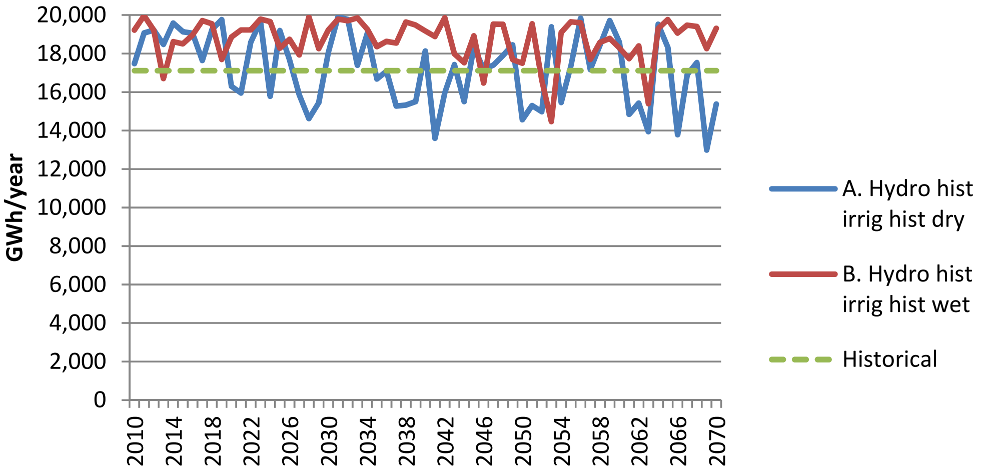


Figure 21. Future monthly generation at Cahora Bassa without new hydropower or irrigation

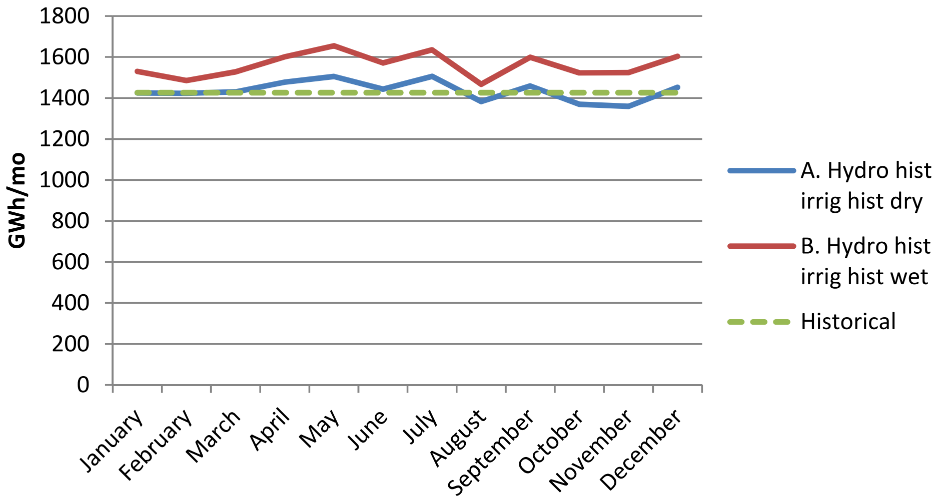
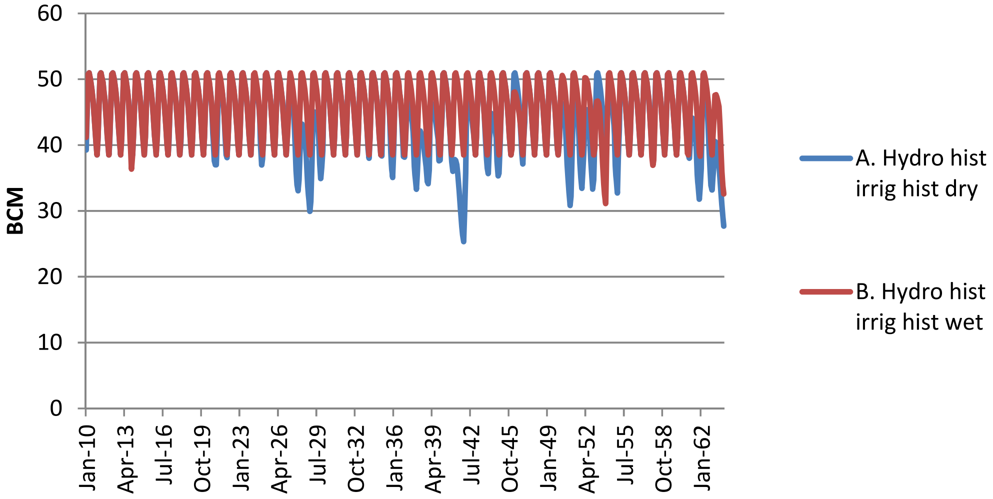
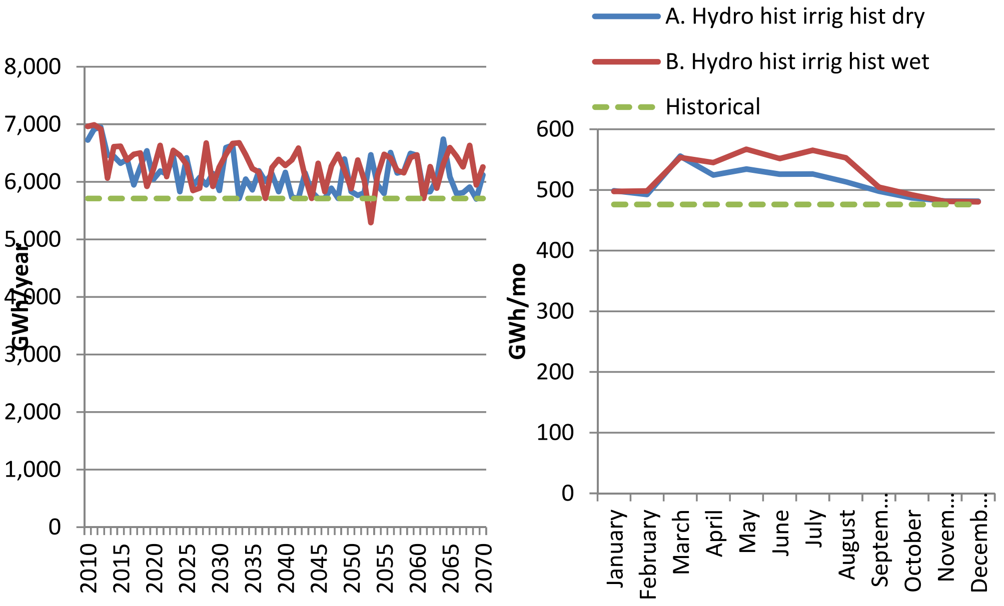


Figure 22. Future reservoir volume at Cahora Bassa without new hydropower or irrigation



For Kafue Gorge Upper, historical modelled production is 5,712 GWh/year (1968-1990), as compared to actual production over a different time period of 5,160 GWh/yr (1993-2012). Kafue Gorge Upper future generation is above this level in both wetting and drying climates, as is monthly production under both climates (Figure 23). This surprising result could be due to the additional releases from Itezhi-tezhi when the hydropower plant is commissioned there in 2014.

Figure 23. Future annual and monthly generation at Kafue Gorge Upper without new hydropower and irrigation

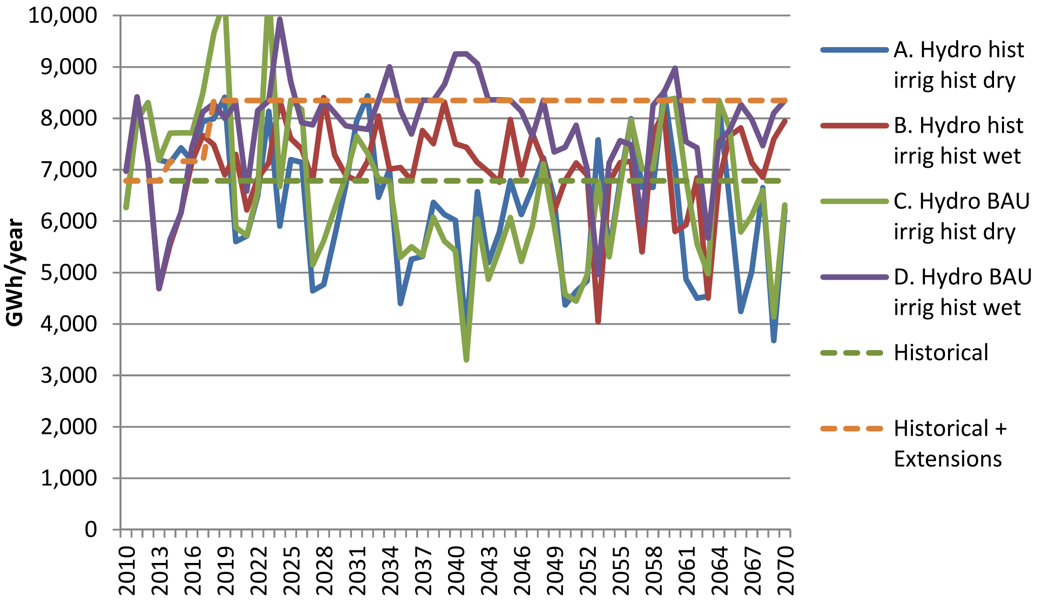


7.3 How will the commissioning of new hydropower plants affect the operation and performance of existing plants?

As discussed earlier, extensions are planned for Kariba North (completed), Kariba South and Cahora Bassa North Bank. The expected additional production from these extensions (as well as the increased maximum turbine flow) is added to the modelled historical generation levels, bearing in mind that most of the extensions are used for peaking power and so have relatively low load factors. More importantly, demand for water from other hydropower plants such as Kafue Gorge Lower, Mphanda Nkuwa, Boroma and Lupata, can also affect hydropower production and reservoir storage at the major existing plants. Batoka Gorge would have less effect from other plants, because it is upstream from the large Kariba reservoir, unless the Kariba operating rules are changed as a result of this new plant. For this phase of the analysis, we maintain the same operating rules at Kariba, to see how this is affected by all upstream and downstream new plants.

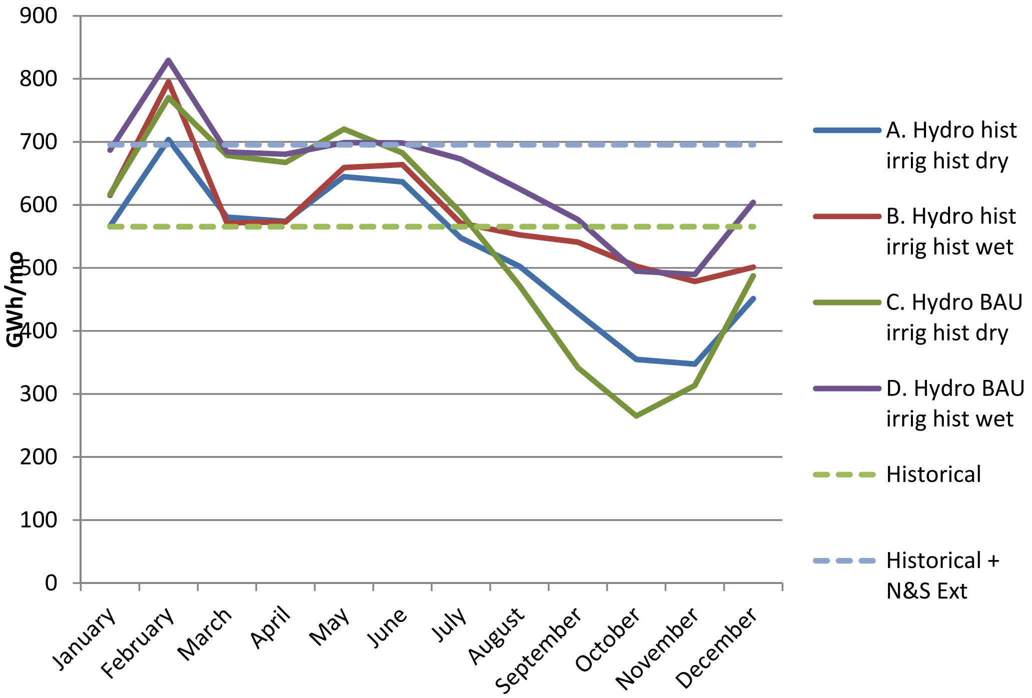
Figure 24 shows that, while increased turbine capacity could allow Kariba to generate at modelled historical levels under a wetting climate (i.e. purple line versus green dashed line), Kariba cannot generally meet the new target production levels under either a wetting or drying climate. The new hydropower development does increase production somewhat under a wetting climate, but does not significantly increase generation for Kariba under a drying climate, because this is already constrained by other system-wide shortages and the need to maintain the net head in the reservoir.

