FUTURE HYDROPOWER OPERATIONS IN THE ZAMBEZI RIVER BASIN

Prepared for the EUROPEAN COMMISSION
JOINT RESEARCH CENTRE

Mauricio E. Arias, PhD

ABSTRACT

The objective of this study was to analyse the impact of hydropower operation on surface hydrology dynamics of the Zambezi river basin, and understanding how such dynamics could be affected by future climate change. This study entailed the synthesis of existing GIS and monitoring data, hydrological data analysis, development of a model application of the Reservoir System Simulator (ResSim) for the Zambezi; verification of the model for historical conditions, and evaluation of the effect of future climate change scenarios on reservoir water levels, river flows, and hydropower generation. This study focused on four large hydropower dams located in the Kafue and Zambezi rivers: Itezhi-Tezhi, Kafue Gorge, Kariba, and Cahora Bassa.

Results from data analysis and modelling for the baseline historical period highlighted how these large dams have affected the intra-annual variability of the Zambezi's river hydrology. At Itezhi-Tezhi, downstream river flow during the wettest month was reduced by 35% when compare to natural conditions, while flows during the driest month increased by 278%. At Kariba, reservoir regulation reduced river flow by 36% during the wettest month and increased it by 234% during the driest month. Regulation by Kafue Gorge dam led to a flow reduction during the wettest month by 18%, and flow augmentation during the driest month by 62%. Regulation of flow by Cahora Bassa is the largest, at 37% of the unregulated flow during the wettest month, and more than a three-fold increase during the driest month.

Future climate change could affect reservoir levels by decreasing reservoir inflows and by increasing evaporation. Results showed a mild decrease in mean annual water levels for all reservoirs, with largest changes expected at Itezhi-Tezhi (-1.3m), with minor (0.1-0.2 m) average values for the other three dams. Comparison of flows downstream of dams shows an overall negative tendency, with largest changes expected during the wet months. Flow changes are

expected to be the largest at Cahora Bassa (-30 to -49%), followed by Kariba (-12 to -51%), Kafue Gorge (-25 to -42%) and Itezhi-Tezhi (-15 to -35%). Changes in water levels and flows could result in mild negative effects on mean average hydropower generation and significant increases in interannual variability; largest changes are expected at Kariba, where annual generation is expected to decrease from 5989 to 4152 Gwh/yr (-28.1 to -0.7%) . At Itezhi-Tezhi, average annual hydropower is expected to change from 675 to 534-536 Gwh/yr (- 21%). At Cahora Bassa, average annual generation (18017 Gwh/yr) is expected to decrease by 2%. At Kafue Gorge, no significant changes were estimated for the mean annual energy production of 1445 kwh/yr. Overall, no major differences in future projections were found among the three future climate change ensemble scenarios, with the exception of a greater increase in interannual variability for the 2.2b (1.5 degree of warming) scenario.

Contents

1 Introduction 5

2 Materials and Methods 6

2.1 Compilation of GIS and infrastructure design information 6

2.2 Indicators of hydrological alteration 7

2.3 Development of reservoir operations model 8

2.4 Simulation Scenarios description 11

3 Results and Discussion 12

3.1 Indicators of hydrological indicators 12

3.2 Comparison of historical observations vs. simulations 18

3.3 Seasonality and dam effects – baseline evaluation 23

3.4 Effects of future scenarios on reservoir water levels 25

3.5 Effects of future scenarios on seasonal river flows downstream of dams 27

3.6 Effects of future scenarios on hydropower generation 31

4 Conclusions 33

References 35

Table of Figures

Figure 1. Geographical scope of the reservoir operations model developed. 10

Figure 2. Indicators of Hydrological Indicators for historical observations at Itezhi-Tezhi. 13

Figure 3. Indicators of Hydrological Indicators for historical observations at Cahora Bassa. 16

Figure 4. Flood duration curves comparing historical conditions for periods of available data for Itezhi-Tezhi 19

Figure 5. Flood duration curves comparing historical conditions for periods of available data for Kariba. 20

Figure 6. Comparison of historical conditions for periods of available data for Kafue Gorge.. .. 21

Figure 7. Comparison of historical conditions for periods of available data for Cahora Bassa. .. 22

Figure 8. Effects of hydropower operations on mean monthly flows for the period of baseline river hydrology 24

Figure 9. Effects of future climate change on mean monthly reservoir water levels.. 26

Figure 10. Mean monthly river flows downstream of dams.. 28

Figure 11. Flow duration curves for flows downstream of dams. 30

Figure 12. Effects of future climate change on total annual energy generation. 32

1 Introduction

Water resources in the Zambezi river basin experience frequent extreme floods and droughts, and climate change is expected to bring even more unfavourable climatological and hydrological conditions (Fant et al., 2013; Schlosser and Strzepek, 2015). Understanding what the implications of future hydrological changes to specific components of the Water-Energy-Food-Ecosystem nexus is critical to robustly project changes to natural resources and well-being of the region. Therefore, the general objective of this study was to analyse the impact of hydropower operation in the surface hydrological dynamics of the Zambezi river basin, and understanding how such dynamics could be affected by future climate change. The overall goal is to provide feedback on how historical and future dam operations affect surface hydrology, so that this information can be used in refining hydrological projections, as well as in broader assessments of the Water-Energy-Food-Ecosystem nexus. This study entailed the synthesis of existing GIS and monitoring data provided by the JRC, Zambezi Water Resources Information Systems (ZAMWIS), and project partners; hydrological data analysis to detect past hydrological alteration; approximation of operation rules based on historical water levels and discharge; development of a reservoir operation simulation model; verification of the model for historical conditions, and evaluation of the effect of future climate change scenarios of reservoir water levels, river flows, and hydropower generation. This study focused on four large hydropower dams located in the Kafue and Zambezi rivers: Itezhi-Tezhi, Kafue Gorge, Kariba, and Cahora Bassa. These dams have been operating for several decades and there is some level of information about their design and operations (Table 1). While there are a few other hydropower projects in the region, they were either too small or too remote to have significant effects on the

Zambezi river proper, or there simply was no information available about them to be able to include them in this study.

Table 1. General hydropower dam characteristics

Feature	Itezhi-Tezhi	Kariba	Kafue Gorge	Cahora Bassa
River	Kafue	Zambezi	Kafue	Zambezi
Year of completion	1977	1959	1973	1974
Installed hydropower capacity (MW)	120	1470	165	415
Water storage (m^3)	7.00E+09	6.48E+10	2.80E+09	6.60E+10
Maximum surface area (ha)	44600	557700	216000	304000
Top of dam elevation (m above sea level)	1031	489	977	329
Maximum dam discharge (m^3/s)	7800	11370	4900	16938

2 Materials and Methods

2.1 Compilation of GIS and infrastructure design information

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

2.2 Indicators of hydrological alteration

An analysis of Indicators of Hydrological Alterations (IHA) was carried out in order to understand how different dam-regulated river flows are from pristine conditions. This is an important analysis to understand the expected present and future level of alteration from dams on river hydrology dynamics. This analysis was carried out using the IHA framework, which is well established and very well documented in the scientific literature (Arias et al., 2018; Cochrane et al., 2014; Dang et al., 2016; Olden and Poff, 2003; Richter et al., 1996). This approach consists of estimating monthly and seasonal metrics from daily depth or flow records which are well understood to have a role in describing river dynamics. Although a total of 32 indicators are estimated, the most commonly assessed are monthly averages and annual extremes (1-day/30-day/90-day minima and maxima). In order to quantify alteration, there needs to be sufficient records prior to the closure of the dam and after it starts operation (At least 15-25 years pre- and post-, for a total time series of 30-50 years). When such lengthy time series is not available, another approach could be to compare indicators upstream and downstream of the dam. In the case of the Zambezi, unfortunately, very limited data are available prior to the construction of dams. Even when data are in fact available, these datasets are sparse geographically and have large data gaps. Table 2 below summarizes the information of the river flow and reservoir level gauges that were evaluated for this study.

Table 2. Summary information of river gauges used.

Station	Dam	Location	Type	Frequency	Data availability	Data missing
3-980 Chirundu (Zambia)	Kariba	Downstream	flow	Daily	1963-2018	77-05; 13-17 (57%)
ZIM_A72_Binga Road Bridge	Kariba	Upstream	flow	Daily	1999-2018	2012-14
ZIM_C112	Kariba	Lake	level	weekly	1960-2018	
4-977 Kasaka (Zambia)	Kafue Gorge	Upstream	flow	Daily	1960-2017	
4-760 Namwala Pontoon (Zambia)	Itezhi-Tezhi	Downstream	flow	Daily	1951-2017	
4-669 Hook Bridge (Zambia)	Itezhi-Tezhi	Upstream	flow	Daily	1973-2017	
310 Zumbo (Mozambique)	Cahora Bassa	Upstream	flow	3-daily	1979-2018	33%
MOZ_100	Cahora Bassa	Lake	level	Daily	1978-2018	
320 Tete (Mozambique)	Cahora Bassa	Downstream	flow	2-daily	1979-2018	

2.3 Development of reservoir operations model

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

For the purposes of this study, the geographical domain of the model had upstream boundaries at the headwaters of the Itezhi-Tezhi and Kariba reservoirs, and downstream at the Tete river gauge on the Zambezi east of the Cahora Bassa. Other than the location of these boundaries, the model included 9 nodes were inflows from tributaries and watershed runoff were added. Flow through the Kafue and Zambezi rivers was characterized with 13 separate segments connecting the four reservoirs. Hydraulic routing through these segments was calculated using the Muskingum-Cunge method, assuming uniform (semi-circular) channels with total width estimated from aerial imagery. All rivers used a Manning's value typical of large rivers (0.04). A schematic of the Zambezi ResSim model is illustrated in Figure 1.

