

# Climate Resilience Assessment for Cahora Bassa

## Final Report

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## Authors

Harald Kling  
Philipp Stanzel  
Felisberto Afonso  
Martin Fuchs

## Date

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## Phone

+43 664 828 72 32

## Project ID

119001210

## E-mail

harald.kling@afry.com

## Address

AFRY Austria GmbH  
Kranichbergg. 4, 1120 Vienna, Austria

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## Executive Summary

The Climate Resilience Guide of the International Hydropower Association (IHA) was applied to assess the climate resilience of hydropower operations at Cahora Bassa dam in Mozambique. The hydropower plant has an installed capacity of 2075 MW and is a major power producer for Mozambique, South Africa and Zimbabwe.

A state-of-the-art modelling system was used, which combines a hydrological model with a reservoir model. The modelling system simulates river inflow from all major tributaries as well as impact of upstream reservoirs (Kariba, Itezihitezhi) on downstream flow conditions. The simulations were run for historic climatic conditions (baseline) and projected future climatic conditions. The climate projections were obtained from the latest generation of coarse resolution Global Climate Models (CMIP6) and from more detailed Regional Climate Models (CORDEX-Africa). Overall about 100 climate model projections were considered for two greenhouse gas emission scenarios (moderate and high emissions), which enabled to assess the uncertainty in future climate projections.

From the simulation results, performance indicators were computed for power generation and flood safety of Cahora Bassa hydropower operations under climatic conditions in the near future (2021-2050) and far future (2071-2100). The results show no major shifts in inflow in the near future, but a tendency to a considerable reduction in inflow and power generation in the far future due to slight decrease in rainfall and considerable warming leading to increased evaporation. In the near and far future the flood risk was determined to stay at a similar level as under current climatic conditions, as the gradually drying climate with reduced mean annual inflow is counter-balanced by increased inter-annual variability. Statistical calculation of extreme flood inflow showed a risk not only under future climatic conditions, but already under current climatic conditions due to limited spillway capacity at Cahora Bassa dam.

A risk and opportunity register was developed to provide an inventory of direct and indirect impacts of climate change on Cahora Bassa hydropower operations. In a Climate Risk Management Plan a set of 14 structural and non-structural adaptation measures was proposed to mitigate risks and maximize opportunities.

To mitigate the flood risk the proposed adaptation measures include inflow forecasting and increased spillway capacity. The projected decrease in future inflow and hydropower generation can be mitigated by extension of Cahora Bassa to a hybrid plant combining hydropower and solar PV. To maximize the indirect climate opportunities due to the expected regional emergence of variable renewable energy (wind, solar) recommendations are given for a strategic shift from baseload generation towards ancillary services and hydro-peaking in combination with downstream Mphanda Nkuwa reservoir. Timelines and priorities for actions are proposed in the Climate Risk Management Plan.

The Climate Risk Management Plan as well as the study results and adaptation options were discussed and aligned with HCB experts and stakeholders in several virtual conferences as well as two site visits in Mozambique, which included also capacity building in the field of climate change assessment and hydrological modelling.

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## Abbreviations

ARA	Administração Regional de Águas
CDM	Clean Development Mechanism
CMIP	Coupled Model Intercomparison Project (climate modelling)
COP	Conference of the Parties to the United Nations Framework Convention on Climate Change
CORDEX	Coordinated Regional Downscaling Experiment (climate modelling)
CRA	Climate Resilience Assessment
CCRM	Coordinator for Climate Risk Management
CRMP	Climate Risk Management Plan
CRU	Climatic Research Unit, University of East Anglia, UK
DSS	Decision Support System (e.g. AFRY's Zambezi DSS)
GCF	Green Climate Fund
GCM	Global Climate Model or General Circulation Model
GFS	Global Forecasting System (National Weather Service, USA)
GPCC	Global Precipitation Climatology Centre, Germany
GPM	Global Precipitation Measurement, NASA, USA
GRDC	Global Runoff Data Centre, BfG, Germany
HCB	Hidroeléctrica de Cahora Bassa
HPP	Hydropower plant
HQ	Flood flow for a given return period, for example 10,000 year flood
IHA	International Hydropower Association
INGD	Instituto Nacional de Gestão e Redução do Risco de Desastres
IPCC	Intergovernmental Panel on Climate Change
JOTC	Joint Operation Technical Committee
MER	Monitoring, Evaluation and Reporting Plan
RCM	Regional Climate Model
RCP	Representative Concentration Pathway (~emission scenario)
SAPP	Southern African Power Pool
SSP	Shared Socio-economic Pathway (~emission scenario)
TCFD	Task force on Climate-related Financial Disclosures
VRE	Variable Renewable Energy
WARMA	Water Resources Management Authority (Zambia)
WMO	World Meteorological Organization
ZESCO	Zambia Electricity Supply Company
ZINWA	Zimbabwe National Watery Authority
ZRA	Zambezi River Authority

# 1 Introduction

This report presents the results of the climate resilience assessment (CRA) for Cahora Bassa hydropower plant, which is located at the Zambezi River in Mozambique and has an installed capacity of 2075 MW.

Chapter 2 provides a general overview about the project background, including study objectives, study area and the methodology for the CRA using the International Hydropower Association's (IHA) Climate Resilience Guide.

Chapter 3 briefly summarizes the project activities, including organization, work plan, site visits and virtual meetings, as well as stakeholders and data collection.

The results of the Climate Resilience Assessment are reported in accordance with the separate phases of IHA's Climate Resilience Guide:

- Initial analysis (Phase 2): chapter 4
- Climate stress test (Phase 3): chapter 5
- Risk and opportunity register: chapter 6
- Climate risk management (Phase 4): chapter 7
- Monitoring, evaluation and reporting plan (Phase 5): chapter 8

Additional information, graphs and data are included in the Appendix (chapter 9).

## 2 Project background

### 2.1 Objectives

As specified in the Terms of Reference this project has the following main objectives:

- To carry out a climate vulnerability assessment for Cahora Bassa hydropower operation, considering current and potential changes in the baseline (climate and other)
- To develop adaptation strategies through iterative risk assessment and management methodologies consistent with the potential sensitivity of the project to climate and other risks

### 2.2 Study area

The main focus of the assessment is on Cahora Bassa hydropower plant. As the inflow to Cahora Bassa depends on the upstream hydrological processes and upstream dam operators, the study area includes the full Zambezi basin upstream of Cahora Bassa dam.

Figure 1 shows an overview map of the Zambezi basin. For Cahora Bassa the main tributaries are the Luangwa River, the Kafue River and the upper Zambezi River (which is controlled by Kariba dam). Any changes in future upper Zambezi flows will also impact Kariba dam releases. Therefore the upper Zambezi catchment must be considered in the CRA for Cahora Bassa.

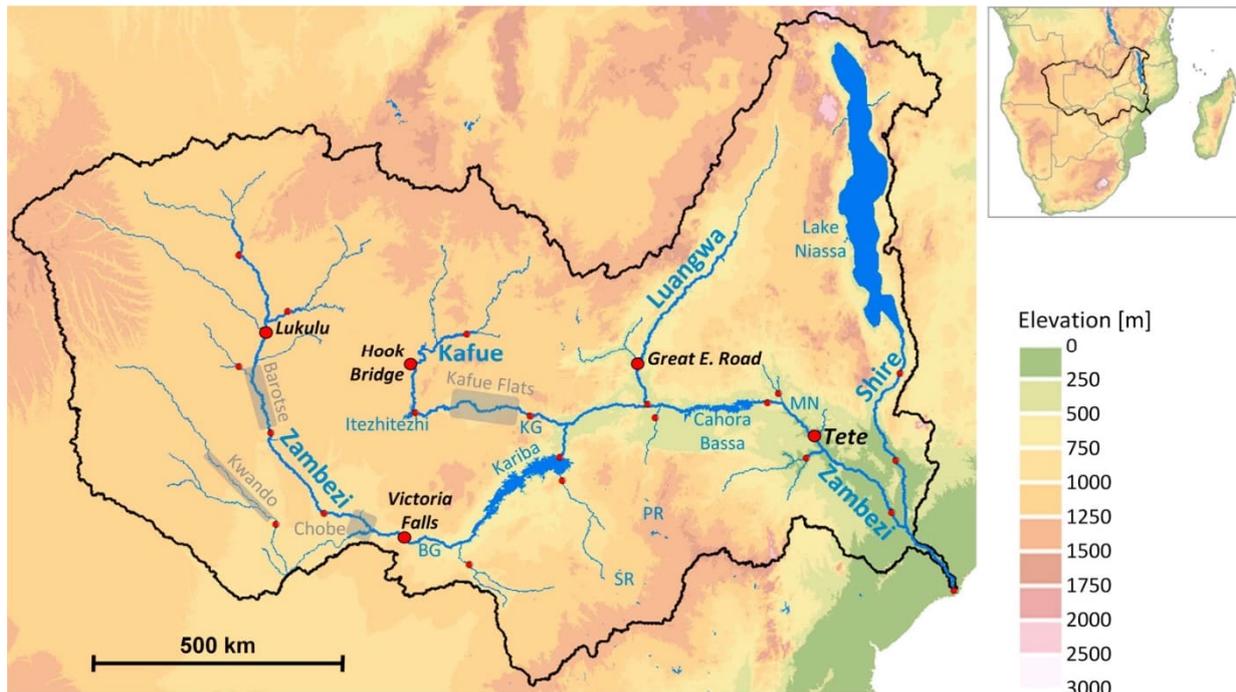


Figure 1: Overview map for the Zambezi basin.

Abbreviations used in the figure:

BG: Batoka Gorge (proposed new dam)

KG: Kafue Gorge

SR: Sanyati River

PR: Panhame (Manyame) River

MN: Mphanda Nkuwa (proposed new dam)

Red points: Key gauges and/or subbasin outlets in AFRY's Zambezi Decision Support System

Shaded areas: Floodplains and major swamps.

An introduction to the Zambezi basin is e.g. available in Kling et al. (2014):

The Zambezi basin is the fourth largest river basin in Africa (after Congo, Nile and Niger) and covers 1.4 Mio km<sup>2</sup>. As in other studies (e.g. Winsemius et al., 2006, Yamba et al., 2011, Beck and Bernauer, 2011) we do not consider the Okavango River as a tributary of the Zambezi, even though in extremely wet years the Okavango system also partly discharges to the Zambezi. The basin is shared by eight countries: Zambia (41.9% of total area), Angola (18.2%), Namibia (1.1%), Botswana (1.5%), Zimbabwe (15.9%), Tanzania (2.2%), Malawi (7.5%), and Mozambique (11.6%). Typical vegetation types are woodland, grassland, and some agricultural areas, and elevation ranges from sea level to approximately 2500 m above sea level.

The source of the Zambezi River is located at Kalene Hills in Zambia and travels roughly 2600 km to the south and east before discharging into the Indian Ocean at the Mozambican coast. Important tributaries from the north are the Kafue River, Luangwa River and Shire River, but there are no significant tributaries from the south. Floodplains and swamps (Barotse Floodplain, Chobe Swamps, Kafue Flats, Kwando Floodplain) are large, seasonally inundated areas of several thousand km<sup>2</sup>. Lake Niassa – or also known as Lake Malawi – is located in the north-eastern part of the basin and is one of the world's largest freshwater lakes (570 km long, 30,000 km<sup>2</sup> surface

area). There are also two large artificial reservoirs for hydropower generation at the Zambezi River (Lake Kariba with 5500 km<sup>2</sup> surface area and Lake Cahora Bassa with 2700 km<sup>2</sup>). Lake Kariba is actually the world's largest artificial reservoir according to storage capacity (200,000 hm<sup>3</sup>, GRanD global data set, Lehner et al., 2011).

Mean annual precipitation (MAP) is approximately 1000 mm/a, of which about 8% generates discharge and the remaining 92% is lost via evapotranspiration. The northern parts are wetter (MAP > 1250 mm/a) than the southern parts (MAP < 750 mm/a). During the dry season there is practically no precipitation. The wet season is during the austral summer and lasts from November to March. In most parts MAP is smaller than annual potential evapotranspiration, with a basin-wide average of 1600 mm/a. Mean discharge at the outlet of the basin is estimated to be approximately 3600 m<sup>3</sup>/s, but discharge shows large seasonal and intra-annual variations. Seasonality in discharge is strongly controlled by seasonality in precipitation, but in addition also retention in large floodplains and swamps as well as artificial reservoirs affect the seasonal discharge. Zambezi floods travel several months from the headwaters in Zambia and Angola until reaching the lower reaches in Mozambique. In contrast, floods from the Luangwa tributary reach the Zambezi River within a few days, with similar peak flow as the upper Zambezi floods, but overall smaller flood volumes.

The Zambezi, Kafue and Luangwa are the most important tributaries for Cahora Bassa. However, there are also several local tributaries and smaller catchments in the vicinity of Cahora Bassa, as shown in the map of Figure 2.

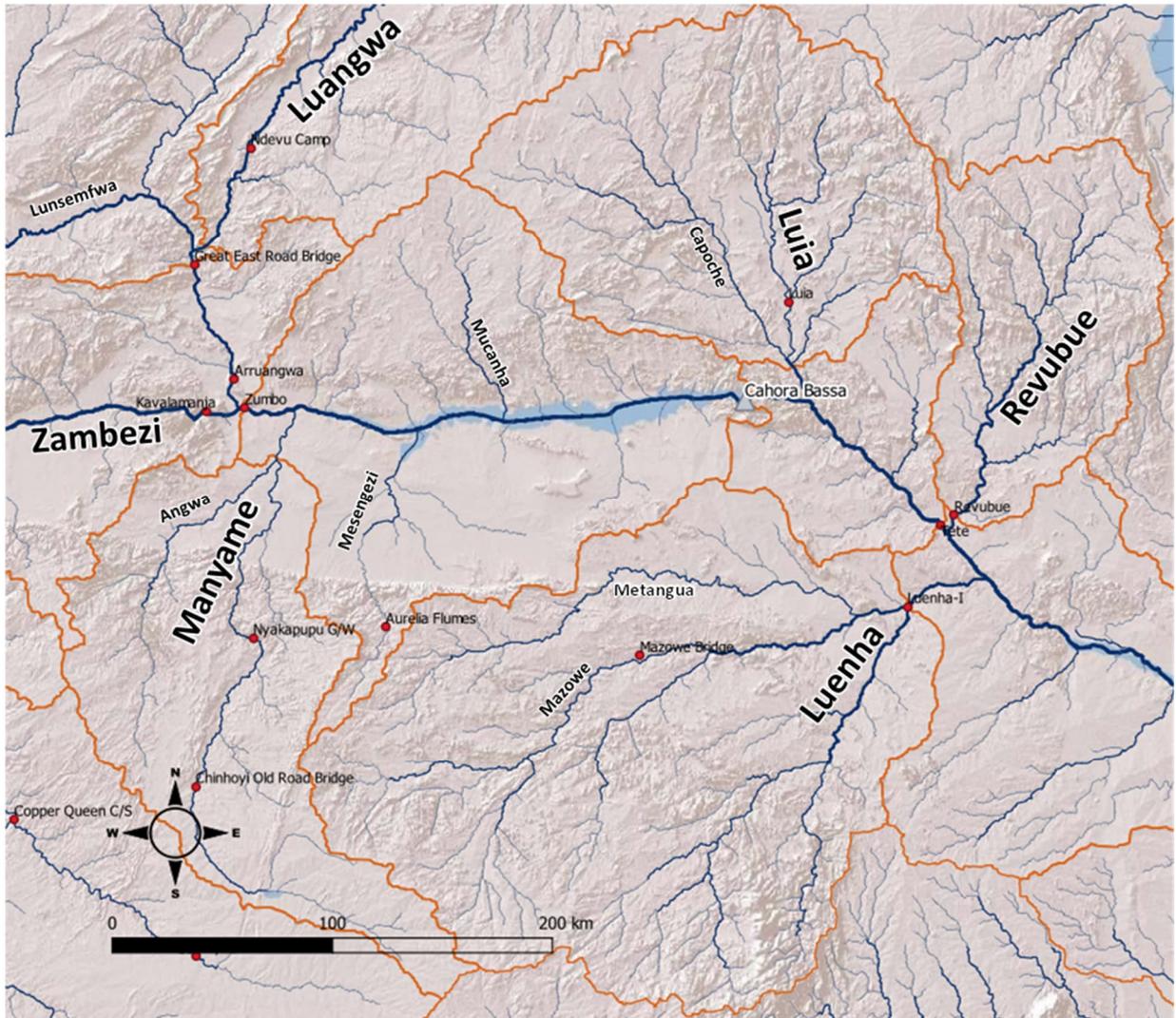


Figure 2: Rivers in the vicinity of Cahora Bassa reservoir. Red points: ZAMWIS gauges. Orange lines: Sub-basin divides of Zambezi DSS.

Figure 3 shows the transmission lines from Cahora Bassa hydropower plant to Zimbabwe and South Africa.



Figure 3: Overview map showing location of main dams (grey triangles) and transmission lines (pink lines) from Cahora Bassa.

## 2.3 Methodology

The methodology in this study closely followed the International Hydropower Association’s (IHA) Climate Resilience Guide, which consists of 5 phases (see figures below).

One of the main outputs is the climate risk management plan (CRMP).

Phase 1 included a climate risk screening. Phase 2 included an initial analysis of the available data. Phase 3 was the most work intensive part with a detailed climate stress test. A hydrological model was used to assess hydropower operations under various climate change scenarios. The Zambezi Decision Support System (DSS), which is an application of AFRY’s Hydro DSS software, was used in the climate stress test (Figure 6). HCB staff was trained on the Zambezi DSS in two site visits. In Phase 4 the climate risk management plan (CRMP) was prepared. In Phase 5 a monitoring, evaluation and reporting plan was developed.

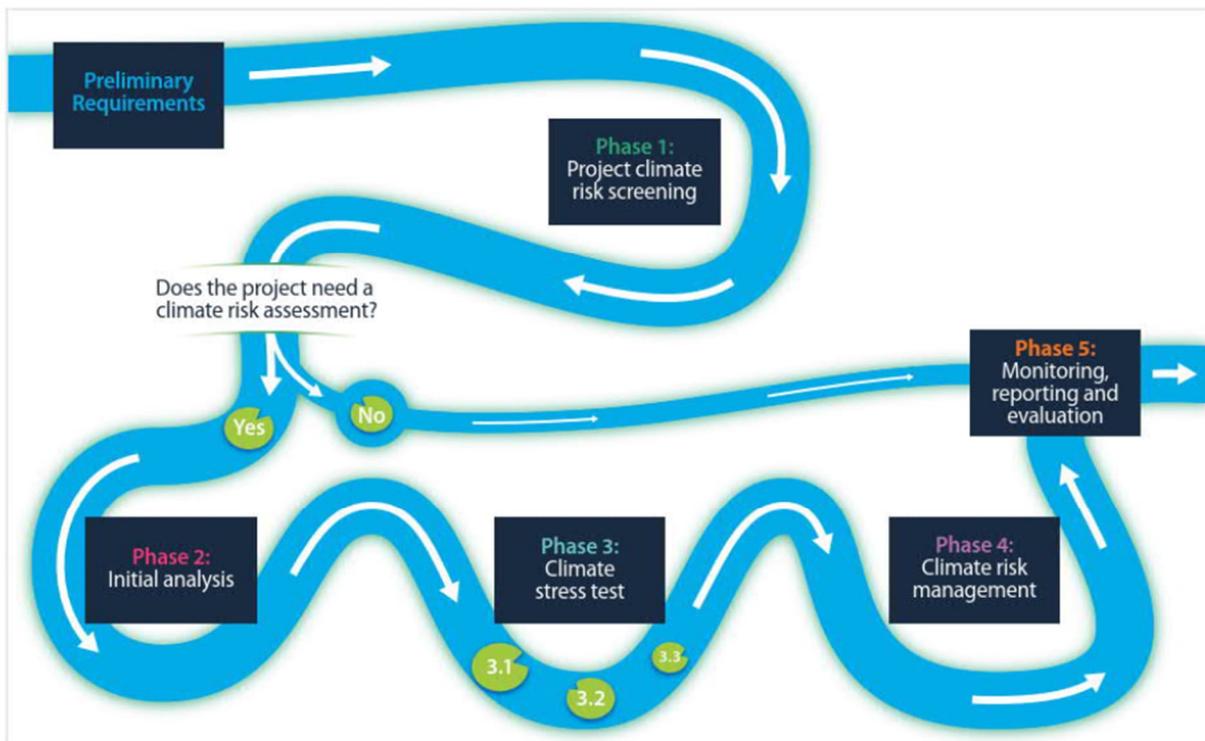


Figure 4: Five phases for climate resilience assessment, as defined in IHA’s Climate Resilience Guide.

Preliminary requirements	Phase 1: Project climate risks screening	Phase 2: Initial analysis	Phase 3: Climate stress test	Phase 4: Climate risk management	Phase 5: Monitoring, evaluation and reporting
<b>Objective:</b> To meet requirements necessary to effectively use and apply the guide.	<b>Objective:</b> To understand the vulnerability of a hydropower project to climate change, considering its geographic, regulatory, technical and socioenvironmental characteristics.	<b>Objective:</b> Based on the analysis of climatic data and the definition of the baseline scenario determine the proper approach for Phase 3 (the climate stress test).	<b>Objective:</b> To assess project performance under different possible future climate scenarios in order to support decision making on resilient design and operation, and to quantify climate risks.	<b>Objective:</b> To adapt the project design – and/or make the project design adaptive – to ensure it is resilient to climate changes, while remaining cost-effective and economically sensible and sound.	<b>Objective:</b> To track how resilient the project is in operation and to allow the Climate Risk Management Plan to be monitored, reported on, evaluated and updated.

Figure 5: Overview about the objectives in the phases of IHA's Climate Resilience Guide.

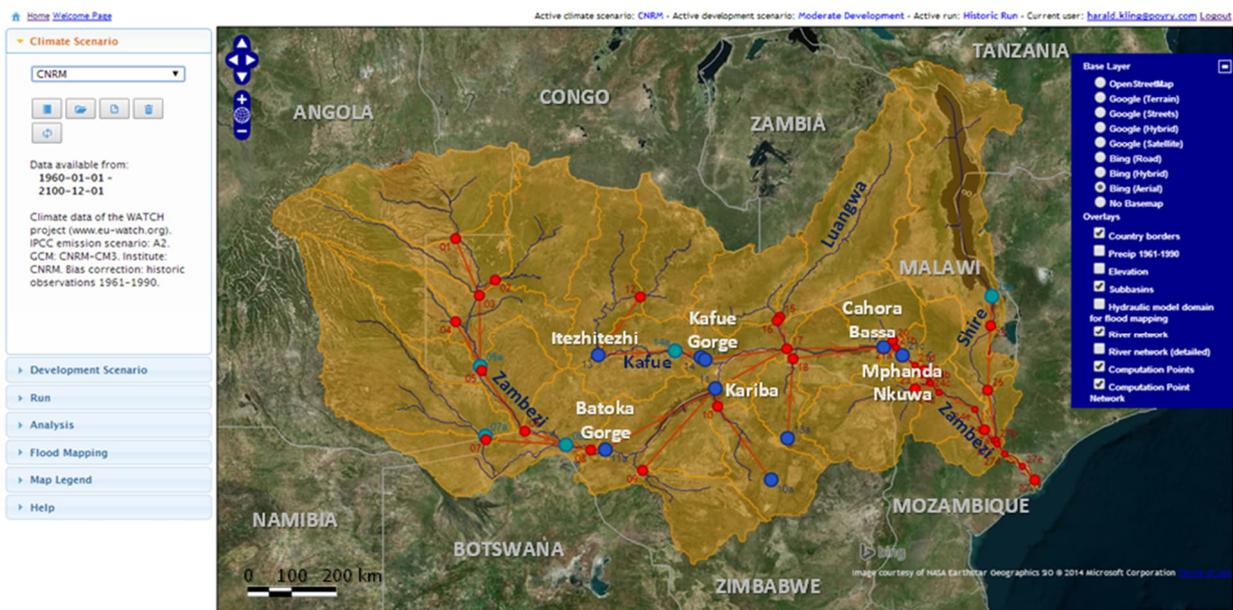


Figure 6: AFRY's Zambezi Decision Support System

### 3 Project activities

The following sections briefly summarize the organization, work plan and project activities undertaken during project execution.

#### 3.1 Organization

AFRY's core team for this assignment is listed below:

Expert	Position	Role
Martin Fuchs, PhD	Project director	Hydropower & Climate Resilience Expert
Harald Kling, PhD	Project manager	Hydrologist
Philipp Stanzel, PhD	Senior expert	Climate Specialist
Felisberto Afonso, MSc	Local expert	Climate and Disaster Risk Management

The above team was supported by additional experts in AFRY's team.

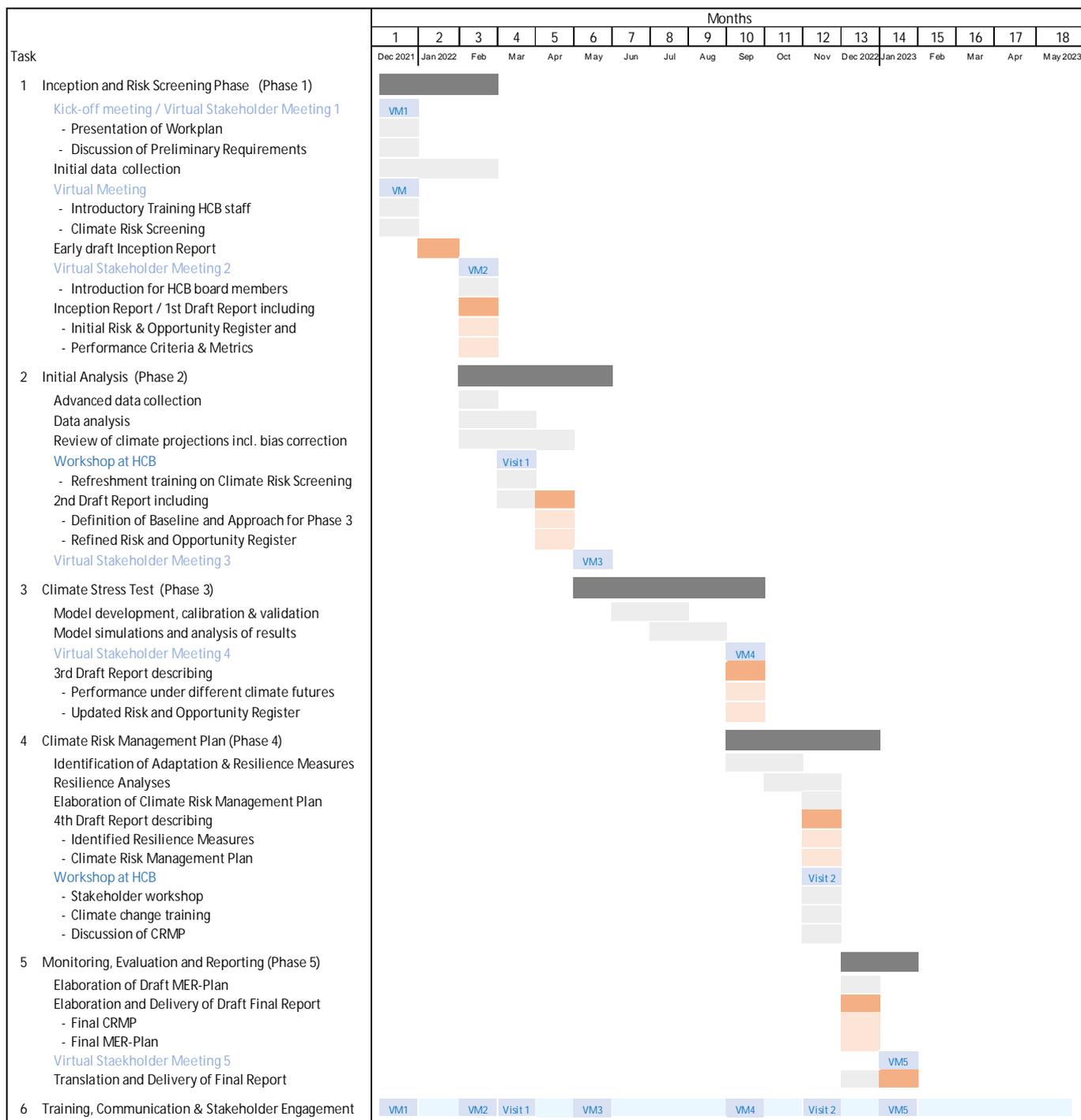
The key technical counterparts for different topics were discussed in the kick-off meeting and agreed between HCB and AFRY:

Topic	HCB counterpart	AFRY counterpart
General project management	Aida Mabjaia	Martin Fuchs
Technical matters, data exchange	Nico Savaoi Manuel Mahunguana	Harald Kling
Climate scenarios	Nico Savaoi Manuel Mahunguana	Philipp Stanzel
Site visit organization, training preparation	Nico Savaoi Manuel Mahunguana	Harald Kling Felisberto Afonso
Stakeholder engagement	Aida Mabjaia	Felisberto Afonso Harald Kling
TelCon planning	Aida Mabjaia	Harald Kling

In April 2022 HCB replaced Ms. Aida Mabjaia with Ms. Edite Nhantumbo as key technical counterpart. During project execution Dr. Fuchs acted as project director and Dr. Kling as project manager on AFRY's side.

### 3.2 Work plan

The work plan is shown below. Compared to the original work plan the main changes were (a) that the first site visit was shifted to phase 2 due to the pandemic situation and (b) that in phase 1 an additional report (Early draft Inception Report) as well as an additional presentation to the HCB Board were included. The phases 4 and 5 were shortened to finish most of the project activities before the end of 2022.



### 3.3 Virtual meetings

The following virtual meetings have been held as online TelCon:

- Kick-off meeting (2021-12-01): Overview about the project, definition of technical counterparts, adjustment of the work plan, etc.
- Data collection workshop (2021-12-07): Technical workshop to discuss data availability and procedure for data collection
- Training workshop for HCB staff (2021-12-21): Introduction to Climate Resilience Assessment
- Presentation to HCB Board (2022-02-22): General introduction to the project
- Presentation to INAM (2022-03-11): Project overview
- Discussion with HCB management (2022-04-01): Detailed discussion of HCB operations and proposed methodology for climate resilience assessment
- Discussion with INGD (2022-04-26): Project overview and discussion of method and data (INGD was represented by Mr. Antonio Queface)
- Discussion with National Directorate for Climate Change (2022-04-28): Project overview and discussion of stakeholder engagement
- Phase 2 main findings (2022-06-09): Presentation and discussion of the main findings of Phase 2 with HCB staff
- Presentation to JOTC (2022-09-29): General project overview for the Joint Operation Technical Committee (JOTC) 32<sup>nd</sup> Technical Meeting (Mozambique, Zambia, Zimbabwe)
- Phase 3 main findings (2022-10-07): Presentation and discussion of the main findings of Phase 3 with HCB staff
- TelCon with DSRAS and World Bank (2022-12-14): Presentation of study overview and climate models, discussion and knowledge exchange with the team for the ongoing World Bank study for Drought sensitivity and resilience assessment for the SAPP (DSRAS)

The presentations have been shared by AFRY with HCB.

Several additional virtual meetings have been held ad-hoc between HCB and AFRY for coordination of project activities (data collection, site visit preparation, discussion about stakeholder engagement, etc.).

### 3.4 First site visit

The first site visit was conducted from March 21<sup>st</sup> to 25<sup>th</sup>, 2022. The schedule is listed in Table 1. Two workshops were held with HCB participants (Table 2, Figure 7 and Figure 8), as well as follow-up discussions during visit of the control room, dam site (Figure 9) and sub-station, as well as meetings with various stakeholders (in Songo, Tete and Maputo).

Table 1: Schedule for the first site visit March 21<sup>st</sup> to 25<sup>th</sup>, 2022.

Day	Time	Activity	Comment
Monday (Maputo)	10:00	Meeting INAM weather forecast	Info on weather forecasts by INAM
	11:30	Meeting INAM climate division	General discussion of CRA study
	15:00	Meeting INGD (Mr. Queface)	Cancelled (Gombe storm), follow-up via TelCon
Tuesday (Songo)	09:00	Visit Revuboe River bridge	Bridge destroyed in latest storm (Ana)
	~13:00	Arrival at HCB	Health check, meeting with HCB partners
Wednesday (Songo)	9:00 – 12:00	HCB Climate Risk Screening Workshop	Discussion of HCB hydropower operations, performance metrics, climate risks
	Afternoon	HCB Site visit	Dam, power house, etc.
Thursday (Songo)	9:00 – 12:00	HCB Climate Change Training	Hands-on training, also using Zambezi DSS modelling tool
	13:00	Inst. Fisheries Research meeting	Discuss fishing activities in Cahora Bassa lake
	Afternoon	HCB follow-up discussions	Zambezi DSS (cont.), data collection
	Evening	Dinner at Montebelo	Follow-up discussions
Friday (Tete)	09:30	ARA Centro meeting	General discussion of CRA study & data collection

Table 2: Workshops with HCB staff during the first site visit.

Day	Activity	Contents	Participants
Wednesday 09:00 – 12:00	Climate Risk Screening Workshop	<ul style="list-style-type: none"> <li>General project background</li> <li>HCB operation targets and operational constraints</li> <li>Climate risk &amp; opportunity register for CRA</li> <li>Performance metrics to be used in CRA study</li> </ul>	HCB staff with advanced knowledge about Cahora Bassa reservoir operation, flood management, daily & seasonal hydropower operation and strategic planning
Thursday 09:00 – 12:00	Climate Change Training	<ul style="list-style-type: none"> <li>Climate models</li> <li>Climate change projections</li> <li>Hydrological modelling</li> <li>Hydropower generation modelling</li> <li>Zambezi Decision Support System</li> </ul>	HCB staff interested in the climate change topic as well as hydrological modelling should participate. The training will also include hands-on computer exercises and trainees need to bring their own laptops.



Figure 7: Climate risk screening workshop.



Figure 8: Climate change training.



Figure 9: Meteorological station at the Cahora Bassa dam.

### 3.5 Second site visit

The second site visit was conducted from November 21<sup>st</sup> to 25<sup>th</sup>, 2022. The activities are listed in Table 3. All activities were in Songo, Mozambique. The main event was the full-day stakeholder workshop where the results of the Climate Resilience Assessment were presented and discussed (Phase 1-4). Participants were from HCB, AFRY, ARA Centro, Mphanda Nkuwa, Fisheries Institute, Eduardo Mondlane University, Meteorological Service (INAM), Zambezi River Authority, etc. (Figure 10). Other important activities included training of HCB staff on climate change and climate resilience (Figure 11) and discussion and update of the Climate Risk Management Plan (see section 7.5), as well as several follow-up discussions.

Table 3: Activities in Songo during the second site visit November 21<sup>st</sup> to 25<sup>th</sup>, 2022.

Day	Time	Activity	Description
Monday	Evening	Preparations for stakeholder meeting	Discussion of workshop contents, translation setup
Tuesday	08:30 – 17:00	Stakeholder Workshop Climate Resilience Assessment	<ul style="list-style-type: none"> <li>• Introduction</li> <li>• Data and methods</li> <li>• Results</li> <li>• Climate Risk Management</li> </ul>
	Evening	Stakeholder dinner	Songo restaurant
Wednesday	09:00 – 16:30	Climate Change Training	<ul style="list-style-type: none"> <li>• Zambezi Decision Support System</li> <li>• Reservoir operation simulation</li> <li>• Hydropower generation</li> <li>• Climate model projections</li> <li>• Climate sensitivity analysis</li> </ul>
Thursday	09:00 – 10:00	Climate Change Training	Continued from previous day
	10:00 – 13:00	Climate Risk Management Plan	<ul style="list-style-type: none"> <li>• Climate risk mitigation measures</li> <li>• Prioritization</li> <li>• Time schedule</li> </ul>
	14:30 – 15:30	Visit of dam	Visit of dam with spillway under operation
	15:30 – 17:30	Wrap-up	<ul style="list-style-type: none"> <li>• Summary of visit, training contents and concluding statements</li> <li>• Follow-up discussions</li> </ul>



Figure 10: Stakeholder workshop for presentation and discussion of the Climate Resilience Assessment.

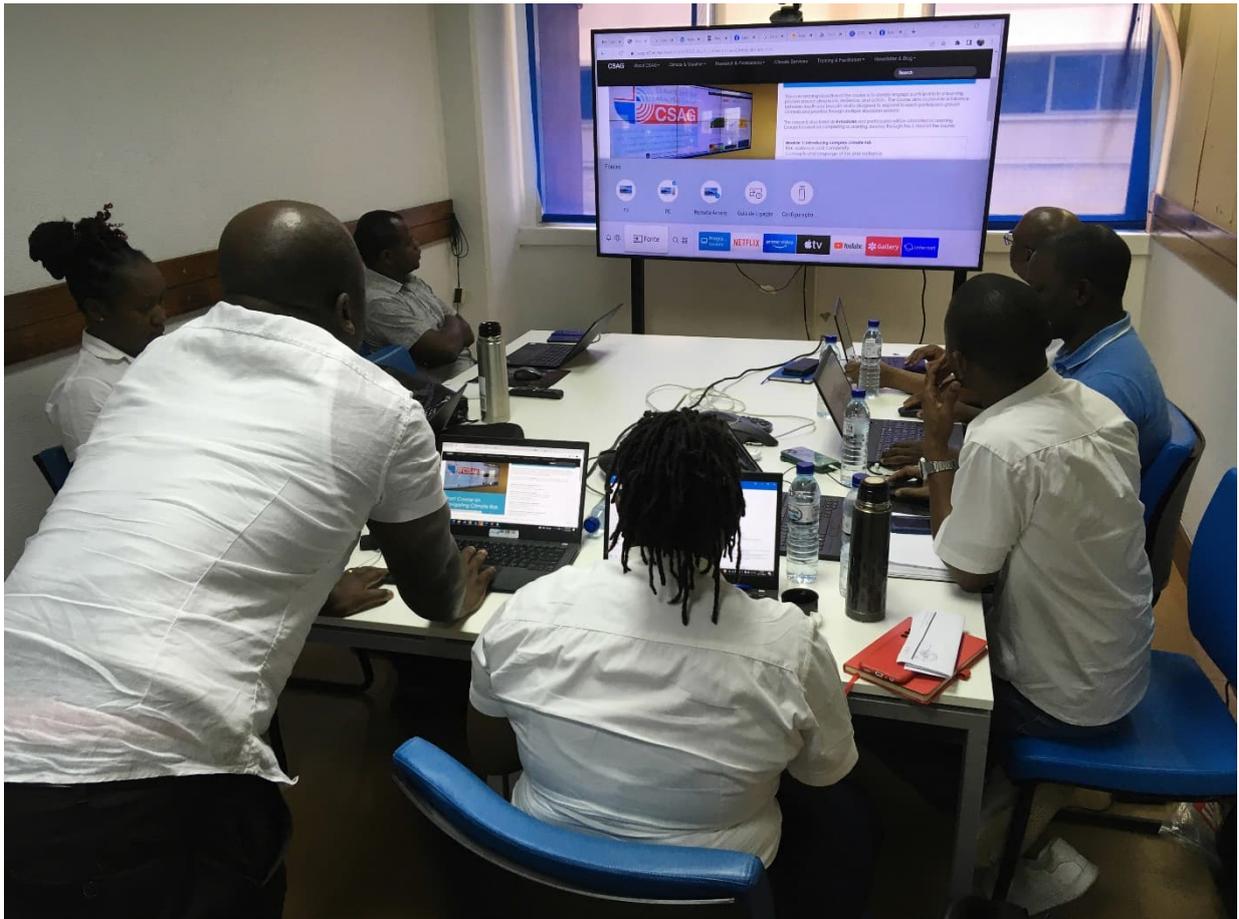


Figure 11: Training of HCB staff on climate resilience during the second site visit.



Figure 12: Two spillway gates under operation during the second site visit.

### 3.6 Stakeholder list

A list of stakeholders was prepared (Table 4). Outreach to stakeholders was initiated by HCB, with support from AFRY where required. Stakeholder engagement was via personal meetings, TelCon and invitation to stakeholder workshop in Songo.

Table 4: List of identified stakeholders

Stakeholder	Country	Comment
Administração Regional de Águas (ARA) Centro	Mozambique	A meeting was held in Tete during the first site visit. Participation in stakeholder workshop during second site visit.
National Institute of Fisheries Research	Mozambique	A meeting was held in Songo during the first site visit. Participation in stakeholder workshop during second site visit.
Instituto Nacional de Gestão e Redução do Risco de Desastres (INGD)	Mozambique	A meeting was scheduled in Maputo during the first site visit but had to be cancelled. A follow-up TelCon was held. Participation in stakeholder workshop during second site visit.
Direcção Nacional de Gestão de Recursos Hídricos (DNGRH)	Mozambique	A meeting was held at ARA Centro, but DNGRH was not contacted in addition, as ARA Centro is part of DNGRH.
Direcção Nacional das Mudanças Climáticas	Mozambique	National Directorate for Climate Change. A TelCon was held to discuss the study. Participation in stakeholder workshop during second site visit.
Instituto Nacional de Meteorologia (INAM)	Mozambique	An initial TelCon and two meetings were held in Maputo during the first site visit (Weather Forecast Division, Climate Division). Participation in stakeholder workshop during second site visit.
Universidade Eduardo Mondlane (UEM)	Mozambique	UEM is informed about the ongoing study. Participation in stakeholder workshop during second site visit.
Electricidade de Moçambique (EDM)	Mozambique	EDM has not been contacted.
Mozal aluminium smelter	Mozambique	Mozal has not been contacted.
Water users	Mozambique	List of water users from reservoir and downstream dam is available at ARA Centro.
Zambezi River Authority (ZRA)	Zambia/Zimbabwe	ZRA was informed about the study as part of the ongoing collaboration of AFRY with ZRA for the Kariba Inflow Forecasting System and in JOTC. Virtual participation in stakeholder workshop during second site visit.
Zimbabwe National Water Authority (ZINWA)	Zimbabwe	ZINWA was contacted and informed as part of the data acquisition activities (Manyame River discharge data).
Zimbabwe Electricity Supply Authority (ZESA)	Zimbabwe	ZESA has not been contacted for data collection. ZESA was briefed on CRA during JOTC meeting.
Water Resources Management Authority (WARMA)	Zambia	WARMA was contacted and informed as part of the data acquisition activities (Luangwa River discharge data).
Zambia Electricity Supply Corporation (ZESCO)	Zambia	ZESCO was contacted and informed as part of the data acquisition activities (Kafue River discharge data). ZESCO was briefed on CRA during JOTC meeting.
ESKOM	South Africa	ESKOM (South African electricity public utility) has not been contacted.
Climate System Analysis Group (CSAG)	South Africa	CSAG is a climate research group at the University of Cape Town, coordinating the CORDEX-Africa climate modelling initiative. CSAG was contacted and informed about the ongoing study.
Southern African Power Pool (SAPP)	regional	SAPP has not been contacted for data acquisition. SAPP was briefed on CRA during JOTC meeting.

### 3.7 Data collection

A list of required as well as optional data was discussed and agreed between HCB and AFRY. There are three types of data that have been collected for this study:

- Data available from HCB
- Data available from local institutions in Mozambique and in the upstream countries
- Data available at global data repositories (e.g. gridded satellite rainfall data, or climate model data)

In general, most of the data collection was finished in Phase 2. Overall, the data collected is sufficient for the purpose of the study. However, some additional data requests were still open and could not be completed in due time:

- WARMA: Luangwa River daily discharge data, in addition to the data already collected for the Luangwa River. The data request has been sent to WARMA. However, from the literature review it appears the discharge data are incomplete and have many data gaps<sup>1</sup>, so the usefulness of the additional data may be limited.

The status of the data collection is listed in Appendix 9.2.

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<sup>1</sup> For example, according to the study of Hulsman (2020) in the period 2002-2016 there are only three complete years of observed discharge data available for the Luangwa River at Great East Road Bridge gauge.

## 4 Initial analysis (Phase 2)

### 4.1 Literature review

Several previous studies have investigated various aspects of hydropower generation, hydrological characteristics and possible impacts of climate change in the Zambezi basin. The study results are either available as scientific papers or in the form of extensive reports (with several hundred pages).

The tables in the Appendix 9.1 list the scientific papers and reports collected in digital format. It is noted that also other studies exist for the Zambezi basin, but the most relevant studies for this assignment are probably included in the tables.

From the sheer size (several thousand pages) of the available literature it is clear that only a high-level screening, but not a full review of the literature can be done.

Overall 37 studies (scientific papers and reports) were identified, which assessed future climate change impacts on runoff conditions in the region of the Zambezi basin. Some of the studies are closely related (e.g. a follow-up study using data of a previous study), but overall it is concluded that different methods, models and data sources provide a good overview about the expected impacts of climate change on future Zambezi River discharge. The 37 studies were summarized (Figure 13) with respect to future changes in long-term mean annual discharge (i.e., inflow to Cahora Bassa reservoir, or runoff in the region):

- 22 studies found that future discharge will decrease
- 12 studies found no considerable change, or the results are not clear if there will be future increase or decrease of discharge
- 3 studies found that future discharge will increase

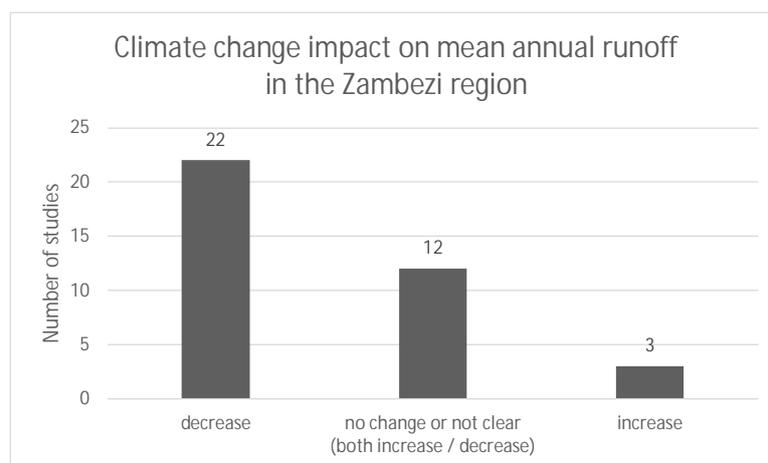


Figure 13: Results of 37 studies, summarized for climate change impact on mean annual runoff in the Zambezi region.

## 4.2 Observed discharge data

### 4.2.1 Data preparation

Observed discharge data were merged from various different sources / gauges, to prepare monthly time-series for the computation points (CP) of AFRY's Zambezi Decision Support System (DSS). This includes the most relevant gauges in the Zambezi basin.

In addition to the data collected from various institutions, observed discharge data were also screened from Pöyry / AFRY project archives, which includes data from:

- DNGRH (former DNA)
- ARA Centro (former ARA Zambeze)
- Malawi Hydrological Service
- etc.

The quality of the observed discharge data varies between gauges and time periods. Therefore, the data preparation included:

- Visual screening of the raw data and correction of apparent errors
- Fill in data gaps where possible
- Comparison of different sources (for the same gauge) and comparison with upstream/downstream gauges to further identify data errors
- Conversion of daily and 3x-daily time-series data into monthly values
- Merging of different data sources (e.g. data availability in different periods) to construct one single time-series. Up to six different data sources were used for one location.