Figure 24. Future annual generation at Kariba with “business as usual” hydropower development



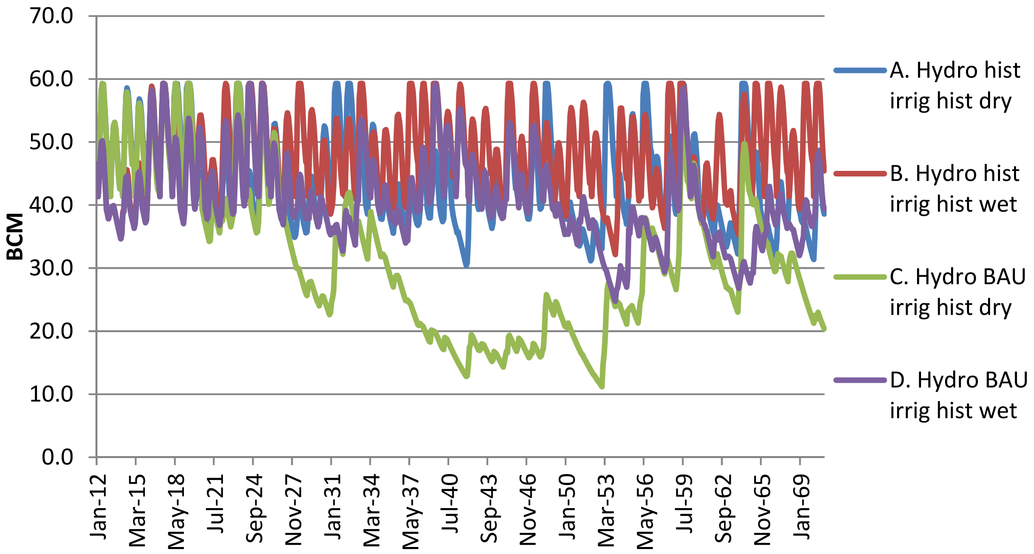
The changes are even more dramatic at a monthly level (Figure 25). In a drying climate with or without BAU hydropower development, low flow season generation (Oct) is less than half of the requirement if both extensions are included. Even the results under a wetting climate are below this target level for almost the entire the year.

Figure 25. Future monthly generation at Kariba with "business as usual" hydropower development



The additional reduction in generation under "business as usual" hydropower development and a drying climate is due in part to much lower reservoir levels, which are drawn down from decadal drought, as shown in Figure 26. The reservoir is drawn down because of the higher energy demand at Kariba as well as higher overall system demands.

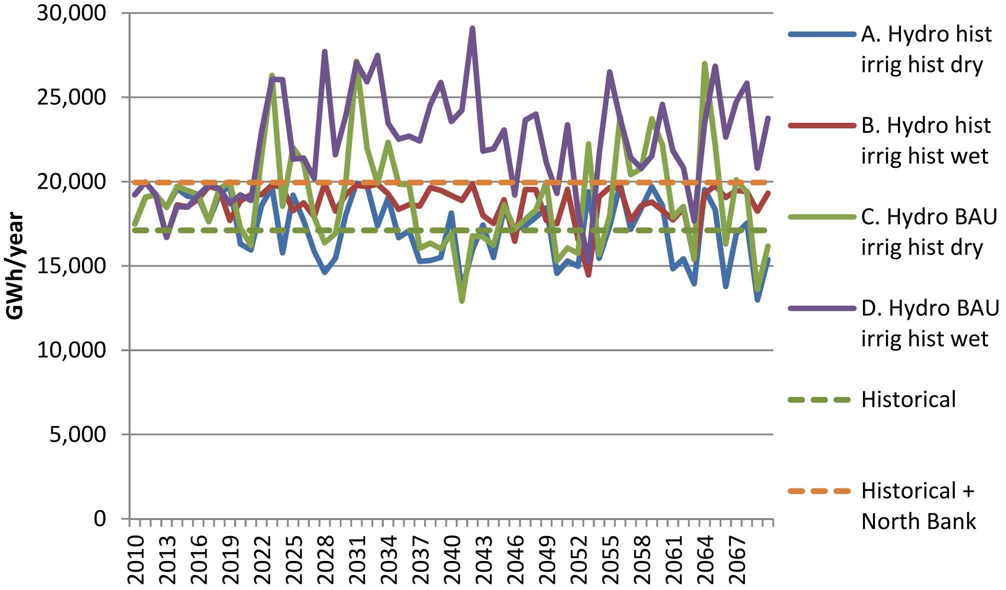
Figure 26. Future reservoir volume at Kariba with "business as usual" hydropower development



For Cahora Bassa, the North Bank extension increases capacity by 1,245 MW, with an expected production of 2,835 GWh/year. This means that the projected load factor for the North Bank extension, according to HCB, is only 26%, as this extension is to be used primarily for peaking power.

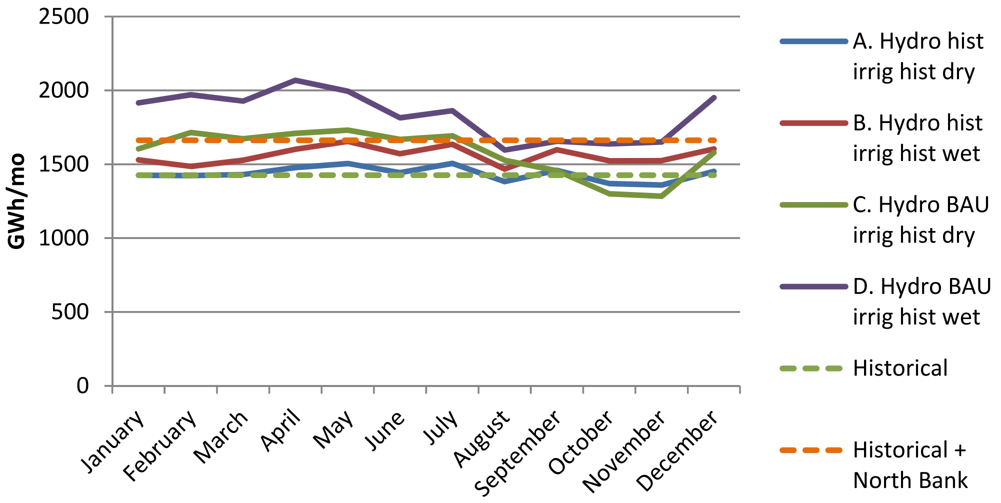
Under a future wetting climate and BAU hydropower development, production can exceed this 74% of the time and mean generation would be significantly higher than the target (111%). Under a drying climate, however, annual production would fall below that target in the large majority of years (69%) (Figure 27). The higher generation levels under a wetting climate are due to both the increased energy demand at Cahora Bassa, but also the increased need for water downstream for the new hydropower plants (e.g. Mphanda Nkuwa, Boroma and Lupata). This water is used to generate more power, because there is excess capacity in the turbines.

Figure 27. Future annual generation at Cahora Bassa with "business as usual" hydropower development



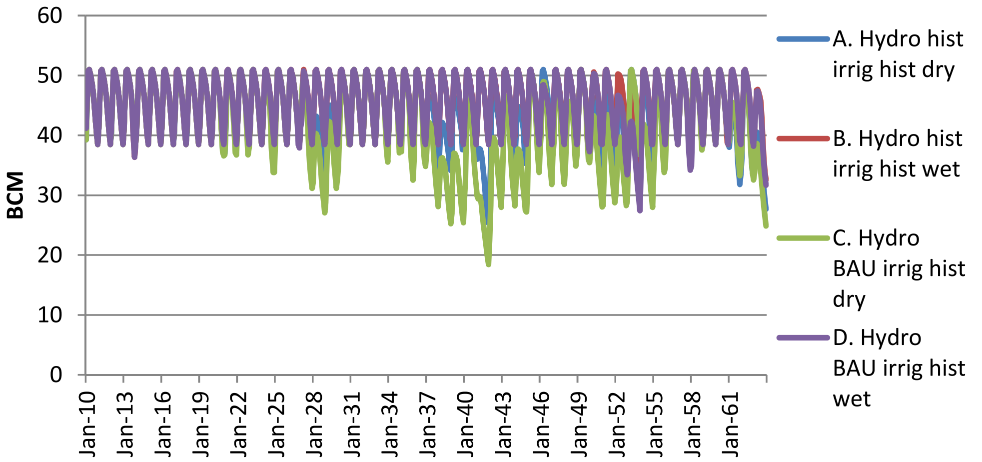
Monthly production is above target for almost all months under a wetting climate, but is below the required level under a drying climate in September to December (Figure 28).

Figure 28. Future monthly generation at Cahora Bassa with "business as usual" hydropower development



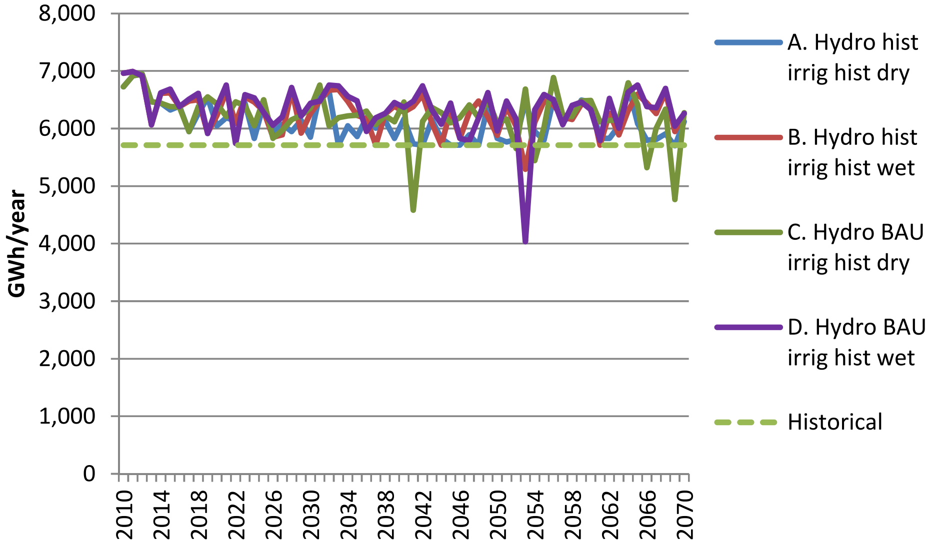
The impact of the drying climate is also seen in reservoir volume, which is considerably lower during the 2040s under the drying climate (Figure 29).

Figure 29. Future reservoir volume at Cahora Bassa with "business as usual" hydropower development



Kafue Gorge is less affected by a projected drying climate than Kariba and Cahora Bassa, and monthly and annual mean generation does not change significantly. During abnormal years, however, annual production does fall below historical levels. This is similar to what has happened in the previous two decades (see Figure 17) and this result further supports the validity of this analytical approach.

Figure 30. Future annual generation at Kafue Gorge Upper with "business as usual" hydropower development



7.4 How will the new hydropower plants perform under different climate futures?

The key new hydropower plants analysed are Itezhi-tezhi, Batoka Gorge, Mphanda Nkuwa, and Kafue Gorge Lower. In addition, Boroma and Lupata are considered briefly. For each of the new plants, annual generation is compared with the target stated by the utilities or, in the case of Boroma and Lupata, in the literature. Only the Mphanda Nkuwa feasibility study reports a variable monthly target generation, however, so for the other plants the monthly target is simply constant.

Mean generation at Itezhi-tezhi in close to or better than the target of 611 GWh/year, and would only fall below this level in 23% of the years under a drying climate (see Figure 31 and Table 33) Not surprisingly, this decline under a drying climate is observed mainly in November and December (see Figure 32).

Figure 31. Future annual generation at Itezhi-tezhi with "business as usual" hydropower development only