Stage-area-volume relationships, conveyance characteristics (e.g., outlet levels and capacity), and other plant characteristics were parametrize with information from ZAMWIS or from WB (2010; see a summary in Table 3). Even though information about guiding water levels was available in WB (2010), there were discrepancies between the prescribed levels and the physical limitations of dams' heights. Thus, a more realistic and reliable approach consisted in using historical average water levels at each reservoir, information that was estimated from the available historical records (Table 4). A sensitivity analysis on the effects of varying these guiding water levels was carried out.

Table 3. Hydropower infrastructure and operations used in baseline model

Characteristic	Kariba	Kafue Gorge	Itezhi-Tezhi	Cahora Bassa
Baseline annual evaporation (mm)	1483	1509	1531	1630
Turbine maximum discharge	1482	261	312	2633
Spillway maximum discharge	9445	4610	5688	14305
Minimum flow (m^3/s)	200	240	109	750
Tailwater control	Stage-discharge	Stage-discharge	Stage-discharge	River gauge discharge (Tete)

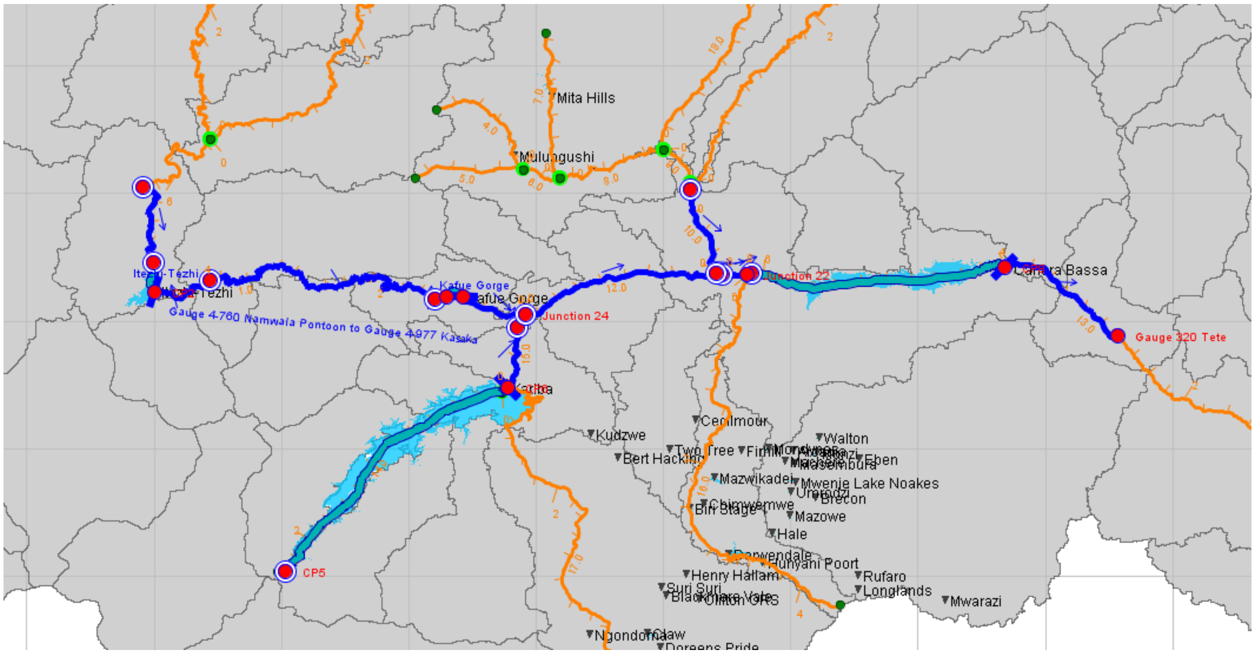


Figure 1. Geographical scope of the reservoir operations model developed.

Table 4. Target water levels used as operation curves in the baseline model. All levels in meters above sea level.

Month	Kariba	Kafue Gorge	Itezhi-Tezhi	Cahora Bassa
January	482.3	975.9	1023.2	317.6
February	482.4	976.0	1024.9	318.7
March	482.9	976.1	1027.1	320.9
April	483.5	976.1	1028.4	322.6
May	483.9	976.1	1028.9	322.6
June	484.4	976.1	1028.7	322.5
July	484.5	976.2	1028.3	322.0
August	484.0	976.2	1027.6	321.6
September	483.7	976.1	1026.7	320.7
October	483.1	976.0	1025.6	321.3
November	482.8	975.8	1024.2	318.9
December	482.5	975.8	1023.1	316.8

2.4 Simulation Scenarios

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

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

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

3 Results and Discussion

3.1 Indicators of hydrological indicators

An IHA analysis with observed river gauge records was carried out to understand what the effects of dam operations on river flows have been in the past. This analysis was greatly constrained by data, as most records available were only for the period of time once dams were already built. Given the date of dam construction (Table 1) and availability of monitoring records (Table 2), such analysis was only successfully implemented at two locations, the furthest upstream (Itezhi-Tezhi) and furthest downstream (Cahora Bassa). At Itezhi-Tezhi, a sharp decreased in flow seasonality was evident since the time of dam completion (Figure 2). Average flows during the dry months of October-December increased from 67 to 176 m^3/s, while flows during the wet months of February-April decreased from 730 to 355 m^3/s. Although most drastic changes occurred during the wet months at different temporal scales (daily, weekly, monthly, trimonthly), relatively large changes were also estimated for dry season indicators at multiple temporal scales. A complete comparison of all IHA indicators estimated for Itezhi-Tezhi is provided in Table 5.

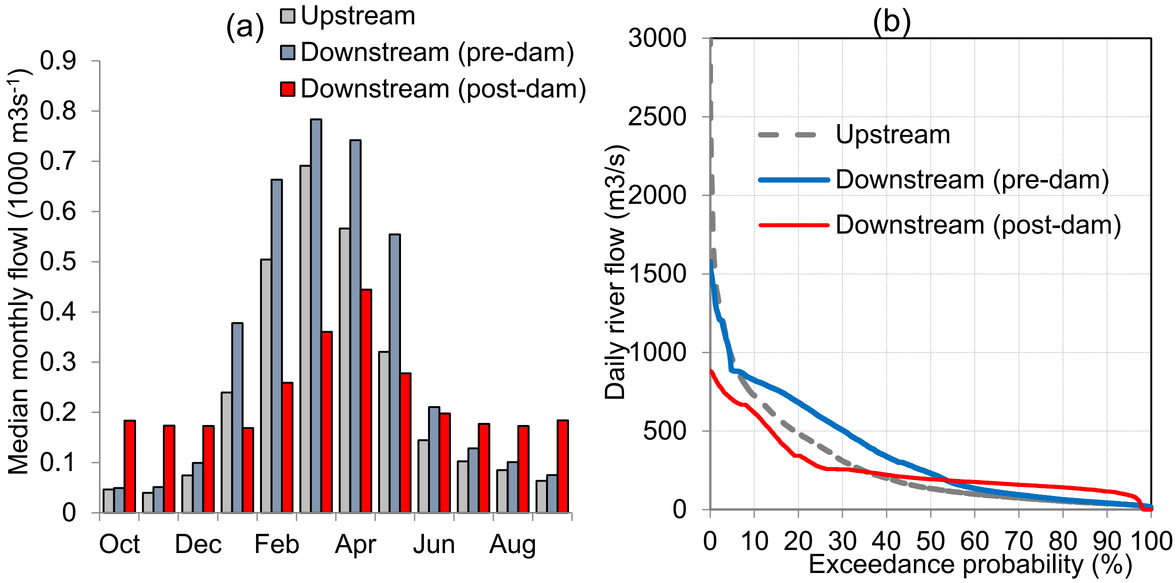


Figure 2. Indicators of Hydrological Indicators for historical observations at Itezhi-Tezhi. (a) Median monthly flows; (b) Flow duration curves. See Table 2 for names of river gauge stations used.

Table 5. IHA results at Itezhi-Tezhi.