Table 5 shows an overview about the final, cleaned and merged monthly time-series data for the computation points of the Zambezi DSS. This also includes data for four additional locations, which were not included in the original Zambezi DSS, but provide valuable information about the hydrological characteristics.

Table 5: Availability of monthly observed discharge data for the computation points (CP) of the Zambezi DSS. Catchment area computed with GIS.

CP	river	location	area [km <sup>2</sup> ]	start	end	availability [%]	data years
1	Zambezi	Chavuma Mission	79,821.3	1959 Oct	2022 Apr	100	62.6
2	Kabompo	Watopa Pontoon	66,459.9	1958 Oct	2022 Apr	100	63.6
3	Zambezi	Lukulu	212,626.3	1953 Oct	2018 Aug	99	64.3
4	Luanginga	Kalabo	32,989.0	1958 Oct	2022 Apr	100	63.6
5	Zambezi	Senanga	288,554.0	1947 Nov	2022 Apr	98	73.3
6	Zambezi	Katima Mulilo	334,882.9	1942 Dec	2021 May	87	68.5
7	Kwando	Kongola	113,501.2	1969 Feb	2003 Sep	89	30.8
8	Zambezi	Victoria Falls	519,398.7	1907 Oct	2022 Apr	100	114.6
9	Gwaai	Kamativi	39,117.8	1955 Oct	2022 Apr	78	51.7
10	Sanyati	Sanyati at mouth	45,340.5	1996 Dec	2022 Apr	100	25.5
11	Zambezi	Kariba	676,964.2	1961 Oct	2022 Apr	100	60.6
12	Kafue	Mswebi	51,043.4	1953 Oct	1992 Dec	98	38.4
13	Kafue	Itezhi-Tezhi	106,570.1	1960 Sep	2018 May	100	57.8
14	Kafue	Kafue Gorge	152,737.1	1953 Oct	2018 May	98	63.7
15	Luangwa	u/s confluence Lunsemfwa	96,838.2	n/a	n/a	0	0.0
16	Luangwa	Great East Road	142,047.9	1949 Jan	1993 Sep	95	42.3
17	Zambezi	Zumbo	1,004,972.4	n/a	n/a	0	0.0
18	Panhane	Panhane near mouth	24,404.3	n/a	n/a	0	0.0
19	Zambezi	Cahora Bassa	1,064,412.8	1975 Feb	2021 Nov	100	46.8
20	Luia	Luia near mouth	28,698.6	n/a	n/a	0	0.0
21	Zambezi	Tete	1,103,392.6	1946 Oct	2022 Mar	100	75.5
22	Revubue	Chingoze	16,262.7	1954 May	2022 Mar	98	66.7
23	Luenha	Luenha 1	53,581.2	1961 Jan	2022 Mar	64	39.4
24	Zambezi	Ponte Dona Ana	1,199,403.2	n/a	n/a	0	0.0
25	Shire	Liwonde	132,277.7	1948 Nov	2007 Oct	99	58.4
26	Shire	Chiromo	151,536.8	1953 Jan	1998 Oct	92	42.1
27	Zambezi	Zambezi Delta	1,372,935.2	n/a	n/a	0	0.0
48	Zambezi	Marromeou	1,372,558.4	1963 May	2013 Jan	66	33.0
49	Kafue	Kafue Hook	95,706.9	1907 Oct	2018 May	100	110.7
50	Manyame	Chinoyi	5,379.4	1964 Oct	2018 Sep	98	53.0
51	Zambezi	Cahora Bassa inflow	1,064,412.8	1975 Feb	2021 Nov	100	46.8
52	Luia	Machize	10,983.6	2010 May	2022 Mar	92	11.0

Examples for the observed discharge data are presented in the figures below. The daily and monthly flow data show the strong seasonality in the natural flow characteristics. However, this is considerably modified by reservoir operation (Kariba at the Zambezi, Itezhitezhi at the Kafue). The Luangwa River provides considerable flood inflow to Cahora Bassa. However, the sum of several additional, mainly ungauged tributaries probably also provides considerable flood inflow to Cahora Bassa. Here, the gauge data from the Luia, Revubue and Manyame (headwater) catchments can be used as proxies for local inflow to Cahora Bassa lake. At these smaller catchments peak monthly flow (in wet years) is roughly summarized as follows:

- Manyame at Chinoyi (5380 km<sup>2</sup>): 200 m<sup>3</sup>/s, i.e. 0.037 m<sup>3</sup>/(s.km<sup>2</sup>)
- Manyame at Mangula Mine Weir (7900 km<sup>2</sup>): 350 m<sup>3</sup>/s, i.e. 0.044 m<sup>3</sup>/(s.km<sup>2</sup>)
- Manyame at Nyakapupu (9740 km<sup>2</sup>): 400 m<sup>3</sup>/s, i.e. 0.041 m<sup>3</sup>/(s.km<sup>2</sup>)
- Luia at Machize (11000 km<sup>2</sup>): 400 m<sup>3</sup>/s, i.e. 0.036 m<sup>3</sup>/(s.km<sup>2</sup>)
- Revubue at Chingoze (16000 km<sup>2</sup>): 600 m<sup>3</sup>/s, i.e. 0.038 m<sup>3</sup>/(s.km<sup>2</sup>)

The sub-catchment between Zumbo (Zambezi River entering Cahora Bassa lake) and Cahora Bassa dam is about 60000 km<sup>2</sup>. Assuming a specific discharge of 0.035 m<sup>3</sup>/(s.km<sup>2</sup>) for peak monthly flow in wet years, this results in a monthly inflow of 2100 m<sup>3</sup>/s from the sub-catchment to the lake. This is a similar magnitude as the floods from the Luangwa River, with a peak monthly flow of about 3000-3500 m<sup>3</sup>/s (compare to Figure 17).

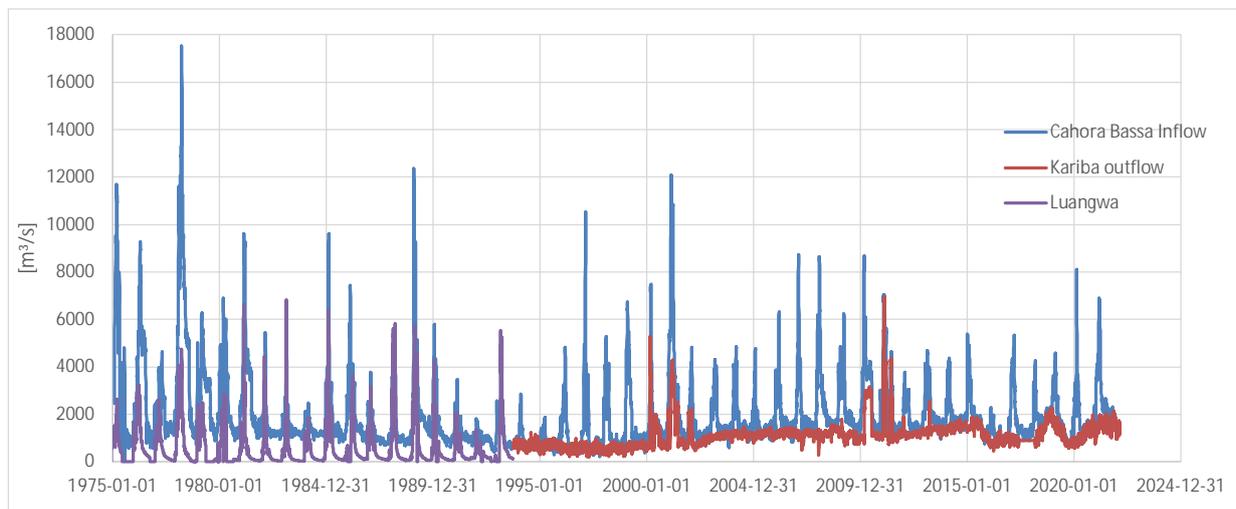


Figure 14: Daily Cahora Bassa inflow (1975-2021) in comparison with observed daily discharge of the Luangwa River @ Great East Road Bridge (until 1993) and Kariba outflow (since 1993)

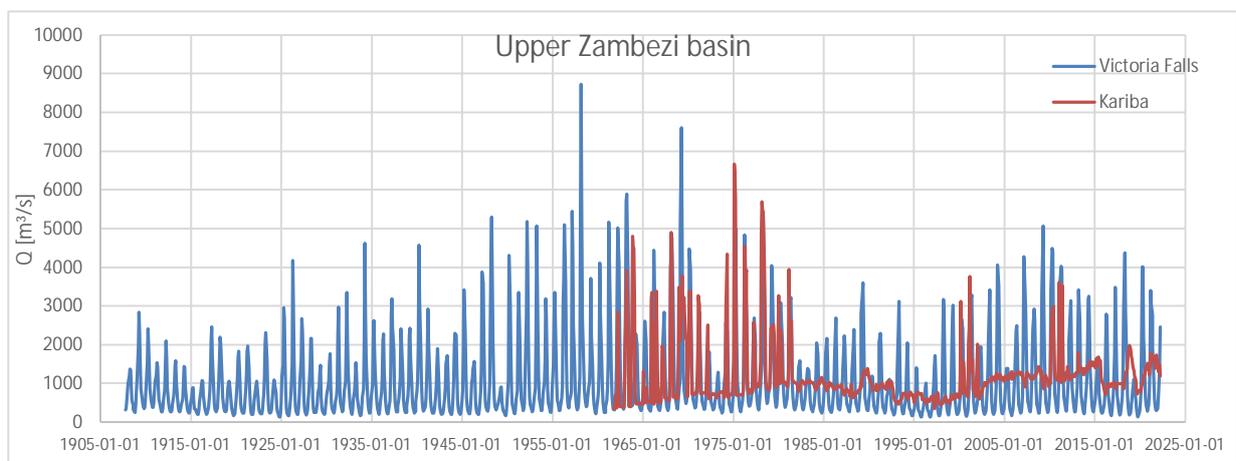


Figure 15: Monthly observed discharge in the Upper Zambezi basin.

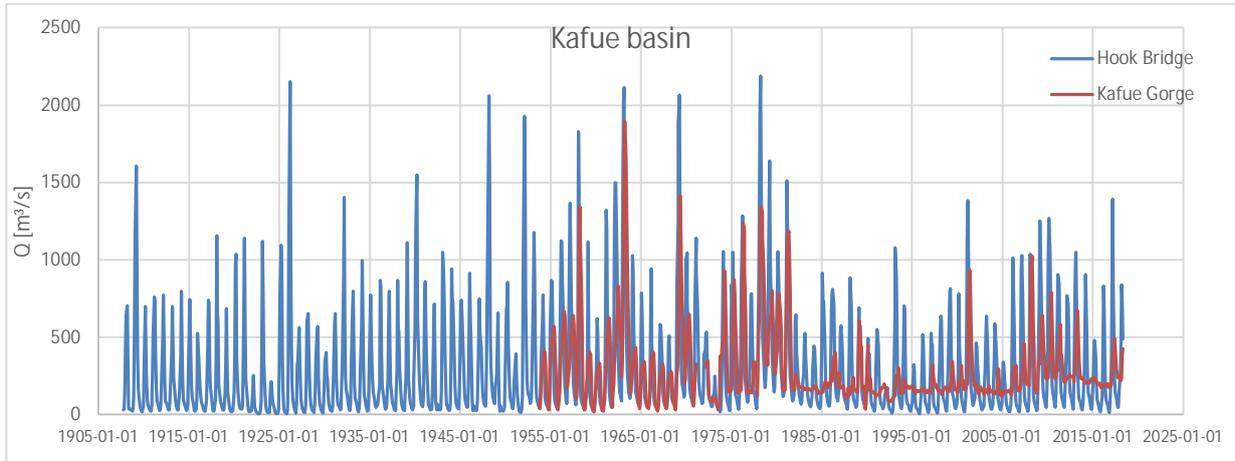


Figure 16: Monthly observed discharge in the Kafue basin.

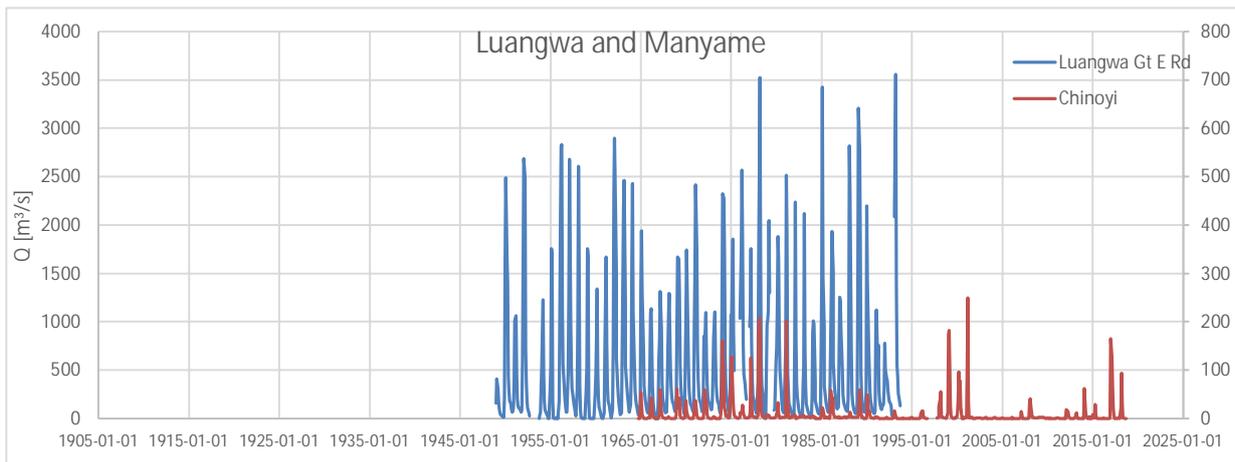


Figure 17: Monthly observed discharge for Cahora Bassa tributaries. Left y-axis Luangwa River (catchment area 142000 km<sup>2</sup>) and right y-axis Manyame River at Chinoyi (gauge in headwater region, catchment area 5380 km<sup>2</sup> at gauge; total catchment area about 25000 km<sup>2</sup> at Manyame mouth).

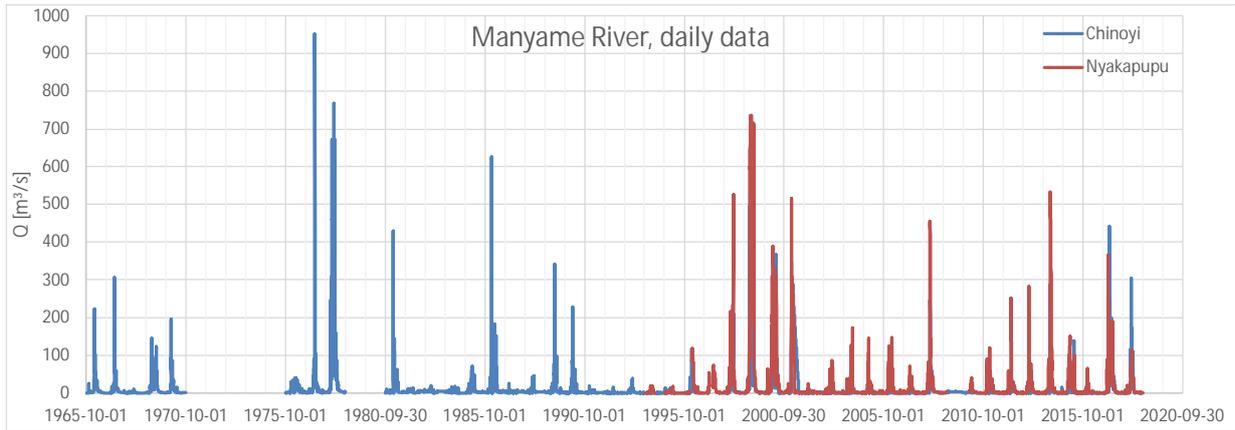


Figure 18: Daily observed discharge for the Manyame River. ZINWA gauges in the headwater region Chinoyi (5380  $\text{km}^2$ ) and Nyakapupu (9740  $\text{km}^2$ ) in Zimbabwe. For the ARA gauge (E-676 Mpanhame, 25000  $\text{km}^2$ ) no rating curve is available.

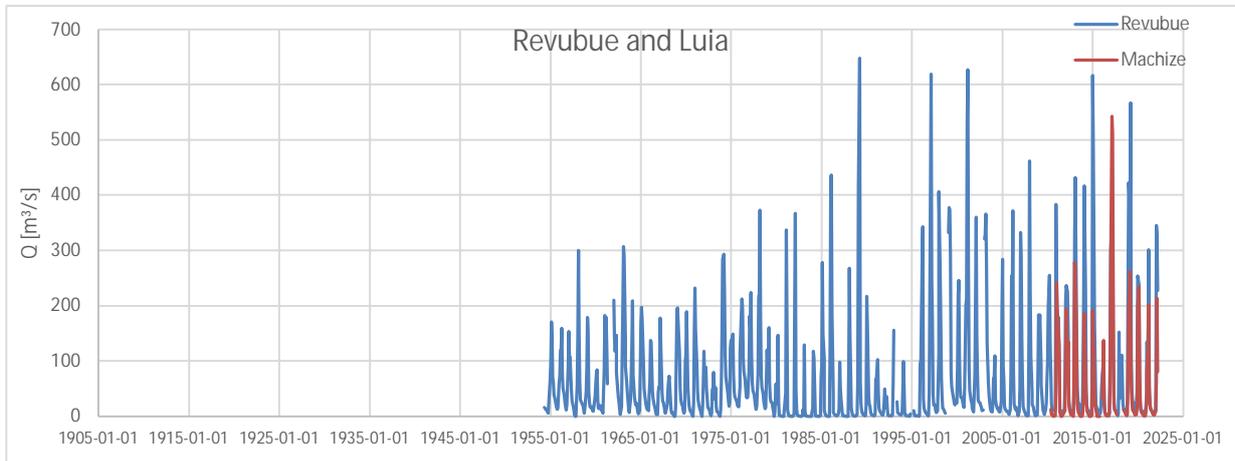


Figure 19: Monthly observed discharge for Zambezi tributaries downstream of Cahora Bassa. Blue: Revubue River at Chingoze (16300  $\text{km}^2$ ). Red: Luia River at Machize (11000  $\text{km}^2$ ).

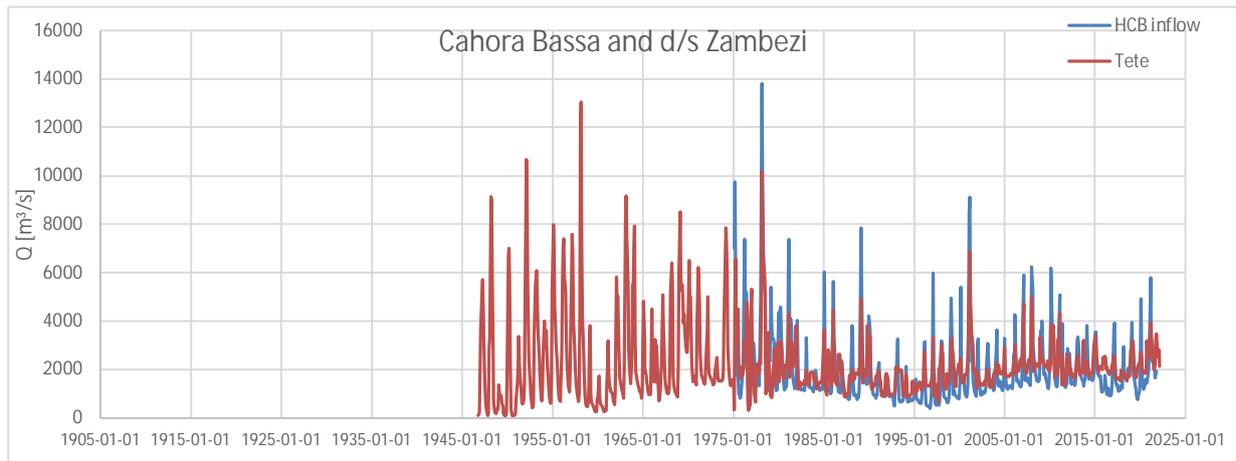


Figure 20: Monthly observed inflow to Cahora Bassa and downstream flow of the Zambezi River at Tete.

#### 4.2.2 Tributary contribution to Cahora Bassa inflow

The long-term mean monthly contribution of inflow to Cahora Bassa as simulated by the Zambezi DSS is shown in Figure 21. Kariba outflow contributes more than 50% to the mean annual inflow to Cahora Bassa. However, there are large seasonal variations in the flow contribution (Figure 22). In the wet season (Jan. to March) the share of the Luangwa River is considerable (up to 40%), whereas in the dry season (May to Nov.) Kariba contributes about 70% to Cahora Bassa inflow.

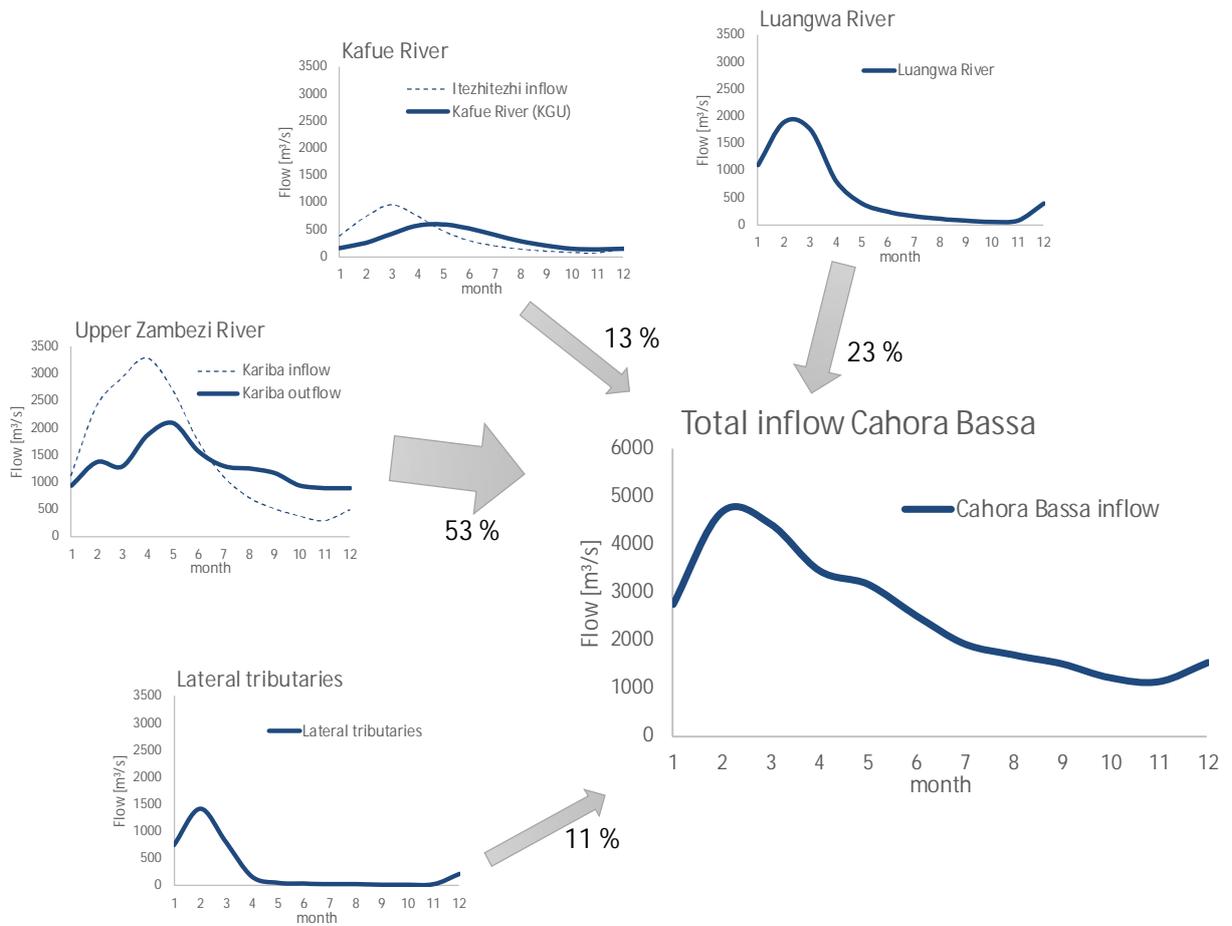


Figure 21: Mean monthly flow for major tributaries and Cahora Bassa inflow. Simulated by the Zambezi DSS for the period 1961-1990. The percentage values give the share of total annual inflow to Cahora Bassa.

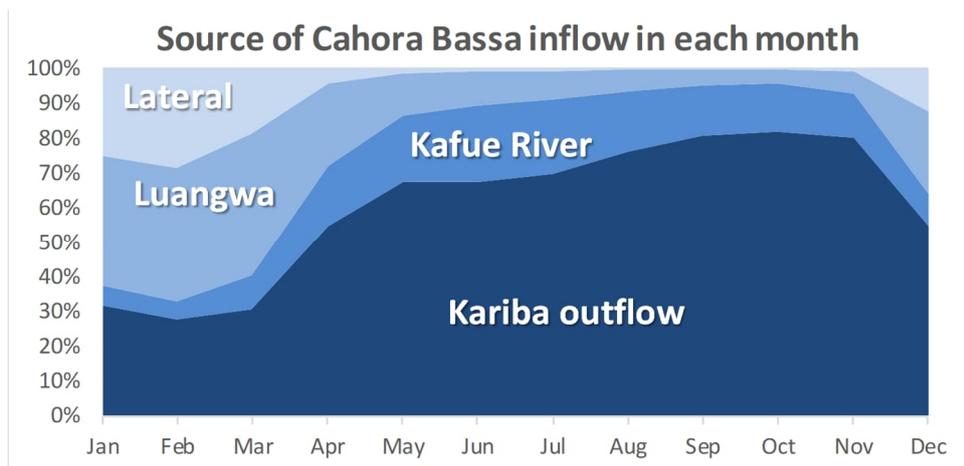


Figure 22: Contribution of tributaries to Cahora Bassa inflow. Long-term mean monthly values as simulated by the Zambezi DSS for the period 1961-1990.

### 4.2.3 Long-term trends in flow

The long-term flow data show distinctive differences between periods with above normal and below normal flow. There is a reasonable correlation between gauge data and observed reservoir outflows. Therefore, it can be assumed that these decadal variations in flow are not data artefacts (e.g. due to sediment impact on the rating curves), but real natural phenomena. The long-term trends depicted in Figure 23 to Figure 25 consistently show:

- Dry period from about 1910 to 1945
- Wet period from about 1950 to 1980
- Dry period from about 1985 to 2000
- Wet period from about 2005 to 2020

This cyclical behaviour of flow conditions has been studied before (e.g. Tyson et al. 2002, July 2003) and is a distinctive feature of the climate in southern Africa.

When analysing individual years it is notable that there is a strong correlation between anomalies in the Upper Zambezi, Kafue and Luangwa flows, as well as the outflow from Kariba and Cahora Bassa reservoirs. This highlights the shared water resources in the Zambezi basin, with rather homogeneous year-to-year variations across river catchments, even though the overall size of the Zambezi basin is quite large.

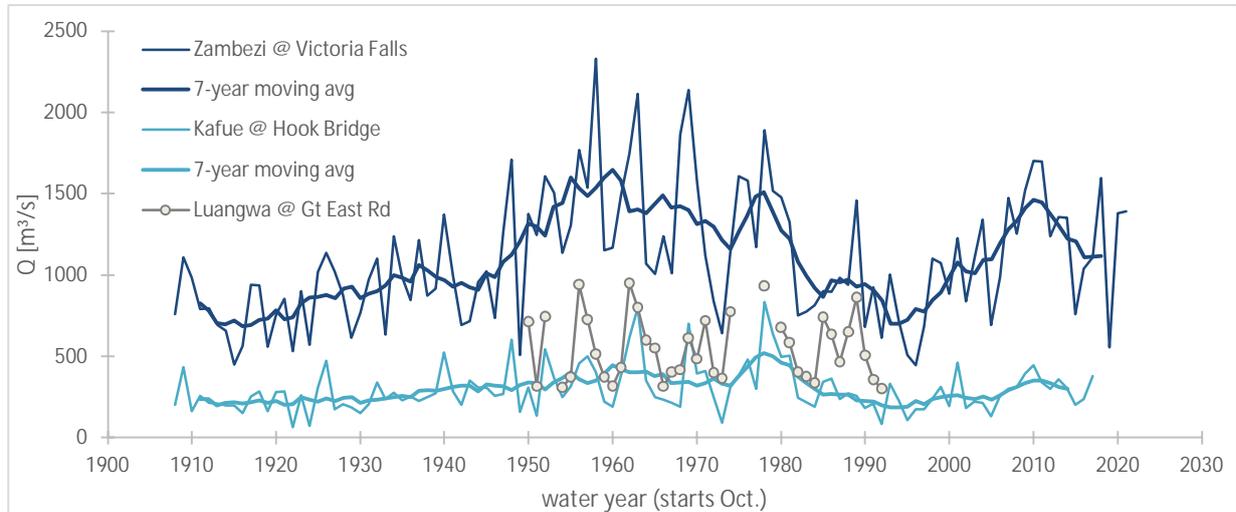


Figure 23: Long-term trends in observed mean annual flow at the Upper Zambezi, Kafue and Luangwa rivers.

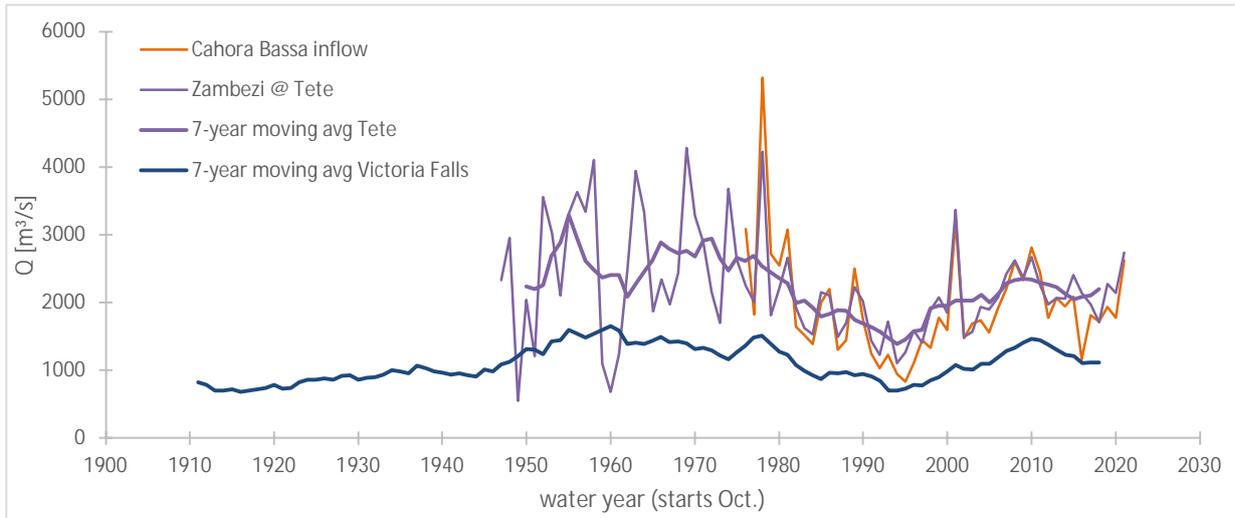


Figure 24: Long-term trends in observed mean annual inflow to Cahora Bassa and Zambezi discharge at Tete. For comparison, also the long-term trend in Zambezi discharge at Victoria Falls is displayed.

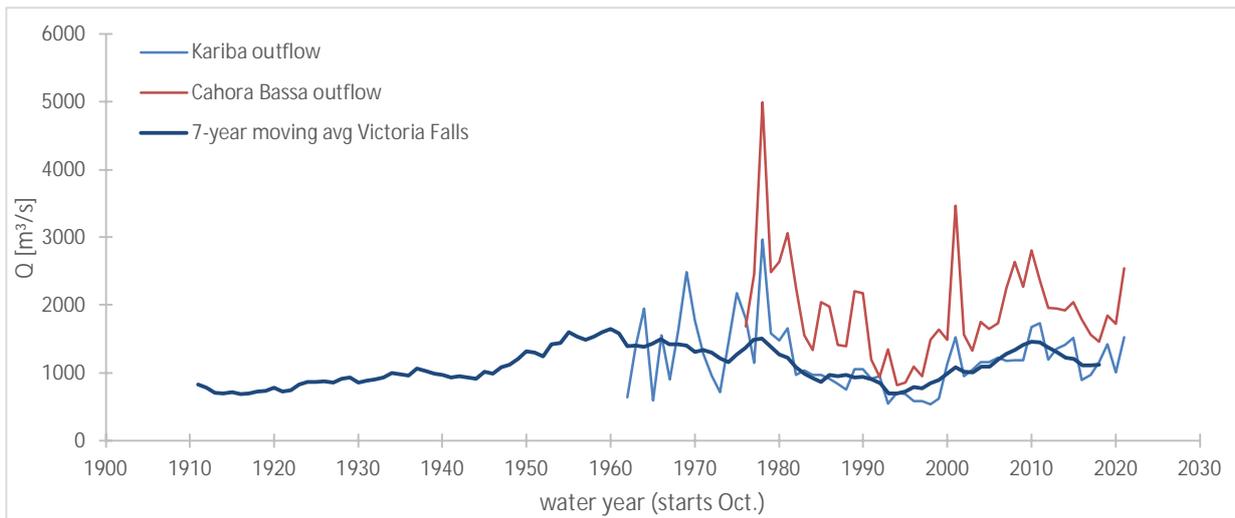


Figure 25: Mean annual outflow from Kariba and Cahora Bassa reservoirs. For comparison, also the long-term trend in Zambezi discharge at Victoria Falls is displayed.

### 4.3 Cahora Bassa hydropower generation

The Cahora Bassa operation data are shown in Appendix 9.3. To double-check the data and test the hydropower calculation with model assumptions, the monthly hydropower generation was simulated using the following inputs and method:

- Daily reservoir water level time-series (model input)
- Daily turbined flow time-series (model input)
- Tailwater rating curve (model equation)
- Representative hydropower parameters (model assumptions):
  - Efficiency 0.93
  - Hydraulic losses 1.286 m
- Simulation of power generation:
  - Equation:  $P_{sim} = Q_{turb} * (RWL - TWL - HL) * \eta * 9.81 / 1000$
  - $P_{sim}$ : simulated power in MW
  - $Q_{turb}$ : turbined flow in  $m^3/s$
  - RWL: reservoir water level in m
  - TWL: tailwater level in m
  - HL: hydraulic losses in m
  - $\eta$ : efficiency in [/]

The daily simulation results were aggregated to monthly time-steps and compared to the available observed hydropower generation data (Figure 26). The simulated and observed hydropower generation agree very well. The correlation of the simulated and observed monthly values is  $r=0.997$  and the bias is only 0.3%. This means that the above assumptions (efficiency, hydraulic losses) and data are plausible and sufficient for calculation of monthly hydropower generation.

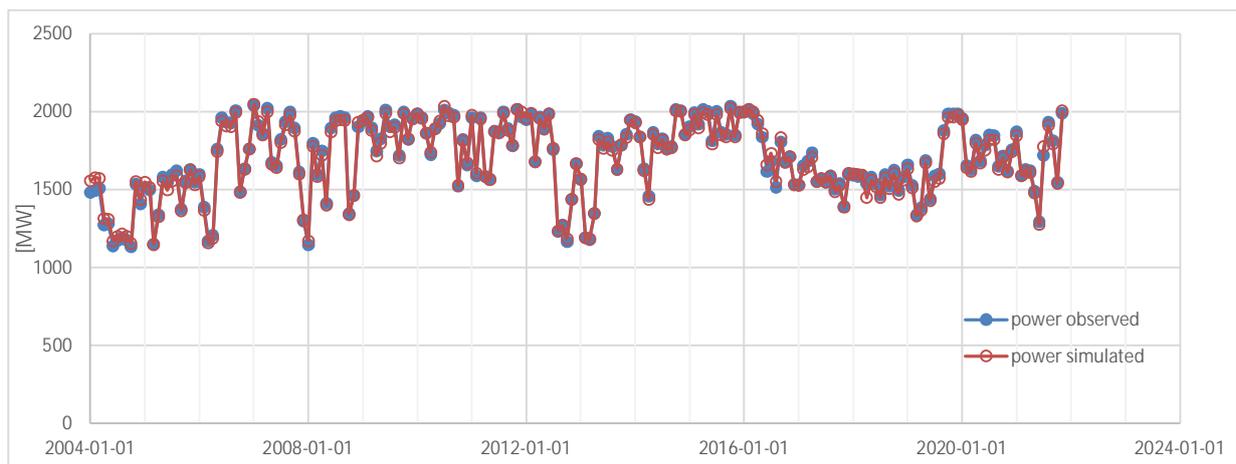


Figure 26: Simulated and observed monthly hydropower generation for Cahora Bassa. Simulation of power generation based on observed water levels and turbined flow data.

## 4.4 Meteorological data

### 4.4.1 Precipitation data

Mean annual precipitation shows large spatial variations in the Zambezi basin (Figure 27). The southern parts are considerably drier than the northern and eastern parts.

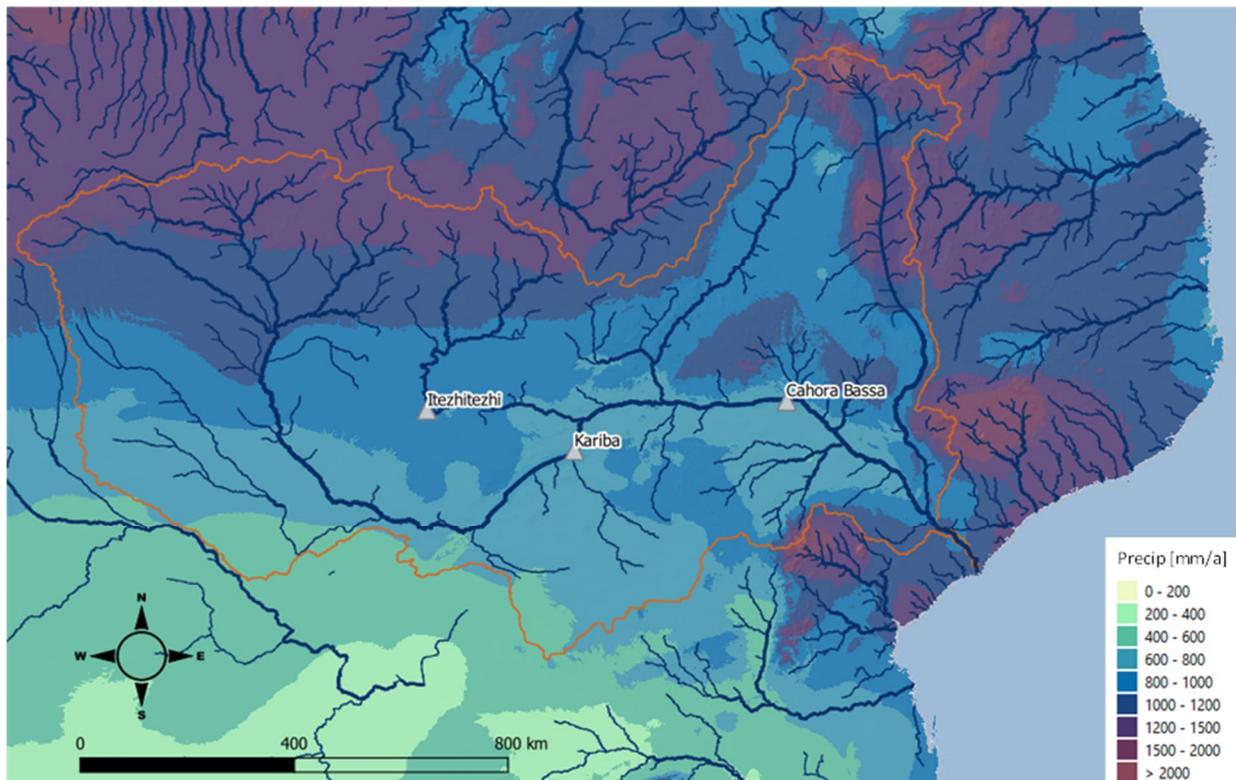


Figure 27: Mean annual precipitation map for the Zambezi basin. Data source: WorldClim.

Precipitation time-series data were collected from various sources, with different characteristics:

- WMO station data: daily resolution, good availability until 1990, but many data gaps after 1990
- GPCP interpolated station data (gridded): monthly resolution, no data gaps, availability until 2019
- GPM satellite-based data (gridded): daily resolution, availability until March 2022 (GPM Late Run)
- various other satellite products: GPM Final Run, RFE, TAMSAT; after initial screening it was concluded that the GPM Late Run data have a similar quality as the other products, and in the further analysis the GPM Late Run data was the only satellite product retained.

The WMO station data were not further analysed due to the many data gaps after 1990. The only station with sufficient precipitation records is HCB's station in Songo.

A comparison of the different data sources shows that the temporal, monthly patterns correspond well (Figure 28). On the annual timescale there are larger uncertainties in the overall precipitation amount. It is believed that GPCC is the most reliable precipitation data source, as this product is the result of a rigorous screening and data homogenization procedure. In the period 1950 to 1990 the station density is highest, and GPCC should have the best quality (Figure 29). However, after 1990 there is a considerable drop in the station density, especially after 2006.

The annual precipitation time-series 1900-2019 is shown in Figure 30. GPCC data before 1920 should be interpreted with caution, as the station density is very low. In the graph there are no strong trends in annual precipitation. The 1950s to 1970s were slightly wetter, whereas the 1980s and 1990s were slightly drier. This is in line with the observed long-term trends in mean annual flow, albeit the trends in discharge are more pronounced than in rainfall, which points to the high sensitivity of flow to even small variations in rainfall.

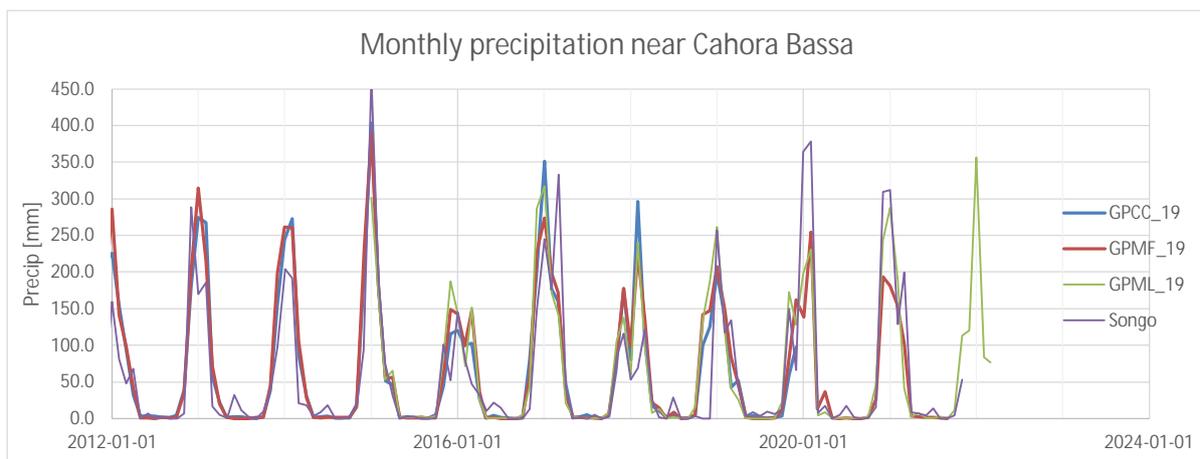


Figure 28: Monthly precipitation near Cahora Bassa. Comparison of different data sources. Blue: GPCC, subbasin average. Red: GPMF (Final Run), subbasin average. Green: GPMML (Late Run), subbasin average. Purple: station Songo.

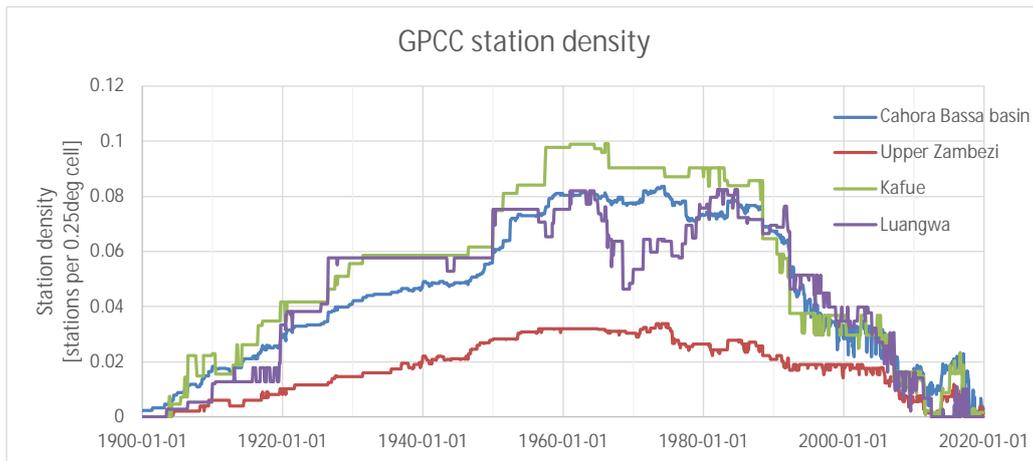


Figure 29: Station density of GPC precipitation product for different parts of the Zambezi basin. Blue: Zambezi basin upstream of Cahora Bassa. Red: Zambezi basin upstream of Victoria Falls. Green: Kafue basin upstream of Kafue Gorge. Purple: Luangwa basin upstream of Great East Road Bridge.

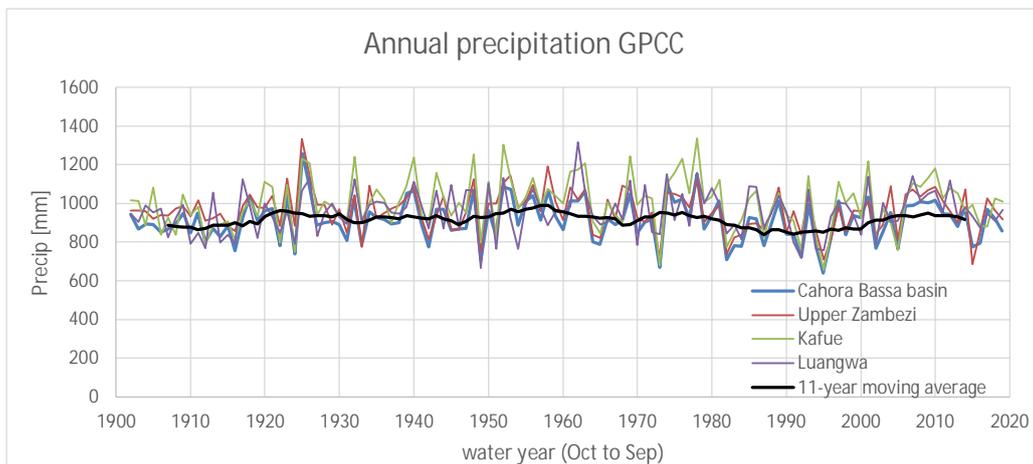


Figure 30: Annual precipitation of GPC product for different parts of the Zambezi basin. Blue: Zambezi basin upstream of Cahora Bassa. Red: Zambezi basin upstream of Victoria Falls. Green: Kafue basin upstream of Kafue Gorge. Purple: Luangwa basin upstream of Great East Road Bridge. Black: 11-year moving average of annual precipitation in the Zambezi basin upstream of Cahora Bassa.