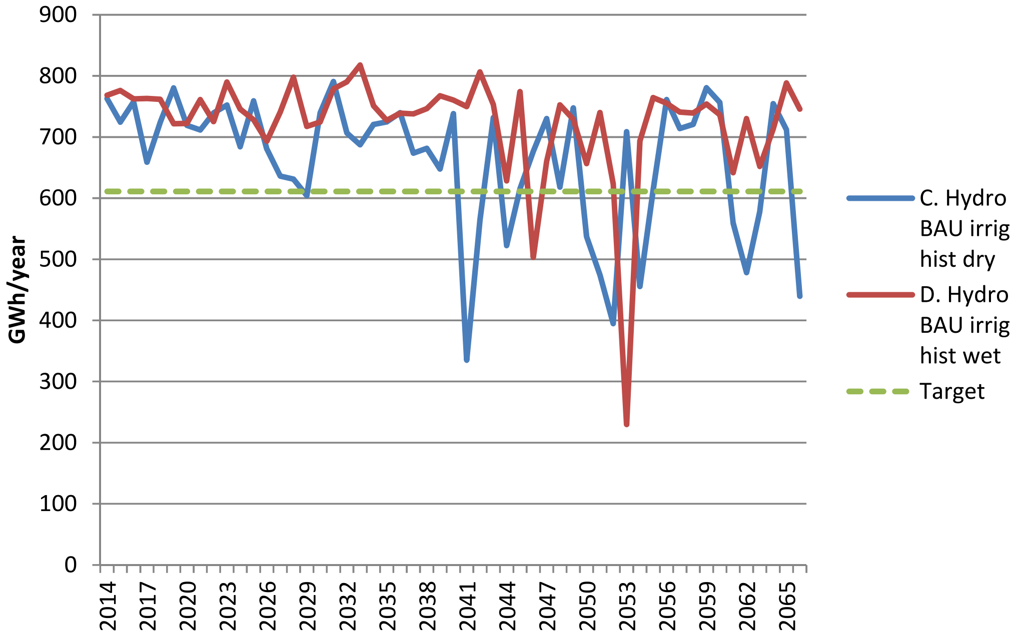
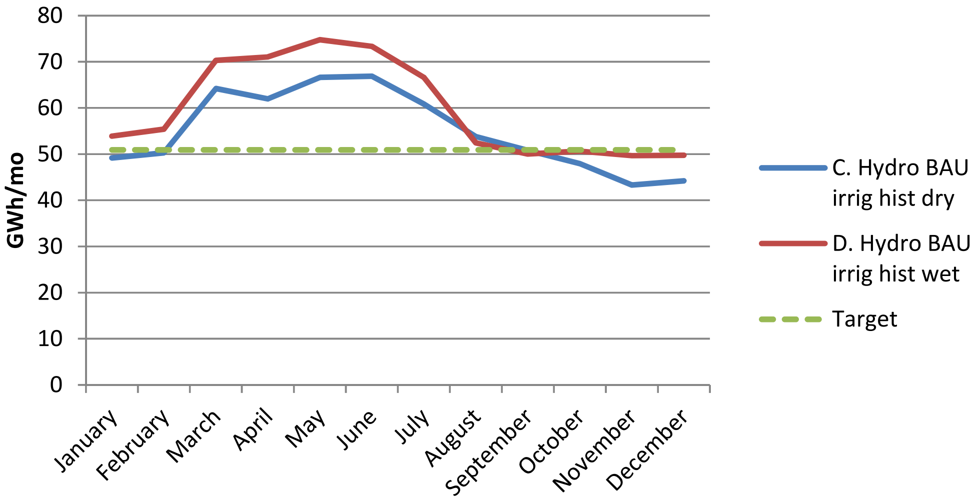
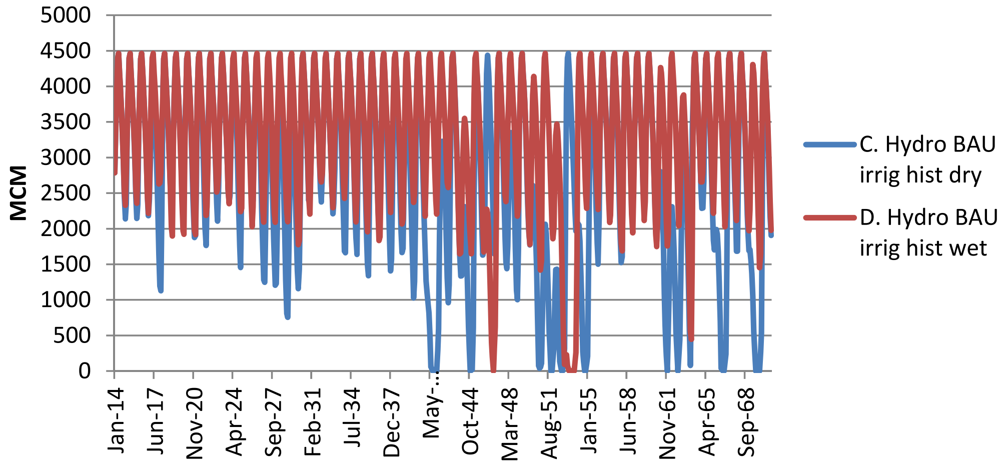


Figure 32. Future monthly generation at Itezhi-tezhi with "business as usual" hydropower development only



In the future dry years, the reservoir is not sufficient to maintain storage levels through extended drought, which also leads to a reduction in hydropower potential due to the drop in net head (see Figure 33). In some years, our analysis projects that production will stop entirely at Itezhi-tezhi because there is not enough water in the system under the "Hydro BAU irrig hist dry" scenario. From the mid-2030s, this happens on average once every four years.

Figure 33. Future reservoir volume at Itezhi-tezhi with "business as usual" hydropower development



According to the ZRA, the Batoka Gorge feasibility study is currently being revised, but the most recent estimate of generation is 8,728 GWh per year. Using this as a target, Figure 34 shows that this target would rarely be met in a drying climate, and would even be missed more than 50% of the time under a wetting climate. Mean generation in 2070-2070 under a drying climate is 15% lower than the target (see Table 33). The monthly generation curves (Figure 35) show low generation levels in the dry season, but this is expected given that Batoka Gorge only has a small reservoir (1,680 mcm) and is meant to operate in conjunction with Kariba.

Figure 34. Future annual generation at Batoka Gorge with "business as usual" hydropower development

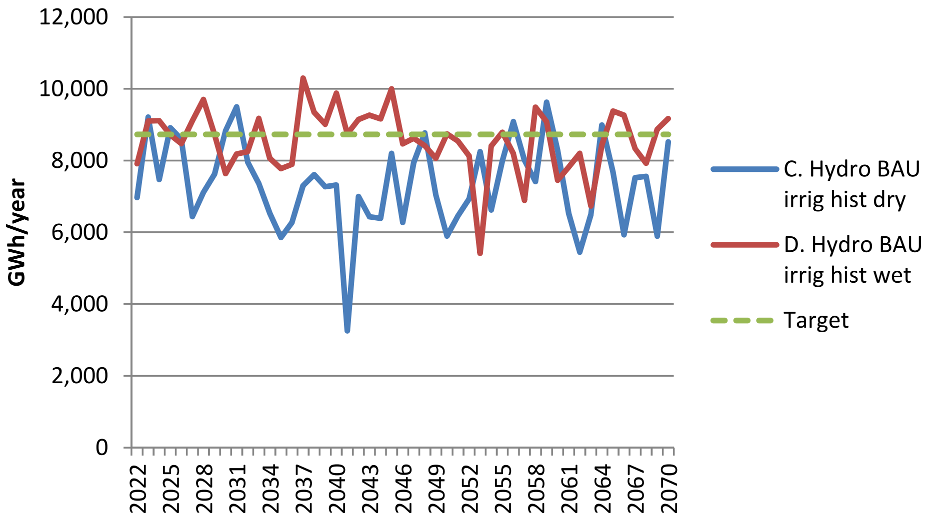
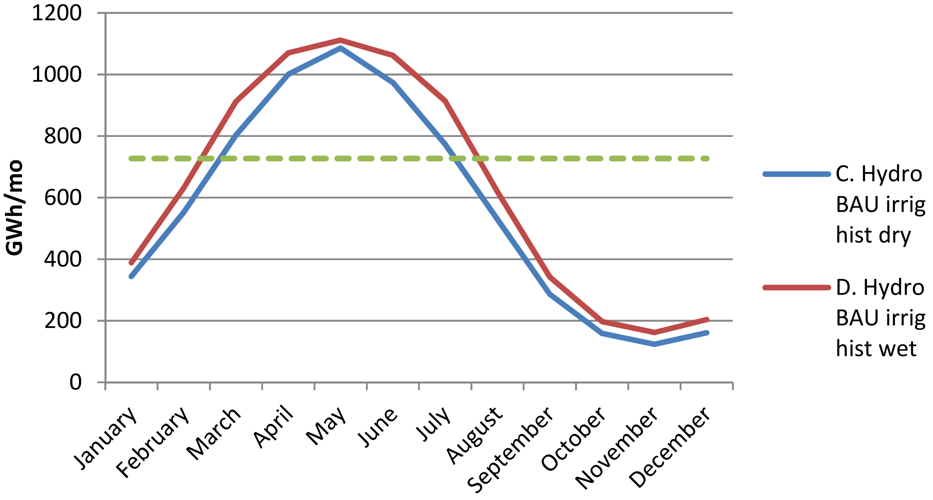


Figure 35. Future monthly generation at Batoka Gorge with "business as usual" hydropower development



Mphanda Nkuwa performs quite well under both climate futures, exceeding the generation target of 8,600 GWh/year in most years (Figure 36). Because Mphanda Nkuwa only has a small buffer reservoir (i.e. 2,324 mcm vs 65,000 mcm for Cahora Bassa), the monthly generation profile follows the Cahora Bassa discharge, and even annual generation shows high volatility. Monthly generation is above the expected level throughout the year under both climate futures.

Figure 36. Future annual generation at Mphanda Nkuwa under "business as usual" hydropower development

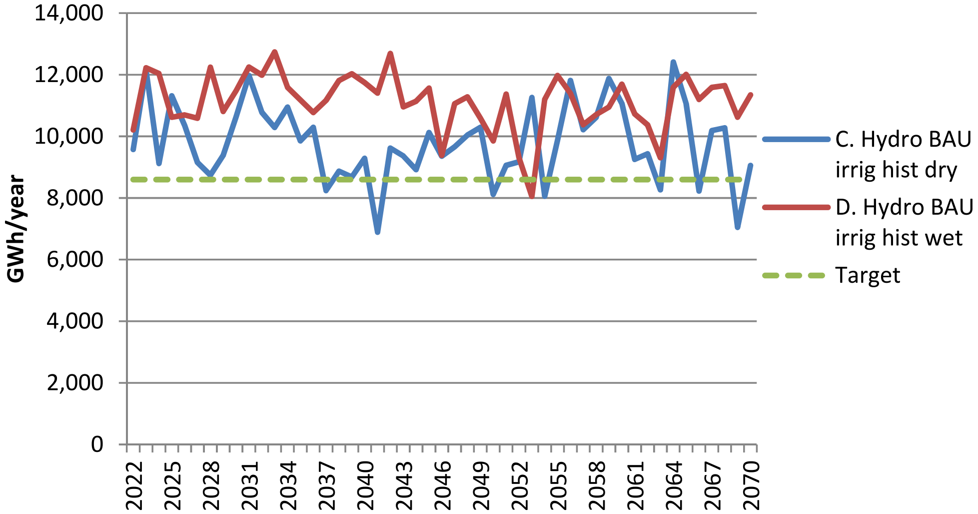
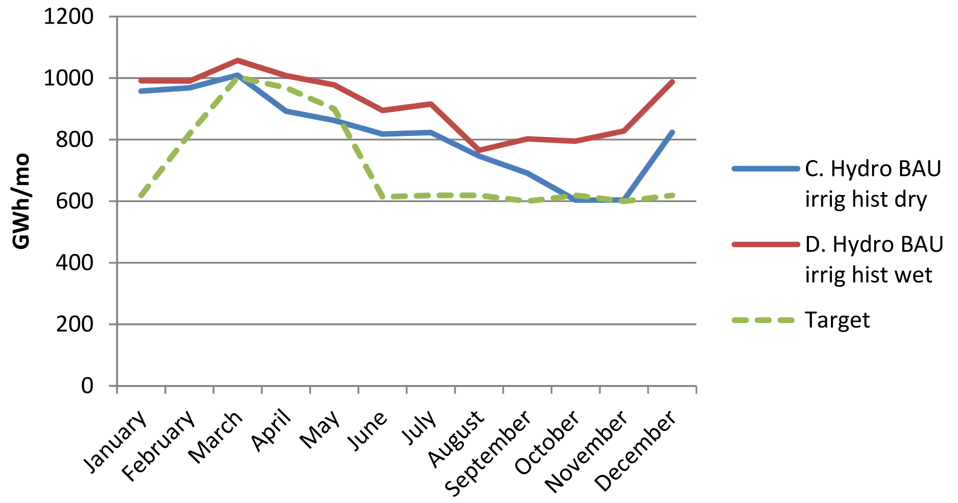
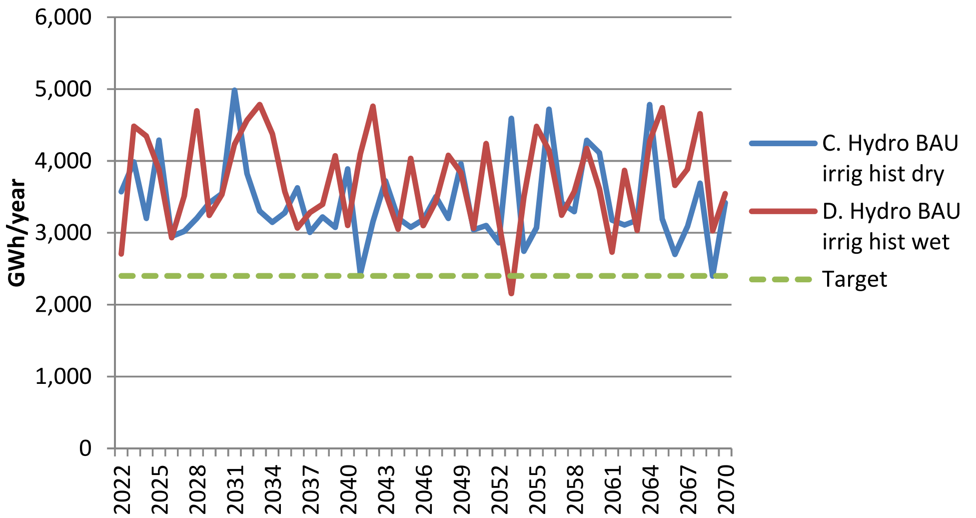


Figure 37. Future monthly generation at Mphanda Nkuwa with "business as usual" hydropower development



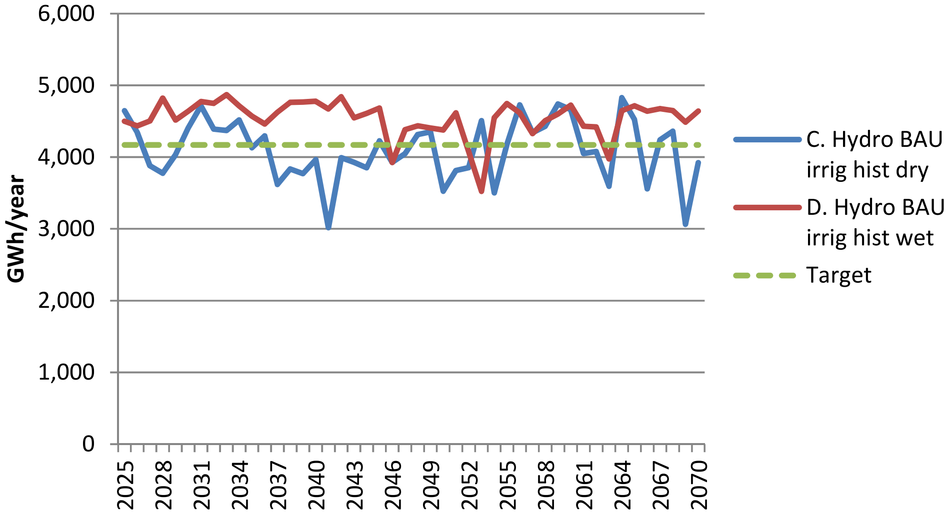
As a run-of-river hydropower plant, Kafue Gorge Lower generation is based entirely on releases from Kafue Gorge Upper. Future generation under both wetting and drying climates is well above the estimated energy demand of 2,800 GWh per year (Figure 38)

Figure 38. Future annual Kafue Gorge Lower generation with "business as usual" hydropower development



Boroma and Lupata are longer term investment options in Mozambique, but are considered under "business as usual" hydropower development from 2025. EDM estimates capacity for Boroma and Lupata at 160 MW and 550 MW, respectively but does not specify a generation target. These plants are also mentioned in the earlier Euroconsult Mott McDonald (2007) study with a load factor of 83% and 87%, respectively (although with higher total capacity). This provides an estimate of 1168 GWh/year at Boroma and 4,171 GWh/year at Lupata. Boroma would meet this in all years under both a wetting and drying climate, but Lupata would fall below the target half of the time under a drying climate (Figure 39).