	Upstream		Downstream (pre-dam)		Downstream (post-dam)	
Period of Analysis:	1974-2017 (44 years)		1952-1977 (26 years)		1978-2018 (34 years)	
Mean annual flow	284.3		353.7		262.7	
Annual C. V.	1.2		0.94		0.72	
Flow predictability	0.51		0.47		0.58	
Indicator	Medians	Coeff. of Disp.	Medians	Coeff. of Disp.	Medians	Coeff. of Disp.
Oct	46.5	0.4731	49.5	1.384	183.5	0.2548
Nov	39.75	0.5346	51.25	1.098	173.6	0.3846
Dec	74.5	0.8926	99.5	1.764	173	0.6228
Jan	239.5	0.7714	378	1.28	169	0.6464
Feb	504.5	0.721	663.3	0.6866	259	1.129
Mar	691	0.699	783.5	0.2859	360.5	1.141
Apr	566.3	0.6779	742	0.3954	444.5	1.136
May	320.5	0.9431	554.5	0.9017	278	1.325
Jun	144.8	0.7142	210.8	2.168	198	0.7412
Jul	102.5	0.6146	128.5	1.625	177.3	0.6189
Aug	85	0.5477	101	1.418	173.1	0.3797
Sep	63.75	0.5294	75.25	1.304	184.2	0.3305
1-day minimum	34.5	0.5725	36	1.014	109	0.3853
3-day minimum	34.5	0.5652	36.17	1.016	110	0.3773
7-day minimum	34.86	0.5482	36.71	0.9971	110.8	0.383
30-day minimum	37.35	0.502	39.87	1.05	116.9	0.4116
90-day minimum	55.99	0.6549	66.4	0.8509	140.8	0.3159
1-day maximum	1029	0.9468	843	0.2429	545.5	0.8556
3-day maximum	1014	0.95	842.3	0.2426	543.8	0.8596
7-day maximum	969.9	0.8224	841.5	0.2433	538.6	0.8635
30-day maximum	808	0.727	826.5	0.2761	495.3	0.9118
90-day maximum	671.8	0.6712	761.7	0.4124	387.4	1.058
Number of zero days	0	0	0	0	0	0
Base flow index	0.1402	1.045	0.1386	0.9607	0.4291	0.7429
Date of minimum	308	0.06148	305.5	0.1011	275	0.3299
Date of maximum	71.5	0.07923	82	0.1011	88	0.1557
Low pulse count	1	1	1	1	0	0
Low pulse duration	81.5	0.7546	112	0.6339	23	3.826
High pulse count	1	0	1	0	0	0
High pulse duration	89	0.9087	124	0.6472	70	1.17
Low Pulse Threshold	64		78			
High Pulse Threshold	400		589.5			
Rise rate	6	0.8125	6	0.5	3	0.865
Fall rate	-3	-0.7917	-2	-0.625	-2.496	-1.07
Number of reversals	32	0.4063	15	0.4333	12.5	1.04

At Cahora Bassa, no records were available before the dam was built, and therefore only the upstream/downstream comparison was carried out. These results show that the seasonal variability upstream of Cahora Bassa has been vastly reduced. For instance, average flows upstream of the reservoir during the dry months of October-December were 1137 m^3/s, while flows downstream during this same period were 1939 m^3/s (Figure 3). During the wet months of February and March, average flows upstream were 2578 m^3/s, but downstream they were 2143 m^3/s. As the flow duration curve indicates (Figure 3b), this reservoir is capable of regulating flows that have a exceedance probability over 30%; equivalent to incoming flows smaller than approximately 2000 m^3/s. Detail results for all IHA indicators estimated at Cahora Bassa are presented in Table 6.

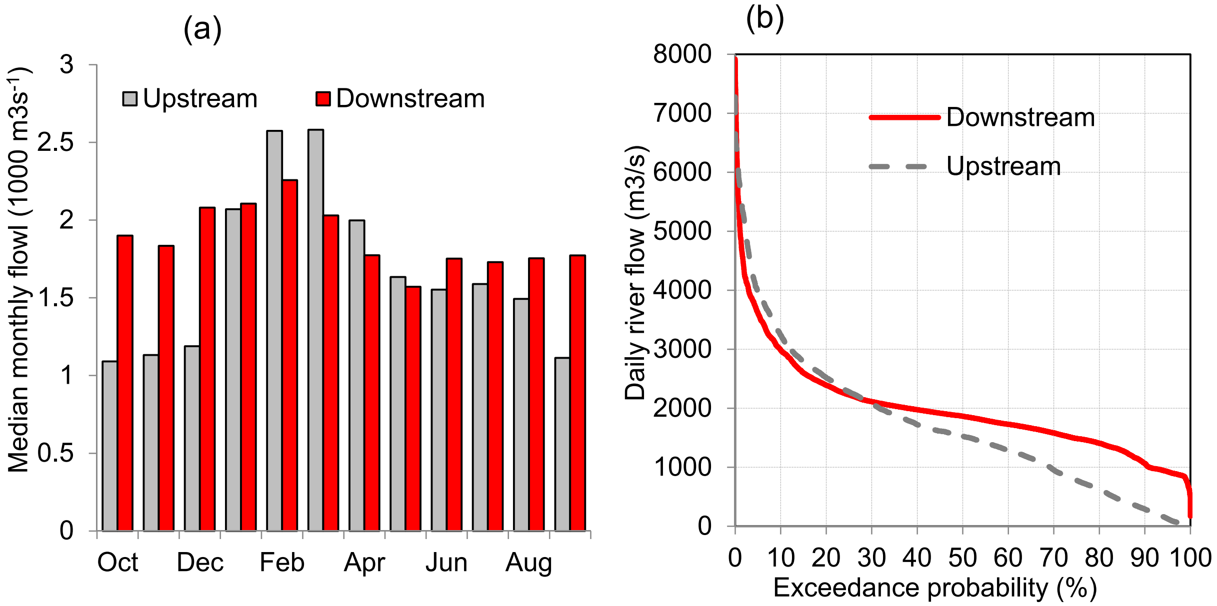


Figure 3. Indicators of Hydrological Indicators for historical observations at Cahora Bassa. (a) Median monthly flows; (b) Flow duration curves. See Table 3 for names of river gauge stations used.

Table 6. Results of the IHA analysis at Cahora Bassa

	Upstream		Downstream	
Period of Analysis:	1980-2017 (29 years)		1980-2017 (38 years)	
Mean annual flow	1685		1984	
Annual C. V.	0.72		0.42	
Flow predictability	0.42		0.62	
Indicator	Medians	Coeff. of Disp.	Medians	Coeff. of Disp.
Oct	1091	0.8857	1901	0.3003
Nov	1132	0.9629	1835	0.2086
Dec	1189	1.051	2081	0.364
Jan	2070	0.6227	2106	0.5128
Feb	2574	0.5754	2257	0.6599
Mar	2582	0.524	2030	0.4119
Apr	1998	0.8069	1774	0.382
May	1634	1.145	1571	0.5005
Jun	1553	1.08	1752	0.4265
Jul	1589	0.8838	1730	0.378
Aug	1493	0.8088	1755	0.3262
Sep	1114	0.8256	1773	0.3806
1-day minimum	615	1.848	834.5	0.5279
3-day minimum	638.3	1.86	1063	0.3819
7-day minimum	656.6	1.854	1128	0.5727
30-day minimum	777.6	1.551	1314	0.489
90-day minimum	1035	1.202	1548	0.4104
1-day maximum	3949	0.5807	4005	0.5627
3-day maximum	3797	0.602	3875	0.5606
7-day maximum	3770	0.5304	3640	0.581
30-day maximum	2974	0.6726	3107	0.59
90-day maximum	2574	0.6304	2444	0.4591
Number of zero days	0	0	0	0
Base flow index	0.3379	1.361	0.6084	0.3831
Date of minimum	283	0.2609	196.5	0.4023
Date of maximum	63	0.09973	37.5	0.1209
Low pulse count	2	2.5	5.5	1.318
Low pulse duration	6	3.021	3	1
High pulse count	2	1.25	6	0.875
High pulse duration	9.75	4.051	4	2.656
Low Pulse Threshold	780		1488	
High Pulse Threshold	2280		2229	
Rise rate	34	0.6618	34	0.8272
Fall rate	-33	-0.4092	-32.5	-0.8462
Number of reversals	114	0.3772	156.5	0.3099

3.2 Comparison of historical observations vs. baseline simulations

In order to verify results from the operations model and ensure that its outcomes were representative of realistic historical conditions, comparisons of flow duration curves were made for reservoir water levels, dam discharges, and downstream river gauges for the periods of available monitoring data. It is important to note that this verification procedure is highly depended on calibration/validation of the SPATSIM hydrological model used to generate upstream river and watershed runoff contributions. An independent calibration/validation procedure, however, was not carried out for this operations model application. It is also important to note that due to the uncertain, stochastic, and non-stationary conditions driving multidecadal reservoirs operations, achieving accurate deterministic validation results is challenging even for well documented systems.

In the case of Itezhi-Tezhi, variability of reservoir water levels simulated was lower than historical records, in particular for periods of low levels (Figure 4a). This was expected though, since not only the inputs of the hydrological model were provided on a monthly scale, but also because the operation guiding curve provided to the model was based on average monthly levels for the entire simulation (i.e., only one value per month was provided). For instance, the lowest water level in historical records was 1010 m asl., whereas in the model was 1016 m asl. Both of these extreme water levels are considerably lower than then minimum monthly level of 1023.1 prescribed to the model, and which was accurately estimated at the 80% exceedance level. Comparison of discharge downstream of the dam (at Namwala Pontoon) demonstrated a much closer distribution match between the simulations and historical records, except for extremely high flows that are only exceed 4% of the time (Figure 4b).