#### 4.4.2 Air temperature data

Air temperature data were collected from three sources, with different characteristics:

- WMO station data: daily resolution, many data gaps, availability until March 2022
- CRU interpolated station data (gridded): monthly resolution, no data gaps, availability until December 2020
- GFS weather model data (gridded): daily resolution, data extracted from AFRY's operational archive, availability until March 2022

The WMO data were collected for 16 stations (Figure 31), and in addition data are also available for HCB's station in Songo.

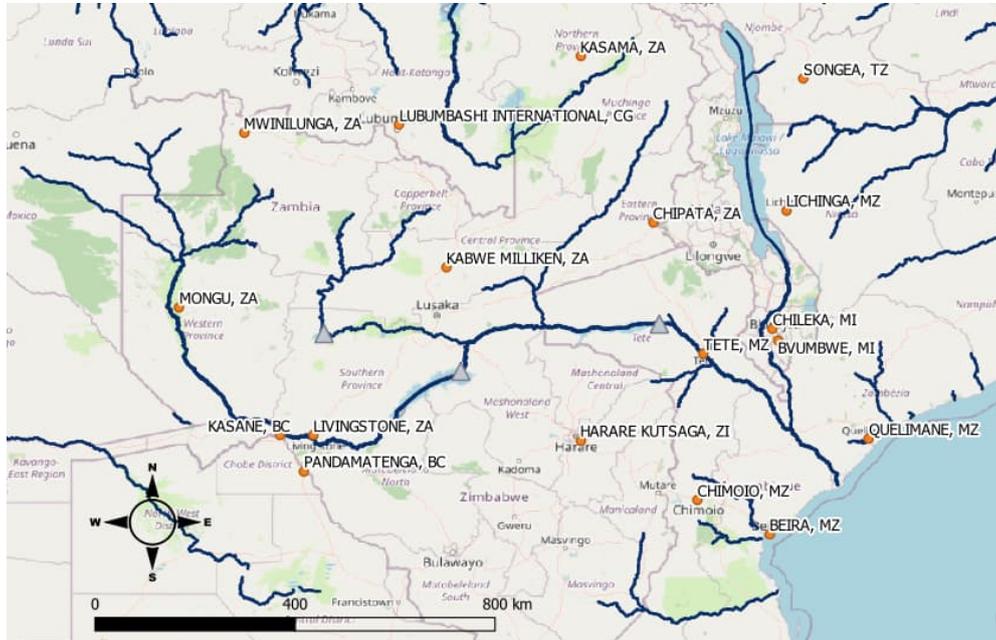


Figure 31: Location of WMO stations where data were collected.

The WMO data include many gaps, which limits the usefulness of the data for studying long-term trends. After extensive gap filling the following continuous time-series were prepared for five stations:

- Chimoio (Mozambique, WMO): 2015-2021
- Harare Kutsaga (Zimbabwe, WMO): 1978-2019
- Kasane (Botswana, WMO): 2001-2021
- Songea (Tanzania, WMO): 2011-2021
- Songo (Mozambique, HCB): 1985-2021

The gap filling made use of the systematic differences between the mean monthly values between stations. For example, at the station Songo the air temperature is about 3 to 5 °C warmer than at the station Harare, depending on the season (Figure 32).

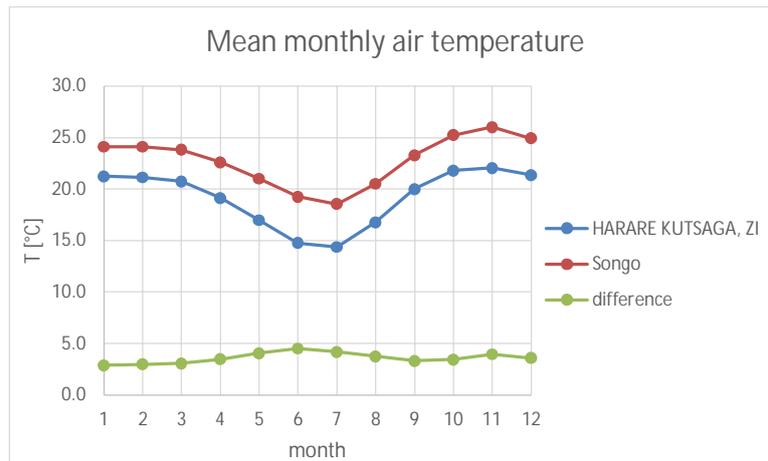


Figure 32: Mean monthly air temperature at two selected stations. Data period 1985-2019.

Figure 33 displays the annual air temperature time-series for the five stations. At Harare (data since 1978) and Songo (data since 1985) there is a warming trend of about 1°C from the 1980s to the 2000s. However, after about 1995 (Harare) or 2005 (Songo) there is no continued warming trend discernible in the data. At the other stations (e.g. Kasane, data since 2000) no warming trend can be detected in the data.

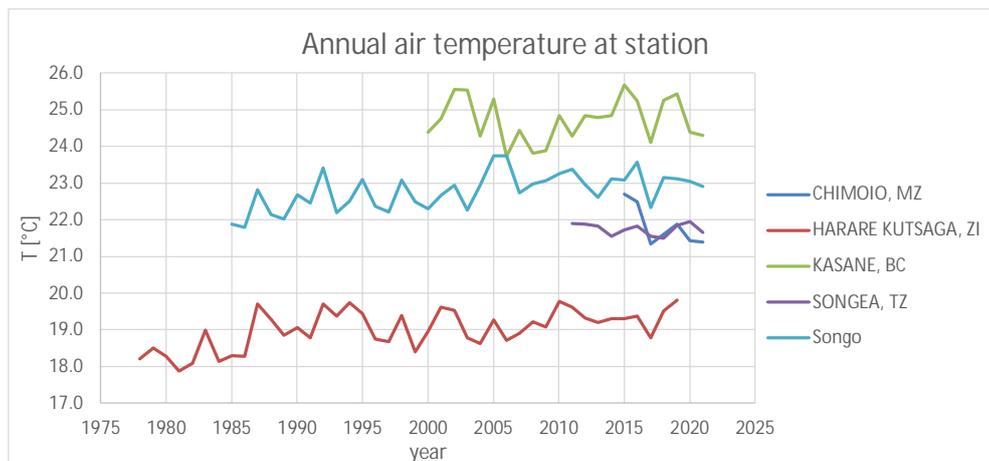


Figure 33: Annual air temperature measured at stations.

The gridded, monthly air temperature data of CRU was averaged over the basin upstream of Cahora Bassa. The annual data show no trend from 1900 until 1980, then there is a gradual warming of about 1°C until 2005, but no further warming trend in the last 15 years (Figure 34). This is in accordance with the trends in the WMO station data discussed above.

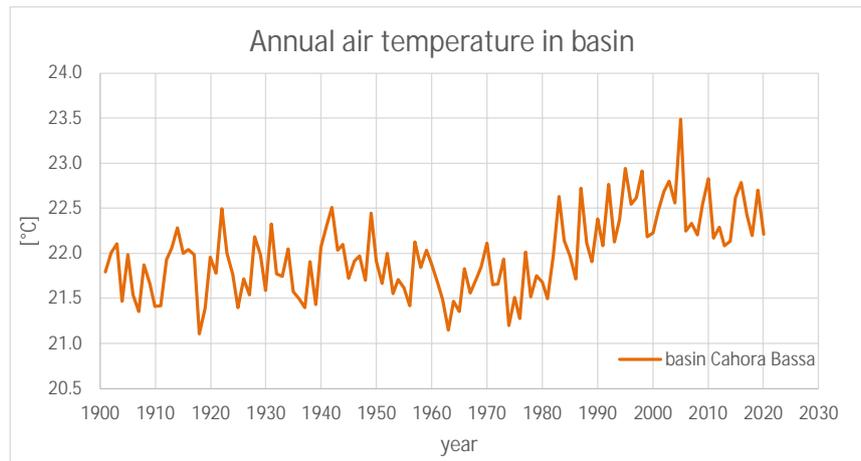


Figure 34: Annual air temperature of gridded CRU data, averaged over the basin upstream of Cahora Bassa.

A comparison of GFS, CRU and station data shows that there is a good agreement between the different data sources on the monthly timescale (Figure 35). Therefore, it is concluded that the CRU time-series (which ends in 2020) can be extended with GFS data (until March 2022). To this end, the (small) systematic bias is corrected for the mean monthly averages 2016-2020 in each subbasin, such that the data can be used for subsequent hydrological modelling.

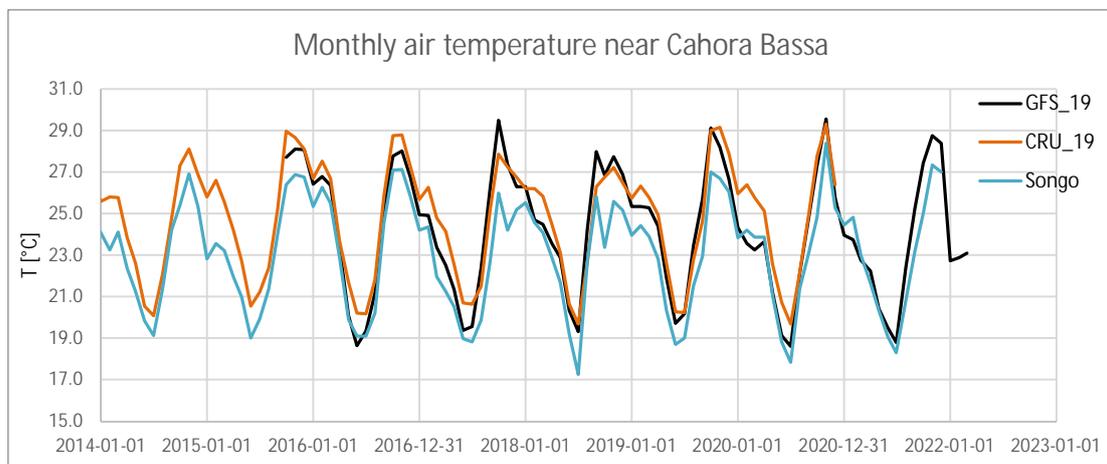


Figure 35: Monthly air temperature near Cahora Bassa. Comparison of different data sources. Black: GFS operational archive, subbasin average. Orange: CRU, subbasin average. Light Blue: station Songo.

## 4.5 Climate model projections

### 4.5.1 Time periods

A common set of time periods needs to be defined for the climate change impact analysis. The definition of the time periods was based on:

- The length of a time period should not be too short, such that the impact of natural climate variability is minimized when summarizing the results. As a minimum, various authors have used 20-year periods, but 30-year periods are recommended for the Zambezi basin, with strong decadal variations.
- Literature review: Ideally, the study results should be comparable, also considering WMO standard periods, IPCC periods, and time periods used in previous climate change studies for the Zambezi region. Even though various different time periods have been used, several authors have used e.g. 1961-1990 as historical reference and 2071-2100 as a far future period.
- Data availability and analysis: The availability/quality of observed, historical climate data decreases considerably after 1990. The same applies to observed discharge at some gauges (e.g. Luangwa River).
- Cahora Bassa hydropower operation data: Cahora Bassa operation data (including inflow) are available since 1975. The data availability is also good in recent years (up until 2022).

Based upon the above considerations and the feedback collected in the workshops (first site visit, as well as follow-up TelCons), the following time periods were defined:

- 1961-1990: Reference period for observed historic climate. Suitable for evaluation of climate models and subsequent bias correction. Commonly used WMO standard period.
- 1991-2020: Baseline period for simulation of Cahora Bassa hydropower operation.
- 2021-2050: Near future period for simulation of climate change impacts in the next three decades.
- 2071-2100: Far future period for simulation of long-term climate change impacts

In addition, at later project stages there was the feedback from stakeholders there is also interest in the results for the intermediate future period 2051-2070. Therefore, results for this intermediate future period are reported in the appendix.

#### 4.5.2 Regional Climate Models CORDEX

Regional Climate Model (RCM) data were obtained from the Coordinated Regional Downscaling Experiment for Africa (CORDEX-Africa), which currently provides the most detailed climate model projections for the African continent. The CORDEX data are available for three types of climate model runs:

- Historical run: 1950-2005, using observed greenhouse-gas concentrations
- RCP4.5: 2006-2100, climate simulation based on a Representative Concentration Pathway with moderate greenhouse-gas concentrations (moderate emission scenario)
- RCP8.5: 2006-2100, climate simulation based on a Representative Concentration Pathway with very high greenhouse-gas concentrations (high emission scenario)

Note that in the period 2006-2020 the greenhouse-gas concentrations are similar in the two RCPs, and any simulated differences in climate (with the same climate model) are mainly related to natural climate variability.

The obtained climate model data have a spatial grid resolution of 0.44 degree (approximately 50 km) and a daily temporal resolution. The variables precipitation (pr) and air temperature (tas) were obtained.

Table 6 provides an overview of the used CORDEX climate models. Overall, there are 5 different RCMs and 10 different driving GCMs, resulting in overall 20 different GCM-RCM combinations. With the two RCP scenarios this results in overall 40 different climate model simulation runs. The climate model ensemble is not homogeneous due to:

- Half of the climate simulations are based on the RCM RCA4 (SMHI).
- Some driving GCMs were used more often (e.g. the GCM ICHEC-EC-EARTH was used by 5 RCMs) than others (e.g. the GCM MIROC5 was used by only one RCM).

This should be considered when interpreting the ensemble spread in the climate change projections. The implications for averaging of simulation results are discussed in the appendix.

Table 6: CORDEX-Africa climate models used in this study.

Climate modelling institution	Acronym	Country	RCM	Driving GCMs (color coded)
Koninklijk Nederlands Meteorologisch Instituut	KNMI	Netherlands	RACMO22T	ICHEC-EC-EARTH
				MOHC-HadGEM2-ES
Danmarks Meteorologiske Institut	DMI	Denmark	HIRHAM5	ICHEC-EC-EARTH
				NCC-NorESM1-M
Climate Limited-area Modelling-Community	CLMcom	Germany	CCLM4-8-17	CNRM-CERFACS-CNRM-CM5
				ICHEC-EC-EARTH
				MOHC-HadGEM2-ES
				MPI-M-MPI-ESM-LR
Sveriges Meteorologiska och Hydrologiska Institut	SMHI	Sweden	RCA4	CCCma-CanESM2
				CNRM-CERFACS-CNRM-CM5
				ICHEC-EC-EARTH
				IPSL-IPSL-CM5A-MR
				MIROC-MIROC5
				MOHC-HadGEM2-ES
				MPI-M-MPI-ESM-LR
				NCC-NorESM1-M
				NOAA-GFDL-GFDL-ESM2M
				CSIRO-QCCCE-CSIRO-Mk3-6-0
				ICHEC-EC-EARTH
Max Planck Institute for Meteorology	MPI	Germany	REMO2009	MPI-M-MPI-ESM-LR

The processing of the climate model data included:

- Download of the raw climate model data from the CORDEX archive in NetCDF format (overall 2100 files and 206 GB for the whole of Africa).
- Extraction of the data for the region of the Zambezi basin and subsequent aggregation from daily to monthly time-steps with the program Climate Data Operators (CDO).
- Calculation of spatially averaged monthly time-series for the 27 sub-basins of AFRY's Zambezi DSS.
- Merging of the historical run and the RCP runs to create continuous time-series 1950-2100.

A comparison between observed and simulated (RCM) precipitation data for the period 1961-1990 is included in the Appendix 9.4.1. Most RCMs are capable of reproducing the seasonality in precipitation, as well as the overall annual precipitation amount. However, a few selected RCMs show considerable biases. These RCMs need to be excluded from the analysis in later stages.

Similar considerations apply for air temperature data (Appendix 9.4.2). Most RCMs provide a reasonable simulation of air temperature when compared to historic observation data. However, systematic biases need to be removed before applying the

data in impact modelling. For at least one RCM the bias is very large. This RCM needs to be removed.

The graphs below summarize the climate change signals from the CORDEX RCMs vs the reference period 1961-1990. Note that the climate simulation in the period 1991-2020 is based on merging the CORDEX experiments “historical” (1991-2005) and “RCP” (2006-2020).

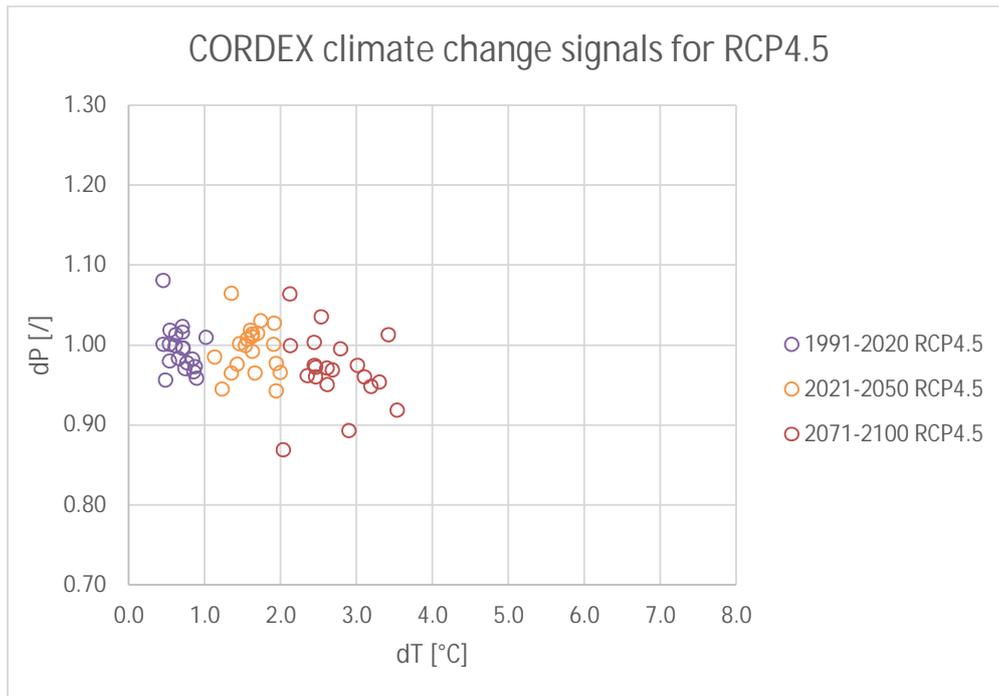


Figure 36: CORDEX climate change signals for moderate emission scenario (RCP4.5). Mean annual values averaged over the Zambezi basin upstream of Cahora Bassa. Reference period 1961-1990. dT: delta in air temperature (future minus reference). dP: ratio in precipitation (future vs reference). Each point represents the results of one CORDEX RCM climate simulation.

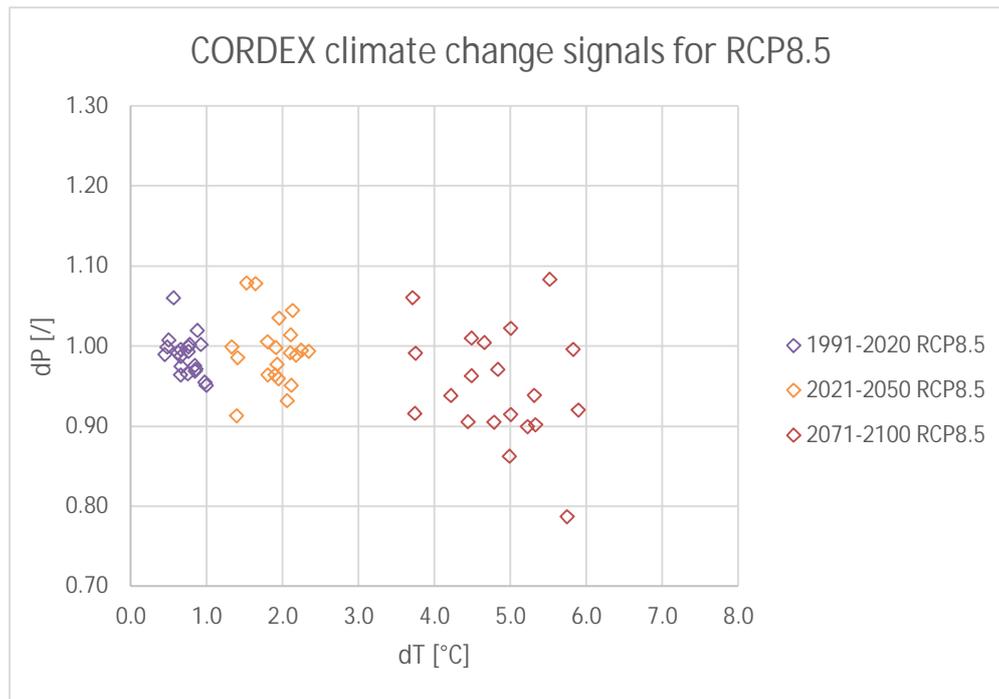


Figure 37: CORDEX climate change signals for high emission scenario (RCP8.5). Mean annual values averaged over the Zambezi basin upstream of Cahora Bassa. Reference period 1961-1990. dT: delta in air temperature (future minus reference). dP: ratio in precipitation (future vs reference). Each point represents the results of one CORDEX RCM climate simulation.

The subsequent processing steps included:

- Selection of representative climate models, also considering the evaluation of climate models with observed climate data. Only those climate models were retained that provided a plausible simulation of historic climatic conditions.
- Bias correction of the climate model data.
- Import of the climate model data into AFRY's Zambezi DSS.

#### 4.5.3 Global Climate Models CMIP6

CMIP6 GCM data were obtained from the Copernicus archive. The climate data were aggregated over a box covering the Zambezi basin upstream of Cahora Bassa. Overall data of 31 GCM runs were analysed for the following periods:

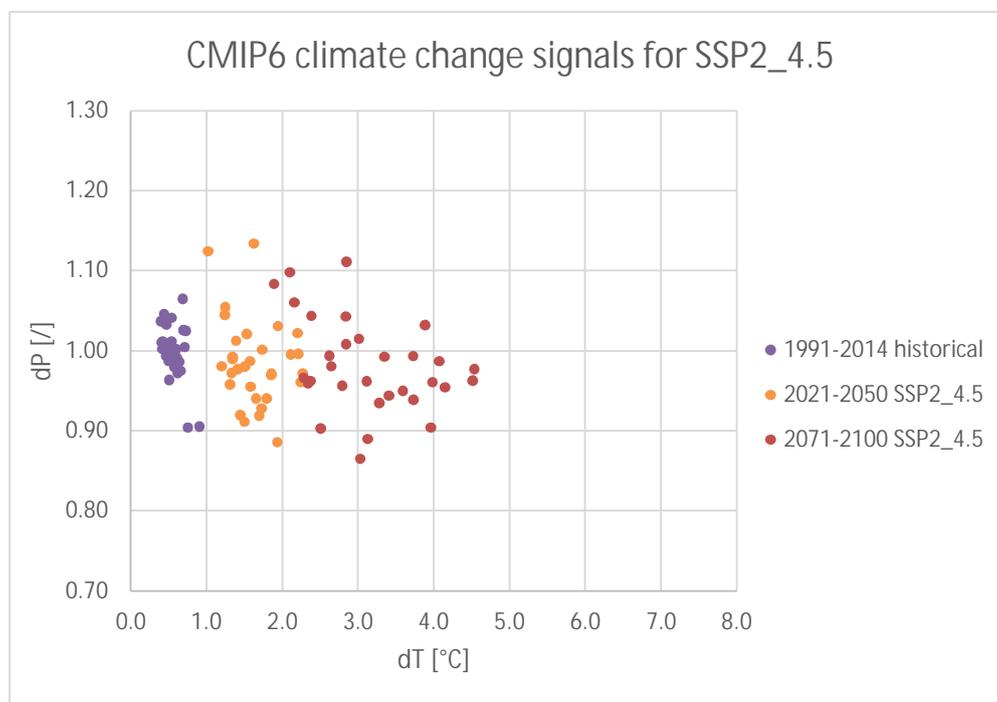
- 1961-1990: historical run
- 1991-2014: historical run
- 2021-2050: climate simulation
- 2071-2100: climate simulation

Three types of experiments were analysed:

- historical
- SSP2\_4.5 scenario: shared socio-economic pathway similar to RCP4.5 (moderate emission scenario)
- SSP5\_8.5 scenario: shared socio-economic pathway similar to RCP8.5 (high emission scenario)

An evaluation of the GCMs for simulation of precipitation in the reference period 1961-1990 is shown in Appendix 9.5. The seasonality (timing) is simulated well by most GCMs, albeit the annual precipitation amounts show considerable bias. Overall, it appears that the quality of the GCM data is not as high as with the CORDEX RCMs.

The climate change signals obtained by CMIP6 are displayed in the figures below.



*Figure 38: CMIP6 climate change signals for SSP2\_4.5 (moderate emission scenario). Mean annual values averaged over the Zambezi basin upstream of Cahora Bassa. Reference period 1961-1990. dT: delta in air temperature (future minus reference). dP: ratio in precipitation (future vs reference). Each point represents the results of one CMIP6 GCM climate simulation.*

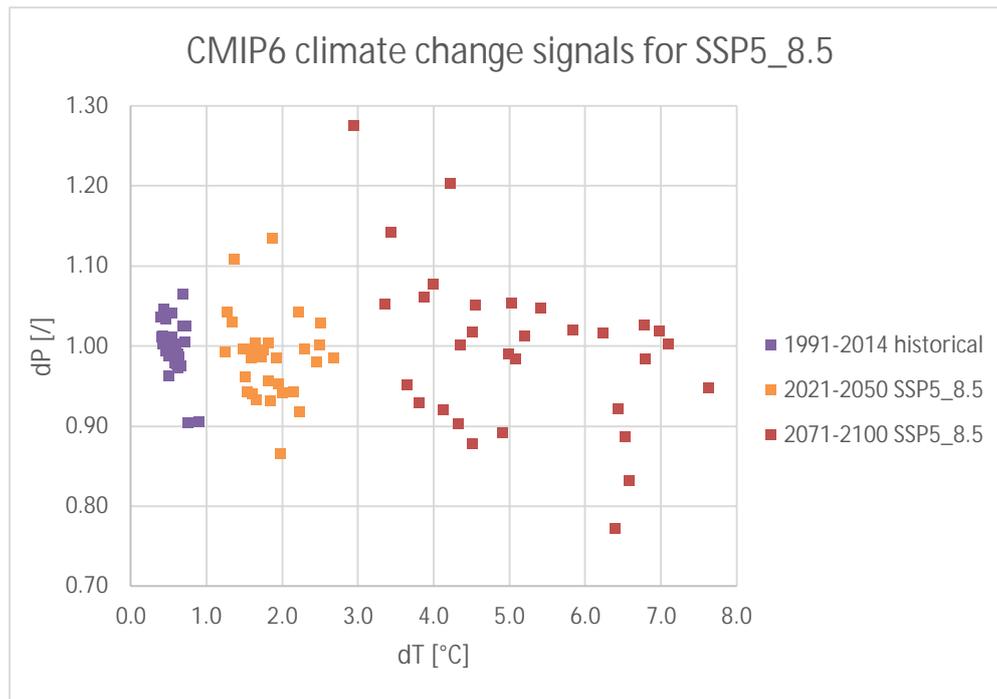


Figure 39: CMIP6 climate change signals for SSP5\_8.5 (high emission scenario). Mean annual values averaged over the Zambezi basin upstream of Cahora Bassa. Reference period 1961-1990. dT: delta in air temperature (future minus reference). dP: ratio in precipitation (future vs reference). Each point represents the results of one CMIP6 GCM climate simulation.

#### 4.5.4 Summary of climate change signals

The table below summarizes the climate change signals discussed in the previous chapters. The mean annual climate change signals were computed versus the reference period 1961-1990 and averaged over the Zambezi basin upstream of Cahora Bassa, for the following variables:

- dT [°C]: change in mean annual air temperature vs the reference period
- dP [']: ratio of mean annual precipitation vs the reference period

Overall the results of CORDEX and CMIP6 agree well, with no pronounced change in precipitation, but considerable warming until the end of the 21<sup>st</sup> century, especially for the high emission scenario.

Figure 40 and Figure 41 visualize the mean annual climate change signals, computed as the median of all CORDEX climate model projections.

Table 7: CORDEX air temperature climate change signals. Summary of 20 RCMs.

CORDEX air temperature change vs 1961-1990						
period	1991-2020	1991-2020	2021-2050	2021-2050	2071-2100	2071-2100
experiment	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
variable	dT [°C]					
lower quartile	0.54	0.65	1.45	1.76	2.45	4.48
median	0.71	0.76	1.63	1.94	2.62	4.91
upper quartile	0.79	0.85	1.78	2.11	3.04	5.32

Table 8: CMIP6 air temperature climate change signals. Summary of 31 GCMs.

CMIP6 air temperature change vs 1961-1990					
period	1991-2014	2021-2050	2021-2050	2071-2100	2071-2100
experiment	historical	SSP2_4.5	SSP5_8.5	SSP2_4.5	SSP5_8.5
variable	dT [°C]	dT [°C]	dT [°C]	dT [°C]	dT [°C]
lower quartile	0.47	1.37	1.57	2.57	4.17
median	0.54	1.59	1.82	3.03	5.00
upper quartile	0.63	1.86	2.08	3.73	6.42

Table 9: CORDEX precipitation climate change signals. Summary of 20 RCMs.

CORDEX precipitation change vs 1961-1990						
period	1991-2020	1991-2020	2021-2050	2021-2050	2071-2100	2071-2100
experiment	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
variable	dP [/]					
lower quartile	0.98	0.97	0.97	0.96	0.95	0.91
median	1.00	0.99	1.00	0.99	0.97	0.94
upper quartile	1.01	1.00	1.01	1.01	1.00	1.00

Table 10: CMIP6 precipitation climate change signals. Summary of 31 GCMs.

CMIP6 precipitation change vs 1961-1990					
period	1991-2014	2021-2050	2021-2050	2071-2100	2071-2100
experiment	historical	SSP2_4.5	SSP5_8.5	SSP2_4.5	SSP5_8.5
variable	dP [/]	dP [/]	dP [/]	dP [/]	dP [/]
lower quartile	0.99	0.96	0.95	0.95	0.93
median	1.00	0.98	0.99	0.97	1.00
upper quartile	1.02	1.01	1.00	1.01	1.05

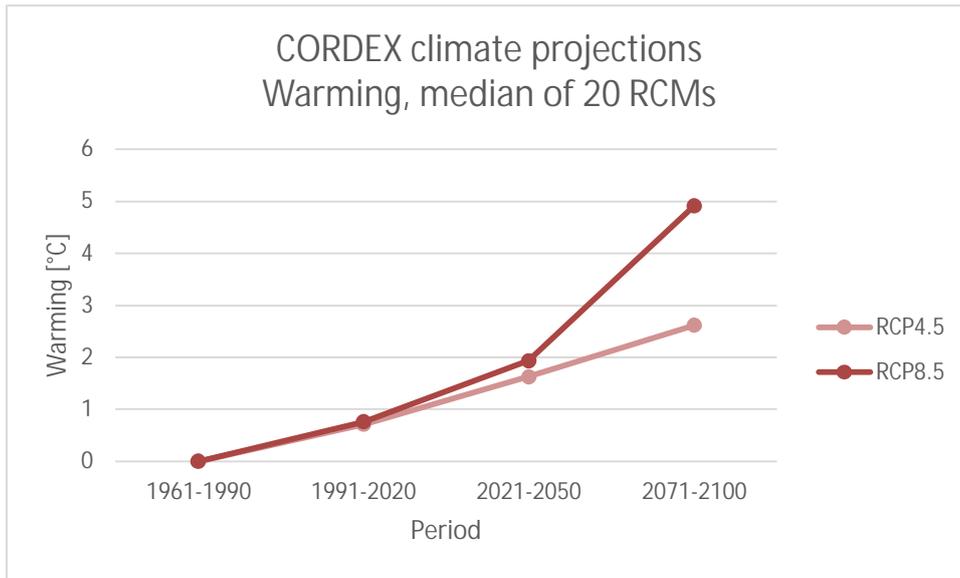


Figure 40: CORDEX air temperature climate change signal for the Zambezi basin upstream of Cahora Bassa. Median of 20 RCMs for two emission scenarios. Mean annual values of 30-year periods.

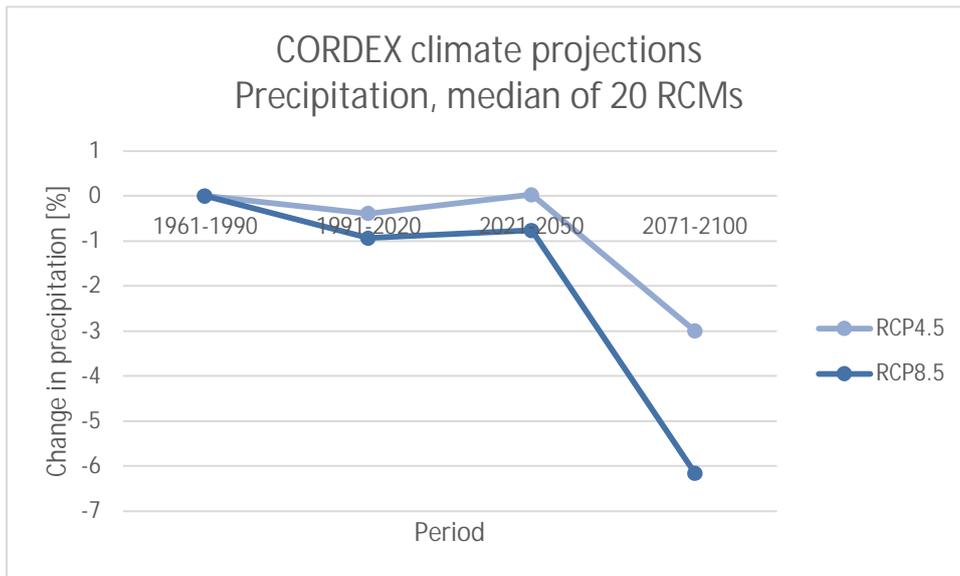


Figure 41: CORDEX precipitation climate change signal for the Zambezi basin upstream of Cahora Bassa. Median of 20 RCMs for two emission scenarios. Mean annual values of 30-year periods.

#### 4.6 Performance metrics

Hydropower operations can be evaluated with respect to (1) generation performance, (2) safety performance and (3) socio-environmental performance. The actual operation is affected by different objectives and constraints, which for Cahora Bassa includes:

- Power generation: Contractual obligations for delivering electricity to South Africa, Mozambique and Zimbabwe.
- Dam flood safety: The maximum spillway capacity of the dam is approximately 13,900 m<sup>3</sup>/s. The design flood inflow (HQ 10,000) is at 28,088 m<sup>3</sup>/s (bi-weekly average, Nippon Koei 2007). As the spillway capacity is considerably lower than the design flood, it is required that the reservoir water level is drawn down before the flood season, such that there is sufficient free storage to attenuate flood inflows. To this end, a flood rule curve is used, which defines maximum allowable water levels for each month. This rule curve was developed and adopted by Hidroelétrica de Cahora Bassa (HCB) and by Direcção Nacional de Águas (the National Directorate for Water, DNA) in 1998. According to the assessment by Nippon Koei (2007), with the given spillway capacity and flood operation rule there would be overtopping of the dam during the design flood.
- Downstream releases and flooding: Tete city is a major urban centre located about 130 km downstream from Cahora Bassa. At Tete the flood warning level is reached at a Zambezi discharge of about 5000 m<sup>3</sup>/s. Therefore, the target in Cahora Bassa operation is to release less than this threshold to avoid flooding in Tete.
- Downstream releases and low-flow: Before the construction of Kariba and Cahora Bassa dams there were extreme low-flow conditions in the Zambezi in the dry season. However, due to constant releases for hydropower generation also in the dry season low flow was considerably enhanced in the last decades. The human activities in the lower Zambezi have adapted to these changed flow conditions.
- Ecological flow releases for the Zambezi delta: No ecological flow requirements are mandatory for the operation for Cahora Bassa. However, several research studies have shown that pre-scribed flooding would benefit the ecological conditions in the Zambezi delta.
- Reservoir uses and water quality: Apart from the storage of water for hydropower operations, the Cahora Bassa reservoir is also used for various other human activities. Currently there are no large-scale irrigation schemes under operation, but human uses include rural drinking water supply, commercial Kapenta fishing and tourism (which includes sportsman fishing). A deterioration of the water quality would negatively impact these activities. The overall importance of these activities is estimated to be small in relation to the importance of the hydropower operations.
- Wildlife habitat: Along the shores of Cahora Bassa reservoir is some prime wildlife habitat, which is partly protected by the proclamation of the new Magoe National Park on the southern shores of the lake. Trophy hunting camps in

adjacent Zimbabwe (Dande North and Dande East) seem to benefit from the seasonal migration of e.g. elephants from Mozambique to Zimbabwe. On the northern shores of the lake a research study (Jacobson et al. 2013) has identified a considerable lion population, which is believed to be one of the largest lion populations in Africa living outside of a protected area.

The performance metrics considered in this study mainly focus on the objectives of HCB for hydropower operations, and not necessarily all of the functions of Cahora Bassa reservoir. The table below presents the definition of performance metrics used in this study.

Table 11: Performance metrics used in this study

Type of performance	Performance metrics
Generation performance	<ul style="list-style-type: none"> <li>• Mean annual generation</li> <li>• Mean monthly generation</li> <li>• Baseload generation: percentage of time at least 4 units are producing power (i.e. power generation greater than 1500 MW)</li> </ul>
Flood safety performance	<ul style="list-style-type: none"> <li>• Extreme flood inflow: monthly flood inflow with a return period of 10,000 years, comparison with monthly design flood inflow of approximately 25,000 m<sup>3</sup>/s</li> <li>• Flood warning level at Tete: Percentage of time where flood discharge at Tete is above the flood warning level of 5000 m<sup>3</sup>/s</li> </ul>

## 5 Climate stress test (Phase 3)

### 5.1 Approach for stress test

Considering the results of the initial analysis (Phase 2), the following approach was applied for the climate stress test.

#### 5.1.1 Hydrological model

AFRY's Zambezi DSS was used as the key modelling platform for the simulation of climate change impacts on Cahora Bassa hydropower operation. To this end, the Zambezi DSS was updated with the following data:

- Update the hydropower operation parameters in Zambezi DSS, based on the Cahora Bassa data received (tailwater curve, efficiency, operation rules, etc.)
- Include new computation points in the Zambezi DSS for:
  - Kafue Hook Bridge
  - Manyame at Chinoyi
  - Luia at Machize
  - Cahora Bassa inflow
- Extend the historic climate data (rainfall, air temperature) until 2021:
  - Rainfall:
    - 1901-2019: GPCC v2020 (replacing the previous version of GPCC)
    - 2020 and 2021: GPM v6 Late Run
  - Air temperature:
    - 1901-2020: CRU v4.05
    - 2021: GFS data, bias correction based on CRU data 2016-2020
- Evaluate the simulation results with the observed flow and reservoir data. Due to the decreasing quality in the rainfall data after 1990, the rainfall data was bias corrected in some years (after 1990) and subbasins.

A comparison between simulated and observed flows is presented in Appendix 9.6. Overall the simulation results with the hydrological model agree well with the available observed flow records, including wet years and dry years (droughts). Therefore, it is concluded that the hydrological model is well suited for the simulation of flow conditions under climate change scenarios.

#### 5.1.2 Climate stress test

For the climate stress test the following approach was used:

- Time periods: As defined in chapter 4.5.1. A further refinement of the time-periods is discussed further below.
- Climate model projections:

- CORDEX RCMs:
  - Exclude poor performing climate model from the ensemble:
    - DMI NCC
  - Bias correction of air temperature data:
    - Bias is corrected as annual average in each subbasin
  - Bias correction of rainfall data:
    - Linear scaling of annual average in each subbasin
    - Scaling of inter-annual rainfall variability in each subbasin
- CMIP6 GCMs:
  - The climate change signals were used to inform on the possible range in the sensitivity analysis, no time-series modelling with CMIP6 data was applied.
- The Zambezi DSS was used for simulation of Cahora Bassa inflow and hydropower operation under climate change scenarios. In the simulations it is assumed that all reservoirs (Kariba, Itezihitezhi, Kafue Gorge Upper, Kafue Gorge Lower, Cahora Bassa) are always under operation, regardless of their commissioning date.
- The simulation results were evaluated with respect to the performance metrics outlined in chapter 4.6.

For the bias correction of RCM rainfall data, two different versions were applied (conservative approach):

- Simulation of reservoir operation: the RCM bias correction was based on the observed climate data of the period 1991-2020, which was a drier period
- Flood frequency analysis of inflow: the RCM bias correction was based on the observed climate data of the period 1961-1990, which was a wetter period

The following simulations were carried out with the Zambezi DSS in the stress test:

- 38 model runs to simulate reservoir operation under climate scenarios:
  - 19 RCM projections under RCP 4.5
  - 19 RCM projections under RCP 8.5
- 38 model runs for flood frequency analysis of inflows:
  - 19 RCM projections under RCP 4.5
  - 19 RCM projections under RCP 8.5
- 1023 (33x31) model runs for sensitivity analysis of climate change signals, combining:
  - 33 warming levels: from 0 to 8°C warming (based on GCM range), in increments of 0.25°C
  - 31 rainfall scenarios: from -30 to +30% (based on GCM range), in increments of 2%

The results were summarized for the following periods:

- Reservoir operation simulations: 30-year periods
  - 1991-2020
  - 2021-2050
  - 2071-2100
- Flood frequency analysis: 50-year periods (to enable more robust calculation of flood values with high return period)
  - 1971-2020
  - 2011-2060
  - 2051-2100
- Sensitivity analysis: 30-year period
  - 1991-2020

### 5.1.3 Uncertainties

In the used methodology, there are several possible sources of uncertainties. This includes:

- Observed climate data: precipitation and air temperature are affected by (a) data quality and (b) natural climate variability
- Hydrological model: (a) model structure, (b) model parameters and (c) reservoir operation rules
- Upstream changes in water resources management: e.g. future development of large-scale irrigation schemes with major water withdrawals reducing downstream flow
- Climate model data:
  - Uncertainty in climate model structure (physical parameterization schemes) affecting long-term climate projections
  - Uncertainty due to emission scenario
  - Natural climate variability
  - Weighting of the different Regional Climate Models (RCMs) in the CORDEX ensemble, with SMHI's RCM dominating the ensemble (see discussion also in Appendix 9.8)
  - In the used bias correction method the first two moments (mean, standard deviation) of annual precipitation are corrected. A remaining bias in monthly frequency distribution and spatio-temporal patterns are not corrected and may impact the runoff simulations with the hydrological model.

- Teleconnections (e.g. El Nino, Indian Ocean Dipole, etc.) are often only poorly represented in climate models, but are expected to exert some control on climate oscillations in South-East Africa.
- Representation of tropical storm systems (intensity, frequency, storm tracks) in climate models is uncertain, but assumed to be of limited significance for the basin upstream of Cahora Bassa. These tropical storm systems form over the Indian Ocean and frequently hit the Mozambican coast, but do not travel further inland upstream of Cahora Bassa, as they lose intensity over hilly terrain.
- Flood frequency analysis: The extrapolation to floods with high return periods (e.g. 10,000-year flood) includes considerable uncertainty and is affected by (a) length of period, (b) choice of frequency distribution (e.g. Gumbel), and (c) the input data (simulated flood values with the hydrological model).

In the set-up of the climate stress test it was aimed at reducing the uncertainty (e.g. in the hydrological model) as much as possible. However, some uncertainty remains, especially with respect to natural climate variability and possible impact of teleconnections (sea surface temperature anomalies) on climate oscillations in the Zambezi basin. The uncertainties are to some extent reported in the results by visualization of the spread with different climate models and emission scenarios. Expert judgement, considering the uncertainties listed above, is used to inform the classification of climate risk in the risk and opportunity register (chapter 6).

## 5.2 Baseline simulation

For the simulation of the baseline period 1991-2020 the hydrological model (Zambezi DSS) was applied with observed climate data, based on the scenario that Cahora Bassa (and all upstream reservoirs) are existing (regardless of commissioning year) and reservoir operation follows typical, current operation rules as of the year 2022. In addition to the simulation results with observed climate reported in this section, the model was also applied with bias-corrected RCM data for the baseline period 1991-2020 and the results are reported in chapter 5.4 together with the climate change projections.

With historic, observed climate the simulation results for the baseline period 1991-2020 are as follows:

- Mean annual inflow to Cahora Bassa: 1844 m<sup>3</sup>/s. This is similar to the observed inflow of 1766 m<sup>3</sup>/s in the same period.
- Mean annual generation at Cahora Bassa: 1704 MW, which is equivalent to an annual energy generation of approximately 14940 GWh. The actual mean power generation of HCB 2004-2021 was 1701 MW, which is similar to the simulation for the baseline period 1991-2020. Compared to the actual values, in

the simulation the two effects of (1) drier climatic conditions in the 1990s (reduced generation) and (2) no unplanned outages (increased generation) cancel out, such that the simulated baseline 1991-2020 is similar to the observed generation 2004-2021.

- Mean monthly generation is given below (in MW) for the simulation of the baseline period 1991-2020:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1538	1679	1827	1837	1797	1763	1738	1727	1708	1651	1585	1596

- Baseload generation: In the simulation for 1991-2020 power generation is at least 1500 MW 80% of the time, i.e. 4 or 5 units producing power. 80% is equivalent to 292 days per year. For comparison, in the period 2004-2021 the observed monthly power generation exceeded 1500 MW during 82% of the time (299 days per year).
- Flood warning level at Tete: In the baseline period 1991-2020 the simulated outflow from Cahora Bassa is greater than 5000 m<sup>3</sup>/s during 0.8% of the time, which is equivalent to 3 days per year. This is identical to the observed value computed from monthly observed outflow in the same period 1991-2020. Note, that in the dry years of the 1990s this threshold of 5000 m<sup>3</sup>/s was never reached, but in the later (wetter) years this threshold was reached in a total of three months.

For the inflow design flood a monthly peak flow of 25,000 m<sup>3</sup>/s is adopted based on the report of Nippon Koei (2007). For more information and results of the flood frequency analysis see chapter 5.5.

### 5.3 Results of sensitivity analysis

The following figures show the sensitivity of mean annual outflow and power generation at Cahora Bassa as a function of changes in mean annual precipitation and air temperature in the upstream catchment. The sensitivity is presented as a percentage of the baseline simulation for 1991-2020.

The results for the sensitivity of power generation to precipitation show that there is only a small upside potential (Figure 42 right part). Under a wetting climate the inflow would increase, but this would result in increased spillway losses and reduced hydraulic head due to higher tailwater levels. Therefore, the increase in power generation is rather

small with approximately +10% power generation under very wet climate conditions, even though the outflow (turbines + spillway losses) increases by about +100% (i.e. doubles) for 20% increase in annual rainfall.

In contrast, under a drying climate (Figure 42 left part) the changes in outflow and power generation correspond very well. For -20% in annual rainfall both outflow and power generation decrease by about -55%. This amplified sensitivity of changes in discharge compared to changes in rainfall is a typical behaviour in semi-arid river basins and is well documented in the scientific literature for the Zambezi (see e.g. Kling et al. 2014).