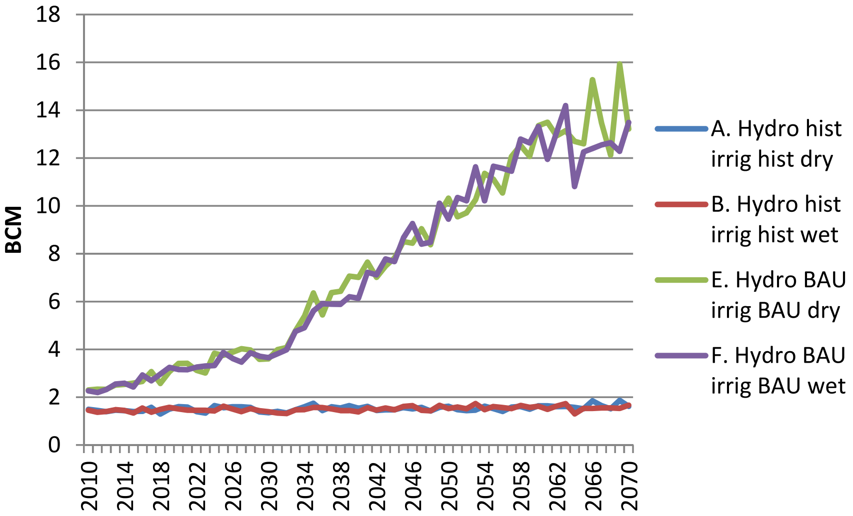
Figure 39. Future annual generation at Lupata with "business as usual" hydropower development



7.5 What additional impact will increased irrigation demand have on the performance of existing and new hydropower plants?

The influence of irrigation demand on two key factors: the absolute growth in water demand from this sector and the priority given to these demands in the modelling. In other words, if demand grows rapidly, but is given a lower priority than hydropower generation or urban consumption, then generation may not be significantly affected. In the previous sections, the hydropower results assumed that irrigation demand had a lower priority than all hydropower plants (see section 5.6). In this section, we present additional scenarios that include both irrigation demand growth and also a change in irrigation demand priority. Irrigation demand itself would rise very rapidly if the equipped area goals explained in section 3.1.2 are reached, as shown in Figure 40. This demand will only be met, however, if there is sufficient water available after other priorities have been met. Under the "Optimistic" irrigation development scenario, the same demand levels would be reached 10 to 20 years earlier.

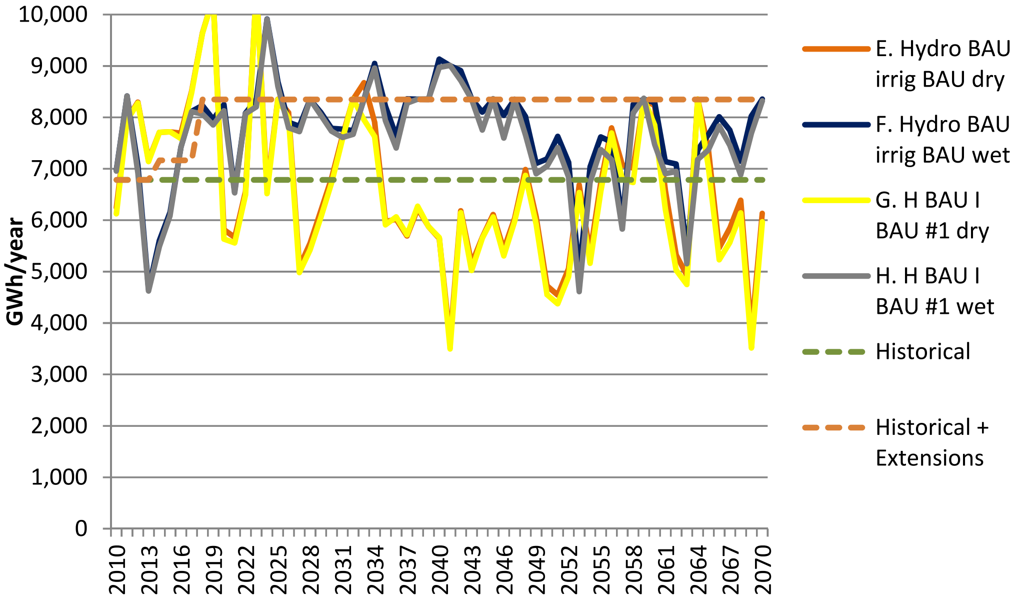
Figure 40. Total Zambezi Basin irrigation demand growth under different climate and development futures



For the major hydropower plants, we can illustrate the impact of irrigation by comparing generation under scenarios for hydropower and irrigation development in which irrigation has a lower priority, with an alternative set of scenarios where irrigation has a higher priority than hydropower. For example, in Figure 41 the “Hydro BAU irrig BAU” scenarios are with hydropower at a higher priority than irrigation, while the “Hydro BAU irrig BAU #1” scenarios are with irrigation at a higher priority than hydropower.

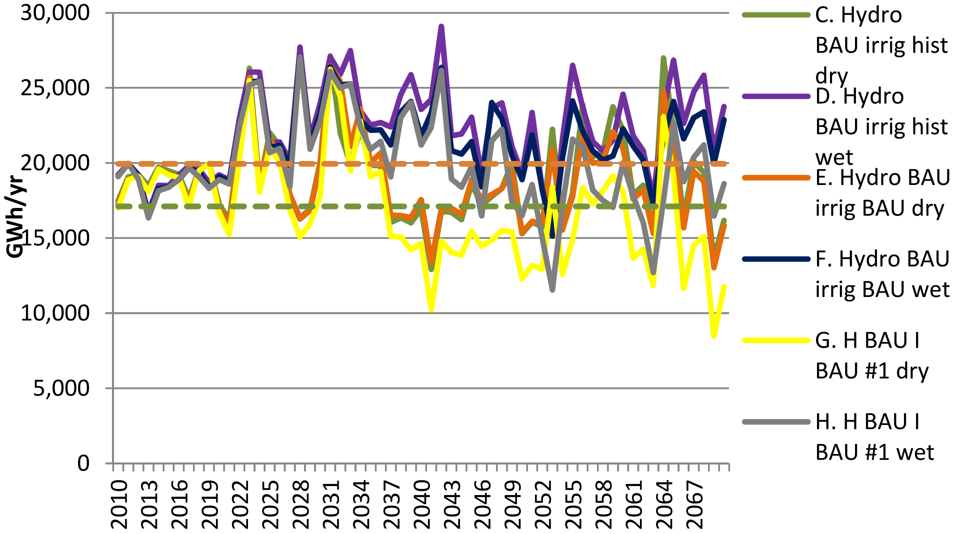
For Kariba, while the climate futures have a dramatic impact on generation, the change in irrigation priority has very little impact, despite the relatively large growth within that sub-basin in irrigation for identified projects (i.e. 97,000 ha) and high level potential (i.e. 470,000 ha). The scenarios with historical irrigation levels (not shown) are almost identical to the “Hydro BAU, irrig BAU” scenarios.

Figure 41. Future annual generation at Kariba with irrigation and hydropower development and priority changes



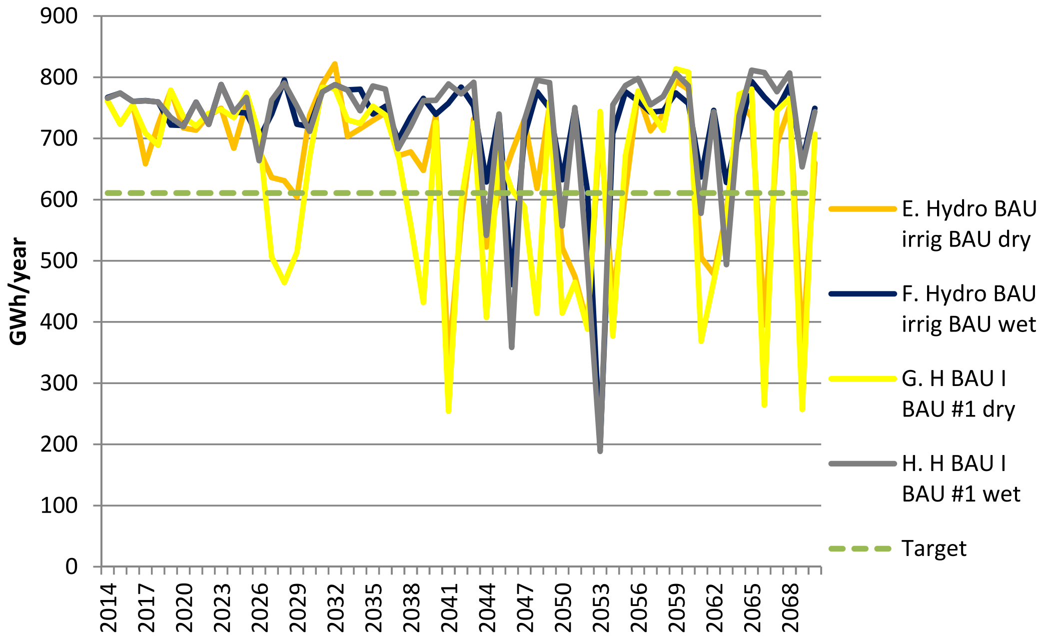
For Cahora Bassa, the picture is different. Over time, as the irrigation area grows, this demand has a significant impact on hydropower generation when it is prioritised (Figure 42). The difference between historical irrigation and business as usual irrigation under the same priorities (i.e. green vs orange and purple versus dark blue) is relatively small (3-6%), but when irrigation is prioritised (i.e. yellow and grey), hydropower production falls by almost 20% under either climate (i.e. yellow versus orange and green), compared to a scenario without any increases in irrigation demand.

Figure 42. Future annual generation at Cahora Bassa with irrigation and hydropower development and priority changes



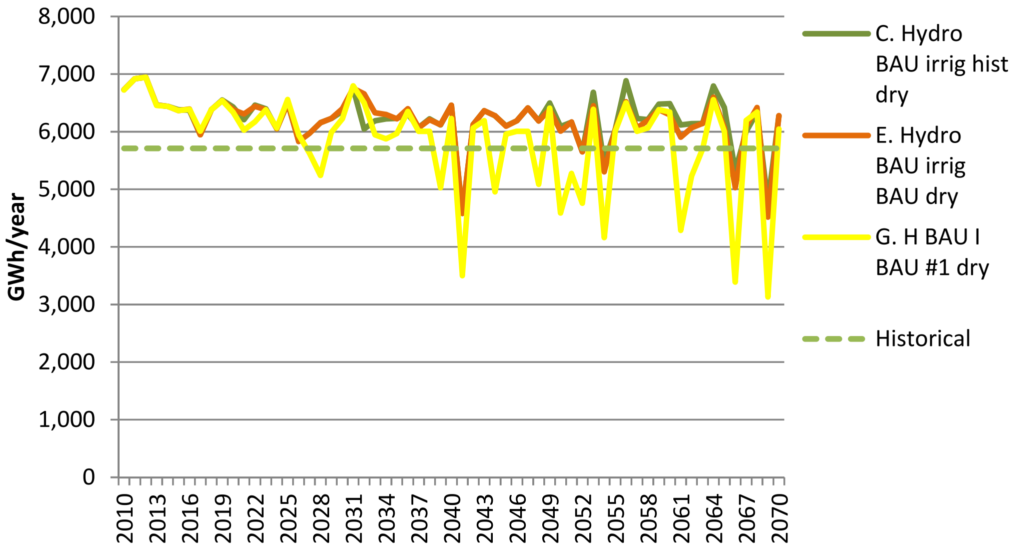
The results for Itezhi-tezhi are more similar to Kariba, in that the change in irrigation priorities has a limited impact on the expected generation, with the exception of the driest years under a drying climate (e.g.2026-28, 2037, 2043, 2048) (Figure 43).