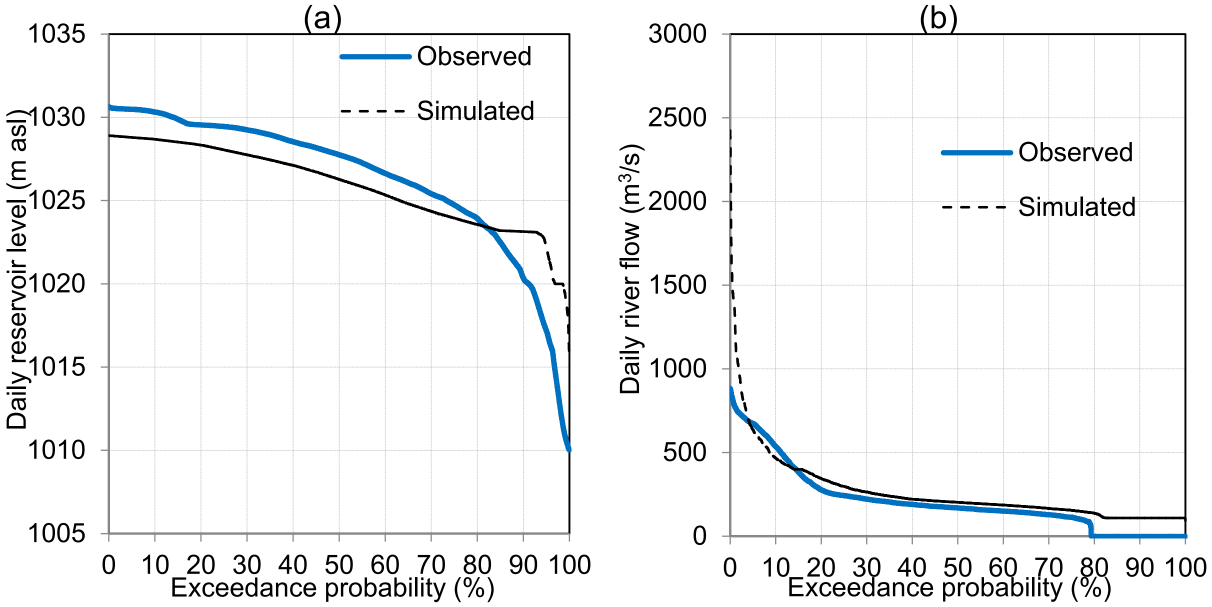


Figure 4. Flood duration curves comparing historical conditions for periods of available data for Itezhi-Tezhi. (a) Reservoir water levels; (b) River flows downstream.

At Kariba, water levels fluctuated much less historically, and the model accurately matched this (Figure 5a). Although prediction of flows with a probability of being exceed 30% of the time was appropriate, the model had a tendency to underpredict flows with an exceedance probability between 5 and 25%, which are representative monthly to trimester maximum flows. The constrain on turbine flows for Kariba (1482 m^3/s, see Table 3) was deemed appropriate as flows exceeded more than 30% of the time followed closely the observed record (Figure 5b).

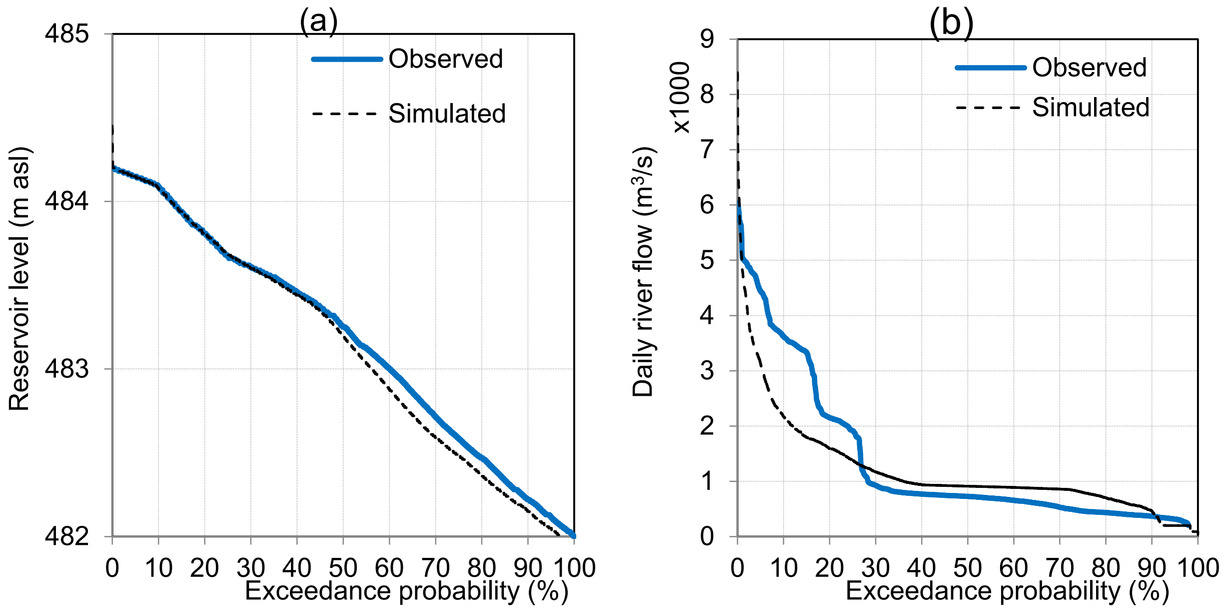


Figure 5. Flood duration curves comparing historical conditions for periods of available data for Kariba. (a) Reservoir water levels; (b) River flows downstream.

Comparison of water levels at Kafue Gorge showed that the model underestimated water levels during the wet months by less than 1m (Figure 6a). Mean water levels and those with an 80% change of exceedance were accurately simulated. No monitoring station capture the sole effect of Kafue Gorge on river flows, as the closest downstream station (Zumbo) is located on the Zambezi well downstream of the confluences of the Zambezi with the Kafue and Luangwa. Thus, effects of operations from Kafue Gorge dam was verified using turbine and spillway discharge as provided by ZAMWIS. Results for the turbine show accurate estimates of mean flows and lower, while a considerable discrepancy occurred for large flows exceeded less than 40% of the time (Figure 6b). While the general distribution of flows from the spillway match well the observations, the model tended to overestimate the amount of time the spillway was active (Figure 6c).