The sensitivity to changes in air temperature is considerably lower (Figure 43). Under a warming scenario of +4°C the mean annual outflow changes by -17% and the power generation by -12%. These changes in power generation are due to reduced inflow (higher evapotranspiration in the catchment areas), higher reservoir evaporation losses (in Cahora Bassa, and also Kariba), but slightly buffered by reduced spillway losses and lower tailwater level (which is beneficial for increasing hydraulic head).

Table 12 and Table 13 summarize the sensitivity of Cahora Bassa outflow and power generation as a function of changes in precipitation and air temperature.

The two-dimensional sensitivity of discharge and power generation to joint changes in precipitation and air temperature is shown in Figure 44 and Figure 45 (also see accompanying figures in plan view in Appendix 9.7). These plots allow to compare the results to any combination of future projected changes in precipitation and air temperature, as e.g. projected by the CMIP6 GCM ensemble (compare to Figure 38 and Figure 39). This is equivalent to a bias correction of GCM data with the delta-change method, under the assumption that there are no changes in the spatio-temporal patterns in rainfall, but only gradual, spatially homogeneous changes in the mean annual values. As this assumption may hold for air temperature, but is unlikely for precipitation, simulations with more detailed climate models (RCMs) and more advanced bias correction methods are carried out and the results are presented in chapter 5.4.

In conclusion, the results of the sensitivity analysis show that:

- Discharge is highly sensitive to changes in precipitation.
- The sensitivity to air temperature is lower.
- Under a wetting climate there is little upside potential for power generation with the current plant set-up.
- Under a drying climate the changes in power generation correspond well to changes in discharge.

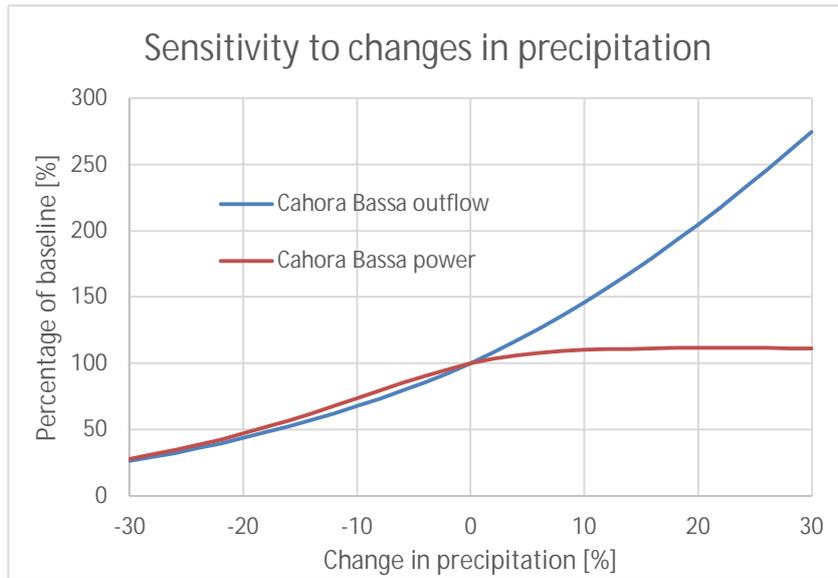


Figure 42: Sensitivity of Cahora Bassa mean annual outflow and power generation to changes in annual precipitation. Compared to baseline simulation 1991-2020.

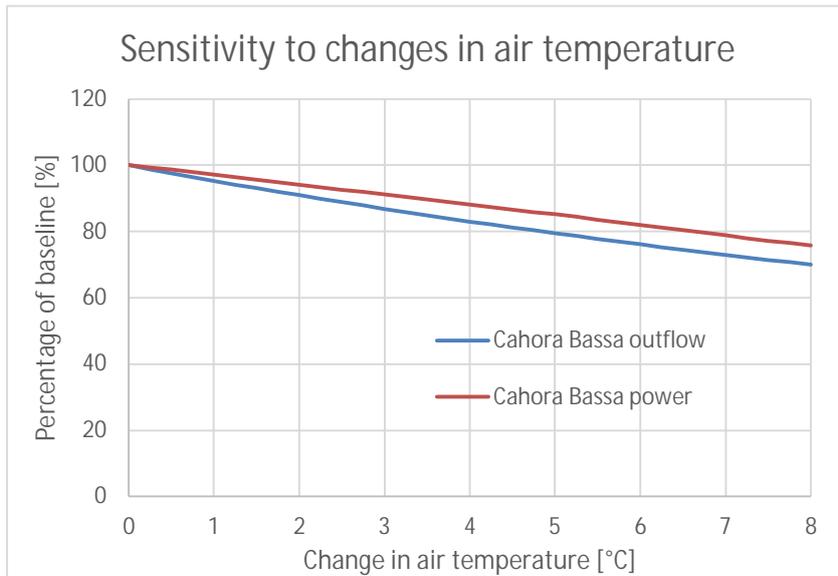


Figure 43: Sensitivity of Cahora Bassa mean annual outflow and power generation to changes in annual air temperature. Compared to baseline simulation 1991-2020.

Table 12: Summary of sensitivity analysis of Cahora Bassa mean annual discharge and power generation to changes in precipitation. Compared to baseline simulation 1991-2020.

Sensitivity analysis for precipitation (baseline 1991-2020)							
Change in precipitation [%]	-30	-20	-10	0	10	20	30
Discharge [m <sup>3</sup> /s]	465.8	773.5	1201.3	1773.4	2588.1	3630.6	4871.8
Power [MW]	477.7	800.1	1257.4	1705.3	1876.0	1904.1	1892.7
Change in Discharge [%]	-73.7	-56.4	-32.3	0.0	45.9	104.7	174.7
Change in Power [%]	-72.0	-53.1	-26.3	0.0	10.0	11.7	11.0

Table 13: Summary of sensitivity analysis of Cahora Bassa mean annual discharge and power generation to changes in air temperature. Compared to baseline simulation 1991-2020.

Sensitivity analysis for air temperature (baseline 1991-2020)					
Change in air temperature [°C]	0	2	4	6	8
Discharge [m <sup>3</sup> /s]	1773.4	1612.2	1471.5	1349.4	1240.7
Power [MW]	1705.3	1603.7	1502.4	1398.4	1291.4
Change in Discharge [%]	0.0	-9.1	-17.0	-23.9	-30.0
Change in Power [%]	0.0	-6.0	-11.9	-18.0	-24.3

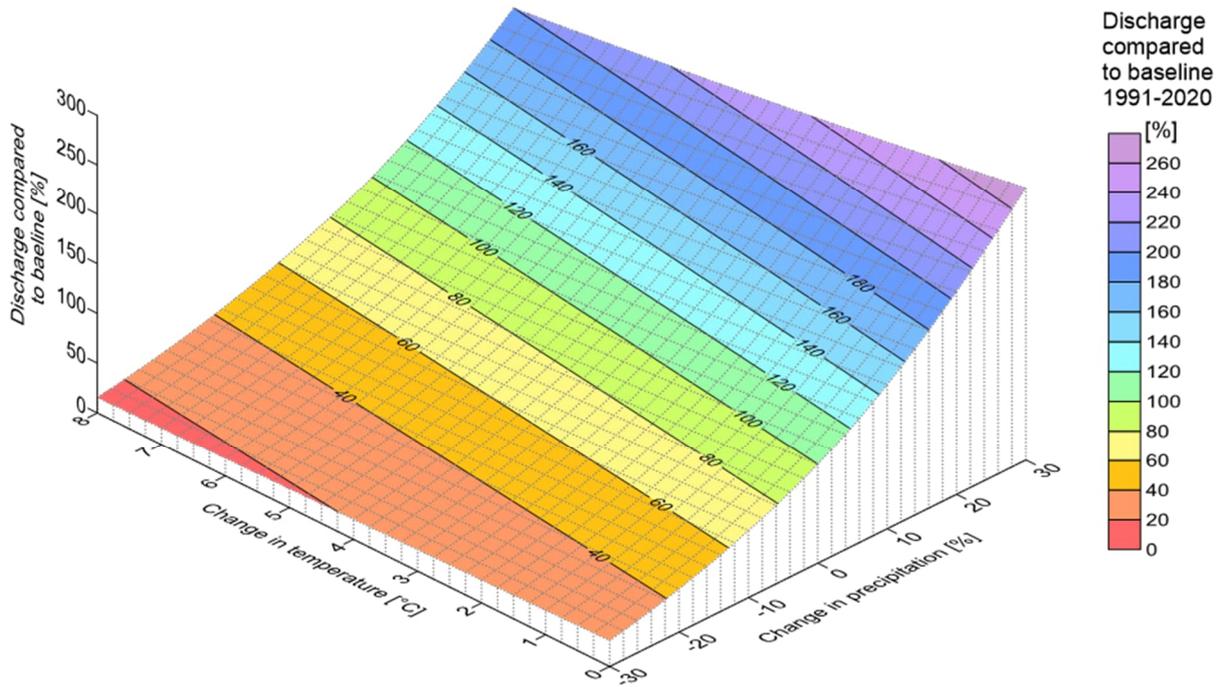


Figure 44: Sensitivity of Cahora Bassa mean annual outflow to joint changes in precipitation and air temperature.

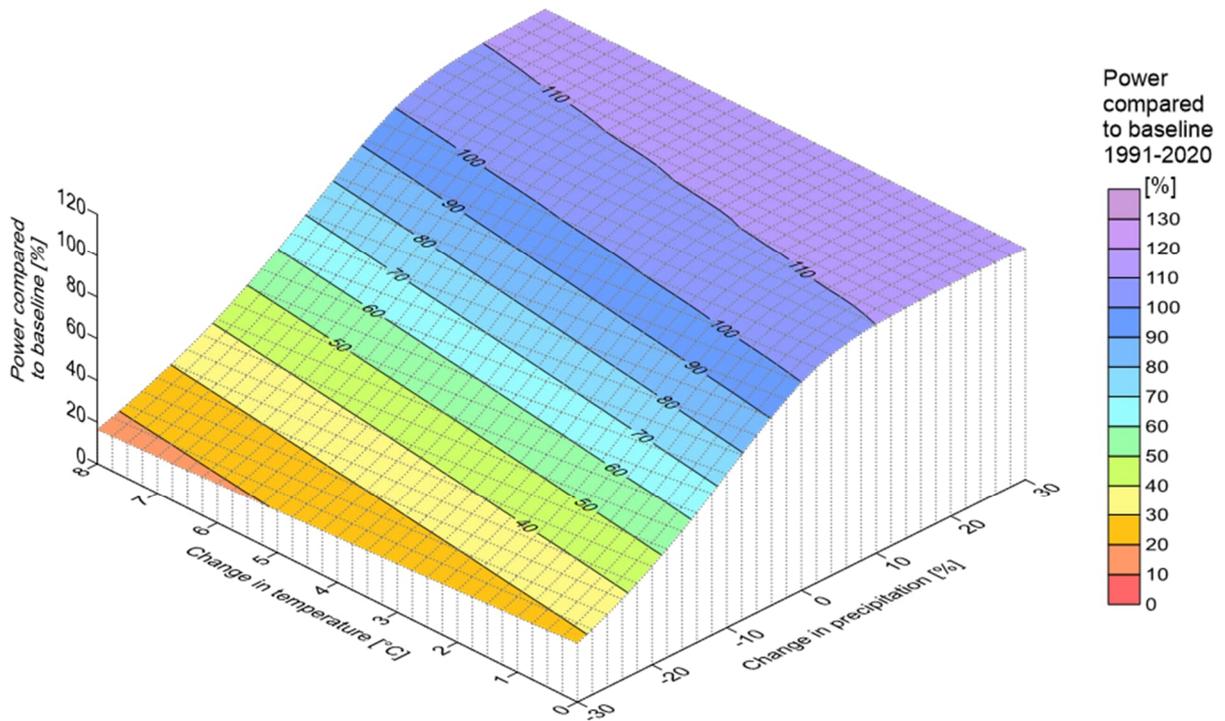


Figure 45: Sensitivity of Cahora Bassa mean annual power generation to joint changes in precipitation and air temperature.

## 5.4 Results for reservoir simulation under climate scenarios

The results for reservoir simulation under CORDEX climate scenarios are presented in the following graphs. For a specific time period and emission scenario there are overall 19 climate change scenario simulation results, based on the RCM projections. The spread in the 19 climate change scenarios was summarized as follows:

- Maximum: highest RCM projection
- Upper quartile: 5<sup>th</sup> highest RCM projection
- Median: 10<sup>th</sup> highest RCM projection
- Lower quartile: 5<sup>th</sup> lowest RCM projection
- Minimum: lowest RCM projection

Graphically the above values are presented as box plots, where the middle line shows the median, the box shows the range between the upper and lower quartile and the whiskers extend to the maximum and minimum values.

In the method outlined above all 19 climate projections are treated equally, even though one RCM (of SMHI) provided more than half (i.e. 10) of the overall 19 climate projections. An alternative method for averaging the climate projections is discussed in Appendix 9.8. Even though the results are slightly different, the overall conclusions remain unchanged.

Mean annual inflow to Cahora Bassa under climate change scenarios shows considerable spread dependent on the climate model (Figure 46, Table 14). In the near future both an increase and decrease in mean annual inflow is possible (also due to natural climate variability). However, in the far future the climate change signal is strong and there is a clear tendency that inflow is projected to decrease considerably. This is the result of superposition of considerable warming (higher evapotranspiration and less runoff generation) and reduced rainfall, as well as higher evaporation losses in upstream reservoirs (Kariba, Itezihetzi) and flood plains (Barotse, Kafue Flats, etc.). Under the low emission scenario (RCP 4.5) inflow is projected to decrease by about 11% (median of 19 RCMs), whereas under the high emission scenario (RCP 8.5) inflow is projected to decrease by about 15%.

A detailed examination of the projected mean annual inflow for the near future shows that under the high emission scenario (RCP 8.5) the inflow is slightly larger than under the low emission scenario (RCP 4.5). Under RCP 8.5 the RCMs show a slight increase in rainfall compared to the baseline period. As the temperature signal is not strong enough, this leads to a slight increase in inflow. This effect is also discernible in the subsequent analysis of mean annual power generation and baseload generation.

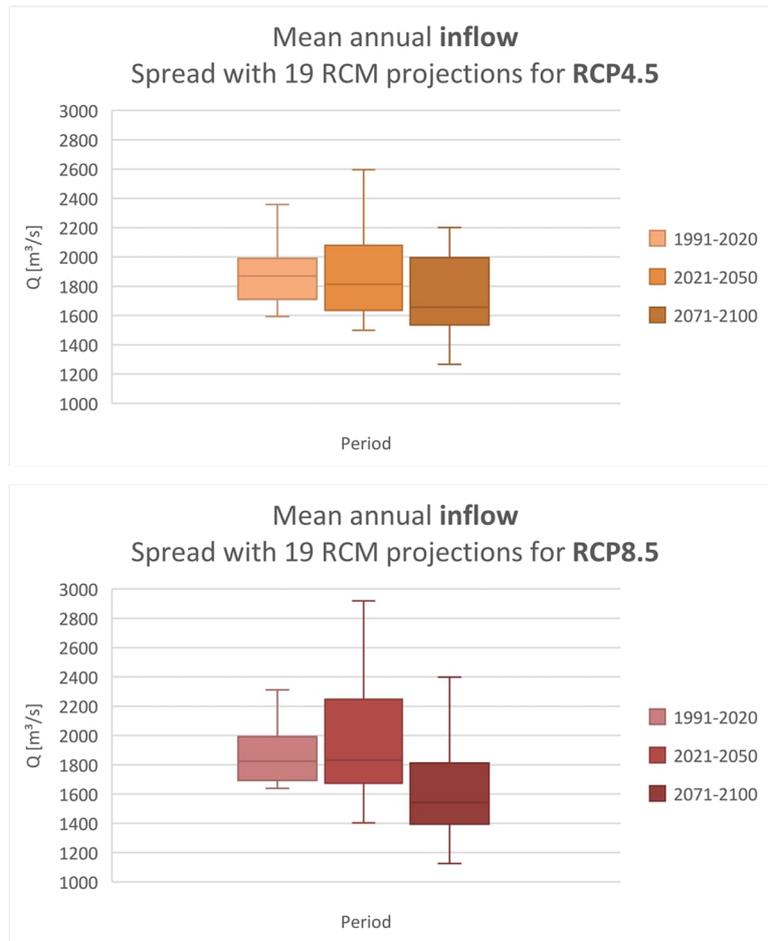


Figure 46: Mean annual inflow to Cahora Bassa under CORDEX climate change scenarios. Boxplots summarize the spread of results with 19 RCM projections. Top: Emission scenario RCP 4.5. Bottom: Emission scenario RCP 8.5.

Table 14: Mean annual inflow to Cahora Bassa simulated under CORDEX climate change scenarios. Summary of 19 RCM projections for two emission scenarios.

Mean annual inflow under climate change scenarios												
	Mean annual inflow [m <sup>3</sup> /s]						Relative change versus (median of) 1991-2020 [%]					
	RCP 4.5			RCP 8.5			RCP 4.5			RCP 8.5		
period	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile
1991-2020	1709.9	1869.8	1990.3	1692.6	1823.4	1991.6						
2021-2050	1635.4	1813.9	2079.8	1673.6	1831.2	2246.0	-12.5	-3.0	11.2	-8.2	0.4	23.2
2071-2100	1536.8	1655.8	1995.6	1394.8	1543.5	1811.2	-17.8	-11.4	6.7	-23.5	-15.3	-0.7

In the near future, mean monthly inflow to Cahora Bassa is projected to be similar to the baseline (median of 19 RCM simulations 1991-2020), as shown in Figure 47 (left

panel). Some RCMs show higher inflow, others lower inflow (shaded areas in the figure) and overall there is no clear climate change signal for the near future. In the far future inflow is projected to decrease in all months, especially under the high emission scenario RCP 8.5. But also under the low emission scenario RCP 4.5 inflow is projected to decrease in all months in the far future (Figure 47, upper right graph), albeit this decrease is very low in August to December, as here the inflow mainly depends on Kariba operations, which shows little variation in the simulation for the near future.

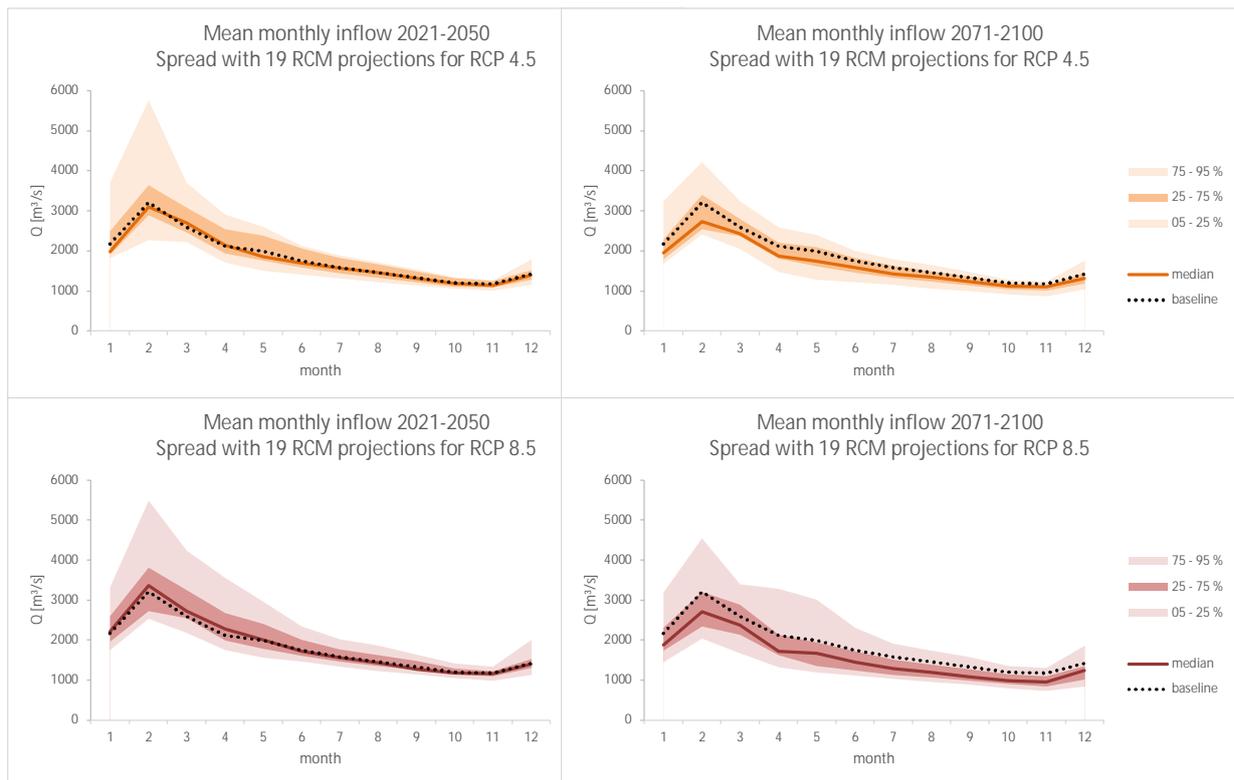


Figure 47: Mean monthly inflow to Cahora Bassa under CORDEX climate change scenarios. The shaded areas summarize the spread of results with 19 RCM projections. The baseline (black dashed line) represents the median of RCM simulations for the period 1991-2020. Top: Emission scenario RCP 4.5. Bottom: Emission scenario RCP 8.5. Left: period 2021-2050. Right: period 2071-2100.

Mean annual power generation is projected to be similar in the near future compared to the baseline (Figure 48 and Table 15), with an annual average of roughly 1700 MW, which is equivalent to an annual energy generation of roughly 14,900 GWh. In the far future, power generation is projected to decrease by 9% under low emissions (RCP 4.5) and 15% under high emissions (RCP 8.5), which is in line with the projected changes in mean annual inflow (compare to Figure 46 and Table 14). Overall the projected changes in power generation are slightly lower than the changes in inflow, as power generation is buffered by the tailwater curve (lower outflow means increased hydraulic

head) and reduced spillway losses. Under a drying climate spillway losses are reduced, and thus turbined flow does not decrease as much as the inflow. On the other hand, this is to some extent counter-balanced by increased climate variability (increased spillway losses in some unusually wet years).

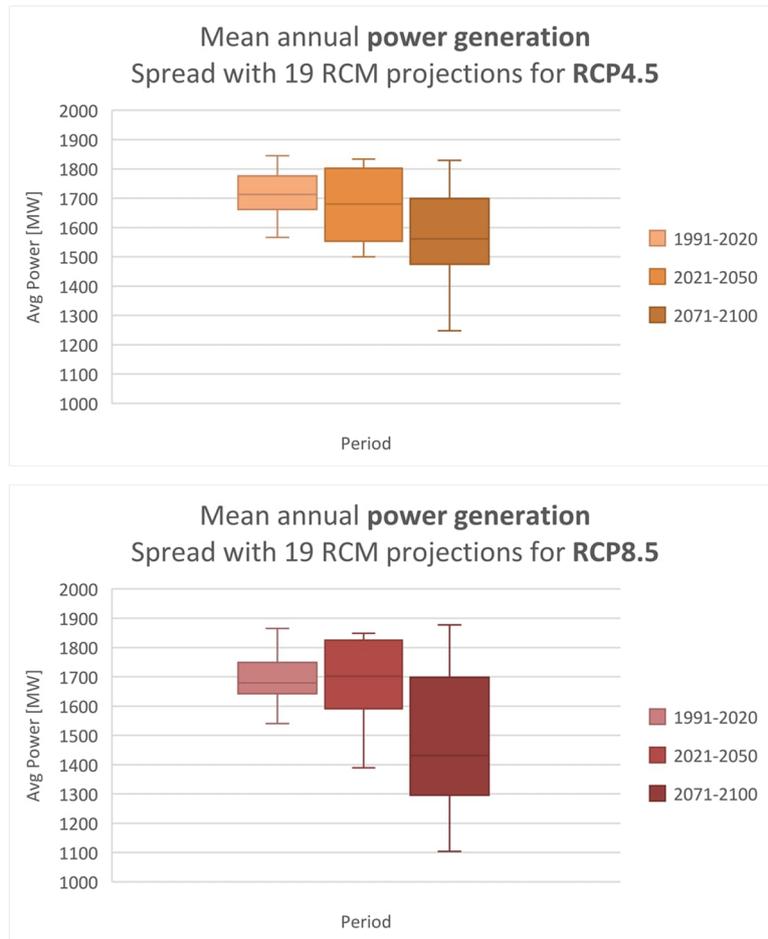


Figure 48: Mean annual power generation at Cahora Bassa under CORDEX climate change scenarios. Boxplots summarize the spread of results with 19 RCM projections. Top: Emission scenario RCP 4.5. Bottom: Emission scenario RCP 8.5.

Table 15: Mean annual power generation at Cahora Bassa simulated under CORDEX climate change scenarios. Summary of 19 RCM projections for two emission scenarios.

Mean annual power generation under climate change scenarios												
period	Mean annual power generation [MW]						Relative change versus (median of) 1991-2020 [%]					
	RCP 4.5			RCP 8.5			RCP 4.5			RCP 8.5		
	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile
1991-2020	1661.3	1712.8	1776.1	1642.5	1679.0	1748.8						
2021-2050	1553.0	1680.1	1801.9	1590.6	1702.2	1824.6	-9.3	-1.9	5.2	-5.3	1.4	8.7
2071-2100	1474.6	1561.6	1699.0	1295.9	1431.4	1698.5	-13.9	-8.8	-0.8	-22.8	-14.7	1.2

Mean monthly power generation is projected to be similar to the baseline in the near future, but to decrease in all months in the far future (Figure 49). Note that this also applies to the low emission scenario RCP 4.5, even though the inflow is not projected to decrease in all months (compare to Figure 47). This is due to increased evaporation losses and overall lower reservoir water levels (cumulative effect of inflow reduction over preceding months).

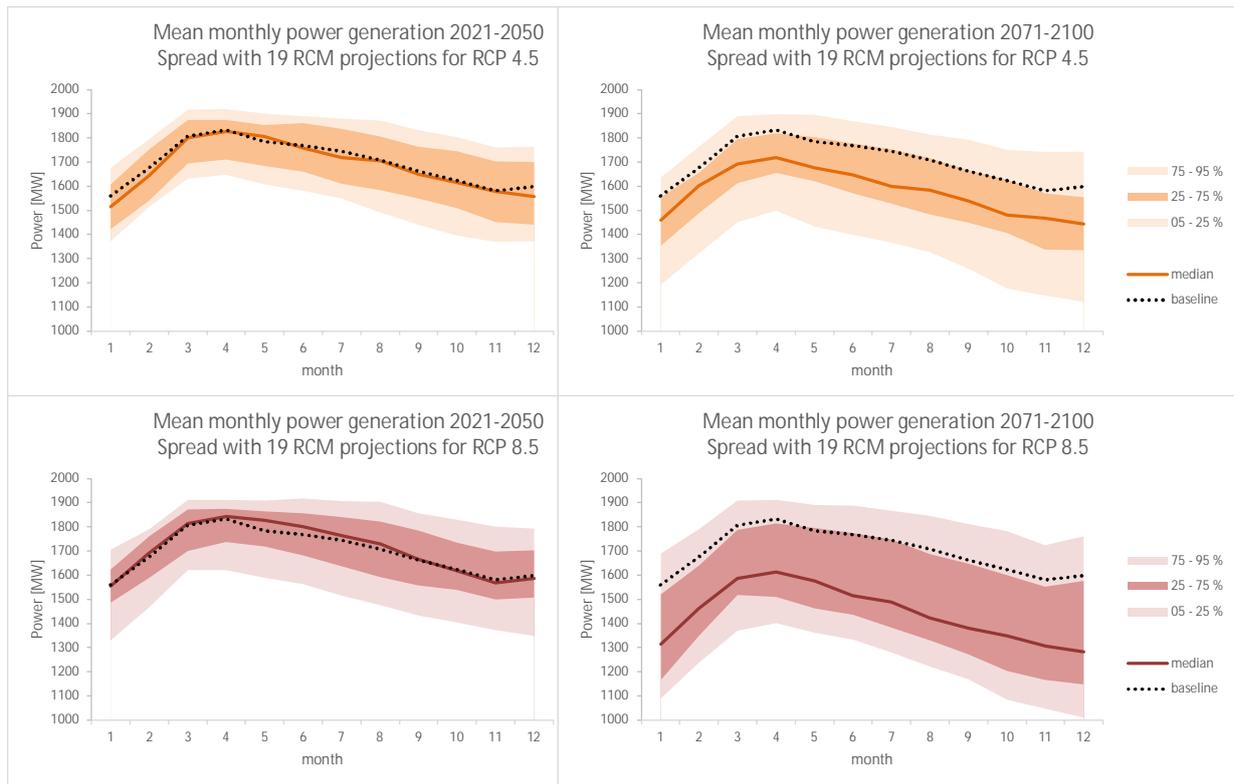


Figure 49: Mean monthly power generation at Cahora Bassa under CORDEX climate change scenarios. The shaded areas summarize the spread of results with 19 RCM projections. The baseline (black dashed line) represents the median of RCM simulations for the period 1991-2020. Top: Emission scenario RCP 4.5. Bottom: Emission scenario RCP 8.5. Left: period 2021-2050. Right: period 2071-2100.

The simulated baseload generation was analysed for the baseline, near future and far future by computing the percentage of time in the 30-year periods the power generation is above 1500 MW, which means that either 4 or 5 units are producing power. In the baseline the baseload generation is met about 80% of the time (Figure 50 and Table 16). A similar value is computed for the near future, meaning that the projections show no change in baseload generation in the near future. However, in the far future the projections show that baseload generation is met only about 67% of the time under the low emission scenario RCP 4.5. This is reduced to 51% of the time under the high emission scenario RCP 8.5. Such a scenario would mean that in a typical year Cahora Bassa can only meet the baseload generation target in 6 out of 12 months.

The baseload power generation evaluated for different percentiles is given in Appendix 9.9 (e.g. p.95, i.e. power generation that is exceeded 95% of the time).

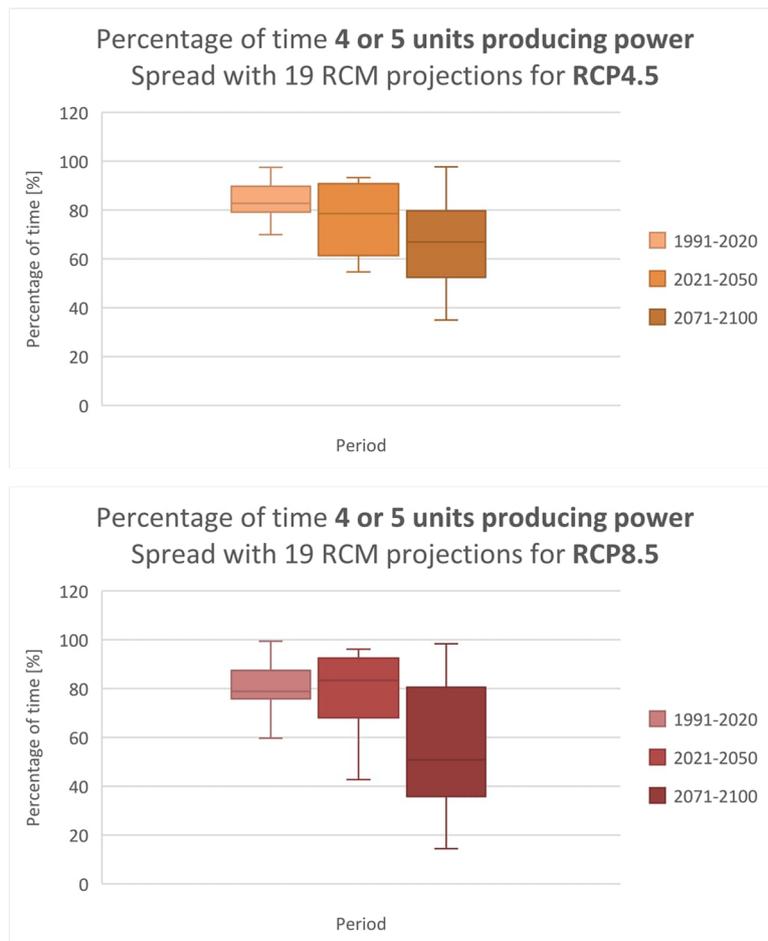


Figure 50: Simulated baseload power generation at Cahora Bassa under CORDEX climate change scenarios. The graph shows the simulated percentage of time the target power generation of at least 1500 MW (i.e. at least 4 units running) is fulfilled. Boxplots summarize the spread of results with 19 RCM projections. Top: Emission scenario RCP 4.5. Bottom: Emission scenario RCP 8.5.

Table 16: Baseload power generation at Cahora Bassa simulated under CORDEX climate change scenarios. Summary of 19 RCM projections for two emission scenarios. The table lists the simulated percentage of time the baseload target of at least 1500 MW (i.e. at least 4 units produce power) is fulfilled.

Baseload power generation under climate change scenarios												
	Percentage of time power generation > 1500 MW [%]						Absolute change versus (median of) 1991-2020 [%]					
	RCP 4.5			RCP 8.5			RCP 4.5			RCP 8.5		
period	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile
1991-2020	79.2	82.8	89.7	75.8	78.9	87.5						
2021-2050	61.4	78.6	90.8	68.1	83.3	92.5	-21.4	-4.2	8.1	-10.8	4.4	13.6
2071-2100	52.5	66.9	79.7	35.8	50.8	80.6	-30.3	-15.8	-3.1	-43.1	-28.1	1.7

The flood warning level is reached at Tete at a flow value of 5000 m<sup>3</sup>/s. Therefore, a target of Cahora Bassa operations is to release less than 5000 m<sup>3</sup>/s to avoid reaching the flood warning level at Tete. The simulation results under climate change scenarios show that in the near future and far future this threshold is rarely reached (Figure 51).

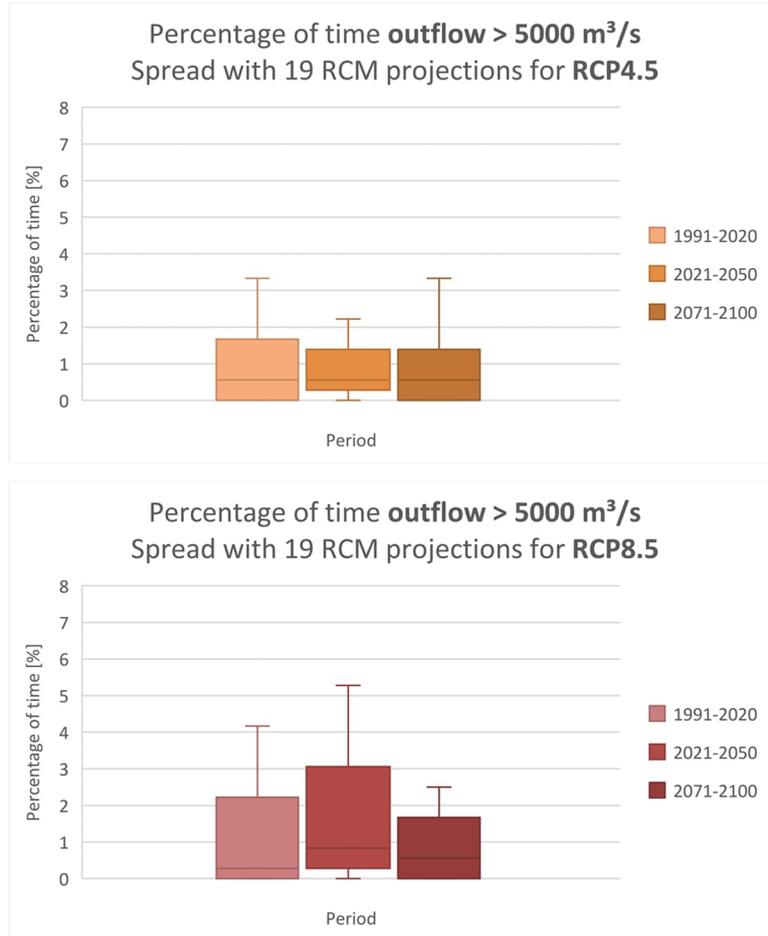


Figure 51: Simulated percentage of time outflow from Cahora Bassa is greater than 5000 m<sup>3</sup>/s under CORDEX climate change scenarios. Boxplots summarize the spread of results with 19 RCM projections. Top: Emission scenario RCP 4.5. Bottom: Emission scenario RCP 8.5.

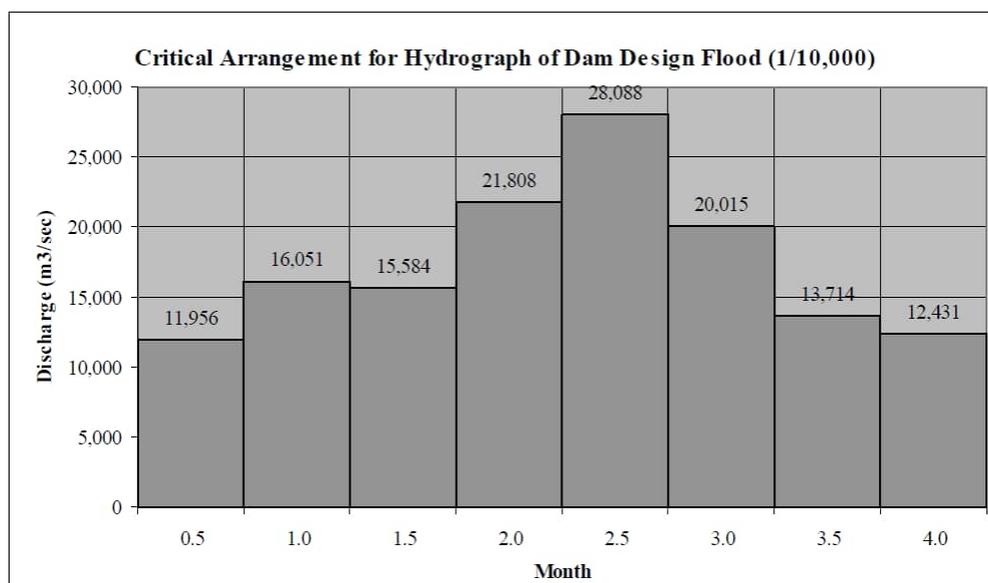
In the figures and tables above the results were presented for the near future period 2021-2050 and the far future period 2071-2100. Results for the intermediate future period 2051-2070 are presented in Appendix 9.10. These results show that in the intermediate future period there is a gradual transition between the results for the near future and far future.

### 5.5 Results for flood frequency analysis under climate scenarios

Cahora Bassa’s inflow design flood is based on a flood with a return period of 10,000 years. The inflow design flood is shown in Figure 52. For the inflow design flood not so much the daily peak, but rather the flow volume over several weeks/months is of key interest, as a considerable share of the inflow is stored in the reservoir to attenuate the flood. Peak monthly flow is a suitable indicator for the inflow volume under flood conditions. The peak monthly flow for Cahora Bassa’s inflow design flood is approximately 25,000 m<sup>3</sup>/s (average of 28,088 in the peak half month and 21,808 in the 2<sup>nd</sup> highest half month, see Figure 52).

The simulation results of Zambezi DSS are used for a subsequent flood frequency analysis of annual maxima of monthly inflow to Cahora Bassa under climate change scenarios. The Gumbel distribution is used for the flood frequency analysis (see example in Figure 53, additional examples are included in Appendix 9.11).

Flood frequency analyses for the historic period 1971-2020 are shown in Figure 54. For the 10,000-year flood there is a considerable spread between the results with different RCM climate simulations. This is due to varying representation of natural climate variability in the climate models and the inherent uncertainty in the estimation of floods with a high return period. Also remaining deficiencies in the bias-corrected RCM climate data has some effect. However, the median of all RCM-based simulations is quite close to the inflow design flood value of 25,000 m<sup>3</sup>/s. In addition, also the flood frequency analysis of observed inflow (black line) and simulated inflow (with observed climate data 1976-2021, red line) are close to the design flood value of 25,000 m<sup>3</sup>/s.



**Design Flood Hydrograph Recommended by TDD Study**

Figure 52: Inflow design flood for Cahora Bassa. Source: Nippon Koei report (2007).

### CLMcom-ICHEC rcp85 1971-2020

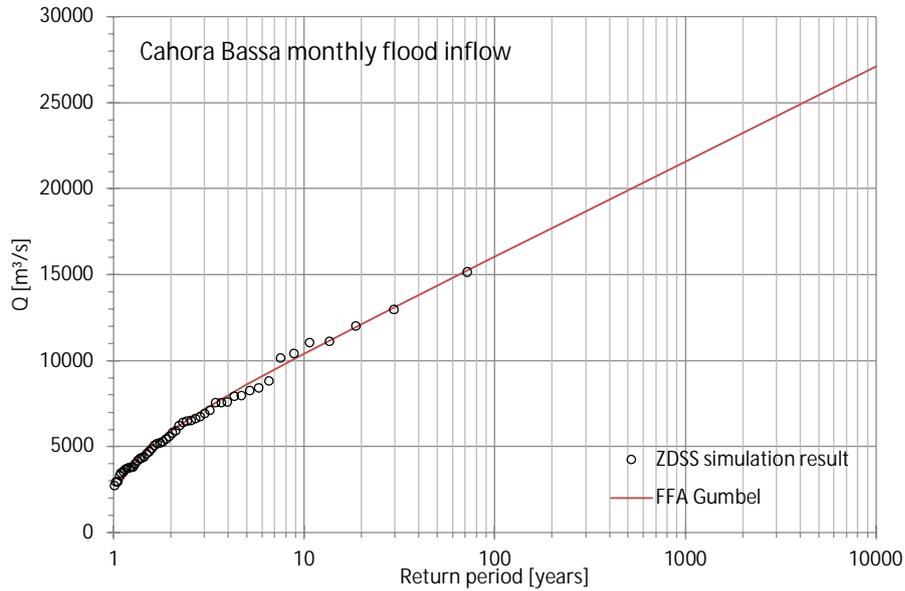


Figure 53: Flood frequency analysis for annual maxima of monthly inflow to Cahora Bassa. Black dots: simulated by Zambezi DSS. Red line: fitted Gumbel distribution. Example for simulation results with input data from the RCM CLMcom-ICHEC for RCP 8.5 in the period 1971-2020.

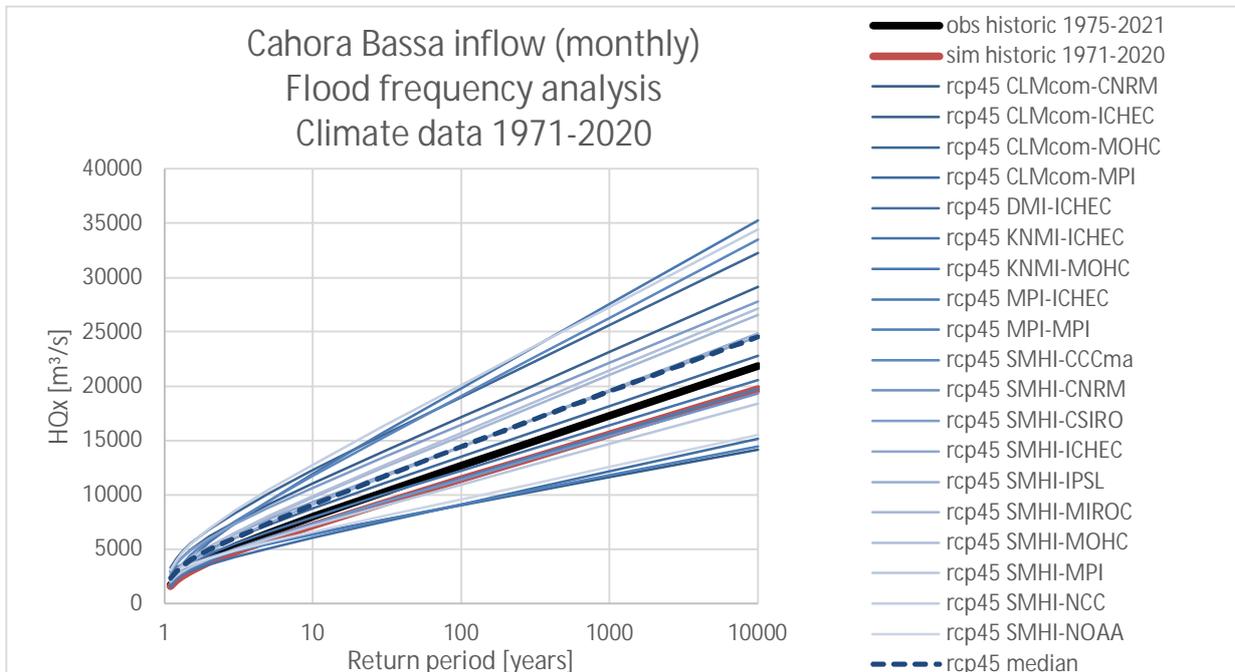


Figure 54: Flood frequency analysis for Cahora Bassa inflow under different climates for 1971-2020. Blue lines: Simulation results with different RCMs. Dashed line: Median of all RCM-based simulations. Red: Simulation result with observed historic climate. Black: Flood frequency analysis for observed inflow data.

The flood frequency analysis was repeated for:

- Three periods:
  - Simulation results for historic period 1971-2020
  - Simulation results for the near future period 2011-2060
  - Simulation results for the far future period 2051-2100
- Two emission scenarios RCP 4.5 and RCP 8.5
- 19 different RCM projections

Overall, the flood frequency analysis was repeated 114 times ( $114 = 3 \times 2 \times 19$ ).

The spread in the simulation results for the 10,000-year monthly flood inflow with 19 different RCM projections was summarized as follows:

- Maximum: highest RCM projection
- Upper quartile: 5<sup>th</sup> highest RCM projection
- Median: 10<sup>th</sup> highest RCM projection
- Lower quartile: 5<sup>th</sup> lowest RCM projection
- Minimum: lowest RCM projection

Graphically the above values are presented as box plots in Figure 55, where the middle line shows the median, the box shows the range between the upper and lower quartile and the whiskers extend to the maximum and minimum values.

Under the emission scenario RCP 4.5 the median of all RCM projections shows no change in future extreme flood inflow, whereas under RCP 8.5 there is a slight increase in future extreme flood inflow as compared to the simulation results in the period 1971-2020. The simulation results also show:

- Increased climate variability may lead to higher extreme flood inflow in the near future (2011-2060), as evidenced by the increased upper quartile of the boxplot.
- Continued drying in the Zambezi basin may lead to a reduction in extreme flood inflow in the far future (2051-2100), as evidenced by the reduced upper quartile of the boxplot.

Table 17 lists a summary of the simulation results for the 10,000-year monthly flood inflow to Cahora Bassa.

In general the simulation results show that the 10,000-year monthly inflow flood is in the range of 20,000 – 30,000 m<sup>3</sup>/s. It has to be noted that with the current operation rules (drawn down of reservoir water level before flood season) and existing spillway capacity a 10,000-year flood inflow would lead to an over-topping of the dam. This emphasizes the need for adaptation as already recommended in the report by Nippon Koei (2007).