Figure 43. Future annual generation at Itezhi-tezhi with irrigation and hydropower development and priority changes



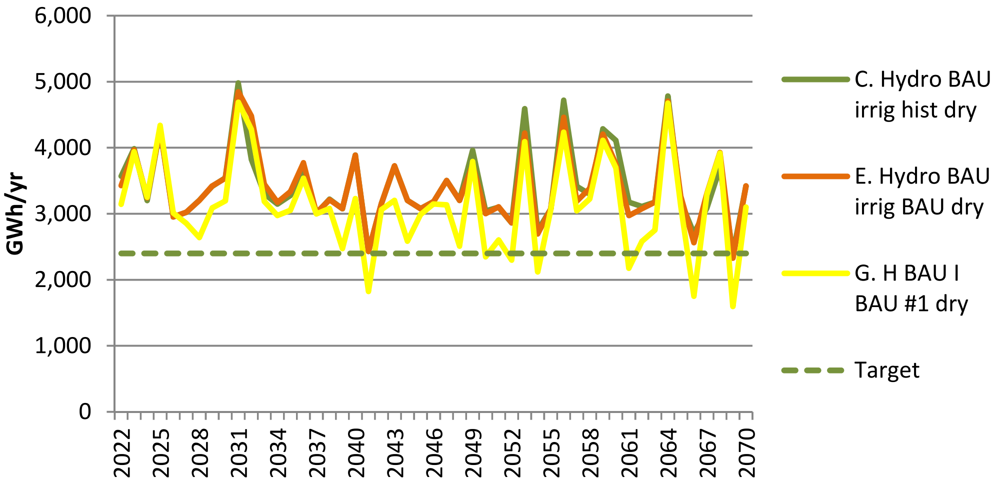
The same would be expected for Kafue Gorge Upper and Lower, since their inflows are based on Itezhi-tezhi releases. While this is true for wetting climates (not shown in figure), under drying conditions, irrigation does impact Kafue Upper and Lower generation significantly when irrigation demand is prioritised under a drying climate (Figure 44 and Figure 45). Mean generation is also below historical levels in a dying climate with prioritised irrigation demand (see Table 32)

Figure 44. Future annual generation at Kafue Gorge Upper with irrigation and hydropower development and priority changes



Note: “Hydro BAU irrig his dry” not visible because it is almost exactly the same data as “Hydro BAU irrig BAU dry”.

Figure 45. Future annual generation at Kafue Gorge Lower with irrigation and hydropower development and priority changes



The results for Mphanda Nkuwa are, not surprisingly, more similar to Cahora Bassa. While irrigation demand limited impact when hydropower is prioritised, once irrigation demand is prioritised generation falls 13-15% in the 2050-2070 period. (see Figure 46, Figure 47 and Table 33).

Figure 46. Future annual generation at Mphanda Nkuwa with irrigation and hydropower development and priority changes (wetting climate)

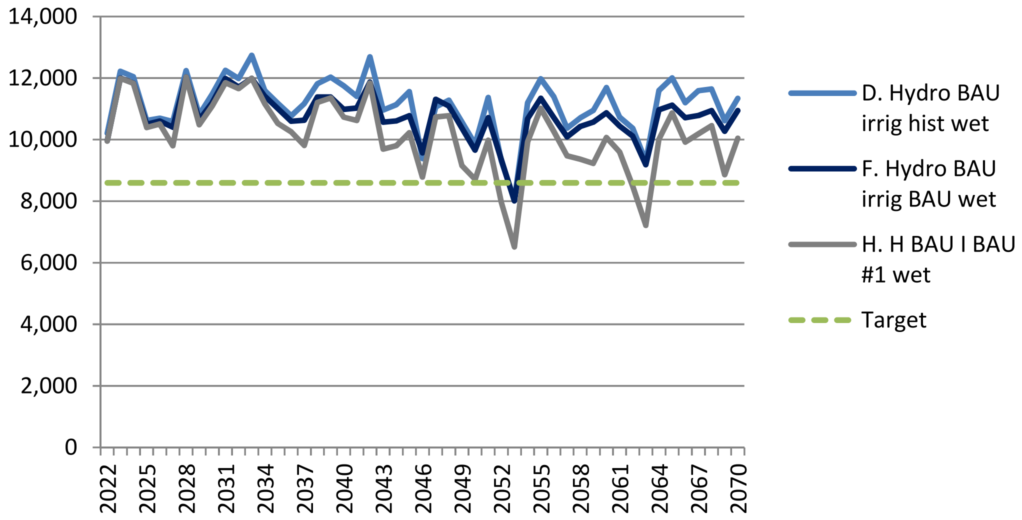
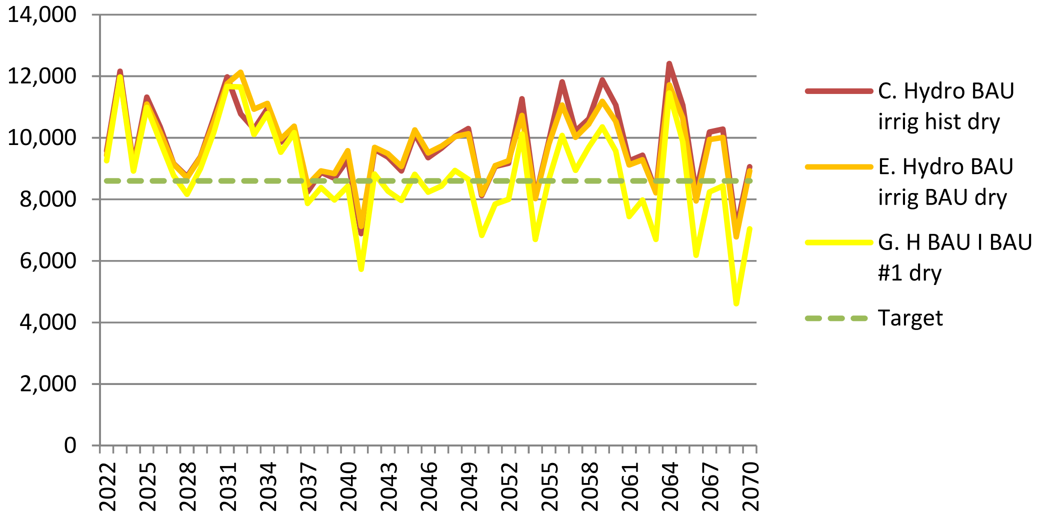
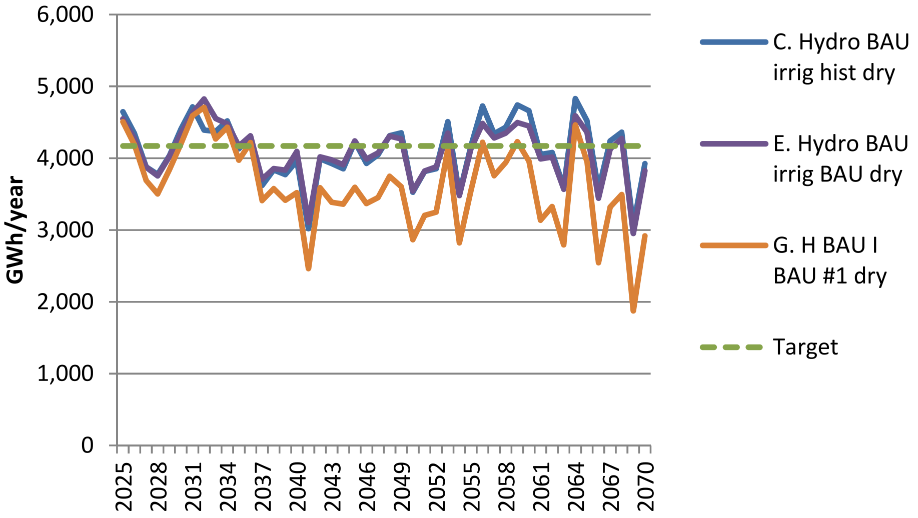


Figure 47. Future annual generation at Mphanda Nkuwa with irrigation and hydropower development and priority changes (drying climate)



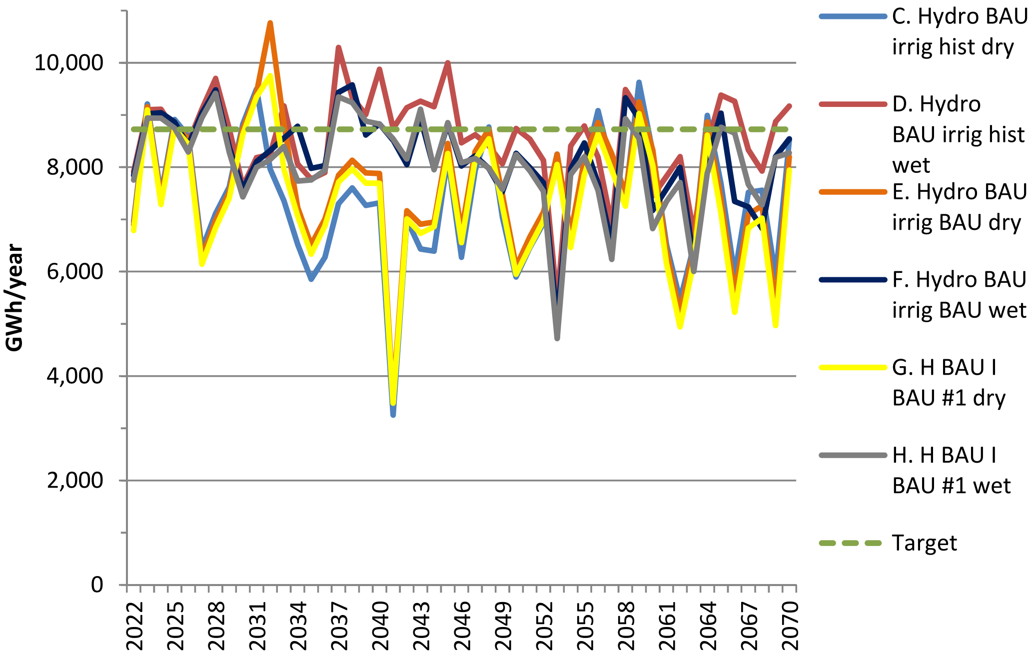
For Lupata, the impact is also noticeable when irrigation is prioritised, and in those scenarios the drop in mean generation is significant (13-17%) (See Figure 48).

Figure 48. Future annual generation at Lupata with irrigation and hydropower development and priority changes (dry climate only)



For Batoka Gorge, making irrigation a priority, on its own, has limited impact, as shown in Figure 49 (e.g. blue, yellow and orange lines follow closely, as do red, dark blue and grey).

Figure 49. Future annual generation at Batoka Gorge with irrigation and hydropower development and priority changes

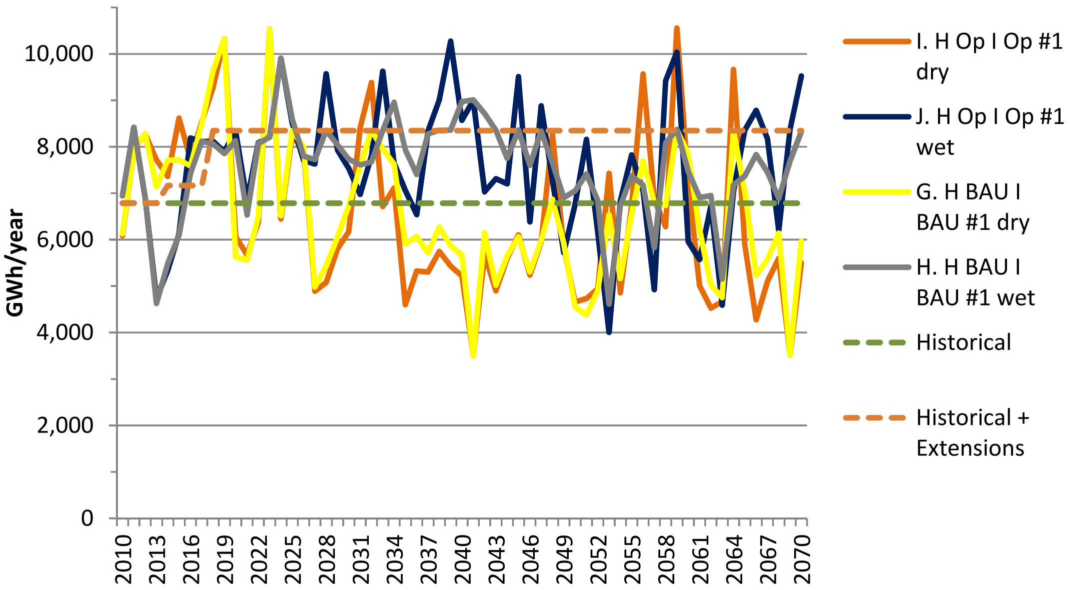


7.6 To what extent does the speed of implementation for hydropower and irrigation affect the results?

The previous section demonstrated that irrigation demand only has a significant impact when it is prioritised over hydropower demand, and then only for certain reservoirs. The development futures discussed earlier include the possibility that irrigation demand could grow more quickly than under the “business as usual” future, and that hydropower development could also be brought forward. Specifically, the year for achieving “identified irrigation projects” is brought forward from 2030 to 2020 and “high level potential” from 2060 to 2040. This means that irrigation demand rises much faster in the 2000-2030 period, and has reached a maximum by 2040. To test the impact of these alternative futures, this section compares the results under the “Hydro BAU, Irrig BAU #1” scenarios (i.e. wet and dry) with alternative “Hydro Op Irrig Op #1” (i.e. hydropower and irrigation optimistic development and irrigation priorities) scenarios.