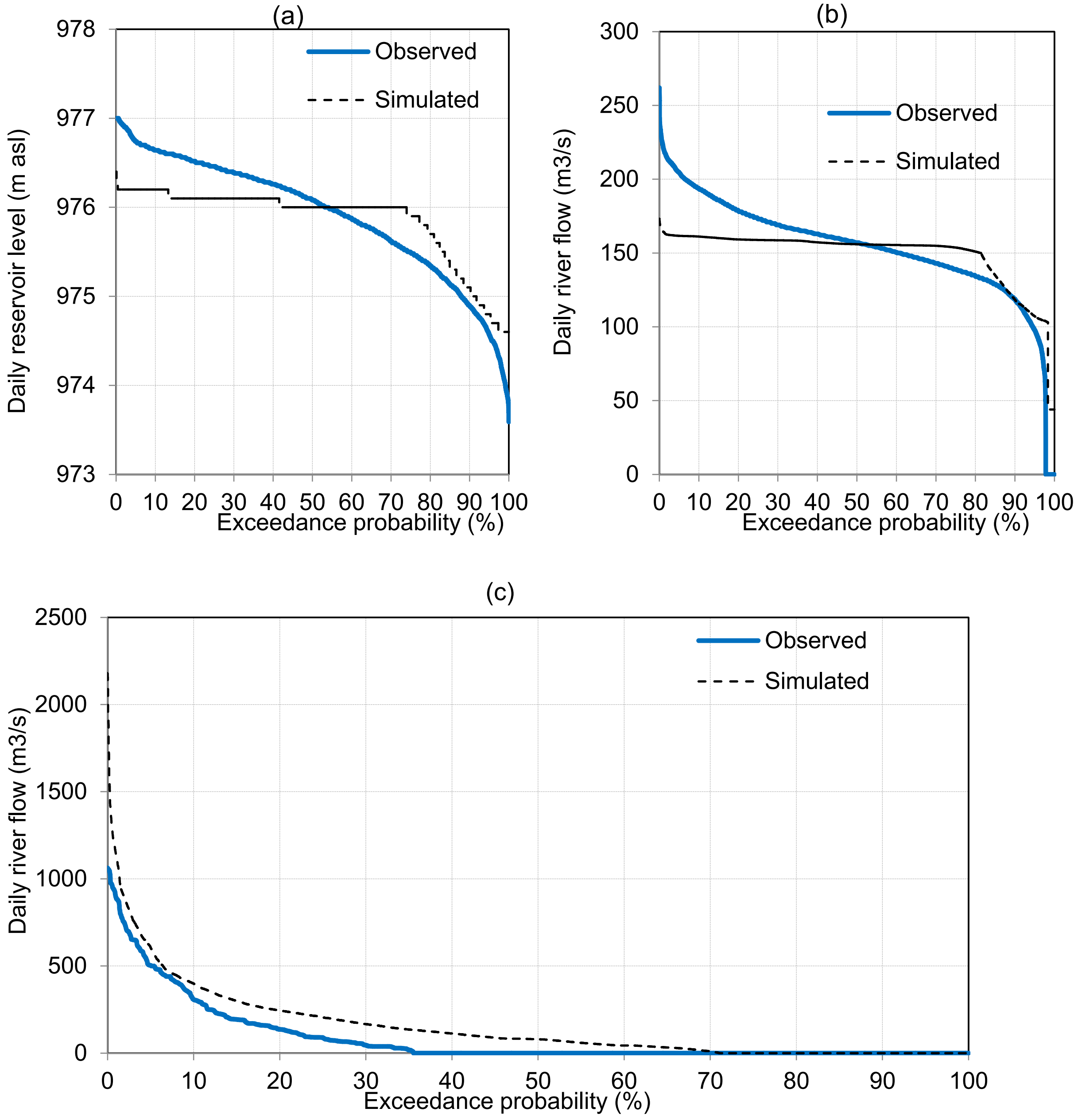


Figure 6. Comparison of historical conditions for periods of available data for Kafue Gorge. (a) Reservoir water levels; (b) turbine discharge; (c) spillway discharge.

At Cahora Bassa, variability in water levels was also underpredicted by the model. This was particularly true for levels exceeded 60% of the time, in which the discrepancy between observed and simulated water levels were greater than 1m (Figure 7a). In terms of river flows, the distribution of flows between observed and predicted values had similar patterns, but flows were consistently overestimated by the model when compared to historical observations (Figure 7b). The persistence of this overprediction while the shape of the exceedance flow curves were similar suggests that the operations model discrepancy is largely associated with inputs from the hydrological model.

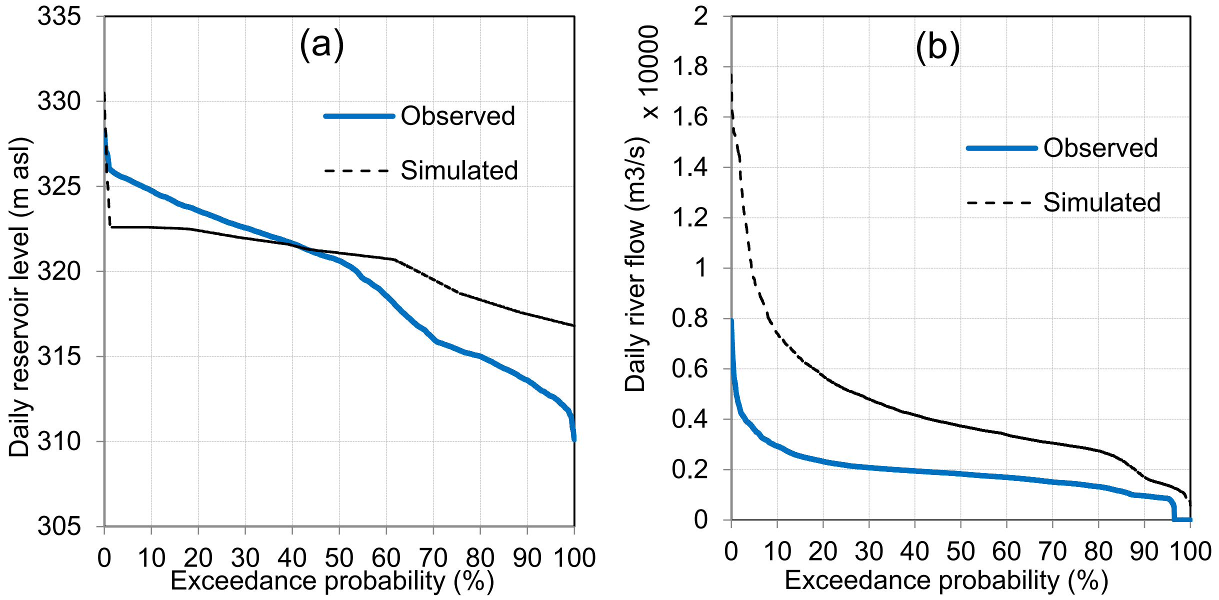


Figure 7. Comparison of historical conditions for periods of available data for Cahora Bassa. (a) Reservoir water levels; (b) River flows downstream.

3.3 Seasonality and dam effects – baseline evaluation

A comparison between simulations considering hydrological conditions without dams and the baseline hydropower operations scenario considered shows that the model can replicate well the alterations to seasonal river flows documented earlier in this document (Section 3.1). In general, all four dams show the expected tradeoff of seasonal flows, with a reduction of flows during the wet months and an increase in flows during the dry months, leading to an overall flattening of the seasonal hydrograph (Figure 8). At Itezhi-Tezhi, river flow downstream of the dam was reduced by 35% during the wettest month (February), while flows during the driest month (September) increase by 278% (Figure 8a). At Kariba, reservoir regulation is relatively similar to Itezhi-Tezhi, with a reduction of 36% during the wettest month (March) and increase by 234% during the driest month (October; Figure 8b). Regulation by Kafue Gorge dam is relatively smaller, with a reduction in flows during the wettest month (February) by 18%, and flow augmentation during the driest month (October) by 62% (Figure 8c). Flows regulation by Cahora Bassa is the largest both in absolute and relative terms; during the wettest month (February), Cahora Bassa regulates 3713 m^3/s, or 37% of the unregulated flow. During the month of lowest flow (October), Cahora Bassa augments natural flows by 2252 m^3/s, which is more than a three-fold increase (Figure 8d).

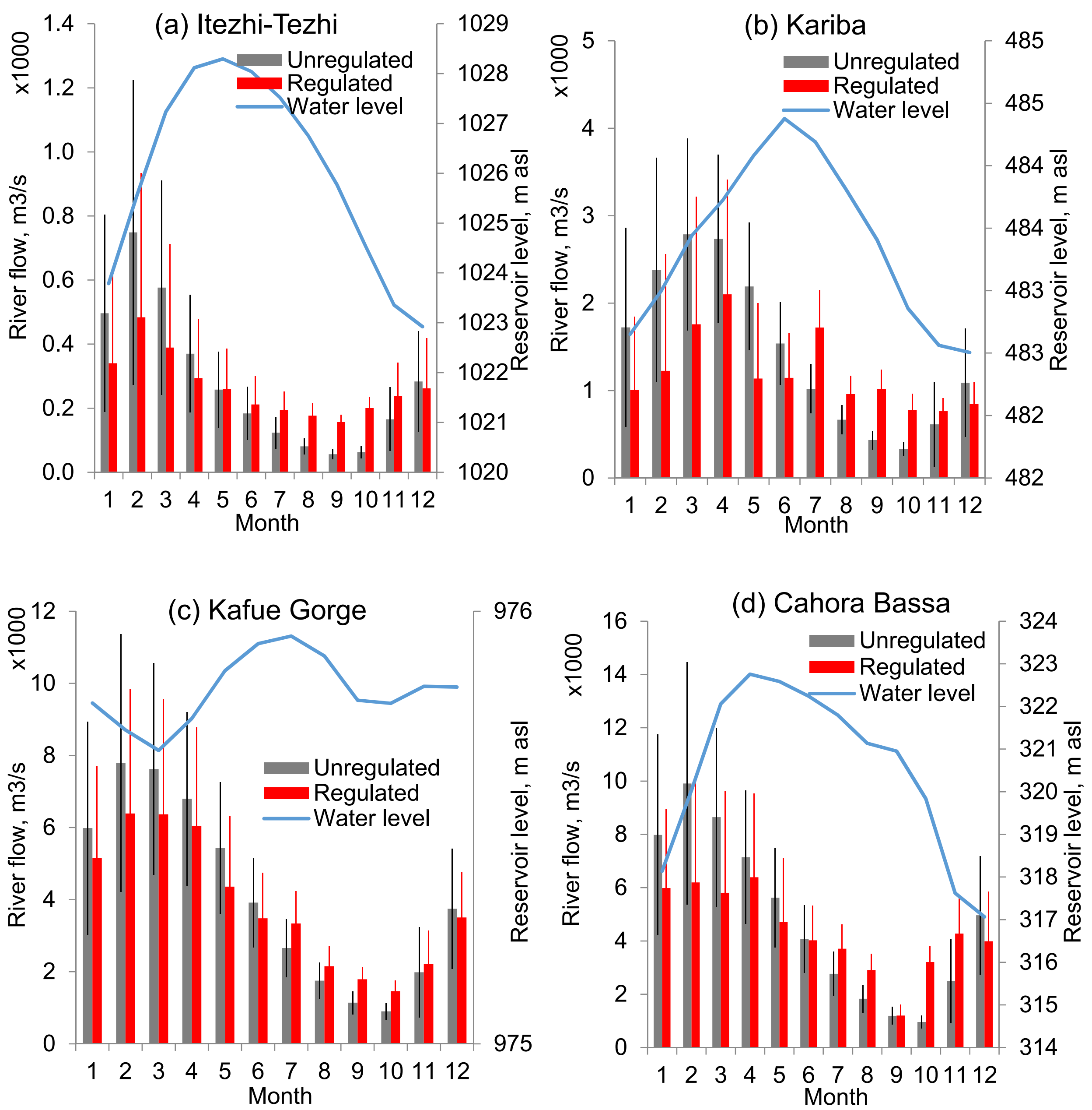


Figure 8. Effects of hydropower operations on mean monthly flows for the period of baseline river hydrology. Error bars represent the standard deviation around each month estimate (n = 114 years).