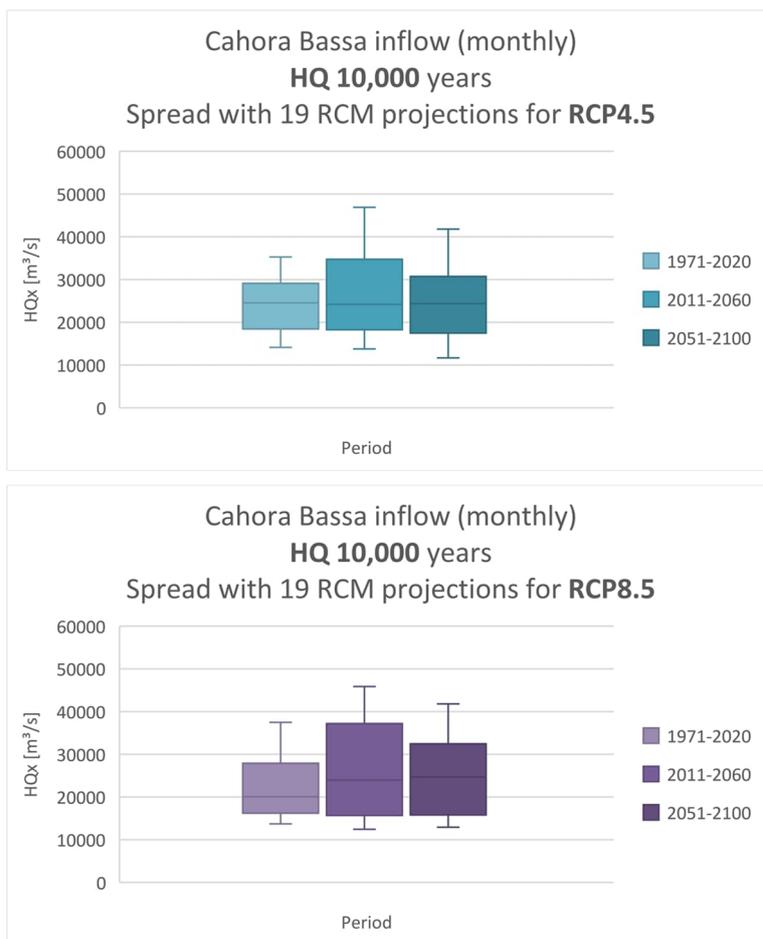


Figure 55: Extreme flood inflow to Cahora Bassa under CORDEX climate change scenarios. Boxplots summarize the spread of results with 19 RCM projections. Top: Emission scenario RCP 4.5. Bottom: Emission scenario RCP 8.5.

Table 17: Extreme flood inflow at Cahora Bassa simulated under CORDEX climate change scenarios. Summary of 19 RCM projections for two emission scenarios. Monthly flood inflow with a return period of 10,000 years computed with the Gumbel distribution.

Extreme flood inflow under climate change scenarios												
period	Monthly HQ 10,000 [m³/s]						Relative change versus (median of) 1971-2020 [%]					
	RCP 4.5			RCP 8.5			RCP 4.5			RCP 8.5		
	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile	lower quartile	median	upper quartile
1971-2020	18,422	24,535	29,115	16,229	20,074	27,931						
2011-2060	18,282	24,208	34,746	15,691	23,980	37,176	-25.5	-1.3	41.6	-21.8	19.5	85.2
2051-2100	17,465	24,397	30,708	15,841	24,706	32,470	-28.8	-0.6	25.2	-21.1	23.1	61.8

## 5.6 Summary and conclusions

A sensitivity analysis was applied, which covers the range of future rainfall and air temperature as projected by the CMIP6 global climate models. The results show the high sensitivity of Cahora Bassa inflow to only small changes in rainfall. Air temperature changes also exert an influence on inflow (due to evapotranspiration losses), but not as strong as rainfall. With the current installed capacity there is little upside potential for power generation under a wetting climate, but considerable downside potential under a drying climate.

In the climate stress test the generation performance and flood safety performance were evaluated under various different climate scenarios as projected by the CORDEX Regional Climate Model ensemble. No relevant change is projected for the near future, but considerable decrease in inflow and power generation is projected for the far future.

The flood frequency analysis of simulated inflow under climate change scenarios shows that under current climatic conditions, as well as in the future, the 10,000-year flood is considerably larger than the spillway capacity. This also applies for the 10,000-year flood in the far future, where increased climate variability offsets the overall trend of reduced inflow due to drier climatic conditions.

## 6 Risk and opportunity register

Based on the information collected (Phase 1 and Phase 2) as well as the climate stress test (Phase 3) a climate risk and opportunity register has been developed and is presented below.

In the presented framework, risk is defined as

$$\text{Risk} = \text{Loss} \times \text{Likelihood}$$

and similarly, opportunity is defined as

$$\text{Opportunity} = \text{Gain} \times \text{Likelihood}$$

This methodology is qualitatively applied for the risk and opportunity register for the near future and far future. The classification is based on expert judgement guided by the simulation results of the climate stress test. Both emission scenarios (RCP 4.5 and 8.5) are treated as equally plausible and are implicitly considered in the expert judgements of climate risks.

The climate risk and opportunity register uses a classification of consequence levels (potential gains and losses, Table 18), likelihood levels (Table 19) and risk and opportunity levels (Table 20). The relation between these different classification levels is shown in Table 21. A verbal description of the classification levels is provided in Appendix 9.12.

Table 18: Consequence levels used for classification of gains and losses

Potential gain			No impact	Potential loss		
High	Medium	Low	None	Low	Medium	High
G3	G2	G1	N0	L1	L2	L3

Table 19: Likelihood levels

Likelihood		
Unlikely	Possible	Likely
1	2	3

Table 20: Risk and opportunity levels

Opportunities					No impact	Risks				
Large	Major	Moderate	Minor	Negligible	None	Negligible	Low	Medium	High	Very high
O4	O3	O2	O1	O0	N0	R0	R1	R2	R3	R4

Table 21: Opportunity (green) and risk (red) levels in relation to potential gains (blue) and losses (orange) as well as likelihood level (grey)

			Potential gain			No impact	Potential loss		
			High	Medium	Low	None	Low	Medium	High
			G3	G2	G1	N0	L1	L2	L3
Likelihood	Unlikely	1	O2	O1	O0	N0	R0	R1	R2
	Possible	2	O3	O2	O1	N0	R1	R2	R3
	Likely	3	O4	O3	O2	N0	R2	R3	R4

The register includes direct and indirect risks and opportunities. Direct risks are caused by climate stressors with direct impact on the inflow regime or the hydropower assets. Indirect risks are caused by climate impacts on other system components (water allocation system, transmission system, electricity market), which subsequently also has an effect on the performance of the hydropower asset.

Table 22 lists the direct risk and opportunity register. The results show that there are mainly direct climate *risks* and apart from one exception no direct climate *opportunities*. For power generation (annual mean, monthly, baseload) the risks are classified as low in the near future, but as high to very high in the far future, as the ongoing climate change will lead to considerably reduced inflow and water resources availability in the far future.

The risk of extreme flood inflow and insufficient flood safety is classified as high to very high in both the near and far future – but also already under current climatic conditions. Of course the probability that a 10,000-year flood actually occurs is quite low, but according to the flood frequency analysis the 10,000-year flood magnitude is considerably larger than the spillway capacity (reservoir storage capacity) and therefore this is a serious concern for flood safety. Even under a drying climate, extreme flood inflow will remain a high risk due to increased rainfall variability.

The risk of reaching the flood warning level for Tete (at an outflow from Cahora Bassa > 5000 m<sup>3</sup>/s) was simulated to slightly increase in the near future, but to decrease in the far future. Future hydropower operations should not be impacted by concerns of flooding at Tete under normal conditions.

Other direct climate risks listed in Table 22 are classified as low to negligible. The likelihood due to ongoing climate change may be high, but the losses are estimated to be low, which results in overall low risks. This includes a qualitative assessment of the risks posed by increased sediment yield or increased lake water temperatures (which is

likely to have negative environmental effects, but negligible impacts on hydropower generation). In the future, transmission lines may be temporarily interrupted by intensified tropical storms, but as this will be rare events and with only temporary effects (repair will be possible), the overall risk is not high. One aspect that is expected to become relevant in the far future is the impact of higher air temperature extremes on equipment in substations and transformers, with potential damages due to heat impact.

Table 22: Direct climate risks and opportunities in the near future (2021-2050) and far future (2071-2100).

Direct climate risks and opportunities						
Climate stressor	Prospect or threat	Description	Time scale	Gain/Loss level	Likelihood level	Opportunity/risk level
Reduced mean annual inflow due to higher air temperature (evapotranspiration) and reduced rainfall	Threat	Decrease in mean annual power generation	near future	L1	2	R1
			far future	L2	3	R3
Changes (decrease) in the seasonal distribution of inflow due to shifts in climate	Threat	Decrease in monthly power generation	near future	L1	2	R1
			far future	L3	3	R4
Reduced dry season flow due to either increased inter-annual rainfall variability (droughts) or due to general decrease in mean annual rainfall	Threat	Reduced availability of baseload power generation	near future	L1	1	R0
			far future	L3	3	R4
Extreme flood inflow due to heavy rainfall	Threat	Insufficient flood safety for statistical 10,000 year flood. Existing spillway capacity too low for safe flood management of extreme flood inflow (10,000 year flood)	current	L2	3	R3
			near future	L3	3	R4
			far future	L2	3	R3
Changes in regular flood inflow (low return period) and resulting reservoir outflow > 5000 m <sup>3</sup> /s	Threat / prospect	More/less frequent occurrence of reaching downstream flood warning level at Tete	near future	L1	2	R1
			far future	G1	2	O1
Increased erosion rate and sediment yield due to increase in rainfall intensity	Threat	Reduced active storage volume in reservoir and higher maintenance costs for turbines due to abrasion	near future	L1	1	R0
			far future	L1	2	R1
Higher extremes of air temperature	Threat	High temperatures affect cooling of substations and transformers. Damage or failure of components due to heat impact.	near future	N0	2	N0
			far future	L1	3	R2
Considerable increase in lake water temperature due to general air temperature warming	Threat	Negative impacts on water quality (environmental concern), but no impact on energy generation	near future	N0	2	N0
			far future	N0	3	N0
More frequent and intense tropical storms causing interruption of transmission lines (especially HVDC line to South Africa)	Threat	Temporal limitation of the ability to deliver/sell electricity to clients (mainly ESKOM)	near future	L1	1	R0
			far future	L1	2	R1

The indirect climate risks and opportunities are listed in Table 23.

Considerable (large scale) upstream irrigation withdrawals are unlikely in the near future, but irrigation development might pose some risk in the far future. Under a warming and drying climate it is likely that there is an increased demand for irrigation

water, which would reduce downstream flow and therefore impact hydropower generation at Cahora Bassa, especially during the dry season.

Regulatory requirements for Cahora Bassa operations may also pose some risk for reduced hydropower generation in the far future. Under a changing climate, more frequent landfall of tropical storms in the lower Zambezi basin may increase pressure to (partly) mitigate the flood situation near the delta by drastically reducing outflow from Cahora Bassa during tropical storms. This would also require lower reservoir levels to have sufficient free storage volume to store the incoming flow volume during the duration of the tropical storm flooding in the lower basin. The lower reservoir levels (lower hydraulic head) would mean reduced power generation.

Similarly, authorities may require that a pre-scribed flooding regime is followed at Cahora Bassa to (partially) restore the sediment balance in the Zambezi delta to combat coastal erosion exacerbated by sea level rise. Especially in a drying climate (where Cahora Bassa would never spill) this pre-scribed flooding may become a requirement due to environmental concerns in the downstream Zambezi River. Pre-scribed flooding would mean reduced power generation as water is released via the spillways and is not turbinated.

An opportunity for HCB will be the expected regional emergence of variable renewable energy (VRE), as this will increase the need for ancillary services for grid stability. Due to the large reservoir HCB can balance intermittency of VRE generation (solar, wind). This could be on the intra-daily, daily and weekly timescale. For the daily and especially intra-daily timescale the hydro-peaking operations (with sudden increase or decrease of outflow) the downstream impacts along the river can be compensated by the construction of Mphanda Nkuwa HPP as a regulating reservoir. The joint operation of Cahora Bassa and Mphanda Nkuwa therefore poses a major opportunity in the near and especially far future. The focus on ancillary services should also be viewed from a strategic point of view, given the projected strong reduction in baseload generation in the far future (see Figure 50 and Table 16 in chapter 5.4).

Under a scenario of very high regional development of VRE also the options of Cahora Bassa North Bank and/or extension of the Cahora Bassa-Mphanda Nkuwa cascade to pump-storage operation are viable options that should be analysed in detail.

Table 23: Indirect climate risks and opportunities in the near future (2021-2050) and far future (2071-2100).

Indirect climate risks and opportunities						
Climate stressor	Prospect or threat	Description	Time scale	Gain/Loss level	Likelihood level	Opportunity/risk level
Considerable increase in water withdrawals due to higher air temperature and increased irrigation demand in upstream basin (e.g. Kafue Flats)	Threat	Decrease in inflow and power generation at Cahora Bassa	near future	L1	1	R0
			far future	L2	2	R2
Regulatory requirement to adapt the existing flood rule curve at Cahora Bassa as a result of frequent landfall of tropical storms in the lower basin	Threat	Reduced power generation due to lower reservoir levels (lower hydraulic head) to provide storage for reducing outflows during floods in the lower Zambezi.	near future	L1	1	R0
			far future	L1	2	R1
Pre-scribed flooding from Cahora Bassa to partially restore the sediment balance in the Zambezi delta to combat coastal erosion exacerbated by sea level rise	Threat	Reduced power generation as water is released via spillway for pre-scribed flooding also in dry years	near future	L1	1	R0
			far future	L1	2	R1
Regional emergence of variable renewable energy and increased need for ancillary services for grid stability	Prospect	Due to the reservoir HCB can balance intermittency of generation with variable renewable energy (solar, wind). Downstream impacts of intra-daily peaking can be compensated by Mephanda Nkuwa HPP as regulating reservoir.	near future	G1	2	O1
			far future	G2	3	O3

## 7 Climate risk management (Phase 4)

Given the climate risks and opportunities identified in chapter 6 various different structural and non-structural (functional) adaptation measures are possible to mitigate the climate risks and to maximize the climate opportunities. Section 7.1 outlines the general process. Sections 7.2 and 7.3 provide a description of the possible resilience measures. The effectiveness of the resilience measures is presented by an updated risk and opportunity register in section 7.4. An implementation schedule (time-horizon, priorities, etc.) for adaptation measures is proposed in the Climate Risk Management Plan (section 7.5).

Important terms and definitions are listed in Appendix 9.14.

## 7.1 Climate risk management process

Climate risk management in hydropower operations and electricity supply must be understood as a continuous process. It requires the assignment of a responsible unit within the organisation, which closely monitors the progress in implementation of the adaptation measures and reports to the management and owners on an annual basis.

Also regular updating of the Climate Risk Management Plan (CRMP) is required. The CRMP is a living document, which needs to be revised, if the risk and opportunity profile of HCB changes. This may be due to availability of new climate projections or due to changes in HCB’s generation portfolio and business activities. In practice this will require the CRMP to be updated every 2-4 years. It is proposed that the first revision of the CRMP should be undertaken during 2025, with an updated plan in force in 2026.

The proposed arrangements for CRMP implementation and monitoring at HCB are described in more detail in Phase 5.

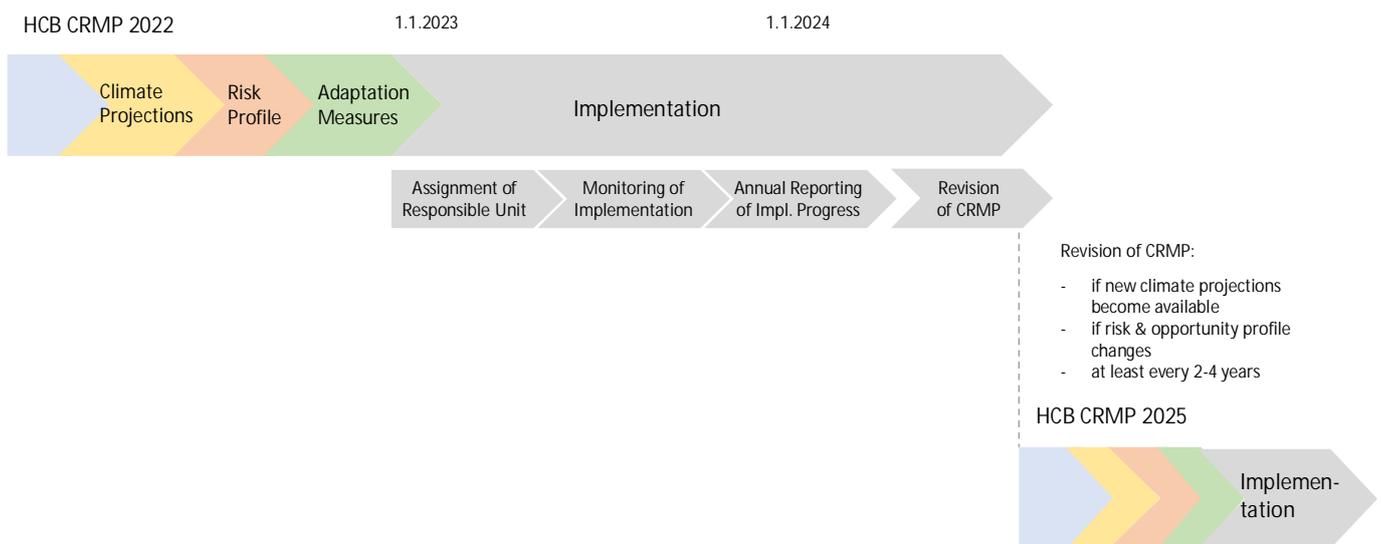


Figure 56: Process of Climate Risk Management Plan implementation and updating.

## 7.2 Non-structural adaptation measures

### 7.2.1 Implementation, monitoring and updating of CRMP

Implementation, monitoring and regular updating of the Climate Risk Management Plan (CRMP) are considered as key processes for increasing climate resilience of HCB's operations. This also includes the nomination of a team for CRMP implementation and clear assignment of responsibilities to different organisational units (within the environmental, water resources and generation divisions as well as the strategic management and planning divisions of HCB). Details on the organisational framework for implementation of the CRMP are given in chapter 7.5.

The first update of the CRMP is proposed for 2025. In this update also the climate change impact assessment shall be further refined considering the latest information from the scientific climate modelling community (e.g. Regional Climate Modelling based on CMIP6 GCMs).

### 7.2.2 Data collection and data sharing

As part of the Joint Operation Technical Committee (JOTC) there is an ongoing collaboration between HCB and upstream dam operators (Zambezi River Authority for Kariba dam, ZESCO for Itzehitezhi dam). The necessity for robust operation planning under climate change renders this existing collaboration very valuable and should be continued and (if possible) further enhanced. This is of high relevance especially due to the high reliance of Cahora Bassa inflow on outflow from Kariba reservoir during the dry season. But also during the wet season, early information (several weeks/months lead time) on potential spills from Kariba will foster early action and flood safety during periods with high inflow at Cahora Bassa. This will help to avoid to some extent critical flood releases and heavy spillway operation from Cahora Bassa.

In addition, it is proposed to improve the monitoring of flow conditions in the Luangwa and Panhame/Manyame rivers, which are important tributaries of Cahora Bassa reservoir. In wet years the dynamic flood contributions from these two rivers are considerable (see analysis in chapter 4.2.2), but no or no reliable rating curves are available for the existing gauges operated by ARA Centro. Therefore, it is proposed to establish rating curves for the following gauges:

- E343: Luangwa River at Zumbo
- E676: Panhame River

The location of the gauges is shown in Figure 57. The establishment of rating curves should be based on:

- Field missions:
  - Bathymetric survey and land survey (of dry riverbed).

- Flow measurements under different conditions (low flow, medium flow, high flow), which requires repeated missions during different times of the year.
- Hydraulic modelling: Simulation of river water levels for different discharge scenarios to establish a rating curve, covering the full range of possible water levels.

An automatic data transfer in near real-time from the gauges to ARA Centro and HCB should be established to ensure that timely information about the evolving flood conditions is available for improved flood management in Cahora Bassa reservoir.

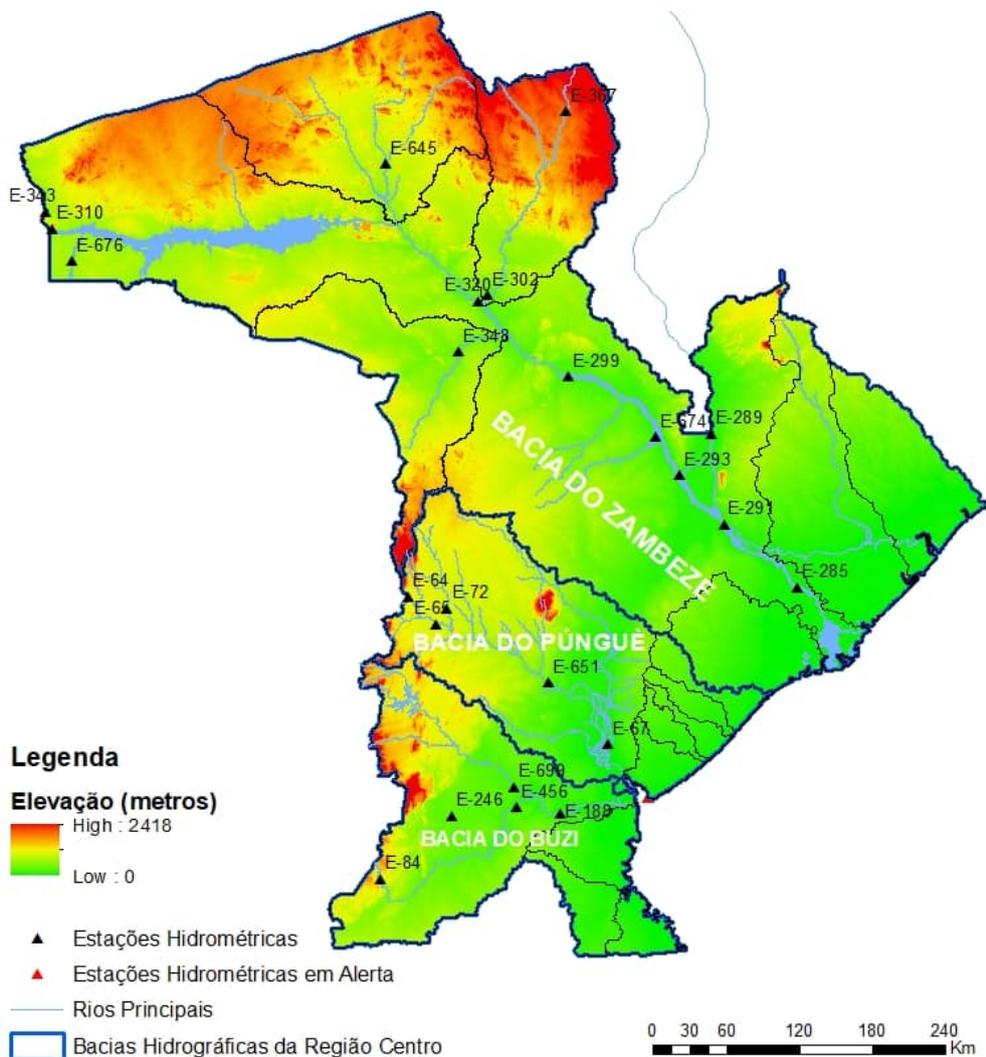


Figure 57: Gauges operated by ARA Centro. It is proposed to establish rating curves for the gauges E343 and E676 to measure inflow to Cahora Bassa reservoir. Map source: ARA Centro.

### 7.2.3 Operational inflow forecasting

Operational inflow forecasting is a tool to obtain quantitative information about future inflow with lead times of several days to months. Various different initiatives have analysed modelling tools and also developed pilot systems in the Zambezi basin (Figure 58 and Figure 59). These initiatives should be further supported and enhanced to increase the forecasting capabilities of water resources managers at HCB.

The focus should be on:

- Inflow forecasting with lead times of several months: This will help the early detection of evolving droughts and floods.
- Ensemble weather forecasts: While weather forecasts are very valuable e.g. for forecasting of tropical storms, there is limited accuracy for lead-times longer than a few days. Therefore, a scenario modelling approach with historical rainfall data (including wet, average and dry years) can inform on the potential spread in the evolving inflow conditions, given the latest in-situ measurements (upstream dam levels, gauge observations) and flow routing.
- Teleconnection indices: Global-scale variations in the status of the ocean and the atmosphere have effects on the development of wet and dry years in the Zambezi basin. The analysis and consideration of such teleconnections can reduce the uncertainty in ensemble forecasts for longer lead-times.
- Ensemble inflow forecasts: Different rainfall data sets and/or hydrological models can be combined to generate inflow ensembles. This helps to quantify the uncertainty in the inflow forecast.
- Reservoir operation modelling: The inflow forecasting system should allow for simulation of different operation strategies given the latest inflow forecasts. This will support HCB's water resources managers with robust decision making.
- The forecasting system can also be extended to include downstream lateral tributaries of the Zambezi, i.e. Luia, Revubue (Figure 60) and Luenha rivers.
- An expansion of the forecasting system for the full lower Zambezi (to the delta) would enable a better coordination of Cahora Bassa releases with downstream flow conditions. Such a system should also be made available to ARA Centro, who can provide the data from their flow gauges. The inflow from the Shire River should be included, which requires that Lake Niassa (Lake Malawi) is simulated with the lake water balance and strong control of downstream flow conditions.

An automatic data exchange and harmonisation of various different inflow forecasting systems used in the basin by Zambezi River Authority (Kariba dam), ZESCO (Itezihitezhi dam and Kafue River) and HCB (Cahora Bassa inflow) should be supported and enhanced.

The operational inflow forecasting should be complemented by capacity building activities to ensure that HCB's water resources managers can make full use of the

available tools to further support robust decision making under flood and evolving drought conditions.

Near real-time satellite rainfall maps and timely rainfall forecasts will also help to monitor the track of tropical storms in the lower basin and evaluate if these storms reach and affect the transmission lines (an example for the tracking of the tropical storm Idai in March 2019 in AFRY’s operational Kariba IFS is shown in Appendix 9.13). Such timely information will help for the early mobilization of maintenance staff for repair works at the transmission lines.

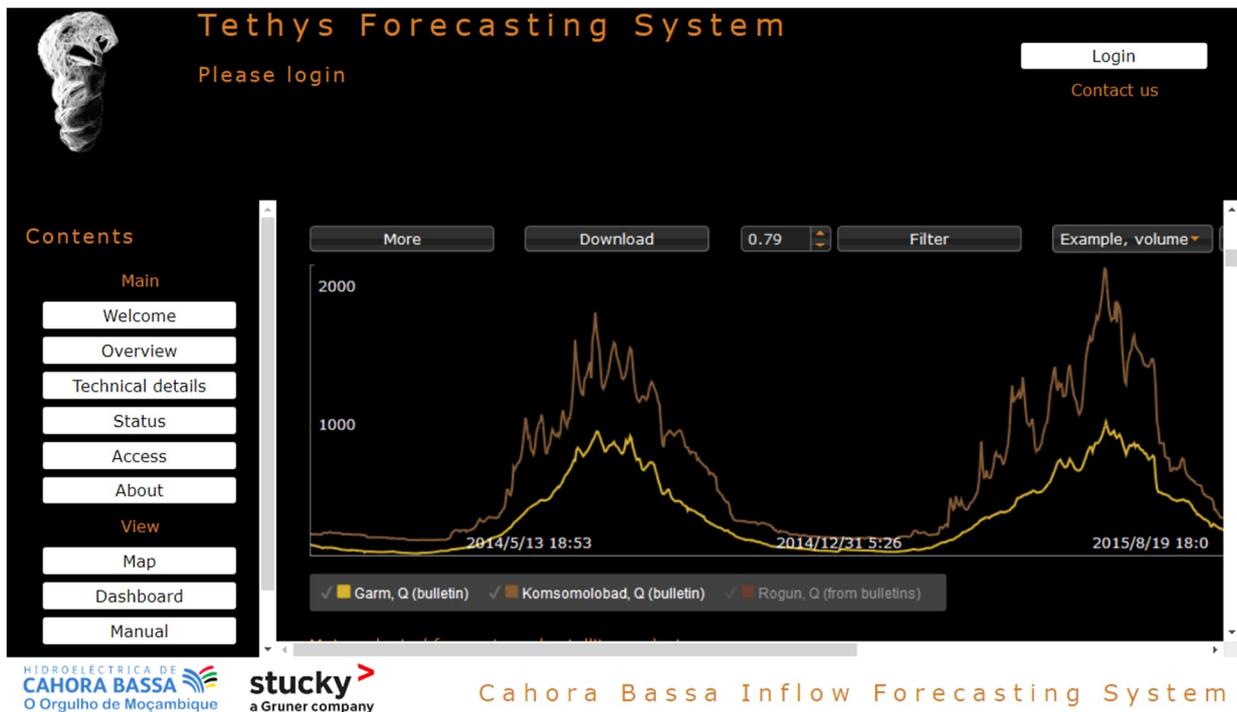


Figure 58: Example for inflow forecasting system of Stucky.

AFRY  
Kariba Inflow  
Forecasting System

Short-term and seasonal  
forecasting of inflows to Kariba  
reservoir.

User:

Password:

Login

[Mail us to get an account.](#)



Figure 59: Example of inflow forecasting system used by the Zambezi River Authority for Kariba reservoir.



Figure 60: Extreme floods at the Revubue River have destroyed the bridge at Chingoze (Tete) in the years 2019 and 2022. Picture source: TOPOSOL, extracted from presentation of Jose Rodrigues Matola.

#### 7.2.4 Extreme flood study

The flood frequency analysis for Cahora Bassa shows that the 10,000-year monthly inflow flood exceeds the spillway capacity, which therefore poses a climate-related risk. It is recommended to conduct an additional study on the processes leading to extreme flood inflow, to determine the critical spatio-temporal rainfall and runoff generation patterns. This study would be similar to a probable maximum precipitation (PMP) and probable maximum flood (PMF) study (which typically is based on individual storm events), but also considering the longer-term (weekly and monthly) rainfall conditions (with several storms) and flow contributions and different response times from the Upper Zambezi, Kafue, Luangwa and local tributaries. Such an analysis would be a considerable task given the large size of the upstream basin and many possible different spatio-temporal rainfall patterns that can lead to extreme flood inflow.

The benefit of such a detailed study on extreme floods is that it will enable conclusions about the critical spatial flood contributions (Upper Zambezi, Luangwa, Kafue, Zimbabwe tributaries) and interpretation of observed flood contributions during an evolving extreme flood. This information is not available by the flood frequency analysis, which merely is a statistical extrapolation of Cahora Bassa total inflow.

The results of the analysis will yield important conclusions about extreme flood generation processes for Cahora Bassa and possible monitoring and early detection of developing conditions conducive for extreme flood inflow, also considering the current hydro-meteorological conditions (linked e.g. also to teleconnection indices like sea surface temperature anomalies in the Indian Ocean). An early detection of conditions that can lead to extreme flood inflow can help to take pro-active measures in reservoir operation (i.e. lowering of reservoir water levels to create sufficient free storage for flood buffering) and can also provide improved inputs/methods/procedures for operational inflow forecasting and flood management.

The extreme rainfall estimates (based on analysis of historic patterns) can also consider climate change by incorporating results with respect to recent trends in the observations and of climate model projections (e.g. based on air temperature using the Clausius-Clapeyron relationship).

The study will also consider the recommendations of the Dam Break Analysis Report (prepared by Mott MacDonald). However, a difference is that the proposed study will not focus on dam break scenarios, but on natural floods caused by rainfall.

### 7.2.5 Revised flood rule curve

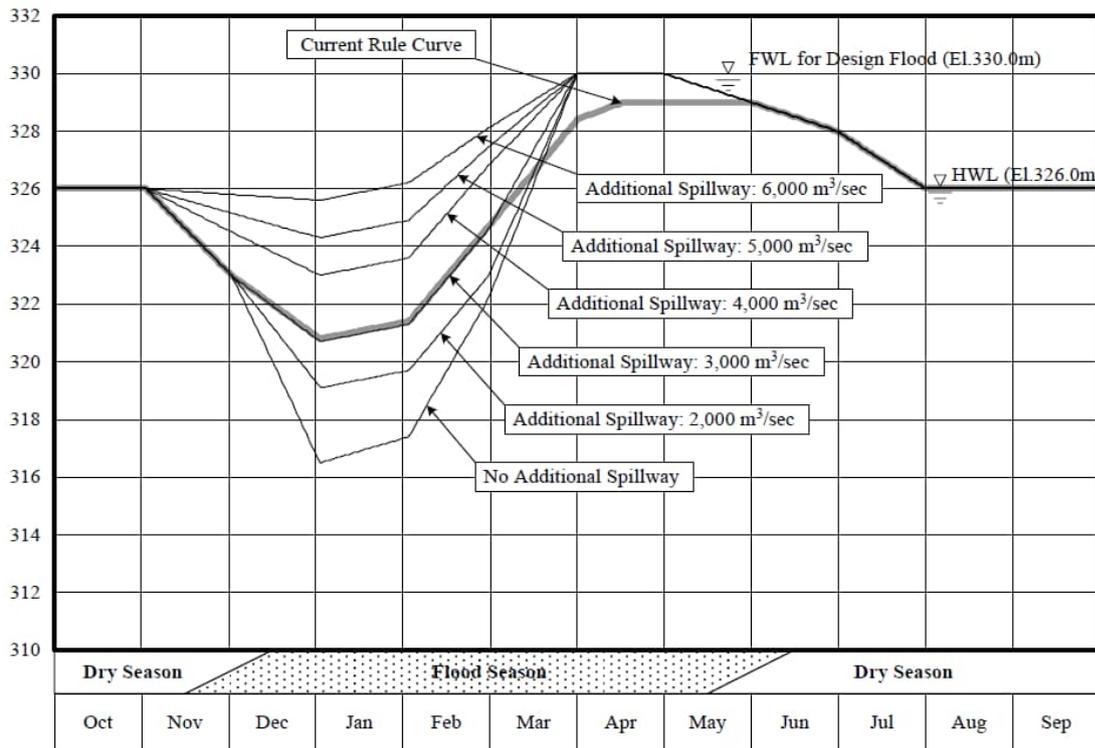
A revision of the flood rule curve can enhance the flood safety for Cahora Bassa, given the limited spillway capacity and the risk of dam over-topping during extreme flood inflow.

Nippon Koei (2007) assessed alternative flood rule curves to avoid over-topping of the dam during the 10,000-year flood inflow. Without any additional spillway capacity, the maximum allowable reservoir water level on January 1<sup>st</sup> was determined to be 316.50 masl (Figure 61), which is considerably lower compared to the current rule curve value of 320.80 masl.

A drawback of the lower reservoir water levels would be reduced hydraulic head and, as a consequence, reduced power generation. The impacts of the low reservoir in January would persist over the following months as a fast refilling is only possible in wet years, but may last several months (or even longer) during dry years and droughts.

A combination of revised flood rule curve (applicable only in wet years) and operational inflow forecasting (continuous monitoring of evolving hydrological conditions) is an option for maximum benefits (flood safety and generation performance).

A revision of the flood rule curve should also consider the ongoing study and outcomes for an Emergency Action Plan (EAP).



**Safety Rule Curve of Each Discharge Capacity of Additional Spillway**

Figure 61: Alternative safety rule curves for reservoir operation (Nippon Koei, 2007).

### 7.2.6 Ancillary services and hydro-peaking

As discussed in chapter 6, an opportunity for HCB will be the regional emergence of variable renewable energy (VRE), as this will increase the need for ancillary services for grid stability. Due to the large reservoir HCB can balance intermittency of VRE generation (solar, wind). This could be on the intra-daily, daily and weekly timescale. For the daily and especially intra-daily timescale, the downstream impacts of the hydro-peaking operations (with sudden increase or decrease of outflow) can be compensated by the construction of Mphanda Nkuwa HPP as a regulating reservoir.

In periods with low inflow, which are likely to become more prevalent under a drying climate, hydro-peaking operations at Cahora Bassa could follow an operation pattern as outlined below:

- In hours with low energy prices because of either (a) low energy demand and/or (b) surplus of electricity produced by VRE: Power generation at HCB is reduced to a minimum to save water.

- In hours with high energy prices because of either (a) high energy demand and/or (b) lack of electricity produced by VRE: Full power generation at HCB, running the turbines at full capacity and high outflow from the reservoir.

Compared to a constant baseload generation, the operation pattern outlined above has the advantage that with the same amount of water, electricity is mainly produced in hours with high energy prices and as a result revenues are increased compared to baseload generation.

This of course requires that the contracts for energy supply also reflect these ancillary services and HCB receives compensation accordingly. Even if these conditions are currently not met, it is expected that the general tendency in the evolving, future energy market will be that this increased need for ancillary services will also be reflected in monetary compensation for companies with the capability for hydro-peaking operations. The possibility for extending or re-negotiating existing energy supply contracts should therefore be monitored and discussed within HCB.

A hydro-peaking scoping study can support HCB's strategic decision making by analysing:

- Hydro-peaking operation scenarios considering downstream environmental flow requirements, under the assumption that Mphanda Nkuwa is not available as regulating reservoir. It is expected that only some limited hydro-peaking operation is possible to avoid adverse downstream environmental effects.
- Hydro-peaking operation scenarios under the assumption that Mphanda Nkuwa can be used as downstream regulating reservoir (to balance outflow variations). Full hydro-peaking operations are possible with abrupt changes in outflow from Cahora Bassa, as Mphanda Nkuwa reservoir can balance the flow variability and there will be no adverse environmental effects in the downstream Zambezi River.
- Calculation of water level fluctuations in the downstream Zambezi River and Mphanda Nkuwa reservoir to determine environmental and physical constraints for hydro-peaking on different timescales (intra-daily, daily, weekly).
- Simulation of energy generation under hydro-peaking scenarios, also considering the effects of fluctuating tailwater levels and turbine efficiencies for energy generation, as well as the impacts on energy generation at Mphanda Nkuwa (due to fluctuating reservoir levels).
- Expected financial benefits for HCB with hydro-peaking operations under a range of price scenarios (peak and off-peak energy prices).

### 7.2.7 Weather insurance against drought

There are a number of financial instruments (e.g., hedging, insurance) which can be applied to mitigate the risk of climate variability (potentially affecting generation targets). Such instruments could create an added value for HCB in the future.

Under a drying climate, insurance against drought and low energy generation is of key interest. Index-based weather insurance against drought is currently mainly offered for the agricultural sector in Africa. An insured company pays a premium to an insurer, and if the weather index (a pre-defined drought indicator) reaches a specific threshold, the insurance automatically pays a compensation. The weather index must be objective without any possibility of tampering. Therefore, satellite-based weather insurance (using e.g. TAMSAT precipitation satellite data) is a possible application.

In order to further develop the understanding of these options, it is recommended to keep informed of emerging financial products and review applicability in the next years.

A weather insurance scoping study can support HCB by:

- Identifying potential insurance companies
- Analysing potential objective weather (drought) indices
- Evaluating the estimated financial benefits for HCB of such an insurance against drought

### 7.2.8 Conjunctive operation with upstream countries

Upstream and downstream dam operators (Kariba, Itezihitezhi, Cahora Bassa) are in regular contact and exchange information via the Joint Operation Technical Committee (JOTC). Data exchange about reservoir water levels and releases is part of JOTC (see section 7.2.2).

It is proposed to move beyond data exchange and further intensify the collaboration between upstream and downstream dam operators, with the long-term objective of a conjunctive operation of the major reservoirs in the basin. Such a conjunctive operation would allow to balance surplus/deficits in water availability (and power generation), especially under a changing climate with increased variability and droughts in the basin.

As an example, as of December 2022 Kariba reservoir is close to reaching the minimum operation level due to high releases in the previous months, which raises concerns at HCB that Kariba releases might be reduced in the following months and years, which may pose problems for HCB's generation during the next dry season. At the same time, HCB had to start spillway operation to lower the reservoir water levels for the upcoming flood season 2023. This is an example of water deficit in Kariba and water surplus in downstream Cahora Bassa reservoir. A conjunctive operation of the two reservoirs can

improve the reliability of the power output of the total cascade. Power generation at Cahora Bassa for upstream countries can help to avoid drawing down Kariba close to minimum operation level, and in return improve the reliability of Kariba outflows in the following dry season.

It is proposed to conduct a detailed study of the expected benefits of conjunctive dam operation. Such a study should be in close consultation with JOTC, as there will be recommendations on improved coordination between Kariba and Cahora Bassa operation. In addition, the study should also consider the hydropower generation at the Kafue River and the expected benefits of conjunctive operation for Mphanda Nkuwa hydropower plant, as it will be located at the most downstream end of the (current) cascade. Furthermore, regional benefits of conjunctive operation for future expansion of the cascade with Boroma, Lupata and Chemba hydropower plants should also be assessed. The outcomes of the study may also provide incentives for upstream countries to invest in hydropower development along the lower Zambezi in Mozambique.

#### 7.2.9 Continuous capacity building

All non-structural measures included in the CRMP shall be complemented by continuous training and capacity building in fields related to climate risk management for staff involved in the different measures and activities. It is recommended to define a team, responsible for climate risk management within HCB, with sufficient resources allocated to participate in training and capacity building activities:

- Participation in hydropower conferences: Learn about the latest trends and developments in the international hydropower community and how climate change is considered for robust decision making. Interesting conferences are organized e.g. by ICOLD or the bi-annual Africa conference series by Hydropower & Dams (next conference in Uganda re-scheduled to July 2023).
- Participate in ICOLD Technical Committee Y Dams & Climate Change: Each country can nominate an expert for this technical committee, which is a great opportunity for knowledge sharing and international experience.
- Capacity building at universities: The cooperation with southern African universities active in climate change research should be continued and intensified, including the Eduardo Mondlane University (Maputo) and the University of Cape Town (South Africa), which offers short courses (e.g., winter school) on climate change organized by the Climate Systems Analysis Group (CSAG).

Furthermore, different collaborations in climate risk monitoring (e.g. INAM) should be supported and active collaborations and contacts should be established/continued. Such

co-operations might also facilitate recruiting of future experts in climate risk management.

It is also proposed that HCB together with AFRY prepare one or two papers summarizing the results of the Climate Resilience Assessment. Possible journals include:

- International Journal on Hydropower and Dams
- Conference paper for ICOLD or Hydro Africa
- other

Finally, the collaboration with INGD should be intensified for continuous community awareness for disaster risk reduction including strengthening of Early Warning System for flooding in the lower Zambezi River (see also section 7.2.3).

#### 7.2.10 Continued access to Zambezi Decision Support System

The Zambezi Decision Support System (DSS) was used for training sessions with HCB staff in the first and second site visits. The Zambezi DSS was originally developed and installed on a server in 2011. This server and software version (2011) are no longer supported by AFRY IT. To ensure continued access by HCB staff to the Zambezi DSS it is proposed to transfer the software to a new server and to also upgrade to the latest software version with improved graphical user interface and more advanced analysis options.

All HCB user accounts, data (climate scenarios), and development scenarios (reservoir operation rules) will be transferred to the new server, but using the latest version of the hydrological model, which was also used by the Consultant in offline-mode for the climate resilience analysis. This new server will also allow to run simulations once new climate model projections become available, for an update of the CRMP in a few years.

Additional training can be offered to further improve the capacity of HCB staff for analysis of runoff conditions in the Zambezi basin and operation rules of Cahora Bassa reservoir under climate change scenarios.

### 7.3 Structural adaptation measures

#### 7.3.1 Additional spillway capacity

Additional spillway capacity to improve flood safety was recommended in various previous studies:

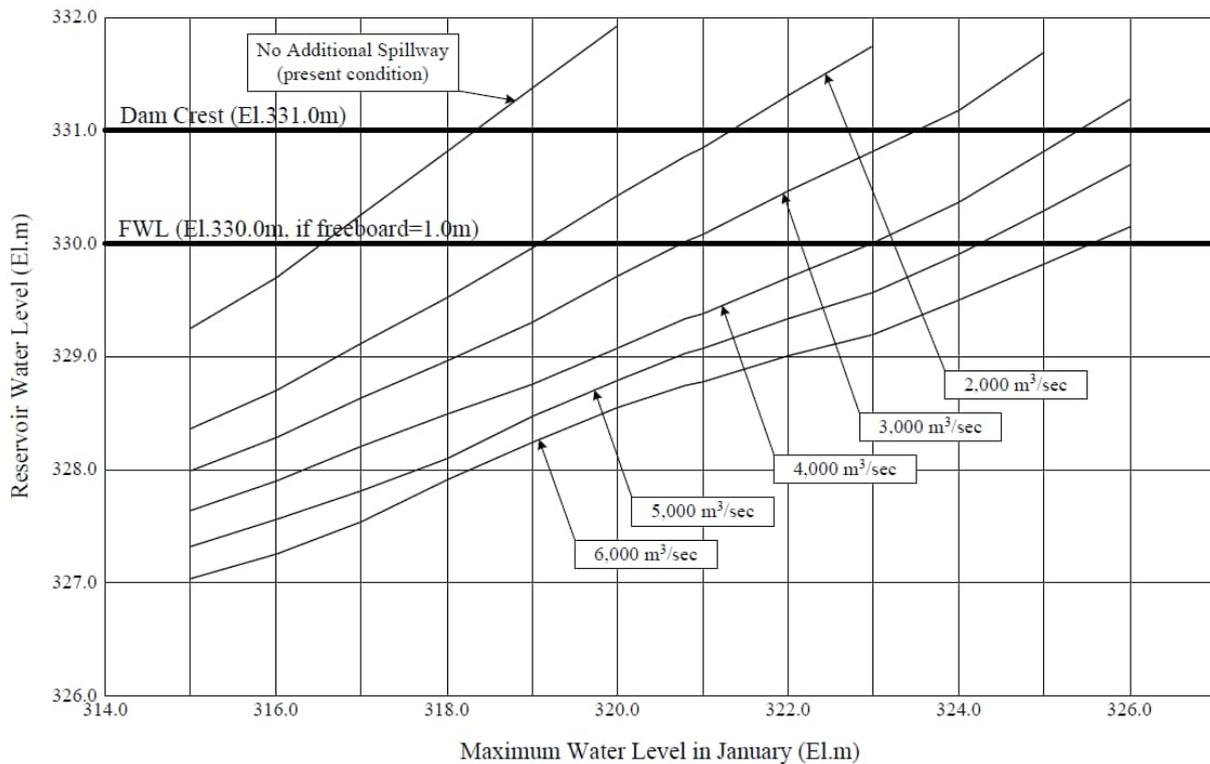
- Pre-Feasibility Report on Cahora Bassa North Bank & Mepanda Uncua by Eskom (1991): 3600 m<sup>3</sup>/s additional spillway capacity

- Feasibility Report on Mepanda Uncua and Cahora Bassa North Project prepared by Joint Venture (JV) of Lahmeyer International (LI), Electricité de France (EdF) and Knight Piésold (2002): 5000 m<sup>3</sup>/s additional spillway capacity
- Report of Cahora Bassa-Central Norte Actualizacao do Anteprojecto by Hidrotécnica Portuguesa (2002): 3600 or 4400 m<sup>3</sup>/s additional spillway capacity
- Technical Due Diligence by Nippon Koei (2007): 4000 m<sup>3</sup>/s additional spillway capacity

The additional spillways can be implemented as tunnels on the North Bank and the costs were estimated at 74 million USD (Nippon Koei, 2007).