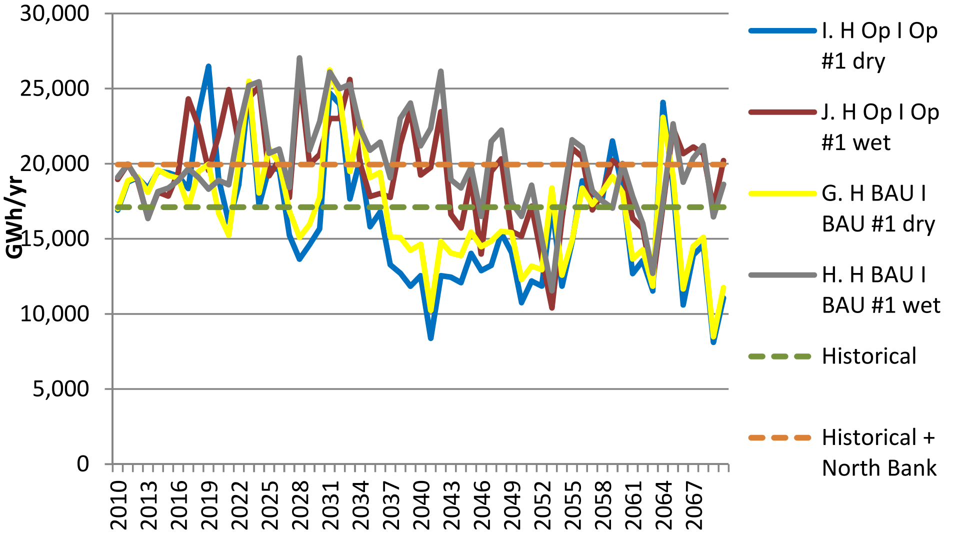
This comparison is illustrated for Kariba in Figure 50 below. While there is increased variation under a wetting climate, overall the impact of more rapid irrigation and hydropower development on generation at Kariba is quite limited, compared to the dramatic impacts of different climate futures.

Figure 50. Future generation at Kariba with different levels of hydropower and irrigation development, all with irrigation prioritised



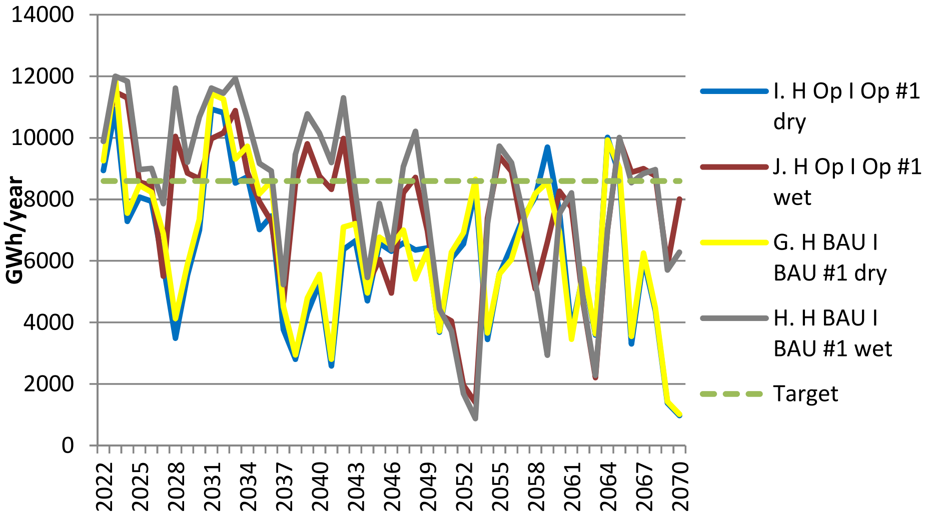
For Cahora Bassa, performance also shows limited overall change based on the pace of irrigation and hydropower development. For both climates, however, more rapid development results in higher generation 2016-2020 (due to earlier implementation of Cahora Bassa North Bank) and somewhat lower generation from 2030 to 2050 due to accelerated upstream abstraction (Figure 51). Mean generation in the later period (2050-2070) for a given climate does not change between these scenarios.

Figure 51. Future generation at Cahora Bassa with different levels of hydropower and irrigation development, all with irrigation prioritised



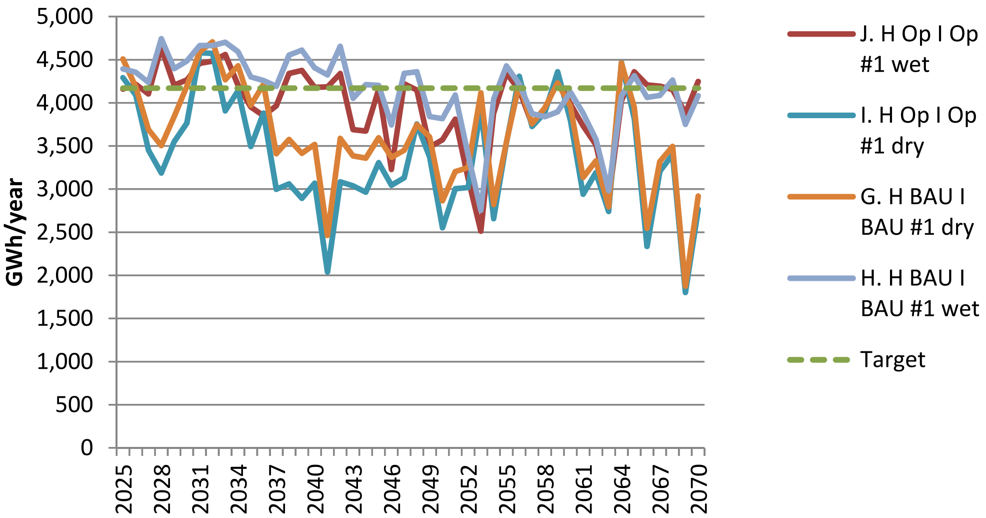
A similar pattern is observed at Mphanda Nkuwa, where mean generation in the later period (2050-2070) is not significantly affected, but performance under a wetting climate is more variable, leading to more years below target generation levels (see red and grey lines versus target in Figure 52).

Figure 52. Future generation at Mphanda Nkuwa with different levels of hydropower and irrigation development, all with irrigation prioritised



For Kafue Gorge Upper, Kafue Gorge Lower, Batoka Gorge and Itezhi-tezhi (not shown), the impact of more rapid irrigation and hydropower development on its own is not a major factor in generation. Boroma and Lupata are only impacted by the more rapid development scenarios under a wetting climate in the 2051-2053 period, although Lupata also losses 5-10% of generation under a drying climate in the 2030s and 2040s as irrigation grows rapidly (see Figure 53).

Figure 53. Future generation at Lupata with different levels of hydropower and irrigation development, all with irrigation prioritised



7.7 Summary

As a way of summarising the results of the analyses and figures presented in this chapter, the tables below show two measures of the impacts climate change and upstream irrigation on hydropower generation. The first is the mean annual generation during 2050-2070 as compared to modelled historical production (existing plants) or a stated target (new plants and expansions). The second is the share of the years (i.e. between 2010 and 2070) in which annual production is below the target level. This second metric is particularly important, because future climates could be more variable. Given that many of the plants currently have spare production capacity (i.e. load factors below 70% or even 50% in some cases), there could be scenarios where mean generation does not change but the number of years below target increases significantly. Note also that Table 31 also shows the share of years below mean generation for the modelled historical period.

Table 31. Summary results for existing hydropower plants under different climates

	2050-70 mean generation/ modelled historical			% years below modelled historical generation		
Scenario	Kariba	Cahora Bassa	Kafue Upper	Kariba	Cahora Bassa	Kafue Upper
A. Hydro hist irrig hist dry	88%	98%	106%	62%	41%	8%
B. Hydro hist irrig hist wet	100%	107%	108%	20%	8%	7%
Modelled Historical				48%	36%	43%

Table 32. Summary results for existing hydropower plants with expansions under different climates and irrigation scenarios

	2050-70 mean generation/target*			% years below target* generation		
Scenario	Kariba	Cahora Bassa	Kafue Upper	Kariba	Cahora Bassa	Kafue Upper
C. Hydro BAU irrig hist dry	76%	96%	107%	77%	69%	8%
D. Hydro BAU irrig hist wet	90%	111%	109%	62%	26%	2%
E. Hydro BAU irrig BAU dry	75%	92%	105%	75%	69%	8%
F. Hydro BAU irrig BAU wet	88%	105%	107%	66%	28%	3%
G. H BAU I BAU #1 dry	73%	76%	96%	79%	85%	25%
H. H BAU I BAU #1 wet	85%	90%	104%	70%	54%	7%

*target is modelled historical generation plus expected generation from expansions at Kariba and Cahora Bassa

Table 33. Summary results for new hydropower plants under different climates and irrigation scenarios

	2050-70 mean generation (GWh)				% years below target generation			
Scenario	Mphanda Nkuwa	Itezhi-tezhi	Batoka	Kafue Lower	Mphanda Nkuwa	Itezhi-tezhi	Batoka	Kafue Lower
Target*	8600	611	8728	2400				
C. Hydro BAU irrig hist dry	9825	614	7387	3427	14%	23%	84%	2%
D. Hydro BAU irrig hist wet	10823	696	8251	3655	2%	4%	53%	2%
E. Hydro BAU irrig BAU dry	9564	613	7284	3366	14%	23%	80%	2%
F. Hydro BAU irrig BAU wet	10377	699	7725	3559	2%	4%	71%	2%
G. Hydro BAU irrig BAU #1 dry	8319	601	7032	3037	45%	33%	90%	14%
H. Hydro BAU irrig BAU #1 wet	9438	695	7637	3431	8%	12%	73%	4%

*target is from utilities or literature

	2050-70 mean generation (GWh)		% years below target generation	
Scenario	Boroma	Lupata	Boroma	Lupata
Target	1168	4171		
C. Hydro BAU irrig hist dry	1403	4119	0%	52%
D. Hydro BAU irrig hist wet	1420	4473	0%	9%
E. Hydro BAU irrig BAU dry	1399	4019	0%	57%
F. Hydro BAU irrig BAU wet	1419	4316	0%	9%
G. Hydro BAU irrig BAU #1 dry	1283	3416	11%	76%
H. Hydro BAU irrig BAU #1 wet	1385	3883	2%	43%

8 Conclusions

The objective of this analysis has been to assess how upstream changes in climate and irrigation demand would affect water availability for major downstream Zambezi Basin hydropower plants. The analysis covers major existing plants (i.e. Kariba, Cahora Bassa and Kafue Gorge Upper), extensions to existing plants (i.e. Kariba North and South bank, Cahora Bass North Bank) and major new plants (i.e. Batoka Gorge, Itezhi-tezhi, Mphanda Nkuwa, Kafue Gorge Lower, and to a lesser extent Boroma and Lupata).

While future climate is subject to scientific uncertainty, the impact of irrigation is a policy uncertainty. This is both because the level of irrigation investment is driven by political and economic priorities, but also because the priority given to irrigation demand versus hydropower demand for water is a political decision – and, in this case, an international political one as well, because of the different countries utilising the resources of the Zambezi. The initial set of scenarios therefore tested the impact of different future climates and levels of irrigation development assuming that hydropower is prioritised over irrigation. Additional scenarios then tested the effect of prioritising irrigation over hydropower, while holding climate and absolute water demand levels constant. The purpose of exploring these alternatives is not to arrive at one “right” answer, but to illustrate the implications of different decisions and possible futures.

Changes in future climate is the overwhelming driver of future production at all hydropower plants. The difference in mean generation under wetting and drying climates is 8-15% for almost all plants (Kafue Gorge Upper and Boroma being the exceptions), and a drying climate generally increases the share of years below target anywhere from 10% to 40%.

Given the constraints of future climate, the expansion of the Kariba appears to be unlikely to reach the planned production levels. Even under a wetting climate, mean generation is 10-15% lower than historical levels, when new hydropower and irrigation demands are considered. Cahora Bassa, on the other hand, could reach the target for the North Bank expansion under a wetting climate, but would often fall short under a drying climate. Kafue Gorge Upper appears to be the exception in that future production levels could actually be higher than historical levels under both a drying and wetting climate, which could be in part to the increased regularity of Itezhi-tezhi releases once hydropower production commences in 2014.