3.4 Effects of future scenarios on reservoir water levels

Future climate change could affect reservoir levels by decreasing river inflows and by increasing evaporation. Overall, results from the simulations show a mild decrease in mean annual water levels for all reservoirs (Figure 9). Such mild changes were expected, because this set of future scenario simulations assumed the same guiding curve as the baseline scenario. That is, the model actually aimed at reaching to the same mean monthly water levels in the future climate change scenarios as it was prescribed for the baseline, so that water levels would only deviate from these guiding levels if the water balance around the reservoir was not satisfactory to meet the guiding curve. Overall, largest changes in mean water levels are expected for Itezhi-Tezhi, for which a median reduction of 1.3 m was estimated. Average values for the other three dams were in the 0.1-0.2 m range. Despite these mild average changes, probably the most concerning finding regarding water levels is the substantial fall in the lower bound of the water level distributions, represented by the 25th percentile and lower. This means that during dry periods, extremely low water levels could actually become even lower than they have been in the past. Focusing on the driest scenario (2.2B), for instance, the 25th percentile (analogous to the 90-day minimum level) could decrease by 0.2-1.0 m depending on the dam, with the greatest shortage expected for Kafue Gorge, followed by Itezhi-Tezhi, Cahora Bassa, and the lowest for Kariba. No major differences in water level projections were found among climate scenarios.

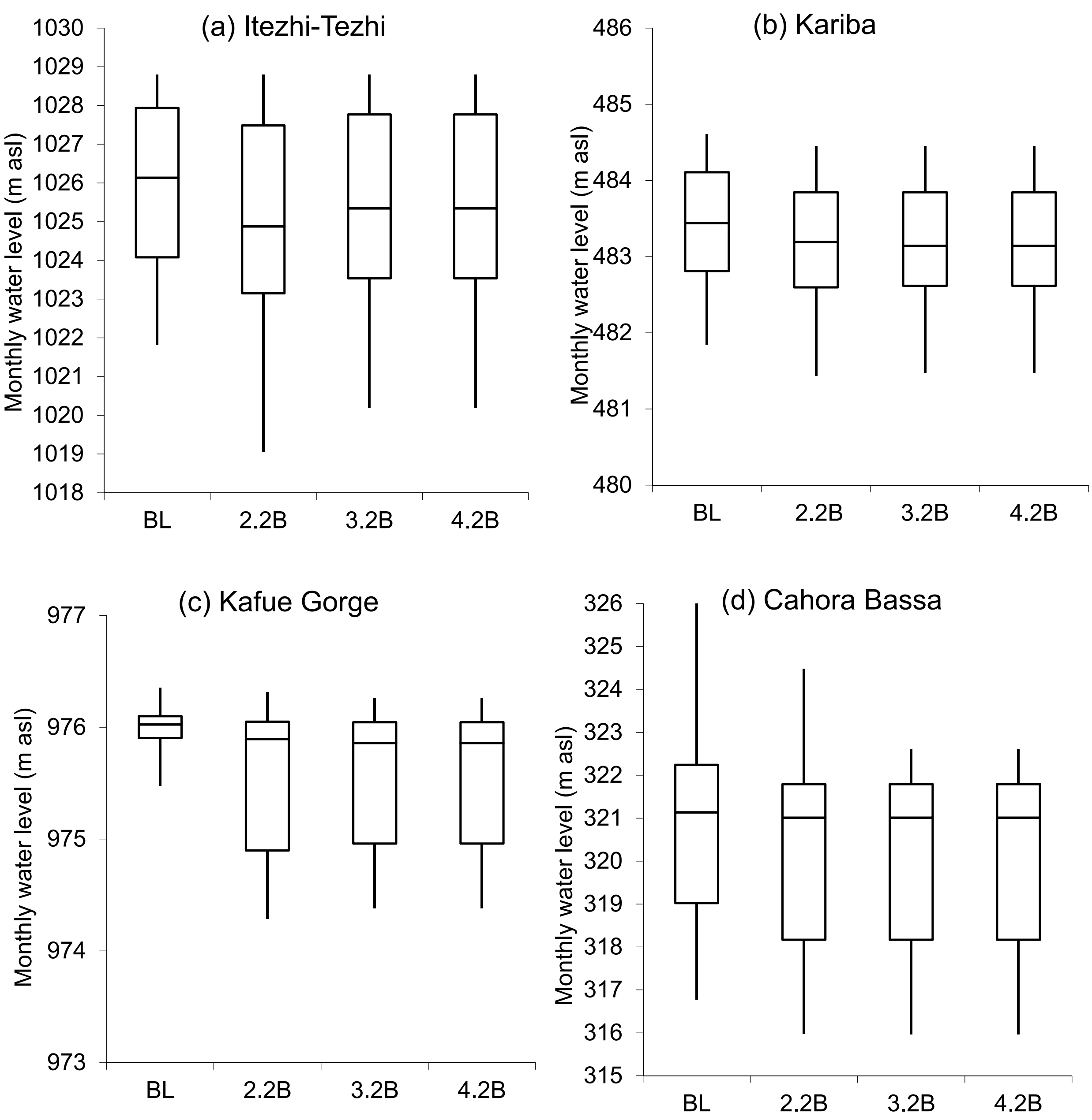
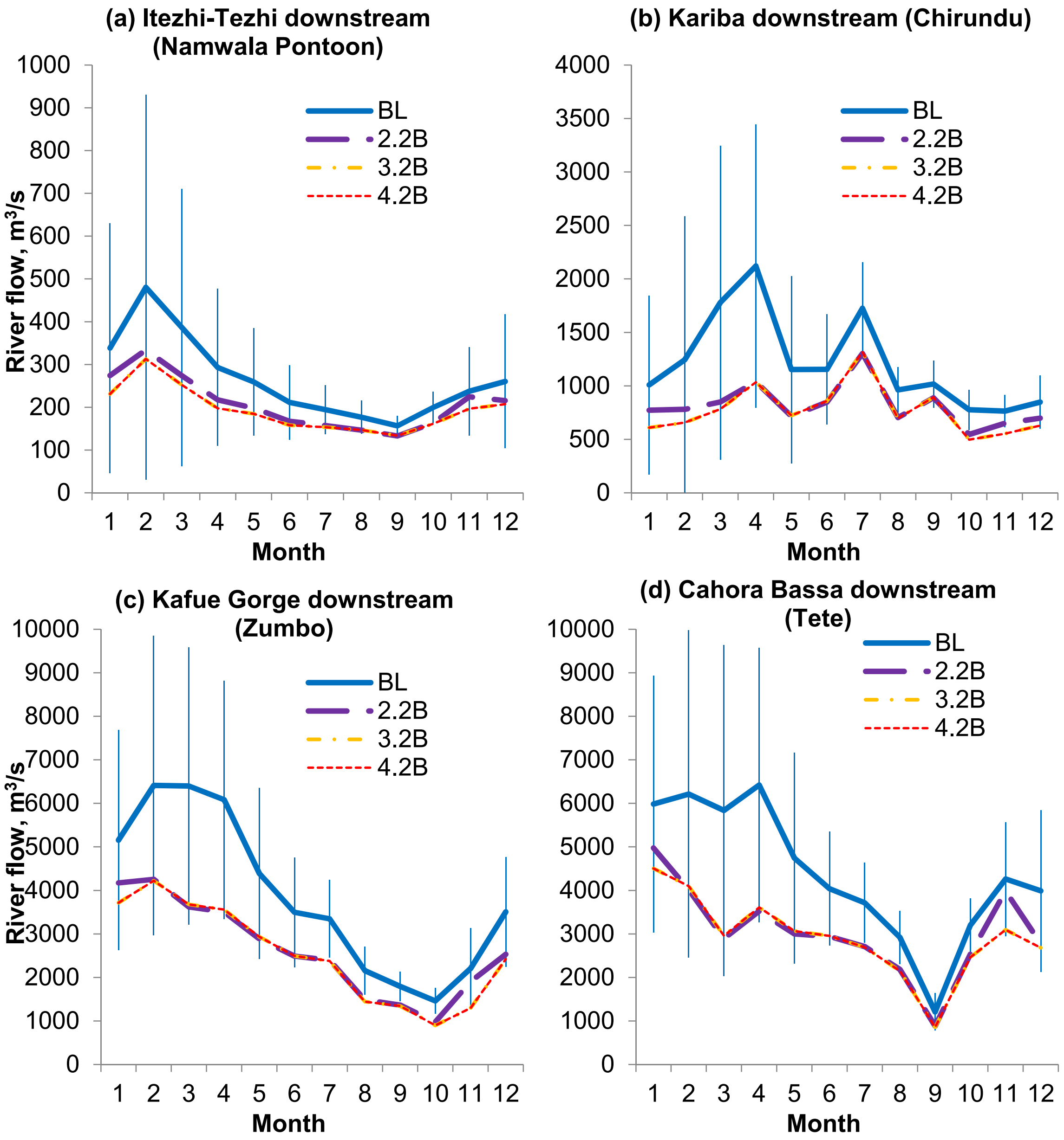


Figure 9. Effects of future climate change on mean monthly reservoir water levels. Upper, middle, and lower divisions on boxplots represent the 75th, 50th, and 25th percentiles, respectively. Upper error bar represent maximum water levels, whereas lower error bars represent one standard deviation.