The improved flood safety with additional spillway capacity under extreme flood inflow were analysed by Nippon Koei (2007). With the current rule curve and existing spillway capacity the 10,000-year flood would lead to an over-topping of the dam (Figure 62, top left curve). With an additional spillway capacity of 4000 m<sup>3</sup>/s there is no over-topping of the dam if the reservoir water level is below 323 m at the start of the flood (Figure 62, third line from bottom).

No additional scoping studies are required, as the general layout and cost estimates are already available but pending management decisions for implementation. It is proposed that over the next years HCB reviews the possible construction of the additional spillway, also considering the planning stages for Cahora Bassa North Bank expansion, as well as alignment with the other (non-structural) flood risk adaptation measures.



### Maximum Water Level of Design Flood (28,100 m<sup>3</sup>/sec) for Each Additional Spillway

Figure 62: Analysis by Nippon Koei (2007) of reservoir water levels with different spillway capacities and extreme flood inflow to Cahora Bassa.

#### 7.3.2 Hybrid power generation with solar PV

Electricity generation with solar PV is a market-ready technology that shows great potential in the sun-rich southern African region. Solar PV is also a business opportunity for HCB to increase capacity and sell electricity while using existing infrastructure (transmission lines). It is an energy source that is not affected by droughts or drying climate.

The intermittency of solar PV electricity generation is due to the diurnal variation of solar irradiance and the effect of clouds. In addition there is also a seasonal variation in solar irradiance.

Solar PV is especially attractive during droughts, which might become more frequent in a drying climate. Solar PV can help HCB to meet contractual obligations for delivering electricity and conserving water during the daytime (while the sun is shining) and continued hydro generation at night-time (with the additional water conserved during the day).

For solar PV two options are possible for installation:

- Standard installation on land
- Floating PV, i.e. installation in the reservoir on the water body

The choice of installation depends on availability of land and other technical considerations for floating PV:

- Higher maintenance costs of floating PV
- Impact of wind and waves on floating PV installations need to be assessed
- Higher efficiency of floating PV due to water cooling

An advantage of floating solar PV for HCB would be that no additional land is required, as the reservoir is already managed by HCB and thus it is expected that installation of floating solar PV can be implemented relatively quickly. A possible layout for a 75 MWp floating solar PV field covering 600,000 m<sup>2</sup> is shown in Figure 63. The mean annual solar resource was estimated as 2022 kWh/m<sup>2</sup> GHI (Global Horizontal Irradiance, estimate by Phelan Energy Group).



Figure 63: Possible location for a 75 MWp floating solar PV field covering 600,000 m<sup>2</sup> just upstream of the Cahora Bassa dam. Picture source: Phelan Energy Group

A scoping study for solar PV is recommended, including technical and economic assessments. This would allow to assess the full potential of solar PV for HCB and the upgrading of Cahora Bassa to a hybrid plant combining hydropower with a solar power plant. An example is the recently constructed Lower Kaleköy HPP with auxiliary solar power plant in Turkey (Figure 64). In this example the planning of electricity dispatching and day-ahead generation forecasts are supported by an operational inflow forecasting system set-up by AFRY. A similar set-up would also be an option for HCB.

A hybrid solution with significant PV capacity in the vicinity of Cahora Bassa and/or Mphanda Nkuwa could also be a key element in a possible future extension to a pump storage plant as discussed in section 7.3.3.



*Figure 64: Example for a hybrid electricity plant combining hydropower with large-scale solar PV. The recently constructed Lower Kaleköy HPP (500 MW) with auxiliary solar power plant (80 MW) in Turkey. Picture source: KALEHAN.*

### 7.3.3 Extension to pump-storage plant

As discussed in chapter 6, it is expected that in the future energy market there will be an increased need for ancillary services to balance the intermittency of variable renewable energy. These imbalances in energy demand and supply will also be reflected in the short-term (spot) energy market prices. Hydro pump-storage plants can help to manage these imbalances in demand and supply and at the same time offer a business opportunity for hydro operators.

A pump-storage plant consists of an upper and lower reservoir. Cahora Bassa reservoir can serve as the upper reservoir, and Mphanda Nkuwa can serve as the lower reservoir. For the powerhouse a similar layout as discussed during the left-bank extension project might be considered, with the power cavern situated at lower elevation.

A simplified, typical operation pattern for a pump-storage plant is as follows:

- During hours with low energy prices (i.e. electricity supply larger than demand) water is pumped from the lower reservoir to the upper reservoir. During this time the hydro operator is consuming power.
- During hours with high energy prices (i.e. electricity demand higher than supply) water is turbined from the upper reservoir to the lower reservoir. During this time the hydro operator is generating power.

An advantage of a pump-storage hydro plant is that it is not affected by reduced inflow under a drying climate (apart from evaporation losses in the reservoirs). Pump-storage operations are applicable under periods of low inflow and high intra-daily energy price variations. In periods with high inflow (rainy season) the cascade can be operated as conventional hydropower plants.

A pump-storage scoping study is recommended to analyse:

- Technical feasibility of upgrading Cahora Bassa and Mphanda Nkuwa to a combined pump-storage plant. Identification of possible locations for the pump-intake (also considering lower reservoir levels in Mphanda Nkuwa).
- Simulation of pump-storage operation and energy generation under scenarios of intra-daily price patterns (when to pump, when to generate). The calculations need to consider the following losses:
  - Pump efficiency
  - Turbine efficiency
  - Hydraulic losses
  - Reduction in gross hydraulic head due to tailwater rating curve, which is several meters for Cahora Bassa when comparing lower tailwater levels without any outflow (i.e. pumping) and higher tailwater levels during turbine operation.
  - Losses in the transmission lines, which are about 11% for the HVDC line (22% overall transmission line losses for a pump-turbine cycle)
  - Slightly reduced generation at Mphanda Nkuwa (due to fluctuating, lower reservoir levels compared to baseload generation at full supply level). This also needs to consider environmental releases from Mphanda Nkuwa during pump periods (with no inflow from Cahora Bassa), resulting in fast draw-down of Mphanda Nkuwa reservoir level.
  - The overall efficiency of a full pump-turbine cycle at Cahora Bassa-Mphanda Nkuwa is roughly estimated at about 60% (including transmission line losses).
- Benefit-cost analysis for different energy price scenarios and different designs of pumps. Given the overall pump-storage efficiency, the required price spread between peak and off-peak energy prices can be calculated, such that the benefits outweigh the costs.

Due to the losses in the transmission lines it might be advisable to also study the combination of pump-storage operation with electricity provided by solar PV located directly in the vicinity of Cahora Bassa (see section 7.3.2). A study on pump-storage operation should also be complemented by an electricity market study, with different scenarios for the mid-term development of the regional power market (SAPP).

#### 7.3.4 Cooling of substations and transformers

In the far future, the projected significant increases in mean and maximum air temperature are expected to have negative impacts on transformers and substations. Rising internal temperature, especially during longer and more intense heat waves, leads to higher energy losses and affects the ageing of transformers and their components.

Adaptation measures to decrease the risk of overheating include all forms of improved cooling of substations and transformers. For existing sites and components, nature-based solutions like additional shading from vegetation can lead to lower temperatures. For new locations or extensions, principles of passive cooling design should be adopted (e.g. choice of cooler locations, shading, natural ventilation). In long-term maintenance planning, it is recommended to consider the procurement of high-quality components with higher resistance to heat and the planning and use of appropriate more effective cooling systems.

Maintenance and replacement of transformers and other substation components also provides opportunities to contribute to climate change mitigation (reduction of greenhouse gas emissions). More efficient cooling can decrease the energy demand for cooling systems. Furthermore, the replacement or avoidance of components that use SF<sub>6</sub> as an insulating and arc quenching gas has a large potential for climate change mitigation, since SF<sub>6</sub> is a highly effective – and therefore harmful – greenhouse gas (with a global warming potential over 20,000 times higher than CO<sub>2</sub>). In addition to the planning of heat adaptation measures for substation components, it is therefore recommended to reduce the contribution to climate change by procuring substation components that use alternatives to SF<sub>6</sub>, which are already available on the market from several providers (e.g. GE, ABB, Hitachi and Siemens).

### 7.4 Risk and opportunity register update with resilience measures

In the previous sections the following non-structural (Nx) and structural (Sx) measures were discussed for climate risk management:

N0: Implementation, monitoring and regular updating of CRMP (section 7.2.1)

N1: Data collection and data sharing (section 7.2.2)

N2: Operational inflow forecasting (section 7.2.3)

- N3: Extreme flood study (section 7.2.4)
- N4: Revised flood rule curve (section 7.2.5)
- N5: Ancillary services and hydro-peaking (section 7.2.6)
- N6: Weather insurance against drought (section 7.2.7)
- N7: Conjunctive operation with upstream countries (section 7.2.8)
- N8: Capacity building in fields related to climate risk management (section 7.2.9)
- N9: Continued access to Zambezi Decision Support System (section 7.2.10)
- S1: Additional spillway capacity (section 7.3.1)
- S2: Hybrid power generation with solar PV (section 7.3.2)
- S3: Extension to pump-storage plant (section 7.3.3)
- S4: Cooling of substations and transformers (section 7.3.4)

The tables below show, separate for direct and indirect climate risks, a mapping how the adaptation measures relate to one or several entries in the risk and opportunity register (compare to chapter 6) to mitigate a climate risk or to maximize a climate opportunity. The effectiveness of the adaptation measures is grouped into “very relevant” (filled dark circles), “relevant” (filled grey circles), and “general” (hollow circles).

For some of the climate impacts classified as low risk R1 (e.g. sedimentation impact on hydropower generation) no adaptation measures are proposed, but for all other climate risks (R2 and higher) climate risk mitigation is recommended. With the adaptation measures in place the table also shows the expected residual risk (or updated opportunity) in the last column on the right. The greatest climate risk for flood safety can clearly be managed well with the proposed adaptation measures. Already under current climatic conditions there is a flood risk. Construction of a new spillway will take at least several years. However, the implementation of the other proposed, non-structural adaptation measures will allow to reduce this risk from very high (R4) to low (R1).

In general, residual climate risks remain in the far future, but this can be offset by seizing the indirect climate opportunities resulting from the emergence of variable renewable energy and the increased need for ancillary services, either by hydro-peaking or upgrade to a pump-storage plant, which may also be combined with solar PV.

Furthermore, the climate risks identified for the far future should be closely monitored and re-assessed in the proposed updates of the CRMP (see section 7.2.1), as the expected impact may change based on e.g. evolving observed climatic conditions, new climate change projections, emerging changes in the energy market, etc.

Table 24: Adaptation measures for direct climate risks/opportunities and updated residual climate risks/opportunities (last column on the right).

				Without mitigation measures	Data collection and data sharing	Operational inflow forecasting system	Extreme flood study	Revised flood rule curve	Ancillary services and hydro-peaking	Weather insurance against drought	Additional spillway capacity	Hybrid plant with solar PV	Extension to pump-storage plant	Cooling substations and transformers	Mitigation measures implemented
Climate stressor	Description	Time scale	Opportunity/risk level	N1	N2	N3	N4	N5	N6	S1	S2	S3	S4	Opportunity/risk level	
Reduced mean annual inflow due to higher air temperature (evapotranspiration) and reduced rainfall	Decrease in mean annual power generation	near future	R1	●	●			●	●		●			R0	
		far future	R3	●	●			●	●		●	●		R1	
Changes (decrease) in the seasonal distribution of inflow due to shifts in climate	Decrease in monthly power generation	near future	R1	●	●			●	●		●			R0	
		far future	R4	●	●			●	●		●	●		R1	
Reduced dry season flow due to either increased inter-annual rainfall variability (droughts) or due to general decrease in mean annual rainfall	Reduced availability of baseload power generation	near future	R0											R0	
		far future	R4	●	●			●	●		●	●		R1	
Extreme flood inflow due to heavy rainfall	Insufficient flood safety for statistical 10,000 year flood. Existing spillway capacity too low for safe flood management of extreme flood inflow (10,000 year flood)	current	R3	●	●	●	●							R1	
		near future	R4	●	●	●	●			●				R0	
		far future	R3	●	●	●	●			●				R0	
Changes in regular flood inflow (low return period) and resulting reservoir outflow > 5000 m³/s	More/less frequent occurrence of reaching downstream flood warning level at Tete	near future	R1	●	●									R0	
		far future	O1	●	●									O1	
Increased erosion rate and sediment yield due to increase in rainfall intensity	Reduced active storage volume in reservoir and higher maintenance costs for turbines due to abrasion	near future	R0											R0	
		far future	R1											R1	
Higher extremes of air temperature	High temperatures affect cooling of substations and transformers. Damage or failure of components due to heat impact.	near future	N0											N0	
		far future	R2										●	R0	
Considerable increase in lake water temperature due to general air temperature warming	Negative impacts on water quality (environmental concern), but no impact on energy generation	near future	N0											N0	
		far future	N0											N0	
More frequent and intense tropical storms causing interruption of transmission lines (especially HVDC line to South Africa)	Temporal limitation of the ability to deliver/sell electricity to clients (mainly ESKOM)	near future	R0											R0	
		far future	R1		●									R1	

Table 25 Adaptation measures for indirect climate risks/opportunities and updated residual climate risks/opportunities (last column on the right).

			Without mitigation measures	Data collection and data sharing	Operational inflow forecasting system	Extreme flood study	Revised flood rule curve	Ancillary services and hydro-peaking	Weather insurance against drought	Additional spillway capacity	Hybrid plant with solar PV	Extension to pump-storage plant	Cooling substations and transformers	Mitigation measures implemented
Indirect climate risks and opportunities				Measures										
Climate stressor	Description	Time scale	Opportunity/risk level	N1	N2	N3	N4	N5	N6	S1	S2	S3	S4	Opportunity/risk level
Considerable increase in water withdrawals due to higher air temperature and increased irrigation demand in upstream basin (e.g. Kafue Flats)	Decrease in inflow and power generation at Cahora Bassa	near future	R0											R0
		far future	R2	●	●			●			●	●		R1
Regulatory requirement to adapt the existing flood rule curve at Cahora Bassa as a result of frequent landfall of tropical storms in the lower basin	Reduced power generation due to lower reservoir levels (lower hydraulic head) to provide storage for reducing outflows during floods in the lower Zambezi.	near future	R0											R0
		far future	R1		●						●			R0
Pre-scribed flooding from Cahora Bassa to partially restore the sediment balance in the Zambezi delta to combat coastal erosion exacerbated by sea level rise	Reduced power generation as water is released via spillway for pre-scribed flooding also in dry years	near future	R0											R0
		far future	R1								●			R0
Regional emergence of variable renewable energy and increased need for ancillary services for grid stability	Due to the reservoir HCB can balance intermittency of generation with variable renewable energy (solar, wind). Downstream impacts of intra-daily peaking can be compensated by Mephanda Nkuwa HPP as regulating reservoir.	near future	O1					●				●		O3
		far future	O3					●				●		O4

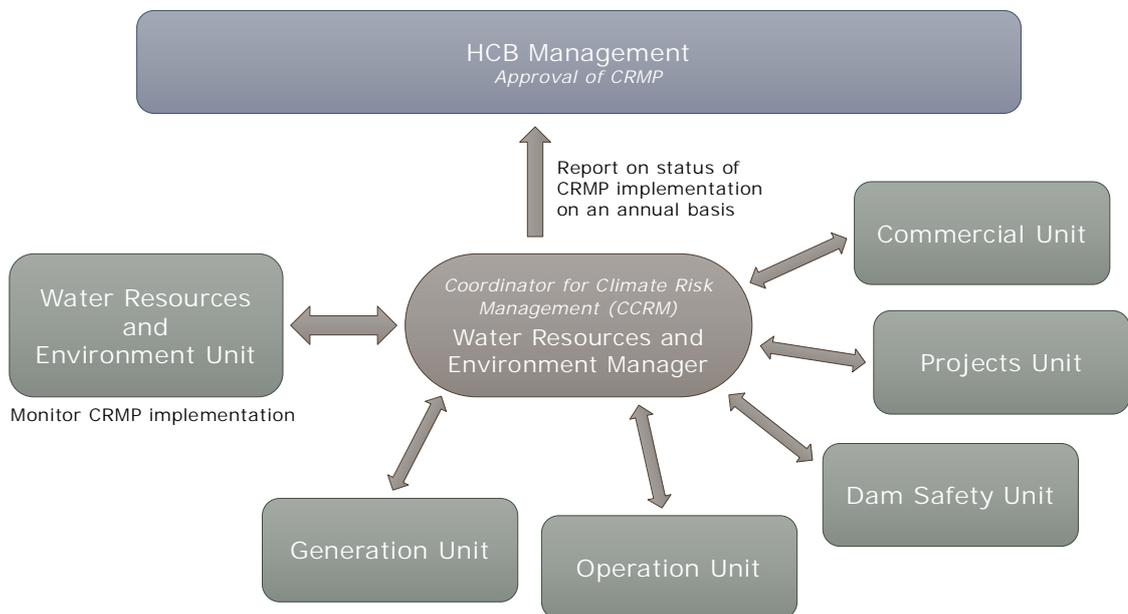
●	very relevant
●	relevant
●	general

## 7.5 Climate risk management plan

Based on the results presented in the previous sections a climate risk management plan (CRMP) is proposed as detailed below. A preliminary draft version of the CRMP was discussed and refined in the second site visit in Songo in November 2022.

### 7.5.1 Organisation

The figure below shows the proposed organisation and responsibilities for the monitoring of and reporting on the implementation of the CRMP. As Coordinator for Climate Risk Management (CCRM) the manager of the Water Resources and Environment Unit is nominated. The CCRM will report on the status of implementation of the CRMP to HCB management, who need to approve and support the CRMP implementation process. The Water Resources and Environment Unit will be the main unit for monitoring the implementation of CRMP, which will require the involvement of the Generation Unit, Operation Unit, Dam Safety Unit, Projects Unit and Commercial Unit.



3

Figure 65: Proposed organisational chart for monitoring of and reporting on the implementation of the Climate Risk Management Plan (CRMP).

### 7.5.2 Implementation

The CRMP shown in Table 26 lists for each adaptation measure (see sections 7.2 and 7.3) several sub-tasks, proposed implementation years, overall priorities and indicative, rough cost estimates for CAPEX and OPEX. Some of the tasks can be done in-house by HCB experts (e.g. monitoring of CRMP implementation), where it was assumed that no additional costs occur for HCB. For the update of the CRMP, costs may occur if not done by HCB staff, but by external consultants.

Also for data collection from upstream dam operators and flow gauges operated by ARA Centro (Luangwa, Panhame rivers) no costs are foreseen. However, it is recommended to establish rating curves for these gauges, which requires field missions for flow measurements, supported by hydraulic modelling for calculation of the rating curves. Currently it is not clear if these works will be carried out by ARA Centro with no additional costs for HCB, or if HCB needs to (partially) cover these costs for establishment of rating curves.

For some adaptation measures an implementation is proposed to start already in the year 2023. For other adaptation measures (scoping studies for ancillary services and pump-storage) it is proposed to start implementation jointly with the first update of the CRMP in the year 2025. This will have the benefit that the latest, evolving market conditions can be considered for a more robust benefit/cost analysis, especially with respect to increased need for balancing power due to the intermittency and expected emergence of variable renewable energy in the southern African power pool. Currently (as of the year 2022) it is assumed that the market conditions and long-term power supply contracts are not favouring hydro-peaking or pump-storage operations by HCB, but this may gradually change over the coming years.

For several adaptation measures the first step is a scoping study. Dependent on the results, more detailed follow-up feasibility/design studies are proposed before an eventual implementation. The scoping studies will enable a high level, rapid assessment and evaluation of the effectiveness of the proposed adaptation measure as well as a refined cost estimation for implementation. This will also allow HCB to appraise the priority for those adaptation measures where Table 26 currently lists the priority as “to be determined” (tbd).

To increase flood safety, a suite of adaptation measures is proposed. The most effective - but also by far requiring the highest investment costs (CAPEX) - is the construction of a new spillway on the north bank. Other, non-structural measures to increase flood safety can be implemented immediately and more cost-effectively, including:

- continued data sharing with upstream dam operators (ZRA, ZESCO),
- establishment of rating curves and data collection from flow gauges (ARA Centro),

- upgrading and implementation of inflow forecasting tools,
- detailed study on extreme floods to increase understanding of regional processes leading to extreme flood inflow, which will allow adaptive and improved flood management,
- implementation of revised flood rule curve,
- and capacity building.

The *combination* of all these measures should lead to a substantial increase in flood safety. Especially the combination of operational inflow forecasting, adaptive application of flood rule curve, and the lessons learned from critical flood generation processes in the extreme flood study should lead to increased flood safety while at the same time minimizing the reduction in power generation.

Other measures and ongoing initiatives for increased flood preparedness are also valuable, including dam break studies and emergency action plans for warning and evacuation of downstream communities. However, this is mainly related to dam break scenarios (e.g. due to upstream dam failure leading to extreme flood inflow) and not the result of climate effects covered in this Climate Resilience Assessment.

The long-term objective of conjunctive operation with upstream dams should be further pursued via JOTC, as this will increase flood safety and enhance water resources management and hydropower generation. A detailed study and workshops with stakeholders can further quantify and promote the expected benefits of conjunctive operation for the major dam operators in the Zambezi basin.

Table 26: Proposed climate risk management plan (CRMP). Cost estimates are indicative only.

Nr	Description	Task	2023	2024	2025	2026	2027	2028	2029	2030-34	2035-50	Priority	rough cost estimates	
													CAPEX	OPEX
N0	Implementation, monitoring and regular updating of CRMP	Monitoring										High	-	0 USD/yr
		CRMP Update										Medium	-	50k USD/upd.
N1	Data collection and data sharing	Upstream dams										High	-	0 USD/yr
		Flow gauges										High	tbd	0 USD/yr
N2	Operational inflow forecasting system	Implementation										High	300k USD	-
		Operation										High	-	20k USD/yr
N3	Extreme flood study	Preparation of TORs										Medium	-	-
		Flood Study										Medium	100k USD	-
		Improved flood mgmt.										Medium	-	0 USD/yr
N4	Revised flood rule curve	Implementation										High	-	tbd
N5	Expanding ancillary services and hydro-peaking	Scoping Study										Low	20k USD	-
		Detailed Market Study										tbd	tbd	-
		Implementation										tbd	-	tbd
N6	Index-based insurance against drought	Scoping Study										Medium	20k USD	-
		Detailed Study										tbd	tbd	-
		Implementation										tbd	-	x Mio USD/yr
N7	Conjunctive operation with upstream countries	Discussion with JOTC and preparation TORs										High	-	-
		Detailed Study										tbd	150k USD	-
		Implementation										tbd	-	-
N8	Capacity building	Continuous										High	-	5k USD/yr
N9	Continued access to Zambezi DSS	Update & transfer to new server										Medium	10k USD	-
		Annual operation										Medium	-	2k USD/yr
		Add. Training										Medium	15k USD/tr	-
S1	Additional spillway capacity	Internal review by HCB										Medium	-	-
		Design & Construction										Medium	100mil USD	-
		Operation										Medium	-	tbd
S2	Hybrid power generation with solar PV	Scoping Study										High	20k USD	-
		Design & Construction										High	8mil USD/5MW	-
		Operation										High	-	tbd
S3	Extension to pump-storage plant	Scoping Study										Low	tbd	-
		Design & Construction										tbd	tbd	-
		Operation										tbd	-	tbd
S4	Cooling of substations and transformers	Continuous										Low	-	tbd

## 8 Monitoring, evaluation and reporting (Phase 5)

The objective of the Monitoring, Evaluation and Reporting (MER) plan is to provide guidance on how to (a) track the climate resilience of the hydropower plant in operation and to (b) monitor the implementation of the Climate Risk Management Plan (CRMP).

Different areas for monitoring are proposed below. It should be noted that climate resilience must, by nature, be evaluated over longer time scales given the nature of climate variability: a sequence of one or two more or less “bad years” (in terms of inflows for hydropower generation or in terms of flood occurrence for dam safety) does not systematically ask for a deep review of resilience measures.

### Monitoring

It is proposed that the monitoring includes:

- Continued measurement and analysis of reservoir inflow, rainfall, and air temperature data (at the Songo station). Any strong deviations from the observed trends in the previous decades should be critically reviewed. In particular, the further evolution of the mean annual air temperature (which did not show a warming trend in the last decade) should be closely monitored. According to the climate model projections, the warming will continue in the future and the current, observed discontinuation of warming might be an artefact of natural climate variability. It is therefore expected that in the next years also the station data should show a continued warming trend. In addition, it should be monitored if the pattern of inter-annual variability in inflow lies within the observed, historic range or if there are emergent trends (e.g. towards reduced inflow, or increased flood extremes), and if these trends are in line with the climate projections identified in the present study. These types of analyses must also consider the impacts of Kariba operations, which may have changed due to the construction of North and South Bank expansions (additional power houses).
- Water resources development in the Zambezi basin upstream of Cahora Bassa should be closely monitored, as they might have impacts on Cahora Bassa inflows, including:
  - New, major dam developments
  - New, major irrigation schemes
  - Changes in operation patterns of existing dams
  - Inter-basin water transfer schemes
- The reports published by the IPCC should be closely followed. In 2022 the Sixth Assessment Report was published, which summarizes the current scientific knowledge about climate change, which is also reflected in the present study (Climate Resilience Assessment for Cahora Bassa). The upcoming publication of

the Seventh Assessment Report should be screened for any major updates on the regional impacts of climate change in southern Africa and the relevance of the different emission scenarios (i.e. RCP 4.5 and 8.5, as used in the present study).

- New developments for global and regional climate models should be monitored, particularly with a focus on projections for southern Africa. In the present study the climate projections were based on CORDEX-Africa RCMs (CMIP5) and, in addition, also on (coarser) GCM projections (CMIP6). Currently (as of December 2022) it is unclear if and when the CORDEX RCMs will be updated with CMIP6 models for the Africa domain. In other parts of the world (e.g. Europe, Australia, etc.) this update of CORDEX RCMs with CMIP6 models is currently ongoing, and it is expected that the same will be done (albeit at a later stage) for the African domain. Another area of interest is if a new generation of convection permitting GCMs become state-of-the-art in climate science, and if this new type of climate models (with much finer spatial discretization and different parameterization for rainfall) yields new insights for future rainfall conditions in southern Africa.
- Political decisions taken at the annual COP events (Conference of the Parties to the United Nations Framework Convention on Climate Change) should be closely followed, as they might have reverberations on the electricity market in SAPP and new financing instruments for climate risk adaptation and mitigation. The latter may also become an attractive source of funding for investments at HCB (examples include Clean Development Mechanism CDM, Green Climate Fund GCF, etc.). Best practices and emerging international standards (e.g. TCFD reporting) should be reviewed.
- The expected emergence of variable renewable energy (VRE, i.e. solar and wind) in the southern African energy market should be closely monitored. The increased need for balancing power and ancillary services for grid stability are an opportunity for HCB, as discussed in chapter 7.2.6. Changes in the electricity market and the price spread between peak and off-peak hours should be tracked, as this is relevant for switching from baseload generation to hydro-peaking (pending suitable power purchase agreements).
- All activities taken by HCB for implementation of the CRMP should be systematically monitored and documented for later reference and review of actions taken.

## Evaluation

If the monitoring proposed above shows new findings or developments, then the potential impacts on the climate resilience of Cahora Bassa and the effectiveness of the climate risk adaptation measures (chapter 7) should be screened and evaluated. In

general, the evaluation should ideally be done by HCB staff, with support from external consultants if required.

For some of the tasks (e.g. assessment of impacts of upstream water resources development) the Zambezi Decision Support System (DSS) can be used to evaluate the expected impacts on hydropower operation at Cahora Bassa. HCB staff have been trained on the system and as one of the climate resilience measures (chapter 7.2.10) it is proposed that HCB staff have continued access to the Zambezi DSS and receive additional training.

Alternatively, the climate sensitivity analysis plots (chapter 5.3) can also be used for a simplified assessment of the expected impacts of new climate model projections (with the caveat that only changes in the mean but not changes in seasonal distribution or inter-annual variability can be analysed).

## Reporting

The monitoring and evaluation activities shall be initiated by the Coordinator of Climate Risk Management (CCRM, see chapter 7.5.1) and the results reported in annual intervals or when there are major new findings. In such a case the CCRM has to analyse if an update of the CRMP is required, which has to be aligned with HCB management.

It is proposed that the first MER report is prepared at the end of 2023. A tentative title for the report is:

- CRA-MER 2023:  
Climate Resilience Assessment – Monitoring, Evaluation and Reporting 2023

With follow-up reports in the upcoming years.

The document structure should include:

- Introduction and objectives of the report
- Monitoring
  - Hydro-meteorology
    - Long-term annual time-series (hydrological years)
      - Air temperature (Songo station)
      - Precipitation (Songo station)
      - Reservoir inflow (annual average)
      - Peak reservoir inflow (monthly or weekly maximum in the year)
      - Low-flow reservoir inflow (lowest monthly inflow)
    - Deviation from the long-term mean (above average / below average)
  - Upstream water resources management

- Zambezi basin upstream of Cahora Bassa
  - Development of new projects?
  - Reservoir operation at Kariba and Itezihitezhi
- International initiatives
  - Report on new developments with respect to IPCC reports, COP events and outcomes, etc.
  - New financing instruments?
- Climate models
  - Report on new developments with respect to climate models (GCMs, RCMs, CORDEX, etc.). Consult with researchers at UEM (Maputo) or CSAG (Cape Town).
  - New research initiatives?
  - Results of other studies in the region (e.g. World Bank drought resilience study)
- SAPP electricity market
  - New major power plants?
  - Emergence of VRE? Subsidies for VRE?
  - Changes in the spot market and intra-daily electricity prices?
- CRMP implementation
  - Report on all activities related to the implementation of CRMP
  - Implementation status:
    - Non-structural adaptation measures
    - Structural adaptation measures
  - Capacity building and outreach activities (courses, conferences, papers, IHA outreach, etc.)
- Evaluation
  - Short chapters on additional analyses (if any)
    - Studies done by HCB staff to evaluate (quantitatively / qualitatively) the relevance of the monitoring results for the climate resilience measures and climate opportunities for Cahora Bassa (e.g. supported by simulations with Zambezi DSS).
  - Conclusions
    - Is a review and update of CRMP required?

The above document structure can be adapted to individual requirements if there are any unforeseen future data sources and/or developments.

## 9 Appendix

## 9.1 Appendix: Literature collection

### 9.1.1 Reports

Institution	Year	Title	Pages	Volume
International Hydropower Association	2019	Hydropower Sector Climate Resilience Guide	75	
Addleshaw Goddard - IHA	2021	An investor's guide to hydropower in Africa	39	
CIIMA Research Foundation	2019	Zambia Disaster Risk Profile	56	
Food Security Policy	2019	Impacts of climate change on water availability in Zambia: Implications for irrigation development	41	Research Paper 146
International Energy Agency	2020	Climate Impacts on African Hydropower	61	
Hidroelétrica de Cahora Bassa	2012	Cahora Bassa North Bank Power Station - Hydrological Study and Hydropower Potential Assessment, Final Report - Appendix	87	
Hidroelétrica de Cahora Bassa	2012	Cahora Bassa North Bank Power Station - Hydrological Study and Hydropower Potential Assessment, Final Report	102	
Government of Portugal, Government of Mozambique	2007	Technical Due Diligence of the Restructuring of Hidroeléctrica De Cahora Bassa	164	
International Crane Foundation, USA; Direcção Nacional de Aguas, Mozambique	2001	Patterns of hydrological change in the Zambezi Delta, Mozambique - Program for the sustainable management of Cahora Bassa Dam and the Lower Zambezi Valley	159	Working Paper #2
International Crane Foundation, USA	2001	Prescribed flooding and restoration potential in the Zambezi Delta, Mozambique - Program for the sustainable management of Cahora Bassa Dam and the Lower Zambezi Valley	72	Working Paper #3
Museum of Natural History - University of Eduardo Mondlane; Maputo, Mozambique	2006	Assessing Environmental Flow Requirements for the Marromeu Complex of the Zambezi Delta: Application of the DRIFT model	163	
UNESCO-IHE (Institute for Water Education)	2008	Regulation and synchronisation of dam operation for environmental flows in the Zambezi River – preliminary analysis	79	Phase I Report
World Commission on Dams, Cape Town	2000	Kariba Dam Case Study - Annexes	76	
World Commission on Dams, Cape Town	2000	Kariba Dam Case Study	202	
International Crane Foundation; Museum of Natural History, Mozambique	1997	Impacts of hydrological changes on the Marromeu Complex of the Zambezi Delta, with special attention to the avifauna	16	
World Rivers Review	1999	Can This River Be Saved? Rethinking Cahora Bassa Could Make a Difference for Dam-Battered Zambezi	5	
Managing Rivers Wisely	2003	Kafue Flats case study	6	
Dams Initiative, Global Freshwater Programme WWF International	2005	Restoring the Kafue Flats - A partnership approach to environmental flows in Zambia	10	
Republic of Mozambique, Technical Unit for the Implementation of Hydropower Projects (UTIP)	2003	Mepanda Uncua and Cahora Bassa North Project, Feasibility Study	339	
Republic of Mozambique, Technical Unit for the Implementation of Hydropower Projects (UTIP)	2001	Mepanda Uncua and Cahora Bassa North Project, Feasibility Study Final Report on Water Resources Management	139	
Republic of Mozambique, Technical Unit for the Implementation of Hydropower Projects (UTIP)	2001	Mepanda Uncua and Cahora Bassa North Project, Feasibility Study Meteorology, Hydrology and Sediment Transport	235	
International Rivers	2012	A Risky Climate for Southern African Hydro	60	
Republic of Mozambique, Technical Unit for the Implementation of Hydropower Projects (UTIP)	2001	Mepanda Uncua and Cahora Bassa North Project, Feasibility Study Final Environmental Impact Assessment	13	

World Meteorological Organisation WMO, USAID/OFDA	2010	Regional Consultation Meeting on Zambezi River Basin Flood Forecasting and Early Warning Strategy & WMO Information System (WIS) and WIGOS Pilot Project	39	
National Institute for Disaster Management (INGC)	2009	INGC Climate Change Report: Study on the Impact of Climate Change on Disaster Risk in Mozambique	338	
National Institute for Disaster Management (INGC)	2012	Responding to Climate Change in Mozambique, Phase II, Theme 5 Water	366	
University of Glasgow	2010	Sustainability of water resources development for Malawi with particular emphasis on North and Central Malawi	412	
World Bank	2010	The Zambezi River Basin, A Multi-Sector Investment Opportunities Analysis - Summary Report	52	1
World Bank	2010	The Zambezi River Basin, A Multi-Sector Investment Opportunities Analysis - Basin Development Scenarios	106	2
World Bank	2010	The Zambezi River Basin, A Multi-Sector Investment Opportunities Analysis - State of the Basin	202	3
World Bank	2010	The Zambezi River Basin, A Multi-Sector Investment Opportunities Analysis - Modeling, Analysis and Input Data	158	4
ZACPRO 6.1.2	2008	Introductory Volume Chapters II (Water Resources and Hydrological Modelling) +III (Comprehensive Summary of Sector Study No. 7)	51	
World Bank	2006	Lower Zambezi River Basin, Baseline data on landuse, biodiversity and hydrology	62	
SWRSD Zambezi Basin Joint Venture	2011	Transboundary Water Management in SADC - Dam Synchronisation and Flood Releases in the Zambezi River Basin project - Executive Summary	802	
SWRSD Zambezi Basin Joint Venture	2010	Transboundary Water Management in SADC - Dam Synchronisation and Flood Releases in the Zambezi River Basin project - Final Inception Report	118	
Southern African Development Community (SADC)	2011	Dam Synchronisation and Flood Releases in the Zambezi River Basin	3	
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 1 - Executive Summary	84	1
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 2 - Enquadramento Metodológico, Justificacao e Descricao do Empreendimento	89	2
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 3 - O Meio Receptor	598	3
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 4 - Impactos, Medidas de Mitigacao e Conclusoes	274	4
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 5 - Plano de Gestao Ambiental	96	5
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 6 - Quadro de Politica de Reassentamento e Compensacao/Plano de Desenvolvimento Comunitario	43	6
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 7 - Processo de Participacao Publica	120	7
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 8 - Pecas Desenhadas	15	8
Hidroeléctrica Mphanda Nkuwa	2011	Mphanda Nkuwa hydropower plant, Tete - Mozambique, Environmental and Social Impact Assessment, Volume 9 - Anexos	392	9

SADC-WD Zambezi River Authority; SIDA DANIDA, Norwegian Embassy Lusaka	2008	Draft Integrated Water Resources Management, Strategy and Implementation Plan for the Zambezi River Basin	181	
SADC-WD Zambezi River Authority; SIDA DANIDA, Norwegian Embassy Lusaka	2007	Integrated Water Resources Management, Strategy for the Zambezi River Basin, Rapid Assessment – Final Report	188	
WWF	2004	The Mphanda Nkuwa Dam project: Is it the best option for Mozambique's energy needs?	66	
Electricidade de Moçambique	2010	Annual Statistical Report	80	
Rhodes University	2015	The use of hydrological information to improve flood management - Integrated hydrological modelling of the Zambezi River Basin	273	
SARDC, SADC, ZAMCOM, GRID-Arendal, UNEP	2012	Zambezi River Basin, Atlas of changing environment	148	
IFC	2011	Climate Risk and Business Hydropower - Kafue Gorge Lower	146	
World Bank	2018	Application of the Hydropower Sustainability Assessment Protocol in the Zambezi River Basin	113	
ZAMCOM	2019	Strategic Plan for the Zambezi Watercourse 2018-2040	72	

### 9.1.2 Scientific papers

Authors	Year	Title	Journal	Volume / Issue	Pages
Aich et al.	2014	Comparing impacts of climate change on streamflow in four large African river basins	Hydrology and Earth System Sciences	18	17
Arndt et al.	2011	Adapting to climate change: an integrated biophysical and economic assessment for Mozambique	Sustainability Science journal	6	14
Arndt et al.	2015	Informed selection of future climates	Climatic Change	130	13
Arndt, Tarp	2015	Climate change impacts and adaptations: lessons learned from the greater Zambeze River Valley and beyond	Climatic Change	130	8
Arndt, Thurlow	2015	Climate uncertainty and economic development: evaluating the case of Mozambique to 2050	Climatic Change	130	13
Beck, Bernauer	2011	How will combined changes in water demand and climate affect water availability in the Zambezi river basin?	Global Environmental Change	21 (3)	12
Beilfuss	2010	Modelling trade-offs between hydro power generation and environmental flow scenarios: a case study of the Lower Zambezi River Basin, Mozambique	International Journal of River Basin Management	8 (3-4)	17
Bertoni et al.	2019	Discovering Dependencies, Trade-Offs, and Robustness in Joint Dam Design and Operation: An Ex-Post Assessment of the Kariba Dam	Earth's Future	7	24
Black et al.	2016	The Use of Remotely Sensed Rainfall for Managing Drought Risk: A Case Study of Weather Index Insurance in Zambia	Remote Sensing	8 (342)	16
Botha et al.	2016	Practical lessons learnt from the rehabilitation of spillway gates at Cahora Bassa Dam	SANCOLD	2a-209	10
Butchart-Kuhlmann et al.	2018	Multicriteria decision analysis framework for hydrological decision support using environmental flow components	Ecological Indicators	93	11

Carvalho, Matsinhe and Oosthuizen	2016	Monitoring system of Cahora Bassa Dam. The past, present and way forward	SANCOLD	6-87	8
Chinowsky et al.	2015	Infrastructure and climate change: a study of impacts and adaptations in Malawi, Mozambique, and Zambia	Climatic Change	130	14
Cohen Liechti et al.	2012	Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi River Basin	Hydrology and Earth System Sciences	16	12
Conway et al.	2015	Climate and southern Africa's water–energy–food nexus	Nature Climate Change	5	10
Conway et al.	2017	Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption	Nature Energy	2	8
Cook et al.	2020	Twenty-First Century Drought Projections in the CMIP6 Forcing Scenarios	Earth's Future	8	20
Coughlan de Perez et al.	2017	Should seasonal rainfall forecasts be used for flood preparedness?	Hydrology and Earth System Sciences	21	8
Di Baldassarre et al.	2010	Flood fatalities in Africa: From diagnosis to mitigation	Geophysical Research Letters	37	5
Dosio et al.	2021	Projected future daily characteristics of African precipitation based on global (CMIP5, CMIP6) and regional (CORDEX, CORDEX-CORE) climate models	Climate Dynamics	57	24
Dutra et al.	2013	Seasonal forecasts of droughts in African basins using the Standardized Precipitation Index	Hydrology and Earth System Sciences	17	15
Falchetta et al.	2019	Hydropower dependency and climate change in sub-Saharan Africa: a nexus framework and evidence-based review	Journal of Cleaner Production	231	19
Fant et al.	2015	An uncertainty approach to assessment of climate change impacts on the Zambezi River Basin	Climatic Change	130	14
Fant, Gebretsadik, Strzepek	2013	Impact of climate change on crops, irrigation and hydropower in the Zambezi River Basin	UNU-WIDER	39	26
Fant, Schlosser, Strzepek	2016	The impact of climate change on wind and solar resources in southern Africa	Applied Energy	161	9
Ficchi et al.	2021	Beyond El Nino: Unsung climate modes drive African floods	Weather and Climate Extremes 33	33	12
Fischer, Knutti	2016	Observed heavy precipitation increase confirms theory and early models	Nature Climate Change	6	7
Gandolfi, Salewicz	1990	Multiobjective Operation of Zambezi River Reservoirs	IIASA	31	32
Gandolfi, Salewicz	1991	Water resources management in the Zambezi valley: Analysis of the Kariba operation	IAHS	201	12
Gardner	2009	Assessing the effect of climate change on mean annual runoff	Journal of Hydrology	379	9
Gebretsadik et al.	2016	Optimized reservoir operation model of regional wind and hydro power integration case study: Zambezi basin and South Africa	Applied Energy	161	9
Gumbo et al.	2021	Assessing water resources availability in headwater sub-catchments of Pungwe River Basin in a changing climate	Journal of Hydrology: Regional Studies	35	13
Gumindoga et al.	2020	The spatio-temporal soil moisture variation along the major tributaries of Zambezi River in the Mbire District, Zimbabwe	Journal of Hydrology: Regional Studies	32	24
Gumindoga et al.	2021	Propagation of CMORPH rainfall errors to REW streamflow simulation mismatch in the upper Zambezi Basin	Journal of Hydrology: Regional Studies	38	14
Hamududu, Killingtveit	2016	Hydropower Production in Future Climate Scenarios: the Case for the Zambezi River	Energies	9	19
Harrison, Whittington	2002	Susceptibility of the Batoka Gorge hydroelectric scheme to climate change	Journal of Hydrology	264	12

Hoekstra	2003	Water Scarcity in the Zambezi Basin in the Long-Term Future: A Risk Assessment	Integrated Assessment	4	20
Hughes, Farinosi	2020	Assessing development and climate variability impacts on water resources in the Zambezi River basin. Simulating future scenarios of climate and development	Journal of Hydrology: Regional Studies	32	21
Hughes, Farinosi	2021	Unpacking some of the linkages between uncertainties in observational data and the simulation of different hydrological processes using the Pitman model in the data scarce Zambezi River basin	Hydrological Processes	35	18
Hughes, Kapangaziwiri, Sawunyama	2010	Hydrological model uncertainty assessment in southern Africa	Journal of Hydrology	387	12
Hughes, Mantel, Farinosi	2020	Assessing development and climate variability impacts on water resources in the Zambezi River basin: Initial model calibration, uncertainty issues and performance	Journal of Hydrology: Regional Studies	32	15
Hulsman et al.	2020	Using altimetry observations combined with GRACE to select parameter sets of a hydrological model in a	Hydrology and Earth System Sciences	24	29
Hulsman et al.	2021	Learning from satellite observations: increased understanding of catchment processes through stepwise model improvement	Hydrology and Earth System Sciences	25	26
Hulsman, Savenije, Hrachowitz	2021	Satellite-based drought analysis in the Zambezi River Basin: Was the 2019 drought the most extreme in several decades as locally perceived?	Journal of Hydrology: Regional Studies	34	13
Jacobson et al.	2013	Distribution and abundance of lions in northwest Tete Province, Mozambique	Tropical Conservation Science	6	21
James et al.	2018	Evaluating climate models with an african lens	American Meteorological Society	2	24
Jury	2003	The coherent variability of African river flows: Composite climate structure and the Atlantic circulation	Water SA	29	10
Jury	2010	Climate and weather factors modulating river flows in southern Angola	International Journal of Climatology	30	8
Jury	2017	Evaluation of satellite-model proxies for hydro-meteorological services in the upper Zambezi	Journal of Hydrology: Regional Studies	13	19
Kalognomou et al.	2013	A Diagnostic Evaluation of Precipitation in CORDEX Models over Southern Africa	Journal of Climate	26	30
Kalumba, Nyirenda	2017	River flow availability for environmental flow allocation downstream of hydropower facilities in the Kafue Basin of Zambia	Physics and Chemistry of the Earth	102	10
Kling	2017	Climate variability risks for electricity supply	Nature Energy	2	2
Kling, Fuchs, Stanzel	2015	Future hydro generation in the Zambezi basin under the latest IPCC climate change projections	Hydropower and Dams	Special Issue	5
Kling, Stanzel, Preishuber	2014	Impact modelling of water resources development and climate scenarios on Zambezi River discharge	Journal of Hydrology: Regional Studies	1	27
Kusangaya et al.	2014	Impacts of climate change on water resources in southern Africa: A review	Physics and Chemistry of the Earth	67-69	8
Lüdecke et al.	2021	Decadal and multidecadal natural variability of African rainfall	Journal of Hydrology: Regional Studies	34	23
Lumbroso, Woolhouse, Jones	2015	A review of the consideration of climate change in the planning of hydropower schemes in sub-Saharan Africa	Climatic Change	133 (4)	13
Masih et al.	2014	A review of droughts on the African continent: a geospatial and long-term perspective	Hydrology and Earth System Sciences	18	15
Mason	2010	Climate variability in civil infrastructure planning	Civil Engineering	163	7

Matos et al.	2010	Analysis of flow regime changes due to operation of large reservoirs on the Zambezi River	Environmental Hydraulics		6
Matos et al.	2013	Can satellite based pattern-oriented memory improve the interpolation of sparse historical rainfall records?	Journal of Hydrology	492	15
Matos et al.	2014	Pattern-oriented memory interpolation of sparse historical rainfall records	Journal of Hydrology	510	11
Matos, Cohen-Liechti, Schleiss	2016	Analysis of future hydropower development and operational scenarios on the Zambezi River basin	SANCOLD	7-31	10
Maure et al.	2018	The southern African climate under 1.5 °C and 2 °C of global warming as simulated by CORDEX regional climate models	Environmental Research Letters	13	9
Mazvimavi	2010	Investigating changes over time of annual rainfall in Zimbabwe	Hydrology and Earth System Sciences	14	9
Mazvimavi, Wolski	2006	Long-term variations of annual flows of the Okavango and Zambezi Rivers	Physics and Chemistry of the Earth	31	8
Meier, Frömetl, Kinzelbach	2011	Hydrological real-time modelling in the Zambezi river basin using satellite-based soil moisture and rainfall data	Hydrology and Earth System Sciences	15	10
Mertens et al.	2013	Adapted reservoir management in the Zambezi river basin to meet environmental needs	Hydropower and Dams	2	5
Michailovsky et al.	2012	River monitoring from satellite radar altimetry in the Zambezi River basin	Hydrology and Earth System Sciences	16	12
Michailovsky, Bauer-Gottwein	2014	Operational reservoir inflow forecasting with radar altimetry: the Zambezi case study	Hydrology and Earth System Sciences	18	11
Muchuru et al.	2014	Seasonal rainfall predictability over the Lake Kariba catchment area	Water SA	40	10
Muchuru, Landman, DeWitt	2016	Prediction of inflows into Lake Kariba using a combination of physical and empirical models	International Journal of Climatology	36	12
Munodawafa, Mazvidza, Mhlanga	2016	Kariba Dam rehabilitation project - Improving spillway capacity through reshaping of the plunge pool	SANCOLD	2a-171	9
Munodawafa, Mazvidza, Mhlanga	2016	Kariba Dam rehabilitation project - Structural improvements to the Kariba Dam spillway upstream control facility to mitigate the effects of alkali aggregate reaction	SANCOLD	2b-37	8
Ndebele, Mashonjowa, Hill	2011	The implications of a changing climate on the Kapenta fish stocks of Lake Kariba, Zimbabwe	Transactions of the Royal Society of South Africa	66	15
Ndhlovu, Woyessa	2020	Modelling impact of climate change on catchment water balance, Kabompo River in Zambezi River Basin	Journal of Hydrology: Regional Studies	27	15
Ndhlovu, Woyessa	2021	Evaluation of Streamflow under Climate Change in the Zambezi River Basin of Southern Africa	Water	13	20
Nicholson	2000	The nature of rainfall variability over Africa on time scales of decades to millenia	Global and Planetary Change	26	22
Nkhonjera	2017	Understanding the impact of climate change on the dwindling water resources of South Africa, focusing mainly on Olifants River basin: A review	Environmental Science & Policy	71	11
Ouedraogo	2017	Modeling sustainable long-term electricity supply-demand in Africa	Applied Energy	190	21
Peleg et al.	2020	Downscaling climate projections over large and data sparse regions: Methodological application in the Zambezi River Basin	International Journal of Climatology	40	23
Phiri et al.	2021	A pseudo-reservoir concept in SWAT model for the simulation of an alluvial floodplain in a complex tropical river system	Journal of Hydrology: Regional Studies	33	18

Ray et al.	2018	Multidimensional stress test for hydropower investments facing climate, geophysical and financial uncertainty	Global Environmental Change	48	14
Schlosser, Strzepek	2015	Regional climate change of the greater Zambezi River Basin: a hybrid assessment	Climatic Change	130	11
Scipal, Scheffler, Wagner	2005	Soil moisture-runoff relation at the catchment scale as observed with coarse resolution microwave remote sensing	Hydrology and Earth System Sciences	9	11
Sheffield et al.	2014	A drought monitoring and forecasting system for sub-Saharan African water resources and food security	American Meteorological Society	6	22
Shela	2000	Management of shared river basins: the case of the Zambezi River	Water Policy	2	17
Spalding-Fecher et al.	2016	The vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change and irrigation development	Mitigation and Adaptation Strategies for Global Change	21	24
Spalding-Fecher et al.	2017	Electricity supply and demand scenarios for the Southern African power pool	Energy Policy	101	12
Spalding-Fecher, Joyce, Winkler	2017	Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wide impacts and policy implications	Energy Policy	103	14
Stanzel, Kling	2014	Future hydropower production in the Lower Zambezi under possible climate change influence	Water SA	40	10
Thiemig et al.	2012	Validation of Satellite-Based Precipitation Products over Sparsely Gauged African River Basins	Journal of Hydrometeorology	13 (6)	24
Tilmant et al.	2010	Optimal Water Allocation in the Zambezi Basin	Proceedings International Environmental Modelling and Software Society	5	10
Tilmant et al.	2011	Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi river basin	Water Policy	14	20
Tilmant, Beevers, Muyunda	2010	Restoring a flow regime through the coordinated operation of a multireservoir system: The case of the Zambezi River basin	Water Resources Research	46	11
Tirivarombo	2017	Hydrological impacts of climate change in the Zambezi River Basin	International Journal of Scientific Research and Innovative Technology	4	16
Trambauer et al.	2014	Identification and simulation of space–time variability of past hydrological drought events in the Limpopo River basin, southern Africa	Hydrology and Earth System Sciences	18	18
Tyson et al.	2002	Millennial to multi-decadal variability in the climate of Southern Africa	International Journal of Climatology	22	13
Uamusse et al.	2017	Climate Change observations into Hydropower in Mozambique	Energy Procedia	138	6
Uamusse, Tussupova, Persson	2020	Climate Change Effects on Hydropower in Mozambique	Applied Sciences	10	12
Valdés-Pineda et al.	2021	Improving Operational Short- to Medium-Range (SR2MR) Streamflow Forecasts in the Upper Zambezi Basin and Its Sub-Basins Using Variational Ensemble Forecasting	Hydrology	8	25
Walling	1984	The sediment yields of African rivers	IAHS	144	19
Winsemius et al.	2006	Comparison of two model approaches in the Zambezi river basin with regard to model reliability and identifiability	Hydrology and Earth System Sciences	10	14
Winsemius et al.	2014	The potential value of seasonal forecasts in a changing climate in southern Africa	Hydrology and Earth System Sciences	18	14

Winsemius, Savenije, Bastiaanssen	2008	Constraining model parameters on remotely sensed evaporation: justification for distribution in ungauged basins?	Hydrology and Earth System Sciences	12	11
Yamba et al.	2011	Climate change/variability implications on hydroelectricity generation in the Zambezi River Basin	Mitigation and Adaptation Strategies for Global Change	16	12
Zimba et al.	2018	Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach	Journal of Hydrology: Regional Studies	15	22

## 9.2 Appendix: Data collection

### 9.2.1 Meteorological data

The collection of meteorological data focussed on the following stations.