Choosing the appropriate target for future generation for new plants is difficult, because feasibility studies are either under revision or incomplete in many cases. Compared to the values stated by the utilities, however, Batoka Gorge is not able to meet the generation target under any scenario. Itezhi-tezhi, on the other hand, generates more than that stated target of 611 GWh/yr in almost all scenarios and Kafue Gorge Lower levels are well above 2400 GWh/yr. Mphanda Nkuwa can also meet the stated targets under almost all scenarios except when irrigation is prioritised over hydropower in a drying climate. For all new plants, the impact of different climate futures is still highly significant

The impact of irrigation depends not just on the level of demand but, more importantly, on the prioritisation given to agricultural demand over hydropower production. For most plants, including "business as usual" irrigation growth only reduces mean generation by up to6%, with Cahora Bassa and Batoka Gorge under a wetting climate at the higher end of this range.

When irrigation is prioritised over hydropower, the impact on generation is significant across many plants. At Cahora Bassa, average generation drops 20% when irrigation is prioritised (see yellow versus green line and grey versus dark blue line in **Error! Reference source not found.**). Mphanda Nkuwa losses 13-15% of average generation (see Table 33). This vulnerability at Mphanda Nkuwa reflects the fact that this plant is basically a run-of-river plant, with only a relatively small reservoir. Prioritising irrigation reduces average generation under a drying climate for Lupata, Kafue Gorge Upper and Kafue Gorge Lower by 17%, 11% and 11%, respectively. Lupata is not only a run-of-river plant, but is also downstream to one of the areas with largest irrigation potential – between Mphanda Nkuwa and the confluence with the Shire River. The impacts on Batoka Gorge and Itezhi-tezhi are very limited, given the small amount of irrigation upstream to these plants. Kariba also has a large enough reservoir to cope with the competing sectoral demands, so the prioritisation of irrigation does not result in significant additional losses of generation.

The relatively low consumption of water in the Zambezi River Basin in the past meant that explicit trade-offs across sectors and across countries, while important at a local level, posed less of a challenge for the basin overall. This is very likely to change in the future, as increased demands from all sectors, and major potential changes in climate, and therefore runoff, will require more explicit agreements on how to best utilise a limited resource.

The dramatic potential impacts of future climate on hydropower potential in the Zambezi River Basin point to the need to explicitly consider climate change in both project planning and overall system expansion planning. This is even truer for future plants, where financial viability and loan repayments will depend on the stability of generation and sales revenue. A key next step in this analysis should be to look at not just how climate and development affect individual plants, but how they affect entire national and regional energy systems. This analysis should also use the most recent climate scenario data available, as this field is evolving rapidly. Although there is increasing cooperation in the basin, major decisions on investment and operation are not necessarily coordinated as effectively as possible, and this will be more complex with four or five major new plant in the basin in the coming 10-15 years. Linking the water modelling to an energy system model for the region would allow for more explicit modelling of the energy, water and economic trade-offs, and a deeper understanding of the real costs of a changing climate.

9 References

Allen, Richard G, Luis S Pereira, Dirk Raes, and Martin Smith. 1998. “Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage Paper 56.” Rome: Food & Agricultural Organisation of the United Nations. http://www.fao.org/docrep/X0490E/x0490e00.htm.

Beilfuss, Richard. 2001. “Prescribed Flooding and Restoration Potential in the Zambezi Delta, Mozambique. Working Paper #4. Program for the Sustainable Management of the Cahora Bassa Dam and the Lower Zambezi Valley”. Baraboo, Wisconsin: International Crane Foundation. http://www.savingcranes.org/images/stories/pdf/conservation/Zambezi_modeling_Working_Paper4.pdf.

Beilfuss, Richard, and Cate Brown. 2010. “Assessing Environmental Flow Requirements and Trade-Offs for the Lower Zambezi River and Delta, Mozambique.” *International Journal of River Basin Management* 8 (2) (June): 127–138. doi:10.1080/15715121003714837.

Beilfuss, Richard, and David dos Santos. 2001. “Patterns of Hydrological Change in the Zambezi Delta, Mozambique. Working Paper #2. Program for the Sustainable Management of the Cahora Bassa Dam and the Lower Zambezi Valley”. Baraboo, Wisconsin: International Crane Foundation. http://www.savingcranes.org/images/stories/pdf/conservation/Zambezi_hydrology_Working_Paper2.pdf.

Burian, Martin, Peter Zhou, Francis Masawi, Francis Yamba, and Florian Baumgard. 2012. “Analysis of Grid Emission Factors for the Electricity Sector in Sub-Saharan Africa”. Roskilde, Denmark: UNEP Risoe Centre.

Chapman, Arthur. 2012. “Socio-Economic Futures of the Zambezi River Basin”. Cape Town: OneWorld Sustainable Investments. www.oneworldgroup.co.za.

Cilliers, J, B Hughes, and J Moyer. 2011. “African Futures 2050: The next Forty Years, Technical Report”. Pretoria: Institute for Security Studies.

ESCOM. 2013a. “Kapichira Power Station - Electricity Supply Corporation of Malawi.” http://www.escom.mw/station-kapichira.php.

———. 2013b. “Personal Communication with Elenestina Mwelwa”Interview by Randall Spalding-Fecher. Data provided in Excel Spreadsheet.

Euroconsult, and Mott MacDonald. 2007. “Integrated Water Resources Management Strategy and Implementation Plan for the Zambezi River Basin. Final Report, Rapid Assessment”. Gaborone, Botswana and Lusaka, Zambia: South African Development Community Water Division and Zambezi River Authority. http://www.elmed-rostov.ru/Projects/Zamwis_php/Reports/RA%20Water%20Resources%20Zambezi%2002Jan2008.pdf.

Gupta, Hoshin V., Harald Kling, Koray K. Yilmaz, and Guillermo F. Martinez. 2009. “Decomposition of the Mean Squared Error and NSE Performance Criteria: Implications for Improving Hydrological Modelling.” *Journal of Hydrology* 377 (1-2) (October): 80–91. doi:10.1016/j.jhydrol.2009.08.003.

HCB. 2013. “Personal Communication with Sergio Elisio”Interview by Randall Spalding-Fecher. Data provided in Excel Spreadsheet.

HMNK. 2012. “Mphanda Nkuwa HPP Project. Technical and Economical Feasibility Study Consolidation [restricted]”. Maputo, Mozambique: Hidroelectrica Mphanda Nkuwa.

Höllermann, Britta, Simone Giertz, and Bernd Diekkrüger. 2010. “Benin 2025—Balancing Future Water Availability and Demand Using the WEAP ‘Water Evaluation and Planning’ System.” *Water Resources Management* 24 (13) (March 24): 3591–3613. doi:10.1007/s11269-010-9622-z.

Howells, Mark, Sebastian Hermann, Manuel Welsch, Morgan Bazilian, Rebecka Segerström, Thomas Alfstad, Dolf Gielen, et al. 2013. "Integrated Analysis of Climate Change, Land-Use, Energy and Water Strategies." *Nature Climate Change* 3 (7) (June 25): 621–626. doi:10.1038/nclimate1789.

Hughes, B. 2010. "International Futures (IFs) Modeling System," www.ifs.du.edu.

Hughes, B, M Irfan, H Khan, K Kumar, D Rothman, and J. Solórzano. 2009. "Reducing Global Poverty: Patterns of Potential Human Progress: Volume 1 Technical Report". Denver, Colorado: Frederick S. Pardee Center for International Futures, University of Denver. http://www.ifs.du.edu/assets/documents/PPHP1/PPHP1FULL.pdf.

Kling, Harald, and Martin Preishuber. 2012. "Zambezi Decision Support System – User's Manual. A Web-Based Decision Support System to Analyze the Impact of Climate Change and Water Resources Development on Runoff in the Zambezi Basin." Vienna: Pöyry Energy GmbH. http://zdss.ingc.gov.mz/help/manual.pdf.

Kling, Harald, Philipp Stanzel, and Martin Preishuber. Submitted. "Impact Modelling of Water Resources Development and Climate Scenarios on Zambezi River Discharge." *Hydrological Sciences Journal*

Mehta, Vishal K., David E. Rheinheimer, David Yates, David R. Purkey, Joshua H. Viers, Charles A. Young, and Jeffrey F. Mount. 2011. "Potential Impacts on Hydrology and Hydropower Production under Climate Warming of the Sierra Nevada." *Journal of Water and Climate Change* 2 (1) (March): 29. doi:10.2166/wcc.2011.054.

MEWD. 2010. "Power System Development Master Plan for Zambia 2010-2030". Lusaka, Zambia: Ministry of Energy and Water Development, Republic of Zambia.

Nexant. 2007. "SAPP Regional Generation and Transmission Expansion Plan Study. Draft Report. Volume 2. Main Report". Submitted to: Southern Africa Power Pool Coordination Centre. San Francisco: Nexant.

PRB. 2013. "DataFinder | U.S. and World Data by The Population Reference Bureau." *Population Reference Bureau*. http://www.prb.org/DataFinder.aspx.

Purkey, D. R., B. Joyce, S. Vicuna, M. W. Hanemann, L. L. Dale, D. Yates, and J. A. Dracup. 2007. "Robust Analysis of Future Climate Change Impacts on Water for Agriculture and Other Sectors: A Case Study in the Sacramento Valley." *Climatic Change* 87 (S1) (December 22): 109–122. doi:10.1007/s10584-007-9375-8.

SADC. 2011. "Dam Synchronisation and Flood Releases in the Zambezi River Basin Project. Annex 2. Concepts and Recommendations for Dam Management". Gaborone: Southern African Development Community. http://agriwaterpedia.info/wiki/File:SADC_(2011)_Dam_Synchronisation_and_Flood_Releases_in_the_Zambezi_River_Basin_Project_Annex_2.pdf.

Sieber, Jack, and David Purkey. 2011. "WEAP: Water Evaluation And Planning System. User Guide". Somerville, MA: Stockholm Environment Institute, U.S. Center. http://weap21.org/downloads/WEAP_User_Guide.pdf.

UNDESA. 2011. "World Population Prospects, the 2010 Revision." *United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section*. http://esa.un.org/wpp/Excel-Data/population.htm.

USBR. 2005. "Reclamation - Managing Water in the West. Hydropower". Washington, D. C.: U.S. Department of Interior, Bureau of Reclamation. http://www.usbr.gov/power/edu/pamphlet.pdf.

Varela-Ortega, Consuelo, Irene Blanco-Gutiérrez, Christopher H. Swartz, and Thomas E. Downing. 2011. "Balancing Groundwater Conservation and Rural Livelihoods under Water and Climate Uncertainties: An Integrated Hydro-

Economic Modeling Framework.” *Global Environmental Change* 21 (2) (May): 604–619. doi:10.1016/j.gloenvcha.2010.12.001.

Walimwipi, Hartley. 2012. “Personal Communication”Interview by Randall Spalding-Fecher. Data provided in Excel Spreadsheet.

World Bank. 2010a. “The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis. Volume 4. Modeling, Analysis and Input Data”. Washington, D. C.: World Bank.

———. 2010b. “The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis. Volume 2. Basin Development Scenarios”. Washington, D. C.: World Bank.

WRC. 2010. “Feasibility Design Study on the Utilization of the Water Resources of the Chobe/Zambezi River. Technical Report, Republic of Botswana Ministry of Minerals, Energy and Water Resources, Department of Water Affairs, Tender No. PR 10/3/1/09, Draft Prefeasibility/Feasibility Design Study Report”. Gaborone: Republic of Botswana Ministry of Minerals.

Yamba, Francis Davison, Hartley Walimwipi, Suman Jain, Peter Zhou, Boaventura Cuamba, and Cornelius Mzezewa. 2011. “Climate Change/variability Implications on Hydroelectricity Generation in the Zambezi River Basin.” *Mitigation and Adaptation Strategies to Global Climate Change* 16: 617–628. doi:10.1007/s11027-011-9283-0.

Yates, David N., and Kathleen A. Miller. 2013. “Integrated Decision Support for Energy/Water Planning in California and the Southwest.” *International Journal of Climate Change: Impacts and Responses* 4 (1): 49–64.

Yates, David, Jack Sieber, David Purkey, and Annette Huber-Lee. 2005. “WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 1: Model Characteristics.” *Water International* 30 (4) (December): 487–500. doi:10.1080/02508060508691893.

ZESCO. 2013. “Personal Communication with Ernest Banda”Interview by Randall Spalding-Fecher. Data provided in Excel Spreadsheet.

ZRA. 2013. “Personal Communication from Clement Mukosa”Interview by Randall Spalding-Fecher. Via email.