3.5 Effects of future scenarios on seasonal river flows downstream of dams

Comparison of flows at the closest station downstream of dams shows an overall tendency to decrease throughout the year, with largest changes (both in absolute and relative terms) expected during the wet months (Figure 11). In general, there was little difference in projections among the three future scenarios, with only noticeable changes during the months of November, December, and January. At Itezhi-Tezhi, largest changes occurred during the wettest month (February), when average flow is expected to decrease by 167 m^3/s, or by 35% from baseline (Figure 11a). Smallest changes are expected for the dry month of September, when flows are expected to decrease from 156 to 134 m^3/s (-15%). At Kariba, largest changes are expected during the month of April, when flows could decrease from 2121 to 1035 m^3/s (-51%), while smallest changes could occur during the month of September, when flows could decrease from 1017 to 893 m^3/s (-12%) (Figure 11b). At Kafue Gorge, largest flow change is expected during the month of March, with a reduction from 6397 to 3677 m^3/s (-42%), while the smallest is expected during the month of September, from 1792 to 1342 m^3/s (-25%) (Figure 11c). At Cahora Bassa, largest changes are expected during the wet month of March, from 5837 to 2959 m^3/s (-49%), and smallest changes are expected during the driest month (September), with a reduction from 1208 to 855 m^3/s (-30%) (Figure 11d). Overall, the net reduction in dam discharges and river flows as a result of climate change is consistent with previous studies of the effects of climate change on Zambezi's water resources using results from the Coupled Model Intercomparison Project used in the Intergovernmental Panel for Climate Change fourth Assessment Report (CMIP3; (Fant et al., 2013).



(a) Itezhi-Tezhi downstream (Namwala Pontoon)

(b) Kariba downstream (Chirundu)

(c) Kafue Gorge downstream (Zumbo)

(d) Cahora Bassa downstream (Tete)

Figure 10. Mean monthly river flows downstream of dams. Vertical error bars represent one standard deviation from the baseline scenario.

Despite differences in the relative changes from month to month, flow duration curves highlight that there could be a generalized net reduction in river flows for most of the time (Figure 11). At Itezhi-Tezhi, no major changes occur for large flows with an exceedance probability smaller than 5%, or for small flows with a exceedance probability greater than 80%

(Figure 11a). At Kariba, no consistent changes are expected for very large flows (exceedance probability < 5%) and for small flows with an exceedance probability greater than 95%. Besides little differences in flows around the 40% exceedance level, flows downstream of Kariba are expected to decrease by up to 638 m^3/s. At Kafue Gorge, a consistent reduction is expected for flows with an exceedance probability greater than 1%, with flow reduction gradually decreasing from a maximum of 1657 at the 20% exceedance level. Most consistent reductions in flows are expected at Tete station downstream of Cahora Bassa, where flows could decrease by 1259-1854 m^3/s for the exceedance probability interval between 20 and 80%. Reduction of peak flows (occurring less than 10% of the time) downstream of Cahora Bassa is also expected, suggesting an overall reduction to flood exposure in this lower part of the river.

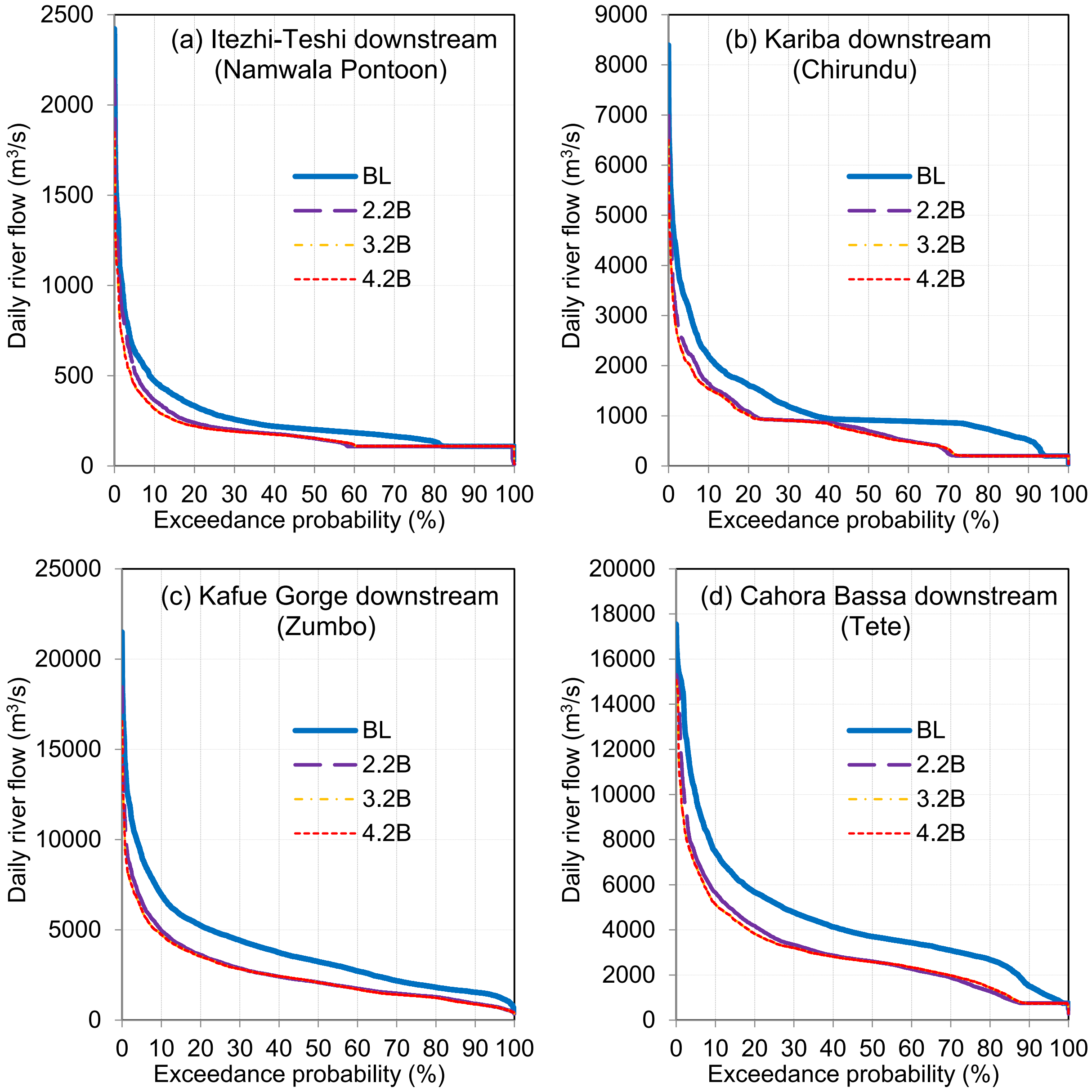


Figure 11. Flow duration curves of future scenarios for flows downstream of dams.

3.6 Effects of future scenarios on hydropower generation

Changes in water levels and flows could result in a negative to neutral effect on hydropower generation (Figure 12). At Itezhi-Tezhi, average annual hydropower is expected to change from 675 to 534-536 Gwh/yr, which is a reduction of 21% for all three future scenarios, though a larger increase in variability was estimated for the 2.2b scenario (Figure 12a). At Kariba, the largest dam in the basin in terms of installed capacity, annual generation is expected to change the greatest, from 5989 to 4152 Gwh/yr, which is a reduction of 28.1-30.7% (Figure 12b). At Cahora Bassa, which has the second largest installed capacity and receives the most river inflow from all dams, average annual generation (18017 Gwh/yr) is expected to decrease by 2% for all scenarios, and interannual variability is expected to increase significantly, in particular for the 2.2b scenario (Figure 12d). At Kafue Gorge, no significant changes were estimated for the mean annual energy production of 1445 kwh/yr. The main reason for this negligible change might be because most of the hydrological changes expected at this location are related to high flows during the wet season, which given the little storage (2.8E9 m^3) and low head (5 m) of this dam, means that most the high flows are discharge through the spillway. Overall, these mild decreases in hydropower generation are in agreement with previous findings for the Zambezi (Fant et al., 2013), and the increase in interannual variability is consistent with findings about future hydropower generation in other large dams around the world (Arias et al., 2020; Piman et al., 2015).