Data	Data provider	Received by AFRY	Comments / next steps	to-do
Station in Songo: <ul style="list-style-type: none"> <li>Daily data</li> <li>Period 1990-2021 (if available)</li> <li>Precipitation [mm]</li> <li>Air temperature [°C], min &amp; max</li> <li>Relative humidity [%]</li> <li>Wind speed [m/s]</li> </ul>	HCB	yes		done
Station at Cahora Bassa dam <ul style="list-style-type: none"> <li>Same data specs as for Songo station</li> </ul>	HCB	n/a	The stations have many gaps/data not reliable	done
Automatic stations in the reservoir (30 km, 60 km, 160 km upstream from dam) <ul style="list-style-type: none"> <li>Same data specs as for Songo station</li> </ul>	HCB	n/a	The stations have many gaps/data not reliable	done
Evaporation: <ul style="list-style-type: none"> <li>Daily data</li> <li>Period 1990-2021 (if available)</li> <li>Evaporation pan Type A in Songo</li> </ul>	HCB	yes		done
Stations operated by ARA <ul style="list-style-type: none"> <li>Daily data</li> <li>Period 1990-2021 (if available)</li> <li>Precipitation [mm]</li> </ul>	ARA	n/a	It was decided not to collect precipitation data from ARA, as sufficient information is available from other sources already collected.	done

In addition, AFRY collected meteorological data from global sources, as listed below.

Data	Data provider	Received by AFRY	Comments / next steps	to-do
Global Precipitation Climatology Center (GPCC): <ul style="list-style-type: none"> <li>• Period 1901-2018</li> <li>• Monthly data, gridded station data</li> <li>• Precipitation</li> </ul>	GPCC	yes	Global data already collected. AFRY processed the data for Cahora Bassa.	done
Global Precipitation Measurement (GPM): <ul style="list-style-type: none"> <li>• Period 2000-2021</li> <li>• Daily data, gridded satellite data</li> <li>• Precipitation</li> </ul>	NASA/JAXA	yes	Global data already collected. AFRY processed the data for Cahora Bassa.	done
Rainfall Estimator African Rainfall Climatology (RFE ARC) <ul style="list-style-type: none"> <li>• Period 1983-2021</li> <li>• Daily data, gridded satellite data</li> <li>• Precipitation</li> </ul>	FEWS NET	yes	Africa data already collected. AFRY processed the data for Cahora Bassa.	done
Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT): <ul style="list-style-type: none"> <li>• Period 1983-2021</li> <li>• Daily data, gridded satellite data</li> <li>• Precipitation</li> </ul>	Univ. Reading	yes	Africa data already collected. AFRY processed the data for Cahora Bassa.	done
Climatic Research Unit (CRU) data: <ul style="list-style-type: none"> <li>• Period 1901-2019</li> <li>• Monthly data</li> <li>• gridded based on station measurements</li> <li>• Air temperature</li> <li>• Potential evapotranspiration (Penman Monteith)</li> </ul>	CRU	yes	Global data already collected. AFRY processed the data for Cahora Bassa.	done
Global Forecasting System (GFS) data: <ul style="list-style-type: none"> <li>• Air temperature data</li> <li>• daily, gridded</li> <li>• From AFRY's operational archive</li> </ul>	NOAA	yes	GFS data was used to fill in remaining data gaps of other sources.	done
CLIMWAT data: <ul style="list-style-type: none"> <li>• Mean monthly meteo station data</li> <li>• Used to compute potential evapo with CROPWAT model</li> </ul>	FAO	yes	Global data already collected. AFRY processed the data for Cahora Bassa.	done

Earth2Observe <ul style="list-style-type: none"> <li>• Potential evapotranspiration data</li> <li>• various methods available, focus on Penman-Monteith data</li> </ul>	Copernicus	yes	Penman-Monteith data-set was downloaded from website.	done
Meteo station data: <ul style="list-style-type: none"> <li>• daily data</li> <li>• precipitation</li> <li>• air temperature</li> </ul>	WMO / NOAA	yes	Many data gaps. Was used to double-check gridded data products.	done

### 9.2.2 Climate model data

Climate model projections were extracted as time-series data from the following data sources.

Data	Data provider	Received by AFRY	Comments / next steps	to-do
CORDEX Africa regional climate model data, precipitation and air temperature	ESGF	yes	Africa-wide data set.	done
CMIP6 global climate model data	Copernicus	yes	AFRY developed a script for processing of the data via an API from the Copernicus website.	done

### 9.2.3 Hydrological data

Daily observed discharge (Qobs) data was collected for the gauges listed in the table below. The time-series should be as long as possible (e.g. 1950-2021). If no Qobs data are available for a gauge, then at least daily observed water level (Wlobs) data shall be collected.

Gauge	Data provider	Received by AFRY	Comments / next steps	to-do
Gauges in Zambia <ul style="list-style-type: none"> <li>Luangwa River at Great East Road Bridge</li> <li>Kafue River at Kafue Hook Bridge</li> </ul>	WARMA	(yes)	AFRY requested data from WARMA with the support of HCB. The data have not been received.  Note: AFRY obtained Luangwa daily Qobs data for the period 1949-1993 from GRDC.  Data for the Kafue River were obtained from other sources.	done
Gauges in Zimbabwe <ul style="list-style-type: none"> <li>Manyame River at Nyakapupu G/W</li> <li>Manyame River at Chinhoyi Old Road Bridge</li> </ul>	ZINWA	yes	AFRY requested and received data for two gauges at the Manyame River (a processing fee applied, which was paid to ZINWA).	done
Gauges in Mozambique: <ul style="list-style-type: none"> <li>Panhame (Manyame) River</li> <li>Zambezi at Tete</li> <li>Luenha River</li> </ul>	ARA	yes	For the Panhame River only water level records are available. Data of several other gauges were also received.	done
Gauges of the Zambezi River Authority, as well as Kariba outflow data	ZRA	yes	As part of AFRY's ongoing collaboration with ZRA for the operation of the Kariba Inflow Forecasting System a good database is already available at AFRY. ZRA granted permission to use data of key gauges for analyses for Cahora Bassa.	done
Dam outflow data of ZESCO <ul style="list-style-type: none"> <li>Itezhitezhi</li> <li>Kafue Gorge Upper</li> </ul>	ZESCO	yes	AFRY asked for permission from ZESCO to re-use data collected in previous studies (Kafue Gorge Lower ESIA).	done
Global Runoff Data Center (GRDC): <ul style="list-style-type: none"> <li>Daily data</li> <li>Monthly data</li> <li>Numerous gauges in Zimbabwe</li> </ul>	GRDC	yes		done

### 9.2.4 Reservoir & dam data

Data about the Cahora Bassa reservoir and dam.

Data	Data provider	Received by AFRY	Comments / next steps	to-do
Elevation (m), volume (km <sup>3</sup> , hm <sup>3</sup> , or m <sup>3</sup> ) area (km <sup>2</sup> ) curve of the reservoir	HCB	yes		done
Reservoir design water levels <ul style="list-style-type: none"> <li>• Maximum flood water level</li> <li>• Full supply level</li> <li>• Minimum operation level</li> </ul>	HCB	yes		done
Spillway capacity <ul style="list-style-type: none"> <li>• Capacity of radial gates</li> <li>• Capacity of surface gate</li> <li>• Total outflow capacity</li> </ul>	HCB	yes		done
Daily reservoir operation time-series data: <ul style="list-style-type: none"> <li>• daily data</li> <li>• period 1976-2021</li> <li>• reservoir water level [m]</li> <li>• inflow [m<sup>3</sup>/s]</li> <li>• outflow [m<sup>3</sup>/s]               <ul style="list-style-type: none"> <li>○ spillway</li> <li>○ turbines</li> <li>○ total</li> </ul> </li> </ul>	HCB	yes		done
Reservoir data measured by environmental team <ul style="list-style-type: none"> <li>• water temperature [°C] in the reservoir</li> </ul>	HCB	yes		done

### 9.2.5 Hydropower data

Data	Data provider	Received by AFRY	Comments / next steps	to-do
Installed capacity [MW]	HCB	yes		done
Turbine/plant design discharge [m <sup>3</sup> /s]	HCB	yes		done
Turbine or plant efficiency (hillcharts) HCB uses a chart that relates turbine power to head and discharge. HCB uses an equation to calculate energy generation	HCB	yes		done
Tailwater rating curve at powerhouse: Relationship between total outflow [m <sup>3</sup> /s] and river water level [m]	HCB	yes		done
Hydraulic head loss [m] at design discharge	HCB	yes		done
Basic info on selling energy to clients (contracts)	HCB	(yes)	An overview has been shared by HCB. More details were discussed during the workshop with AFRY.	done
Power generation [MW] or energy generation [MWh] time-series data: <ul style="list-style-type: none"> <li>monthly data</li> <li>period 2000-2021</li> </ul>	HCB	yes		done
Time-series data of tailwater level at the powerhouse	HCB	no, data not measured	HCB informed AFRY that a gauge might be installed in the future to measure the tailwater level at the powerhouse. Currently, the tailwater level is calculated from the outflow data.	done

### 9.2.6 Transmission line data

Data	Data provider	Received by AFRY	Comments / next steps	to-do
Basic info on transmission lines	HCB	yes		done
Location of transmission lines (as map, or ideally as GIS shape file)	OSM	yes	The shape files were extracted from Open Street Map (OSM).	done

### 9.3 Appendix: Cahora Bassa data

Key data for Cahora Bassa are presented in the tables and figures below.

The reservoir storage volume depends on the reservoir water level and is computed with the following equation:

$$VOL = 0.22218 * (RWL - 256.5)^{2.95873}$$

where:

VOL is the reservoir storage volume in [hm<sup>3</sup>]

RWL is the reservoir water level in [m.a.s.l.]

Table 27: Key features of Cahora Bassa reservoir

Variable	Value
Max flood level	329 m
Full storage level	326 m
Target level for refilling	325.5 m (approximately)
Target level for drawdown	> 310 m (approximately)
Min operation level	295 m
Dead storage volume	10,906 hm <sup>3</sup>
Full storage volume (at 326 m)	62,610 hm <sup>3</sup>
Useful volume	51,704 hm <sup>3</sup>
Max flooded area	2900 km <sup>2</sup>

Table 28: Key features of Cahora Bassa powerhouse (South Bank)

Variable	Value
Number of turbines	5
Turbine power (nominal)	415 MW (nominal power at head of 103m, 450 m <sup>3</sup> /s turbine flow)
Turbine power (max)	484 MW (at head of 119m, 450 m <sup>3</sup> /s turbine flow)
Installed capacity	2075 MW
Maximum turbine flow	2250 m <sup>3</sup> /s
Tailwater level	204.98 (for 2250 m <sup>3</sup> /s total discharge)
Hydraulic losses	1.286 m (hydraulic loss at design discharge for CBS 415 MW/unit)
efficiency	92 % (approximately, depends on hill-chart)

Table 29: Key features of transmission lines from Cahora Bassa

Line	Type	Voltage [kV]
to Matambo (line 1)	HVAC	220
to Matambo (line 2)	HVAC	220
to Bindura, Zimbabwe	HVAC	330
to Apollo, South Africa (line 1)	HVDC	533
to Apollo, South Africa (line 2)	HVDC	533

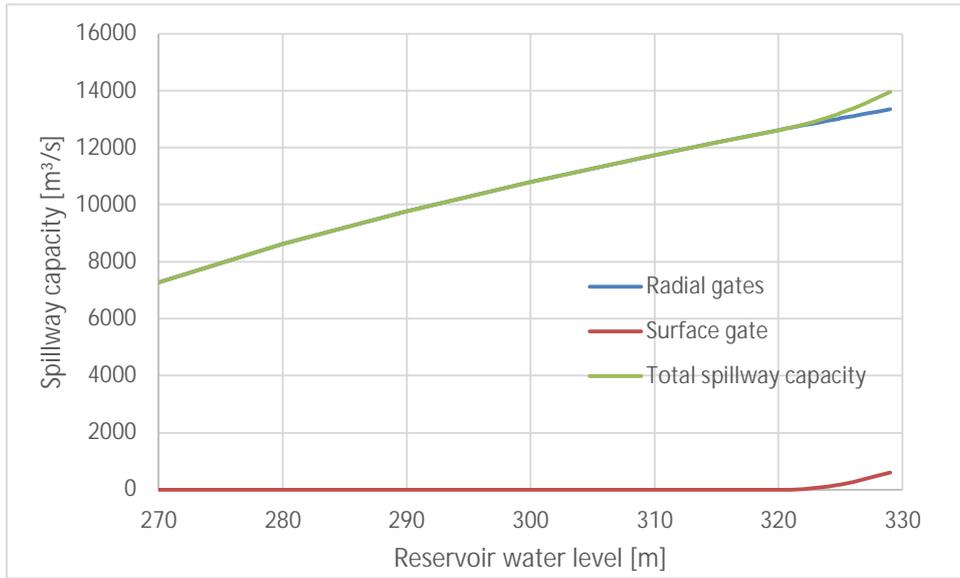


Figure 66: Spillway capacity as a function of reservoir water level

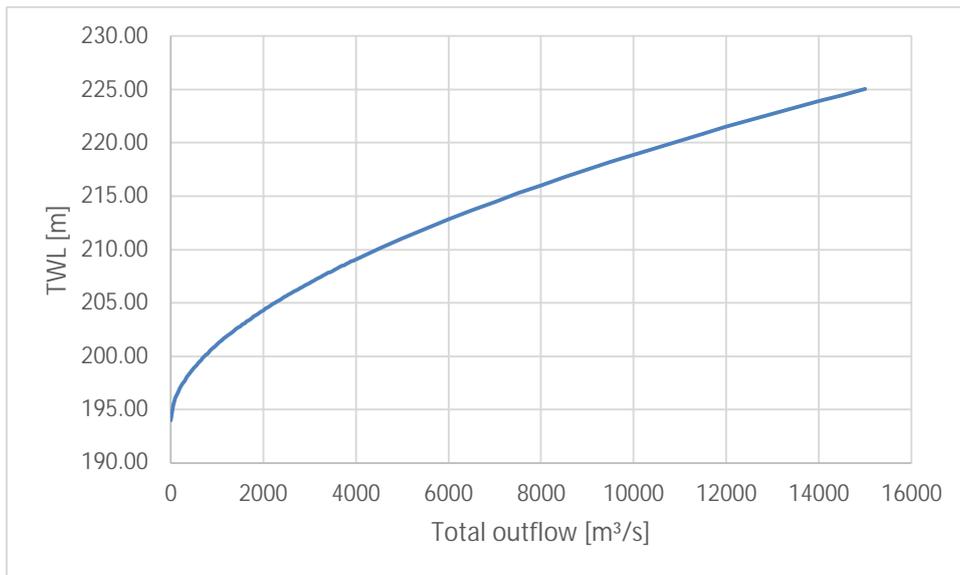


Figure 67: Tailwater level (TWL) as a function of total outflow

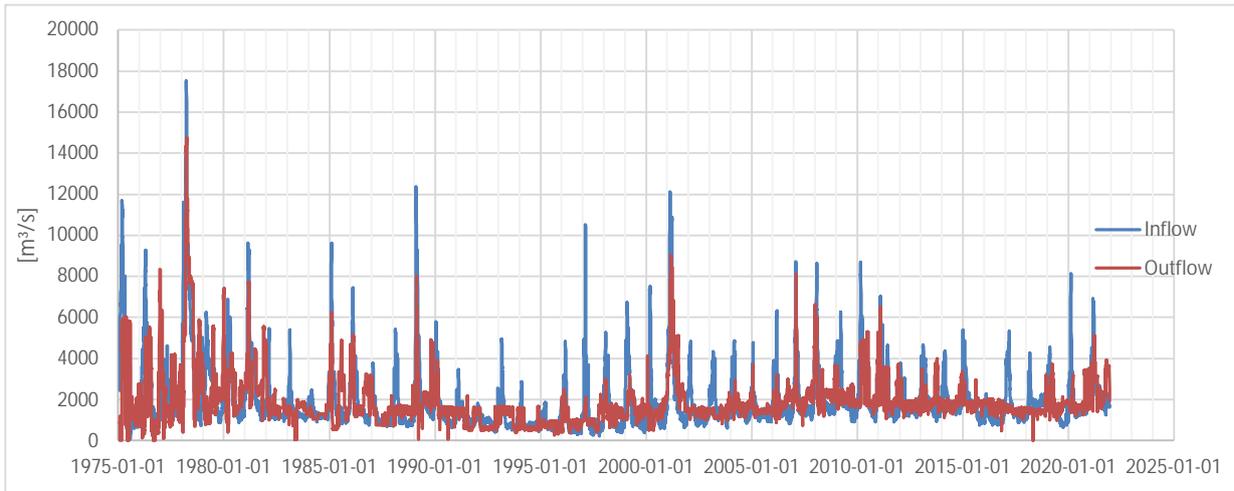


Figure 68: Daily inflow and outflow for Cahora Bassa reservoir, data 1975-2021

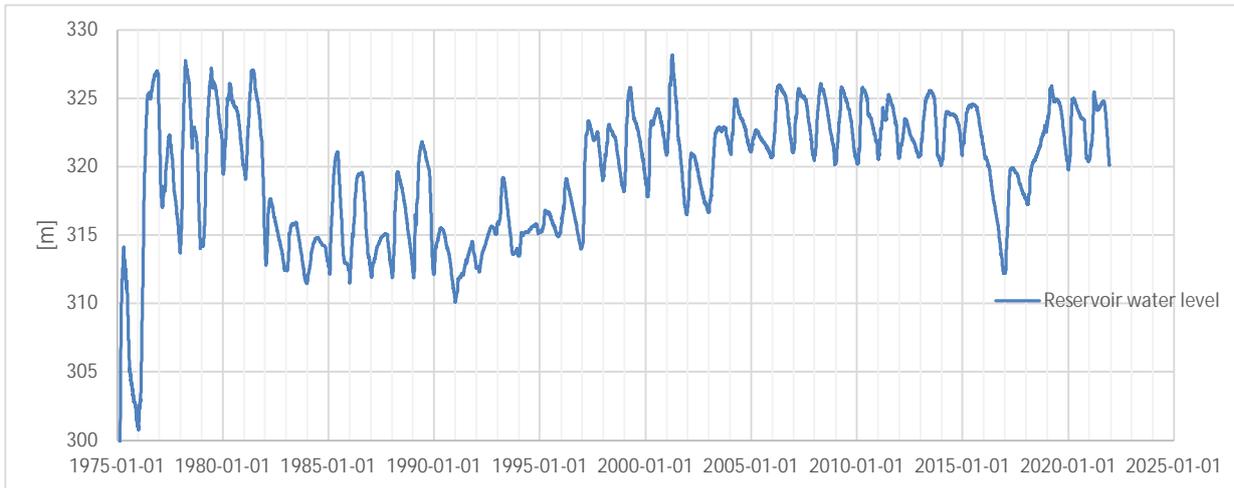


Figure 69: Daily reservoir water level in Cahora Bassa, data 1975-2021

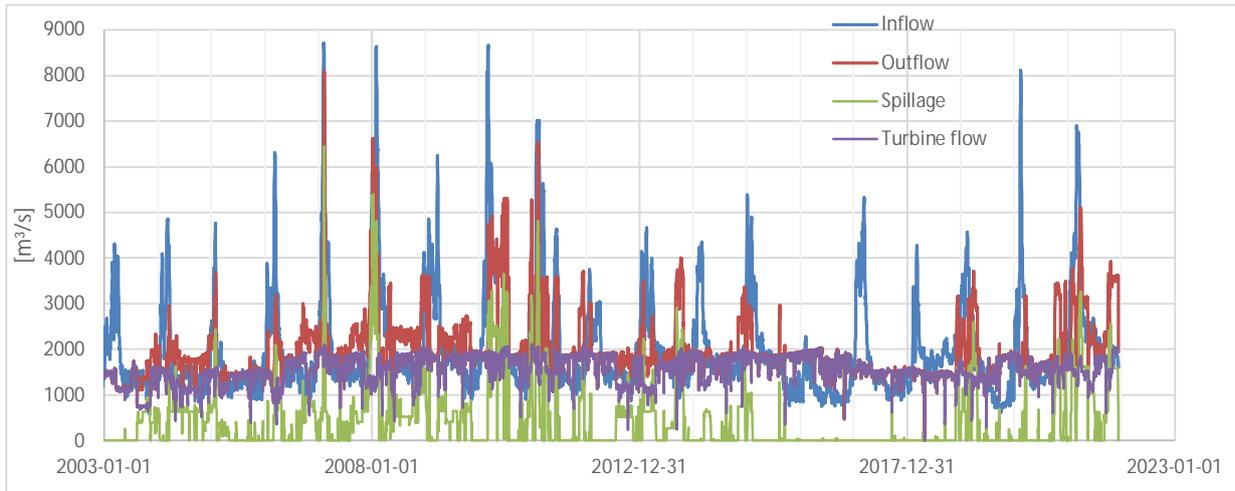


Figure 70: Daily reservoir operation data of Cahora Bassa since 2003

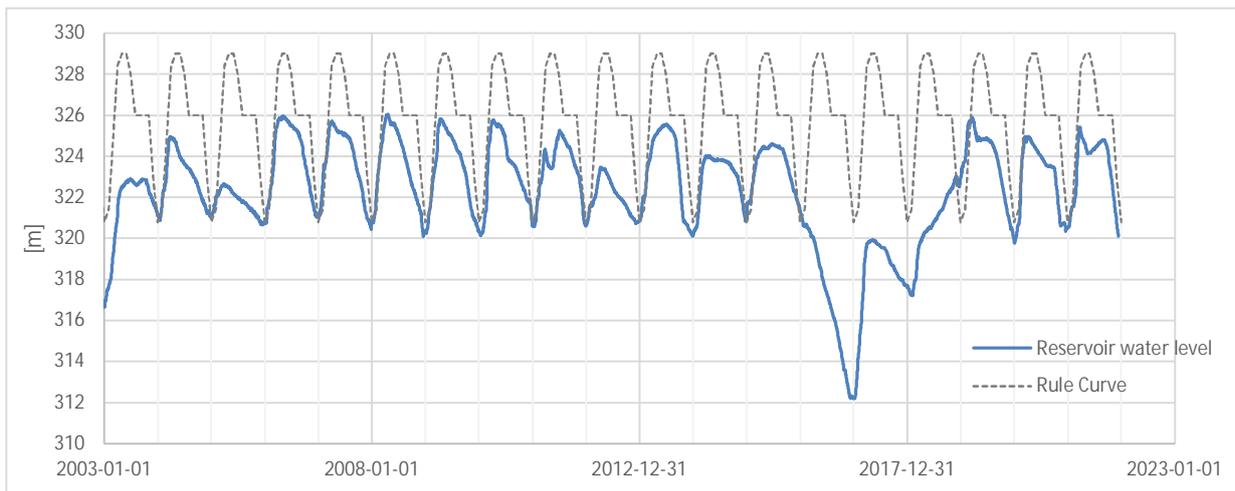


Figure 71: Daily reservoir water level and rule curve for Cahora Bassa, data since 2003

## 9.4 Appendix: CORDEX climate model data

The CORDEX climate model data were summarized for the following spatial entities (subbasins “sb”):

- Cahora Bassa basin: average for sb 1-19 in Zambezi DSS, upstream HCB dam
- Upper Zambezi: average for sb 1-8 in Zambezi DSS, upstream Victoria Falls
- Kafue basin: average for sb 12-14 in Zambezi DSS, upstream KGU
- Luangwa basin: average for sb 15-16 in Zambezi DSS, upstream Gt E Rd Bridge

These spatial entities are only used for the purpose of preparing graphs. The actual model simulations are based on the time-series data in 27 subbasins of AFRY’s Zambezi DSS.

The following naming convention is used:

- The experiment name includes first the RCM, then the GCM abbreviation

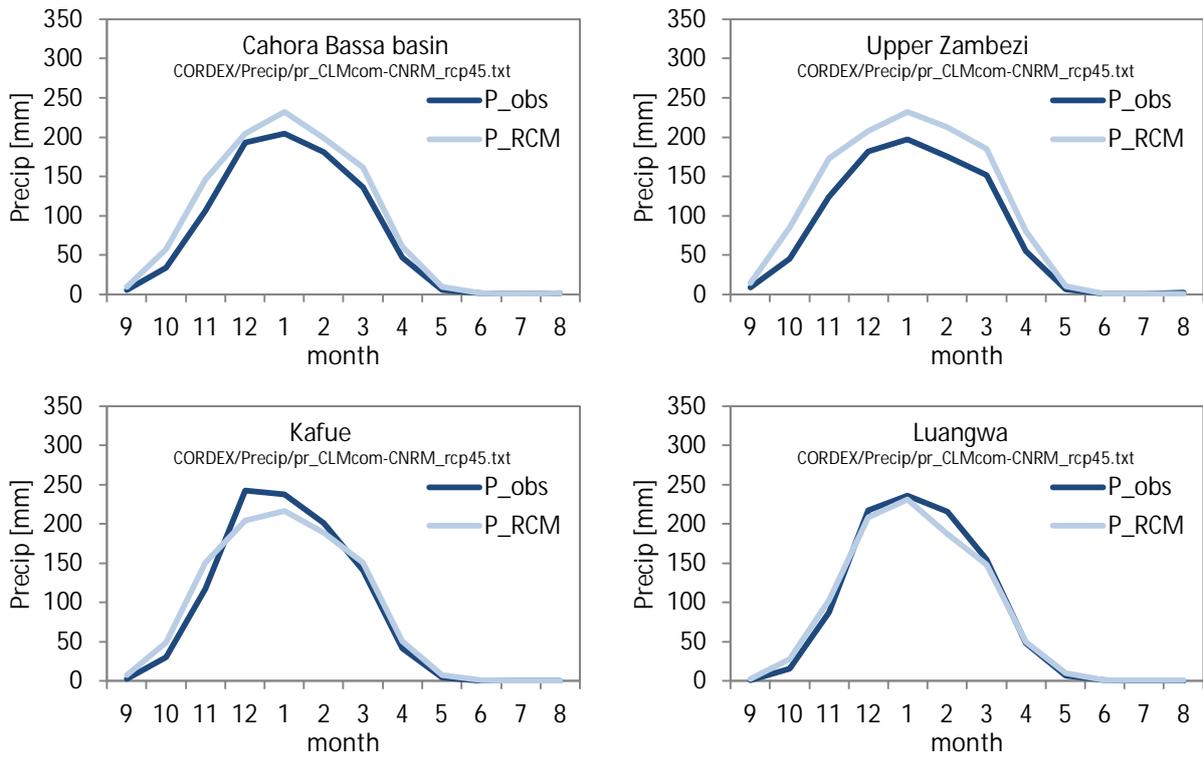
Note that the merged time-series climate model data 1950-2100 (historic & RCP) have identical results for RCP4.5 and RCP8.5 before 2005 (e.g. in the period 1961-1990).

### 9.4.1 Evaluation of historic precipitation 1961-1990

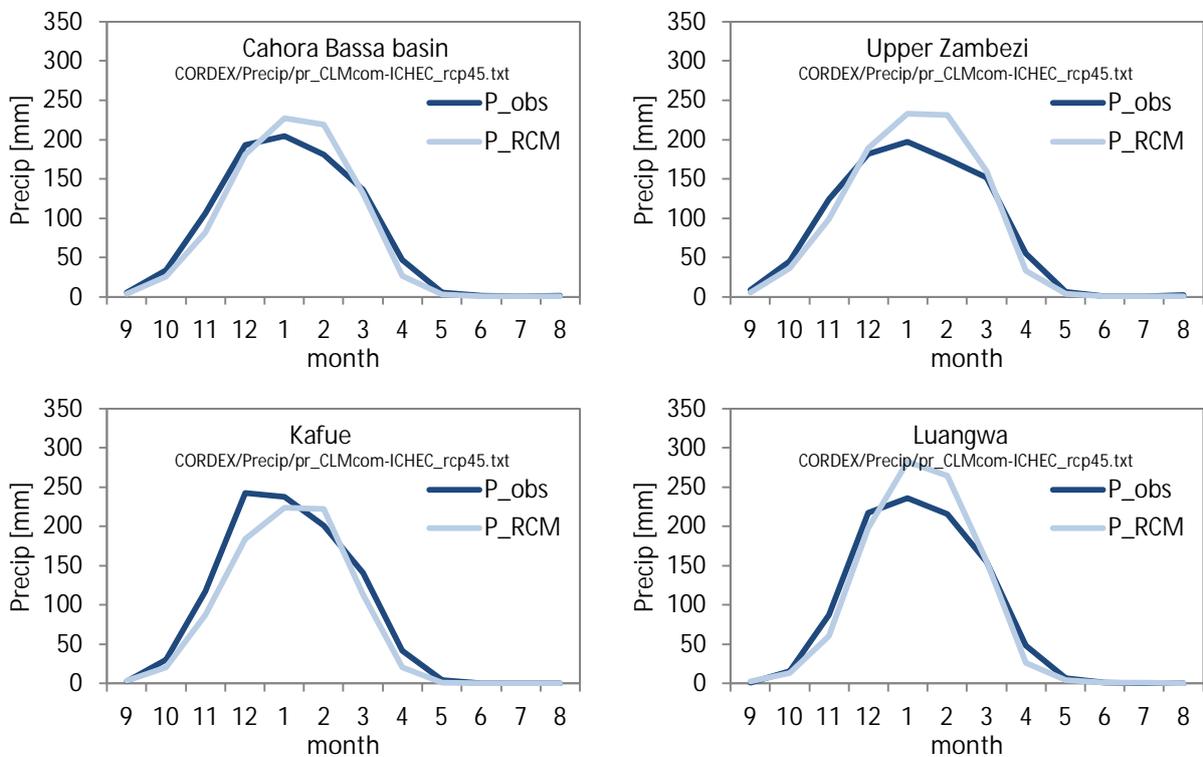
The graphs below show a comparison of simulated and observed mean monthly precipitation in the period 1961-1990, with the following specifications:

- P\_obs: observed precipitation data of GPCC
- P\_RCM: simulated precipitation data of RCM