Annex A. Hydropower Plant and Reservoir Data

Table 34. Volume-elevation curve for Cahora Bassa

volume (mcm)	0	4745	10689	17963	26699	37026	51704	62977	65991
elevation (m amsl)	295	300	305	310	315	320	326	330	331
area (km^2)	838	1065	1317	1597	1902	2233	2665	2974	3054
spillway (cms)	6760	7990	9060	10020	10890	11700	12600	14173	15683

Source: (HCB 2013; Beilfuss 2001)

Table 35. Turbine efficiency rating for Cahora Bassa

net head (m)	90	95	100	105	110	115	120	125	125	130
Efficiency	89.3%	92.7%	95.8%	95.6%	95.6%	95.9%	95.6%	95.2%	94.2%	92.9%

Source: (Beilfuss 2001)

Table 36. Design Flood Rule Curve for Cahora Bassa

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Level (m amsl)	321.7	323.6	325.6	325.7	325.4	325.1	324.5	324	323.1	322.2	321.3	320.6

Source: ZDSS (modified from HCB data, based on observation of more recent actual operation)

Table 37. Tailwater curve for Cahora Bassa

Discharge (cms)	0	500	1000	2000	3000	5000	8000	10500	15000	22000
Level (m amsl)	194	198.89	201.08	204.29	206.86	211.05	216.05	221.5	226.14	232

Source: (Beilfuss 2001; HCB 2013)

Note: Maximum turbine flow at Cahora Bassa is 2,250 cms (HCB)

Table 38. Volume-elevation curve for Lake Kariba

volume (mcm)	54	2272	6706	11278	15911	20613	25962	30408
elevation (m amsl)	475.5	476	477	478	479	480	481	482
area (km^2)	4354	4405	4507	4608	4709	4811	4901	4991
spillway (cms)					7528	7751	7973	8168

volume (mcm)	35427	40568	45778	51088	56507	64798	76854
elevation (m amsl)	483	484	485	486	487	488.5	489.5
area (km^2)	5081	5171	5261	5350	5440	5577	5671
spillway (cms)	8381	8584	8786	8974	9161	9445	9515

Source: (Beilfuss 2001)

Table 39. Design Flood Rule Curve for Lake Kariba

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Level (m amsl)	485.15	484.15	485.7	487.5	487.5	487.5	487.5	487.5	487	486.5	486	485.5

Source: (ZRA 2013; SADC 2011), ZRA Personal Communication.

Table 40. Tailwater rating curve for Lake Kariba

Discharge (cms)	0	479	719	959	1319	1518	3000	9000	12000	15000
Level (m amsl)	380	383.7	384.86	386.19	387.67	388.48	391.96	399.87	402.55	404.55

Source: (Beilfuss 2001)

Table 41. Volume-elevation curve for Kafue Gorge Upper

Volume (mcm)	0	20	69	170	423	785	1178	2845

Elevation (m amsl)	972.3	973	974	975	976	976.6	977	978
Area (km^2)	20	35	70	142	430	805	1175	2160
Spillway (cms)	780	1076	1420	1804	2220	2496	2668	3132

Source: (Beilfuss 2001)

Table 42. Volume-elevation curve for Itezhi-tezhi

Volume (mcm)	699	894	1119	1377	1673	2008	2387	2814	3291	3551	4118	4746	5439	5624	7049
Elevation (m amsl)	1006	1008	1010	1012	1014	1016	1018	1020	1022	1024	1026	1028	1029	1029.5	1035
Area (km^2)	90	105	120	138	158	177	203	224	253	284	314	346	364	374	446

Source: (Beilfuss 2001)

Table 43. Design Flood Rule Curve for Itezhi-tezhi

Month	Jan	Feb	Mar	Apr	May	Jun
Elevation (m amsl)	1023.5	1025.9	1027.5	1028.5	1028.6	1028.2
Month	Jul	Aug	Sep	Oct	Nov	Dec
Elevation (m amsl)	1027.6	1026.8	1025.7	1024.5	1023.2	1022.5

Source: (Beilfuss 2001)

Table 44. Volume-elevation curve for Mphanda Nkuwa

Elevation (m)	145	150	155	160	165	170	175	180	185	190	195	200	205	210	215	220
Area (km2)	4	6	10	13	17	24	32	41	51	62	73	84	97	109	123	136
Volume (mcm)	14	39	79	137	212	313	452	634	863	1,144	1,480	1,872	2,324	2,838	3,418	4,065

Source: (HMNK 2012)

Table 45. Volume-elevation curve for Batoka Gorge

Elevation (m)	620	640	660	680	700	720	740	760	780	800
Area (km2)	1.30	3.80	5.65	9.22	12.48	16.15	20.24	25.07	30.72	37.31
Volume (mcm)	0	51	146	294	511	798	1161	1615	2172	2853

Source: (HMNK 2012)

Table 46. Volume-elevation curve for Devil's Gorge

Elevation (m)	468	476	484	492	500	508	516	524	532
Area (km2)	8.8	21.5	37	56.8	80	104.3	132.7	165.4	203.1
Volume (mcm)	83.6	153.5	384.2	760	1002	2040	2995	4182	5643
Elevation (m)	540	548	556	564	572	580	588	596	
Area (km2)	246.7	297.3	352.9	424.6	497	570	666	762	
Volume (mcm)	7443	9663	12218	15853	19560	23268	28547	33947	

Source: (HMNK 2012)

Annex B. Irrigation area data

Table 47. Current irrigated area by crop and sub-basin

					Dry season crops							Perennial crops						Wet season crops						
World Bank (WB) subbasin name	Irrigation abstraction point	Subbasins ZDSS	WB sub-basin	Abstraction Point (WB)	Winter Wheat	Winter Rice	Winter Maize	Vegetables	Beans	Winter Cotton	Other	Sugar-cane	Tea	Coffee	Citrus	Banana	Pasture	Maize	Soy-beans	Sor-ghum	Cotton	To-bacco	Rice	Equipped area (ha)
Upper Zambezi	IA1	1	12			1000		750							750									2500
Kabompo	IA2	2	13		136			64			45				23		82	88				48		350
Lungue Bungo	IA3	3	11			500		250							250									1000
Luanginga	IA4	4	10			250		250							250									750
Barotse	IA6	6	9		78			36			26				13		47	51				27		200
Cuando / Chobe	IA7	7	8	I.08.01-3	0	350	0	145	0	0	0	0	0	0	125	0	0	0	0	0	0	0	0	620
Kariba	IA8	8	6	I.06.01-4	613	0	0	278	0	0	202	21	2	4	99	0	356	387	8	0	10	209	0	1575
Kafue	IA13	12.13	7	I.07.01	4135											42			4135					4177
	IA14	14	7	I.07.03	1275							33068		596		82			773			502		35021
Kariba	IA9	9	6	I.06.09	503			84			126	356	42	63	42		84	121	131		171	81		1300
	IA10	10	6	I.06.10	8362			1394			2090	5920	697	1046	697		1394	2007	2174		2843	1338		21600
	IA11a	11	6	.06.07-	389	0	0	123	0	0	113	137	16	24	48	0	149	173	50	0	66	99	0	999
	IA11b	11	6	06.11-1	836	0	0	415	0	500	297	0	0	0	137	25	502	562	0	0	500	293	0	2712
Luangwa	IA15	15	5	I.05.02	464			250	24		47				155		60	302				162		1000
	IA16	16	5	I.05.01	4225			2275	217		433				1408		542	2746				1479		9100
Mupata	IA17a	17	4	I.07.05	960														960					960
	IA17b	17	4	.04.01-	5240	0	0	1072	0	0	1277	3618	426	1069	646	0	852	1311	1329	0	1737	864	0	14200
	IA18		2	I 02.01	8552			1426			2137	6055	713	1063	713		1426	2053	2224		2908	1368		22085
Tete	IA19	18,	2	I.02.02				10																10
	IA21		2	I.02.03					2						8			1						10
	IA24		2	I.02.04			95	170							50			48	17	8	23			315
	IA23		2	.02.05-	4898	0	0	817	60	0	1224	3468	408	613	408	0	817	1206	1285	5	1679	784	0	12713
Lake Malawi /	IA25	25	3	03.04-1	0	13250	2804	1277	0	0	0	6000	2060	0	0	0	0	1402	505	224	673	0	13250	25391
Shire	IA26	26	3	.03.01-	0	450	775	50	0	0	0	13750	2000	0	0	0	0	388	140	62	186	0	450	17025
Zambezi Delta	IA27	27	1					666				5666			666									6998
Total					40666	15800	3674	11802	303	500	8017	78059	6364	4478	6488	149	6311	12846	13731	299	10796	7254	13700	182611

Source: (World Bank 2010a)

Table 48. Identified irrigation projects area by crop and sub-basin

					Dry Season Crops							Perennial Crops						Wet Season Crops						
World Bank (WB) subbasin name	WB sub-basin	Subbasins ZDSS	Abstraction Poin	Irrigation abstraction	Winter Wheat	Winter Rice	Winter Maize	Vegetables	Beans	Winter Cotton	Other	Sugar-cane	Tea	Coffee	Citrus	Banana	Pasture	Maize	Soy-beans	Sor-ghum	Cotton	To-bacco	Rice	Equipped area (ha)
Upper Zambezi	12	1		IA1								5000												5,000
Kabompo	13	2		IA2	2455			1145			819				409		1472	1596				859		6,300
Lungue Bungo	11	3		IA3		250		125							125									500
Luanginga	10	4		IA4		5000																		5,000
Barotse	9	6		IA6	1603			3801			1				1601		2	1042				561		7,008
Cuando / Chobe	8	7	08.01-	IA7	150			150				0	0	0	0	0	0	0	0	0	0	0	0	300
Kariba	6	8	06.01-	IA8	539		5000	1681			161	166	20	29	3070	0	222	5254	2061	2300	80	144	0	13,346
Kafue	7	12,13	I.07.01	IA13	5760			120							120				5760					6,000
Kafue	7	14	I.07.03	IA14						80		6570									80			6,650
Kariba	6	9	.06.0	IA9	219			37			55	155	18	27	18		37	52	57		74	35		566
	6	10	.06.1	IA10	2014			336			504	1426	168	251	168		336	483	524		685	322		5,203
	6	11	06.07-	IA11a	539	0	0	181	0	0	161	166	20	29	70	0	222	254	61	0	80	144	0	1,388
	6	11	6.11-	IA11b	37649	0	0	6306	0	0	9417	26586	3130	4696	3146	0	6319	9076	9763	0	12767	6042	0	97,249
Luangwa	5	15	.05.0	IA15	687			370	35		70				229		88	361				361		1,479
	5	16	.05.0	IA16	3570				200						355		525	2658				1113		4,651
Mupata		17	I.07.05	IA17b	950											10			950					960
		17	04.01-	IA17c	1611	0	0	777	0	0	319	905	107	1261	670	0	213	523	332	0	434	320	0	5,863
		18	02.01	IA18	2912			486			728	2062	242	363	242		486	699	758		991	466		7,521
Tete	2	19	.02.0	IA19																				0
		21	.02.0	IA21			75		75									75	27	12	36			150
		24	.02.0	IA24	11000													5500	1980	714	2640			11,000
		23	2.05-	IA23	1418	0	0	4236	4000	0	354	1004	118	177	118	0	236	2340	1088	320	1442	227	0	11,661
Lake Malawi / Shire	3	25	3.04-	IA25	0	11030	7611	1929	942	503	1812	0	60	0	0	0	0	4277	1541	685	2053	0	11040	23,887
		26	03.01-	IA26		4919	12460	0	0	6172	954	11120	0	0	0	0	0	7803	3816	754	83	0	4919	35,625
Zambezi Delta	1	27		IA27		22055						55000											22055	77,055
Total					73076	43254	25146	21680	5252	6755	15355	110160	3883	6833	10341	10	10158	41993	28718	4785	21445	10594	38014	331,903

Source: (World Bank 2010a)

Table 49. High level potential irrigation area by crop and sub-basin

					Dry season crops							Perennial crops						Wet season crops						
World Bank (WB) subbasin name	WB sub-basin	Sub basins ZDS	Abstraction Poin	Abstra-ction pt	Winter Wheat	Winter Rice	Winter Maize	Vegetables	Beans	Winter Cotton	Other	Sugar-cane	Tea	Coffee	Citrus	Banana	Pasture	Maize	Soy-beans	Sor-ghum	Cotton	To-bacco	Rice	Equipped area (ha)
Upper Zambezi	12	1		IA1		5000		2500							2500									10000
Kabompo	13	2		IA2	3897			1817			1300				649		2337	2533				1364		10000
Lungue Bungo	11	3		IA3		5000		2500							2500									10000
Luanginga	10	4		IA4		5000		2500							2500									10000
Barotse	9	6		IA6	2287			5424			1				2285		3	1487				801		10000
Cuando / Chobe	8	7	08.01-	IA7				3000				12000												15000
Kariba	6	8	06.01-	IA8			5000	1500							3000			5000	2000	2300				12300
Kafue	7	12,13	I.07. 01	IA13																				0
		14	I.07. 03	IA14	12000			250		150		12350			250				12000		150			25000
Kariba	6	9	.06.09	IA9																				0
	6	10	.06.10	IA10																				0
	6	11	06.07-	IA11a																				0
	6	11	06.11-	IA11b	167095	0	0	53595	0	0	48916	57559	6777	10166	20857	0	65035	75281	21137	0	27640	43037	0	430000
Luangwa	5	15	.05.02	IA15																				0
	5	16	.05.01	IA16	15408			3125	833		591				2888		2155	10197				6044		25000
Mupata		17	I.07. 05	IA17a																				0
		17	04.01-	IA17b																				0
		18	02.01	IA18																				0
Tete	2	19	.02.02	IA19	50000			25000	25000									37500	13500	6000	18000			100000
		21	.02.03	IA21																				0
		24	.02.04	IA24	50000			25000	25000									37500	13500	6000	18000			100000
		23	02.05-	IA23																				0
Lake Malawi /	3	25	03.05-	IA25		42280	4974	2487					259					2487	895	398	1194		42280	50000
Shire		26	03.01-	IA26		27023	114932	20162	14015	18481	28757	76631						68058	26795	9764	24329		27023	300001
Zambezi Delta	1	27		IA27		25000						75000											25000	100000
Total					300687	109303	124906	148860	64848	18631	79565	233540	7036	10166	37429	0	69530	240043	89827	24462	89313	51246	94303	1207301

Source: (World Bank 2010a)