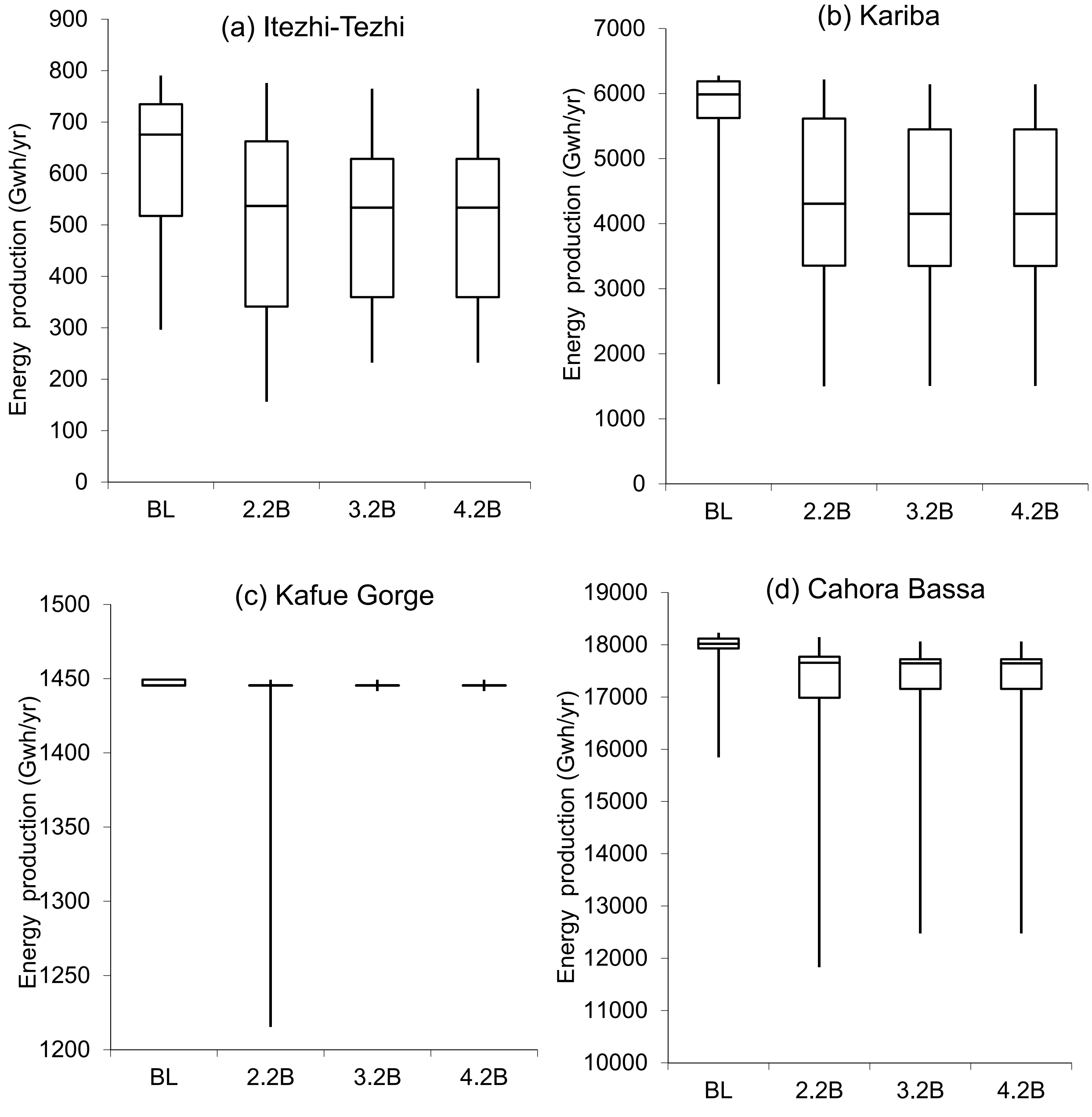


Figure 12. Effects of future climate change on total annual energy generation. Upper, middle, and lower divisions on boxplots represent the 75th, 50th, and 25th percentiles, respectively. Upper and lower error bars represent maximum and minimum annual energy production.

4 Conclusions

This study investigated the effects of future climate change on operations of large hydropower dams in the Zambezi River Basin. This was carried out using a well-established reservoir operation model (ResSim) driven by results from simulations with the watershed hydrology model Pitman/SPATSIM. A baseline analysis of past hydrological alterations was also carried out with available records in order to understand the effects of historical operations of the four major hydropower dams in the basin.

Results from data analysis and simulations for the baseline historical period showed dams have modified the natural flow regime of the Kafue and Zambezi rivers by increasing river flows during the drier months (July-November) and by decreasing flows during the wetter months (January-May). The combinations of these monthly changes have led to the flattening of the distinct seasonal pulse in this river system. This study recommends a more rigorous model verification procedure in order to reduce the uncertainty associated with model prediction.

Major changes to the dynamics of the surface hydrology of the Zambezi are expected as a result of climate change. Lower rainfall and higher evapotranspiration will lead to overall lower runoff generation and water availability. These changes are expected to alter the surrounding hydrology of all four dams investigated, and therefore their operations. Reservoir water levels are expected to decrease, exacerbating extreme low levels during periods of drought. This decrease in holding capacity will be reflected in a net decrease in water availability downstream of dams. Reduction of river flows is expected for all months of the year, in particular during the wet season. As a result of water level and flow reductions, hydropower generation of three of the dams studied (Itezhi-Tezhi, Kariba, and Cahora Bassa) are expected to decrease. This study recommends a closer look at the effects of climate change on different dam structures (turbines vs. spillways), and how the operation guiding curves could be adjusted to offset the detrimental effects of climate change on hydropower and other aspects of the Water-Energy-Food-Ecosystem nexus.

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

References

Arias, M.E., Farinosi, F., Lee, E., Livino, A., Briscoe, J., Moorcroft, P.R., 2020. Impacts of climate change and deforestation on hydropower planning in the Brazilian Amazon. Nature Sustainability. https://doi.org/10.1038/s41893-020-0492-y

Arias, M.E., Lee, E., Farinosi, F., Pereira, F.F., Moorcroft, P.R., 2018. Decoupling the effects of deforestation and climate variability in the Tapajós river basin in the Brazilian Amazon. Hydrological processes 32, 1648–1663. https://doi.org/10.1002/hyp.11517

Cochrane, T.A., Arias, M.E., Piman, T., 2014. Historical impact of water infrastructure on water levels of the Mekong River and the Tonle Sap system. Hydrol. Earth Syst. Sci. 18, 4529–4541. https://doi.org/10.5194/hess-18-4529-2014

Dang, T.D., Cochrane, T.A., Arias, M.E., Van, P.D.T., de Vries, T.T., 2016. Hydrological alterations from water infrastructure development in the Mekong floodplains. Hydrological Processes 30, 3824–3838. https://doi.org/10.1002/hyp.10894

Fant, C., Gebretsadik, Y., Strzepek, K., 2013. Impact of climate change on crops, irrigation and hydropower in the Zambezi River Basin (No. 9292306162). WIDER Working Paper.

Hughes, D.A., Farinosi, F., 2020. Assessing development and climate variability impacts on water resources in the data scarce Zambezi River basin. Part 2: Simulating future scenarios of climate and development. Journal of Hydrology: Regional Studies Under review.

Hughes, D.A., Mantel, S.K., Farinosi, F., 2020. Assessing development and climate variability impacts on water resources in the data scarce Zambezi River basin. Part 1: Initial model setup. Journal of Hydrology: Regional Studies Under review.

Klipsch, J.D., Hurst, M.B., 2013. HEC - ResSim Reservoir System Simulation Version 3.1 User Manual (Computer Program Documentation). US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center, Davis, CA (USA).

Lehner, B., Grill, G., 2013. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrol. Process. 27, 2171–2186. https://doi.org/10.1002/hyp.9740

Olden, J.D., Poff, N.L., 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Res. Applic. 19, 101–121. https://doi.org/10.1002/rra.700

Piman, T., Cochrane, TomA., Arias, M.E., Dat, NguyenD., Vonnarart, O., 2015. Managing Hydropower Under Climate Change in the Mekong Tributaries, in: Shrestha, S., Anal, A.K., Salam, P.A., van der Valk, M. (Eds.), Managing Water Resources under Climate Uncertainty, Springer Water. Springer International Publishing, pp. 223–248.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. Conservation Biology 10, 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x

Schlosser, C.A., Strzepek, K., 2015. Regional climate change of the greater Zambezi River Basin: a hybrid assessment. Climatic change 130, 9–19.

Vogel, R.M., Fennessey, N.M., 1994. Flow-duration curves. I: New interpretation and confidence intervals. Journal of Water Resources Planning and Management 120, 485–504.

WB, 2010. The Zambezi River Basin A Multi-Sector Investment Opportunities Analysis (No. Volume 3 State of the Basin). The World Bank, Washington DC.