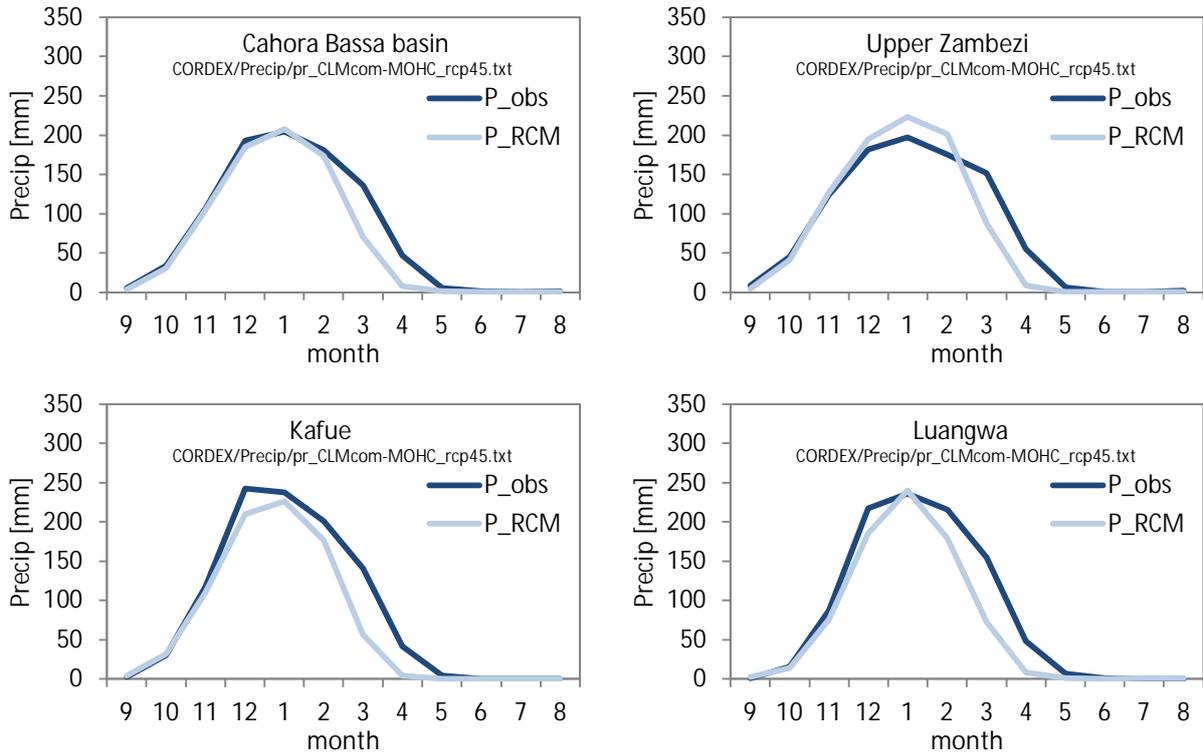
CLMcom-CNRM, 1961-1990



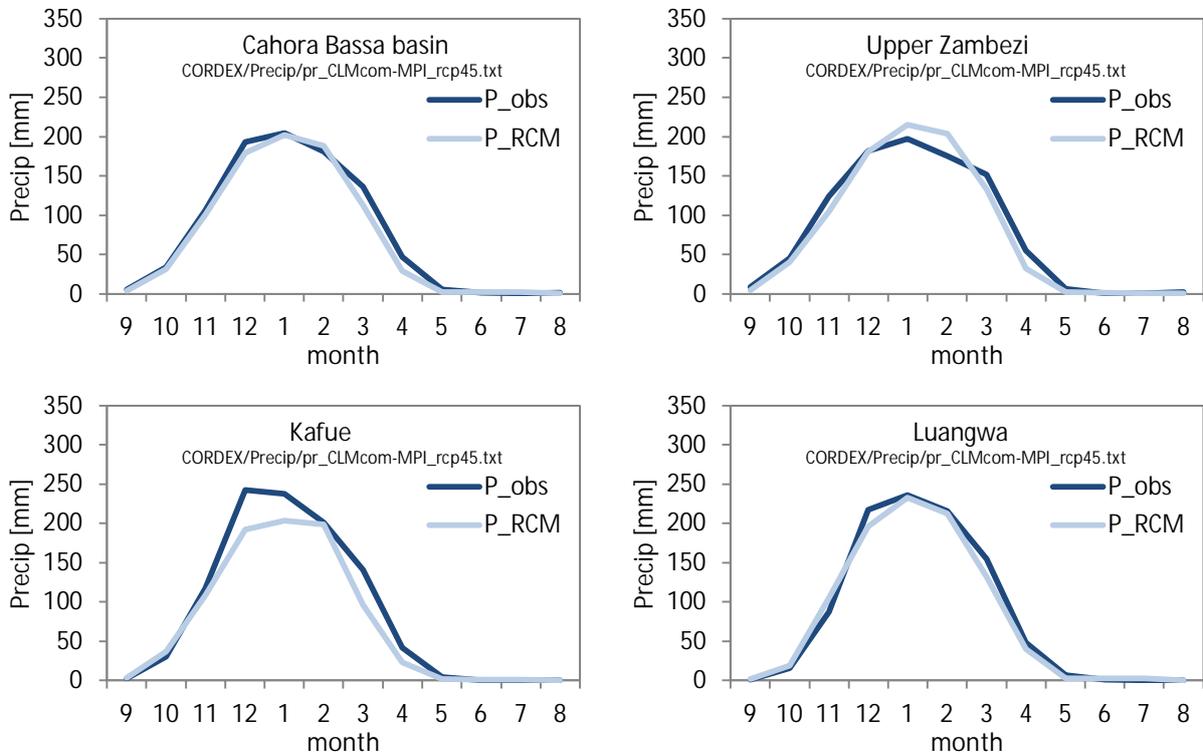
CLMcom-ICHEC, 1961-1990



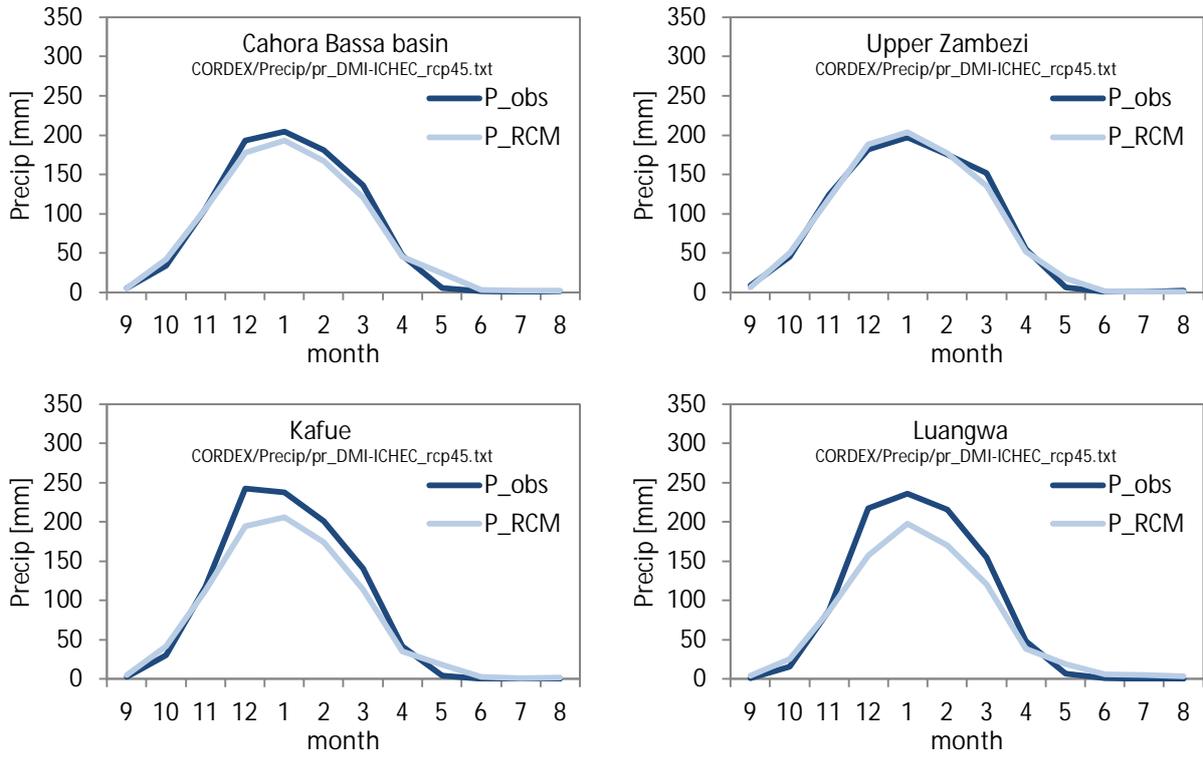
CLMcom-MOHC, 1961-1990



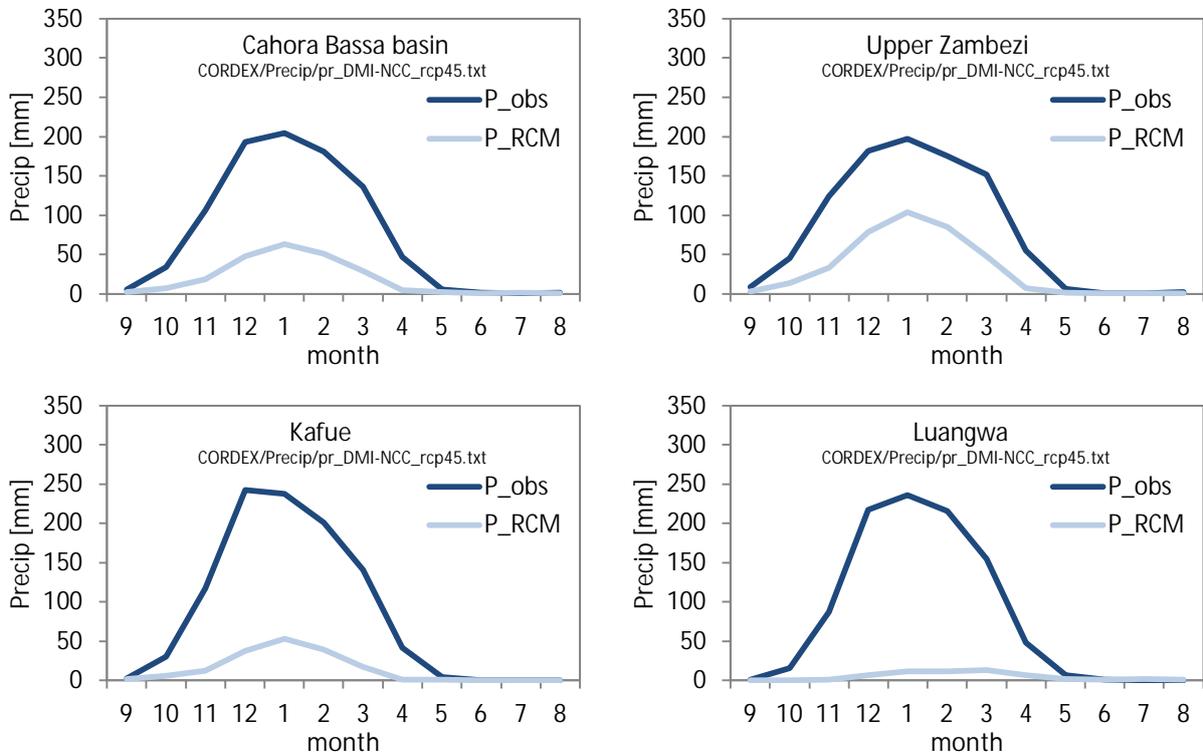
CLMcom-MPI, 1961-1990



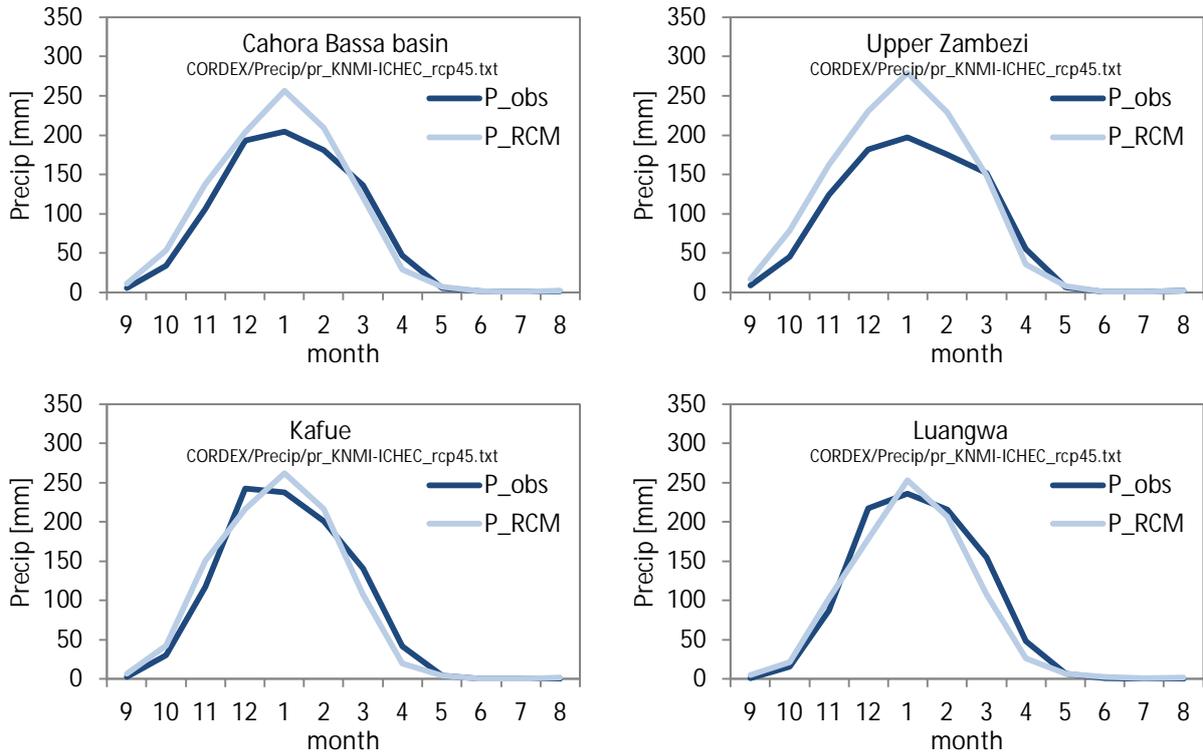
**DMI -ICHEC, 1961-1990**



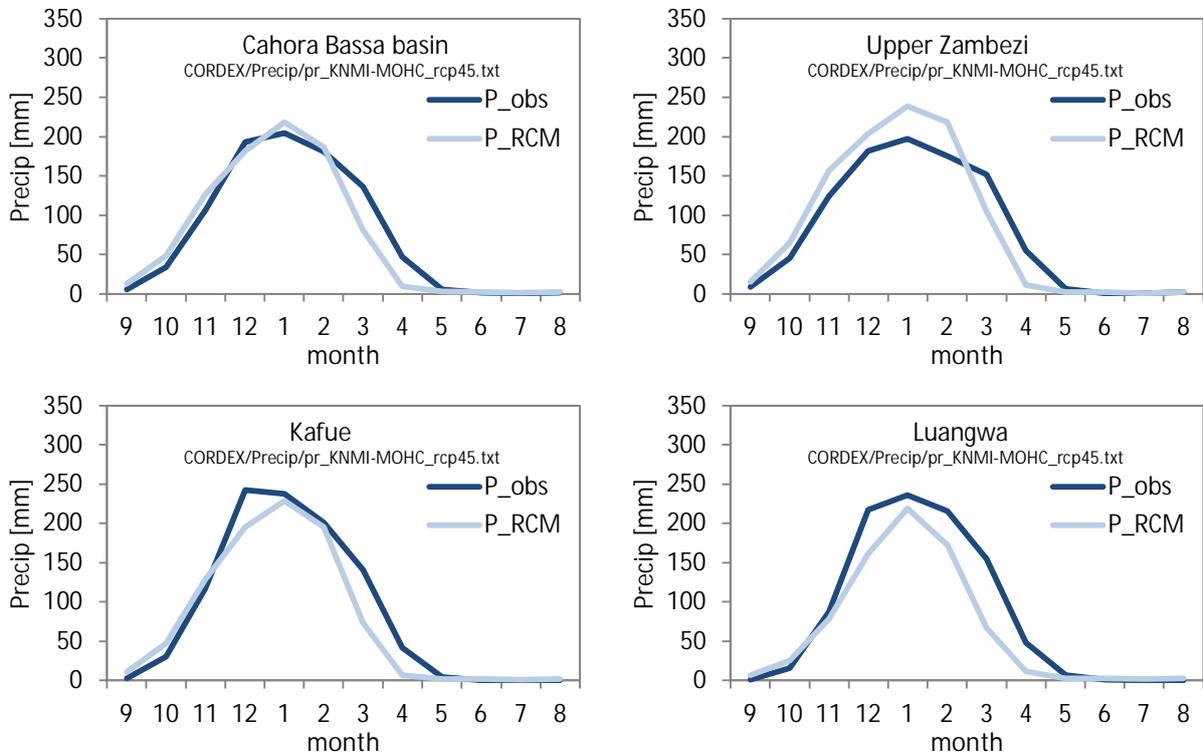
**DMI -NCC, 1961-1990**



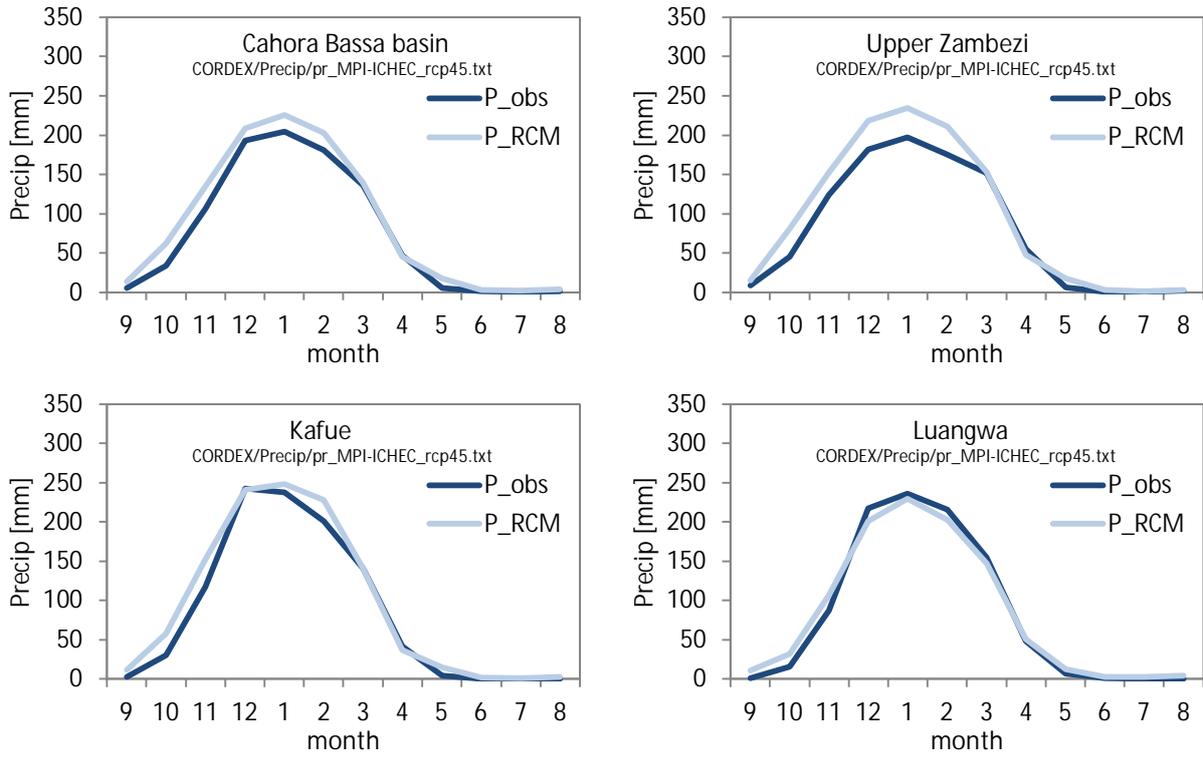
**KNMI -ICHEC, 1961-1990**



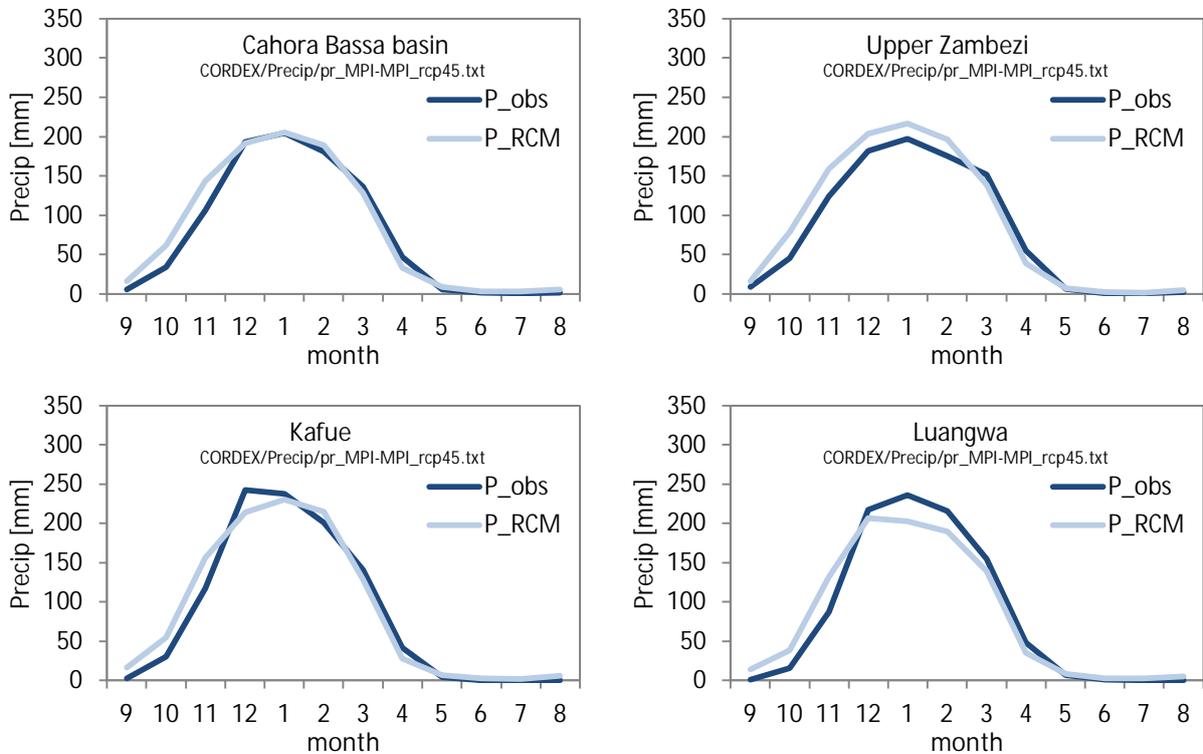
**KNMI -MOHC, 1961-1990**



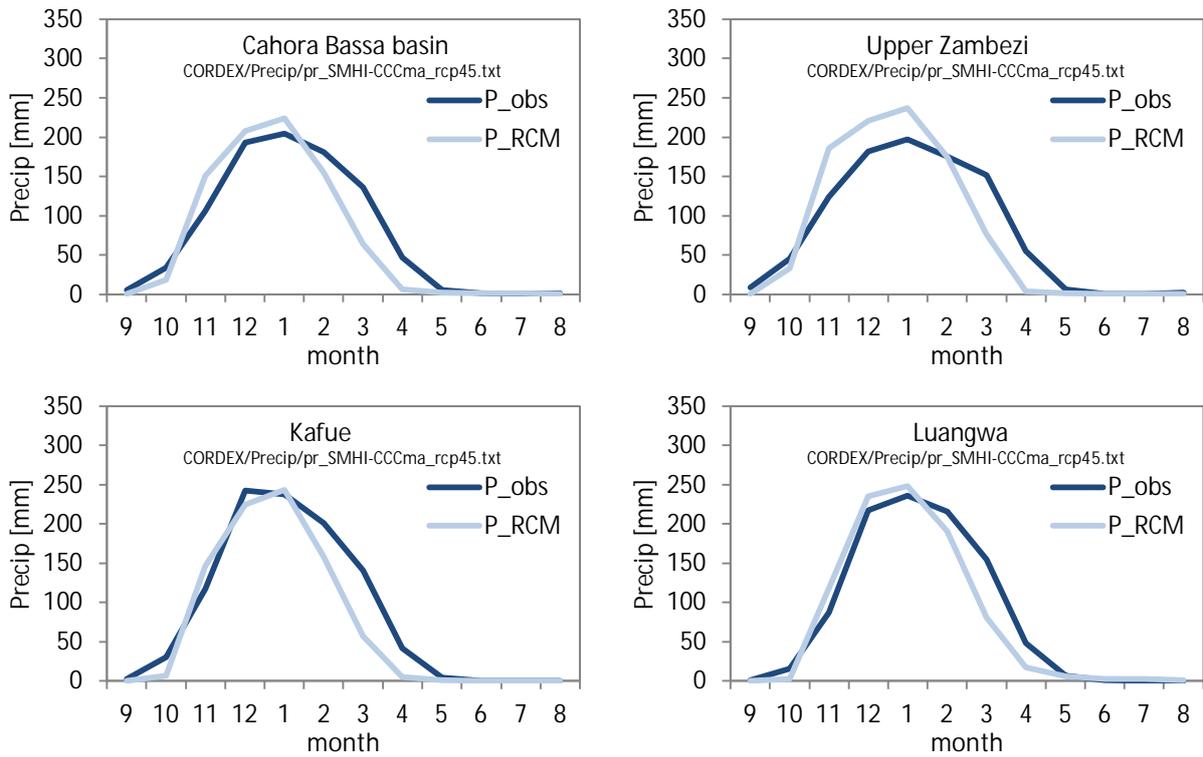
MPI-ICHEC, 1961-1990



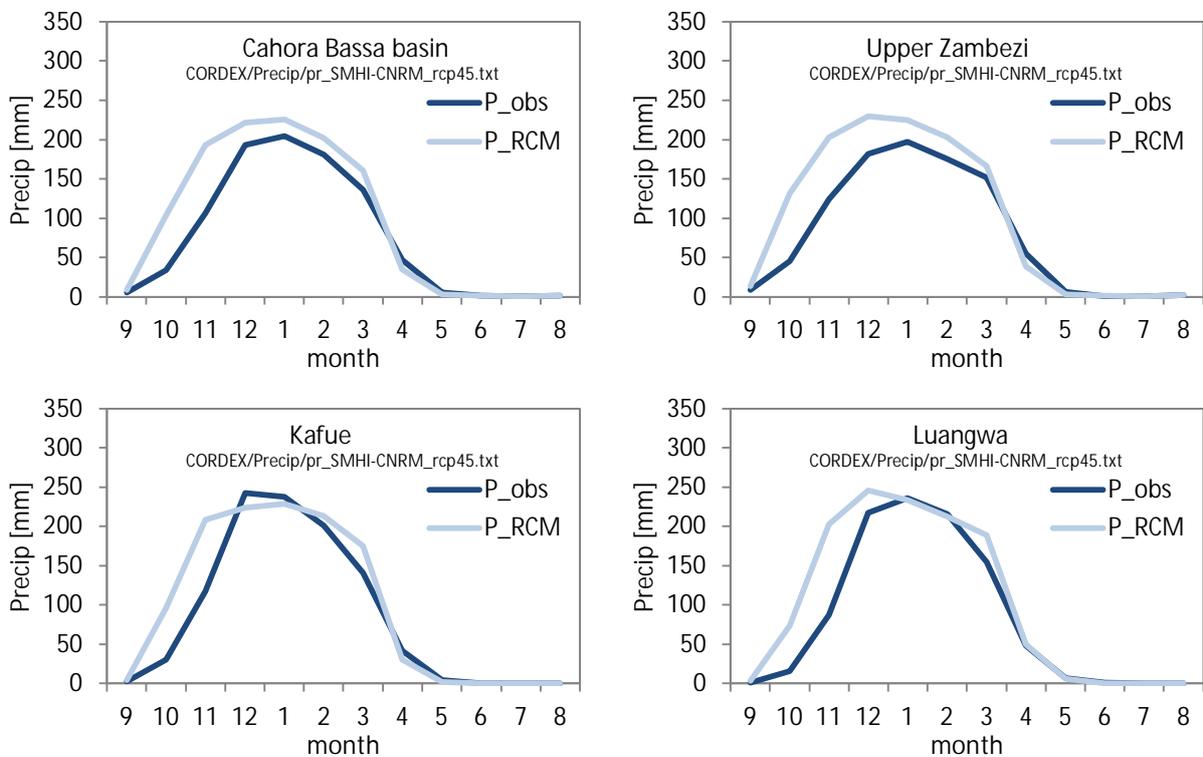
MPI-MPI, 1961-1990



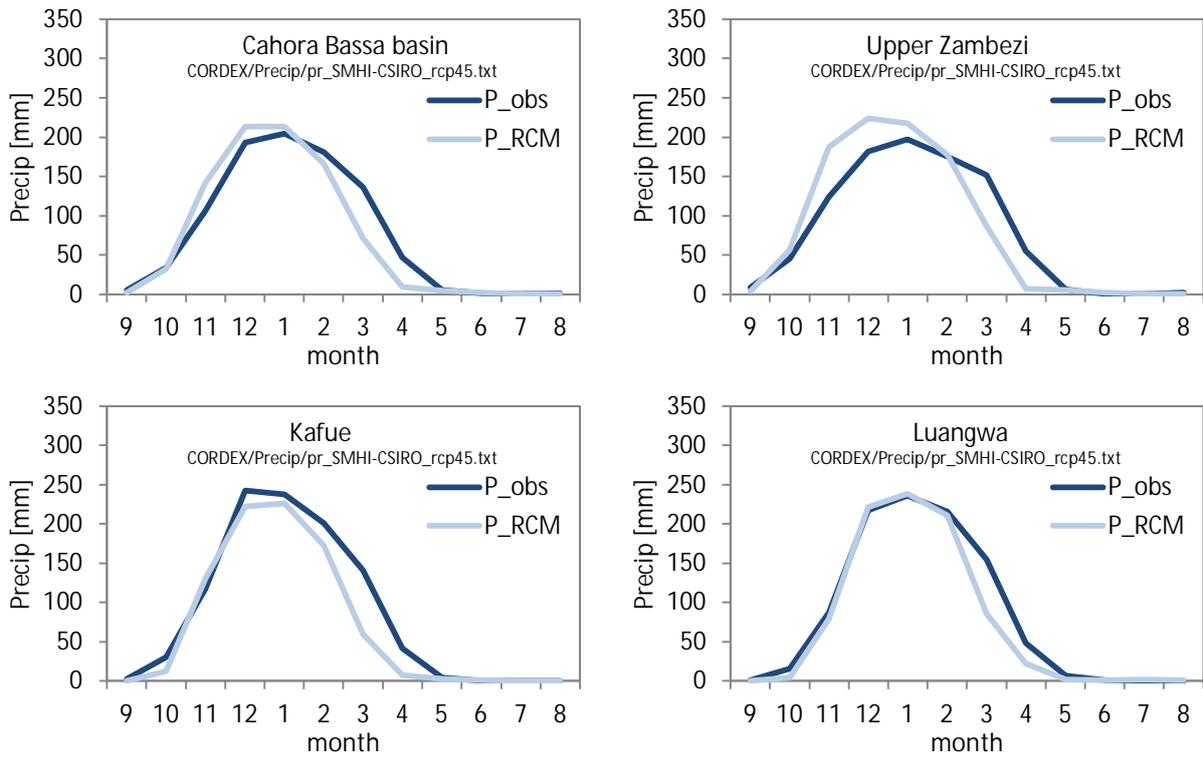
SMHI -CCCma, 1961-1990



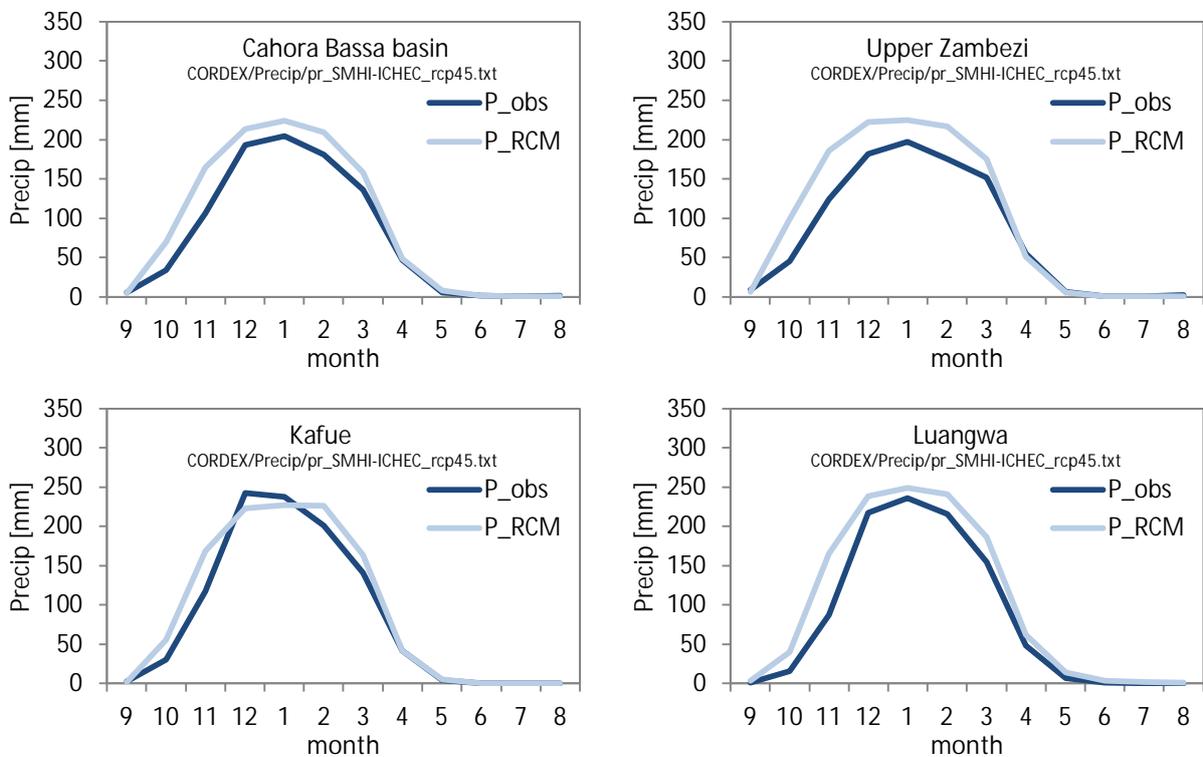
SMHI -CNRM, 1961-1990



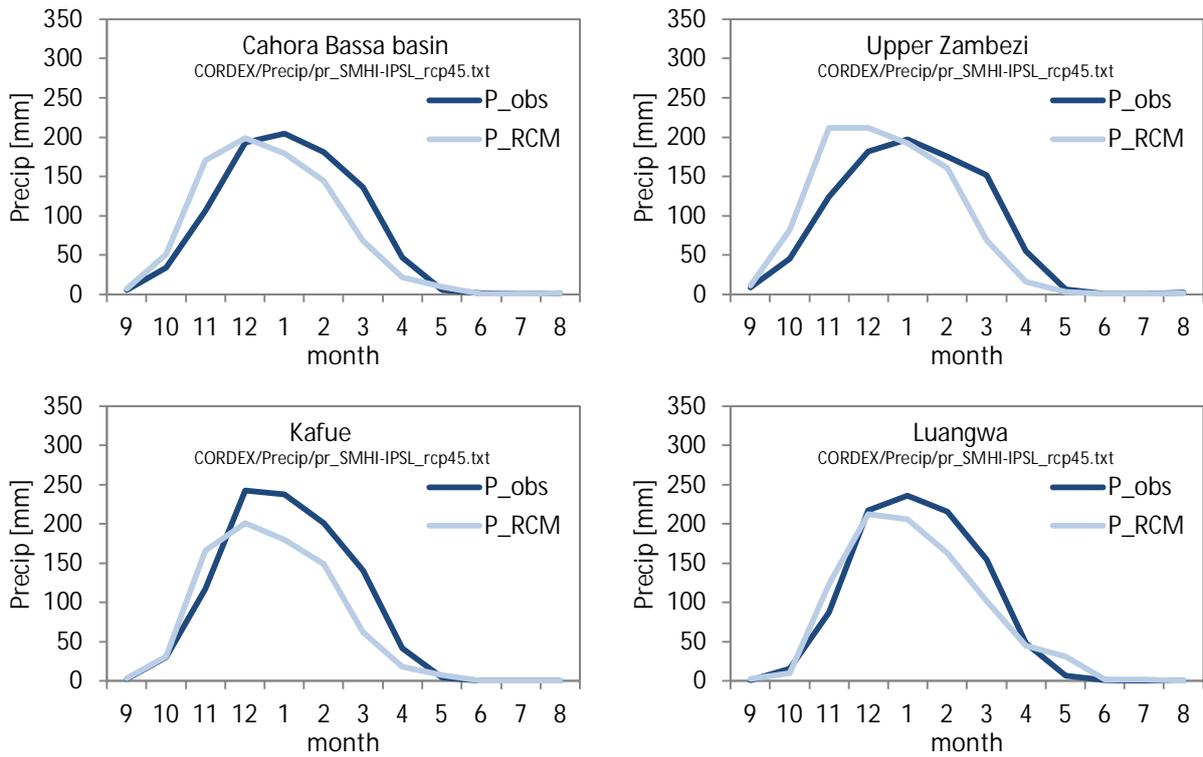
SMHI -CSIRO, 1961-1990



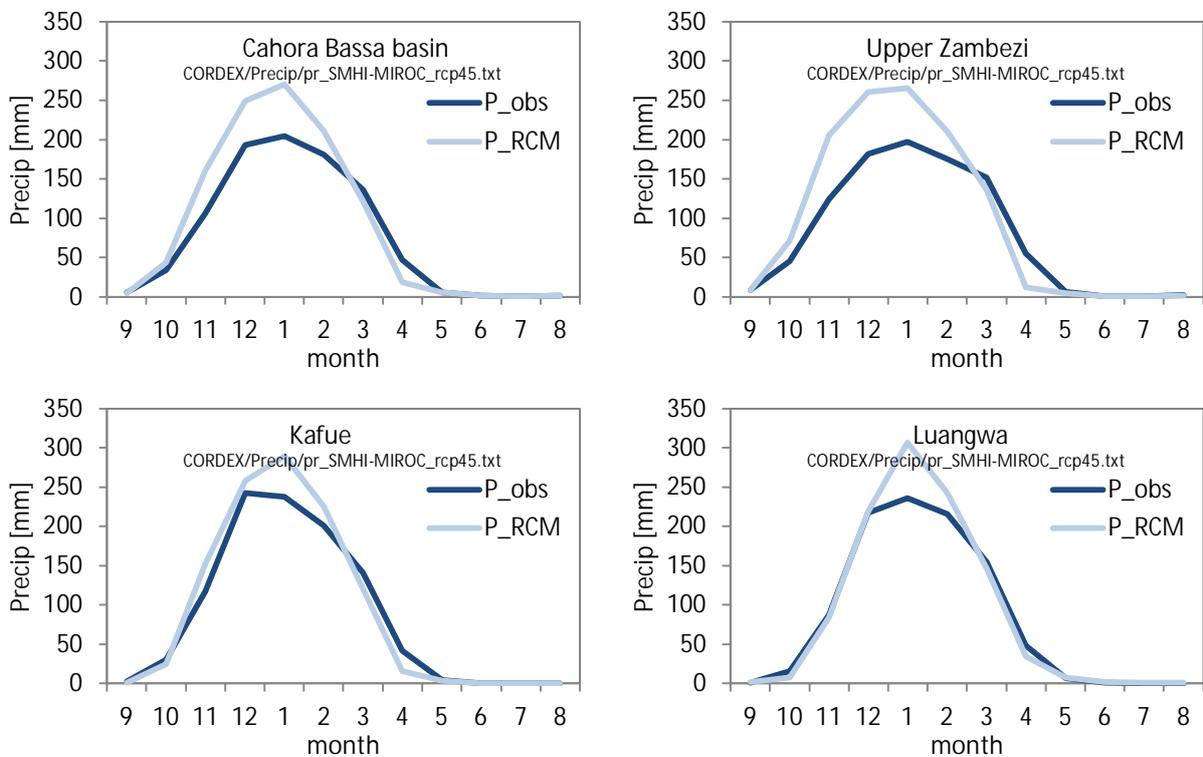
SMHI -ICHEC, 1961-1990



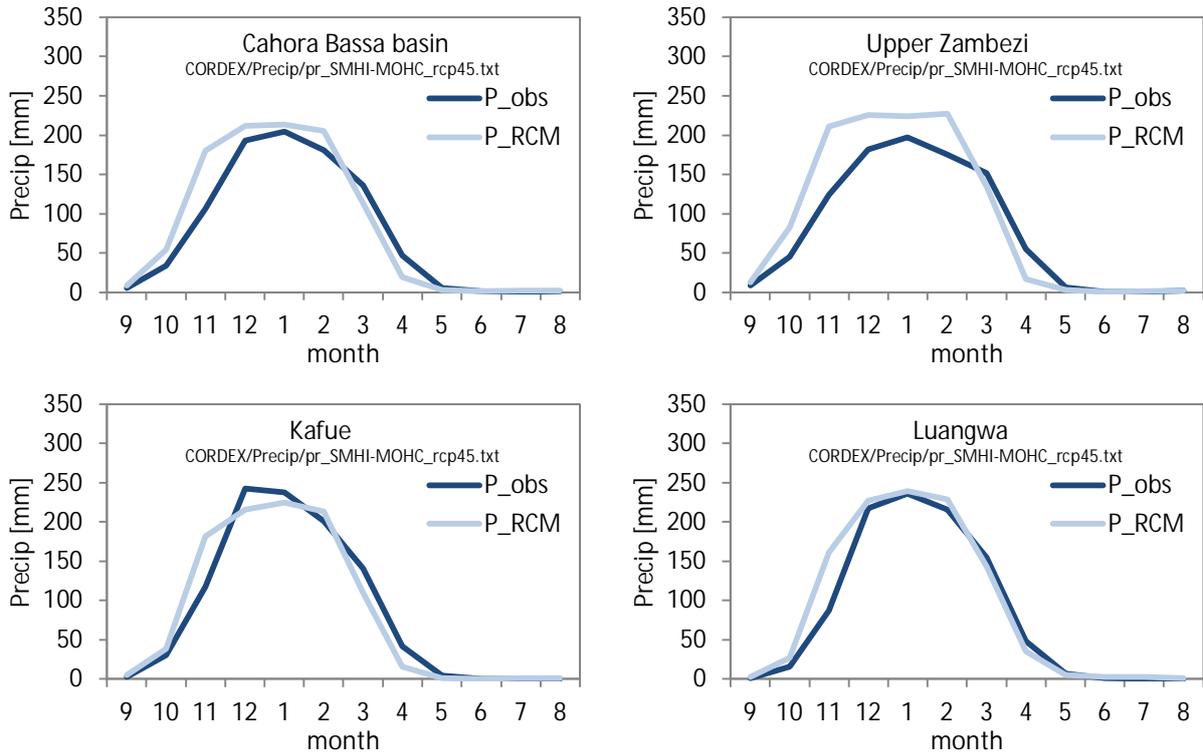
SMHI-IPSL, 1961-1990



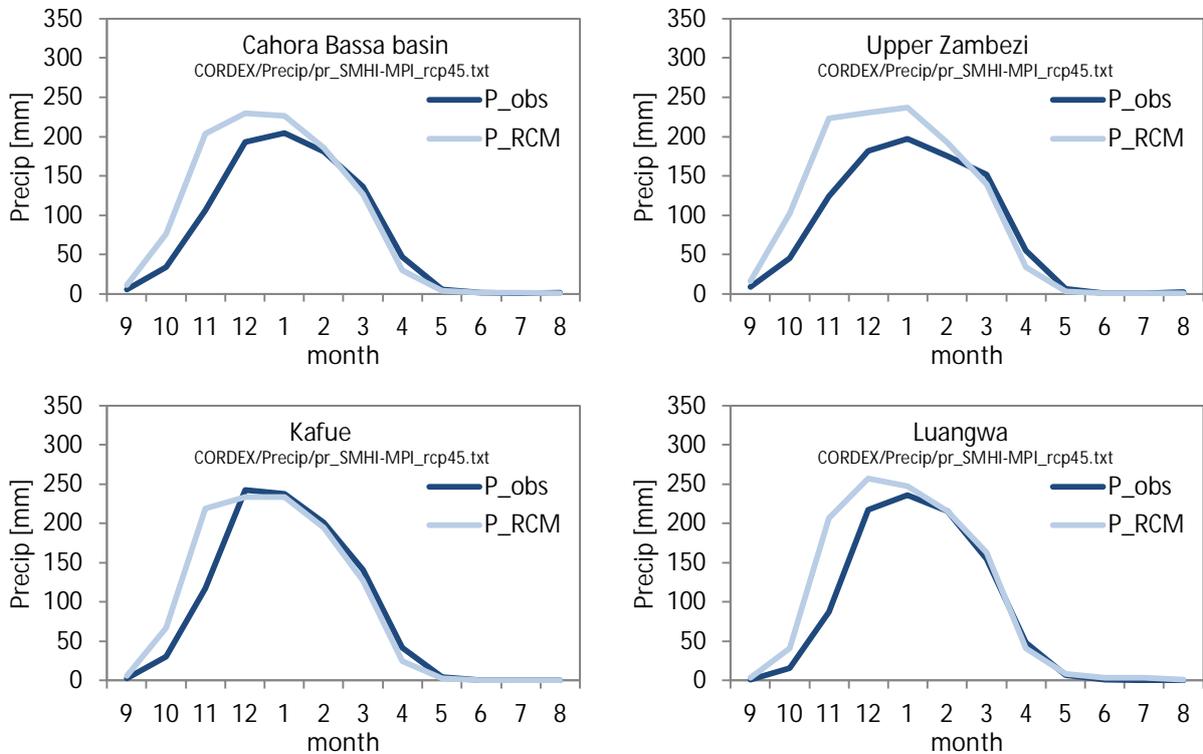
SMHI-MIROC, 1961-1990



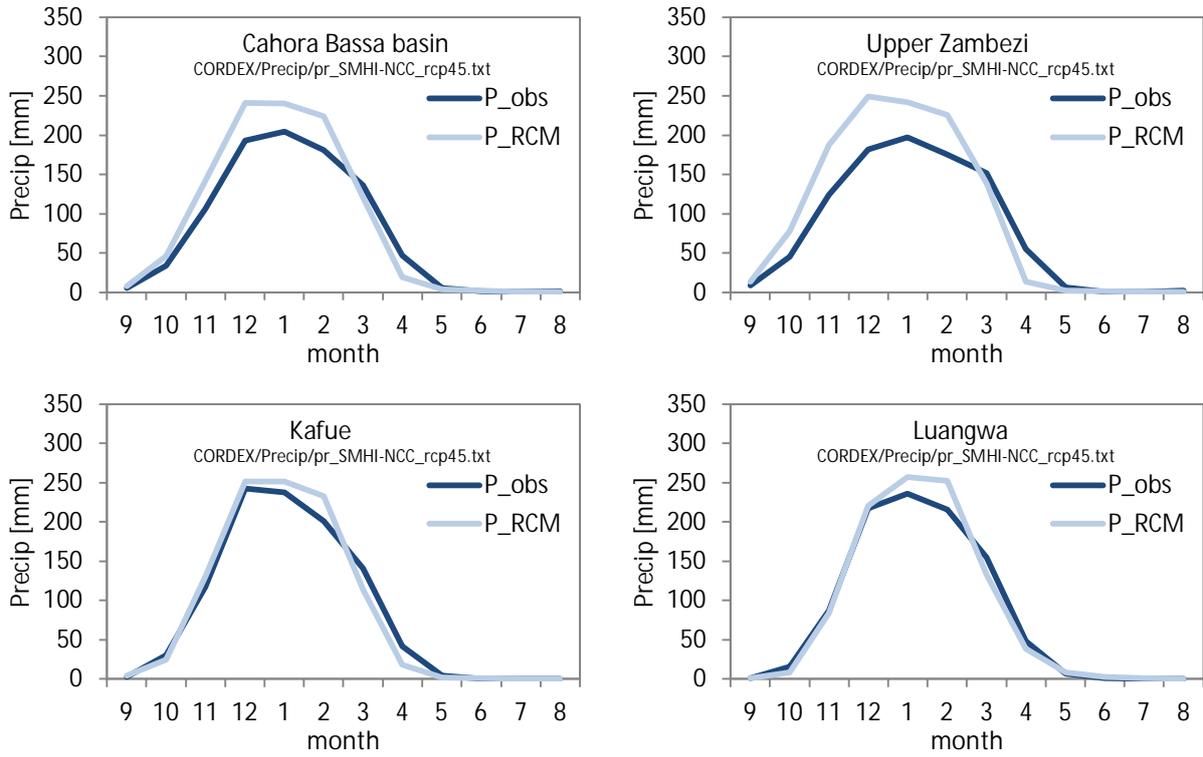
SMHI-MOHC, 1961-1990



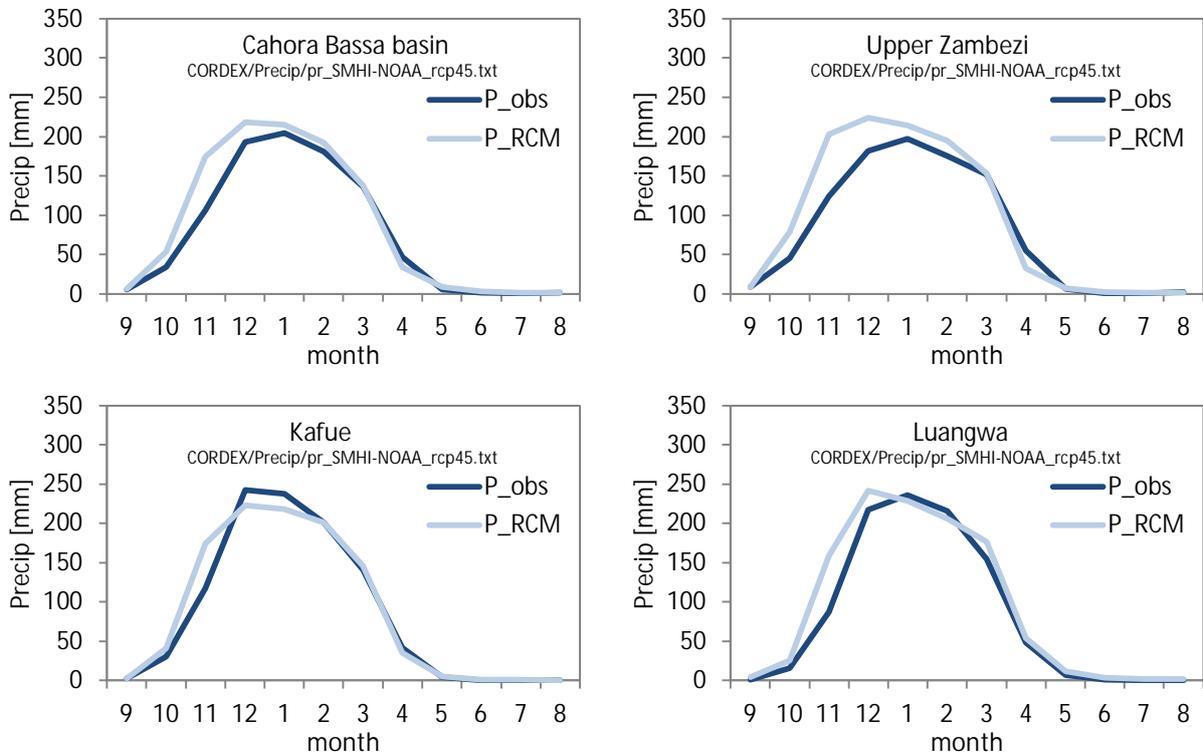
SMHI-MPI, 1961-1990



SMHI -NCC, 1961-1990



SMHI -NOAA, 1961-1990

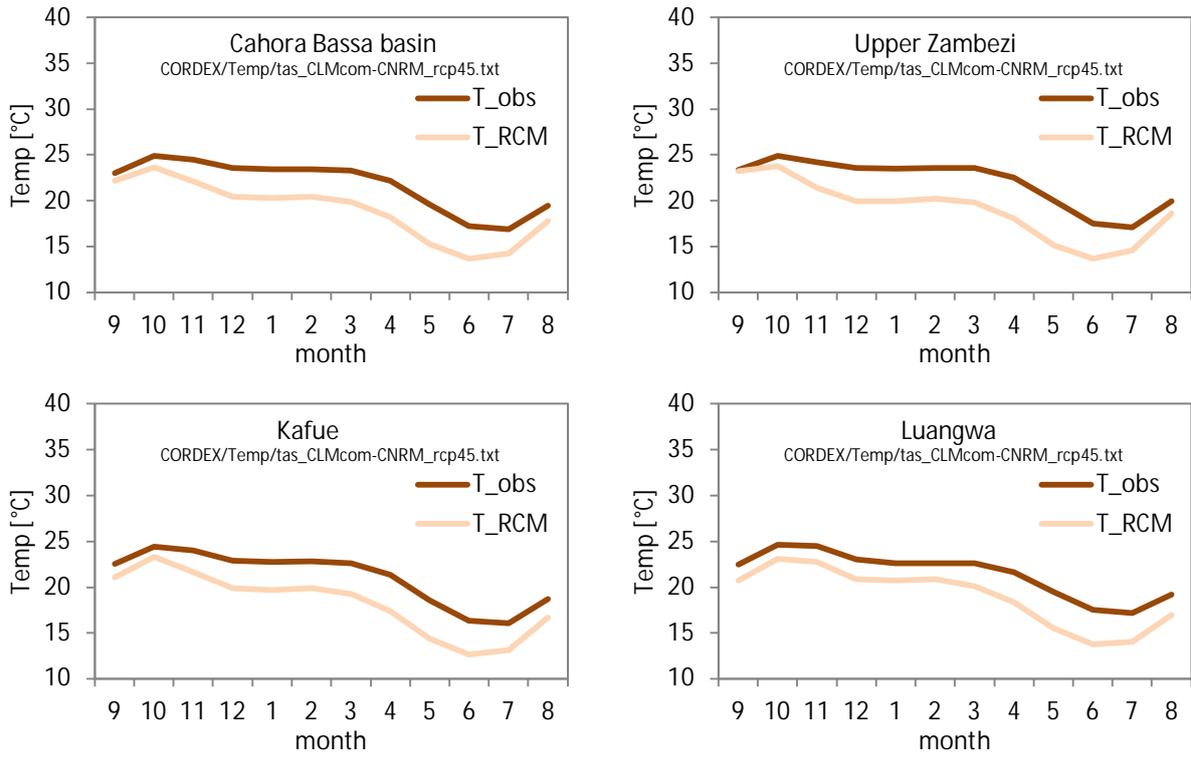


#### 9.4.2 Evaluation of historic air temperature 1961-1990

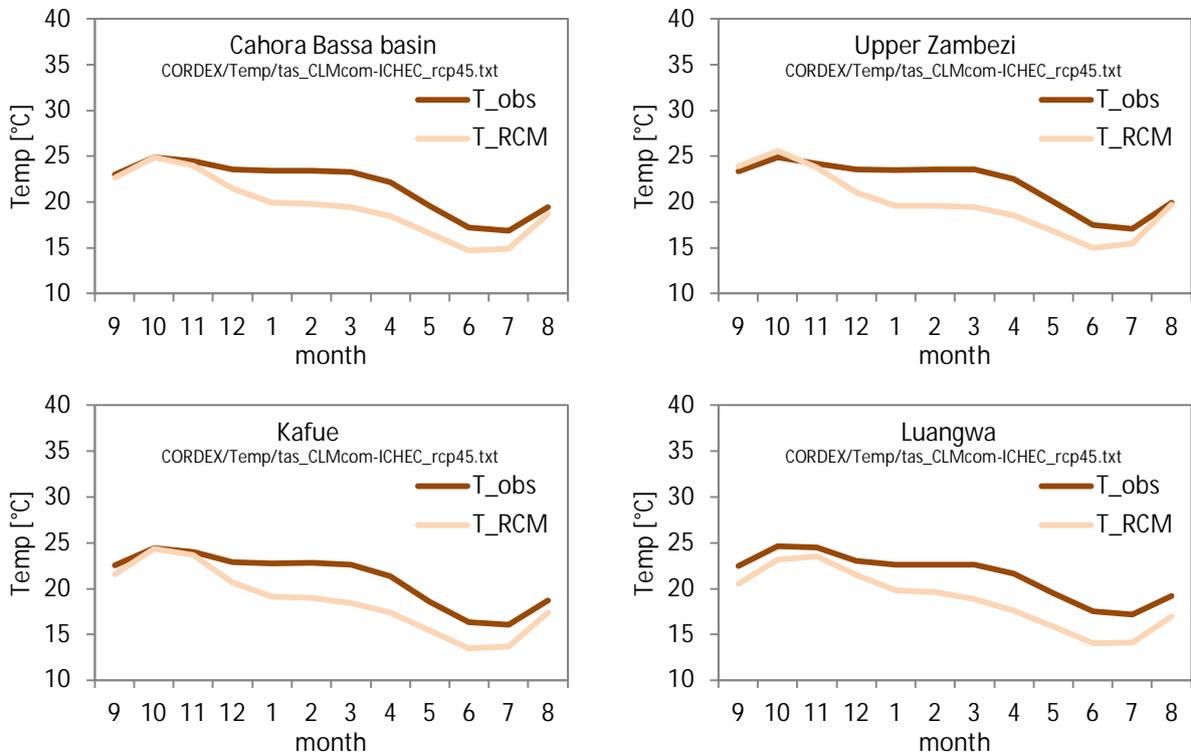
The graphs below show a comparison of simulated and observed mean monthly air temperature in the period 1961-1990, with the following specifications:

- T\_obs: observed air temperature data of CRU
- T\_RCM: simulated air temperature data of RCM

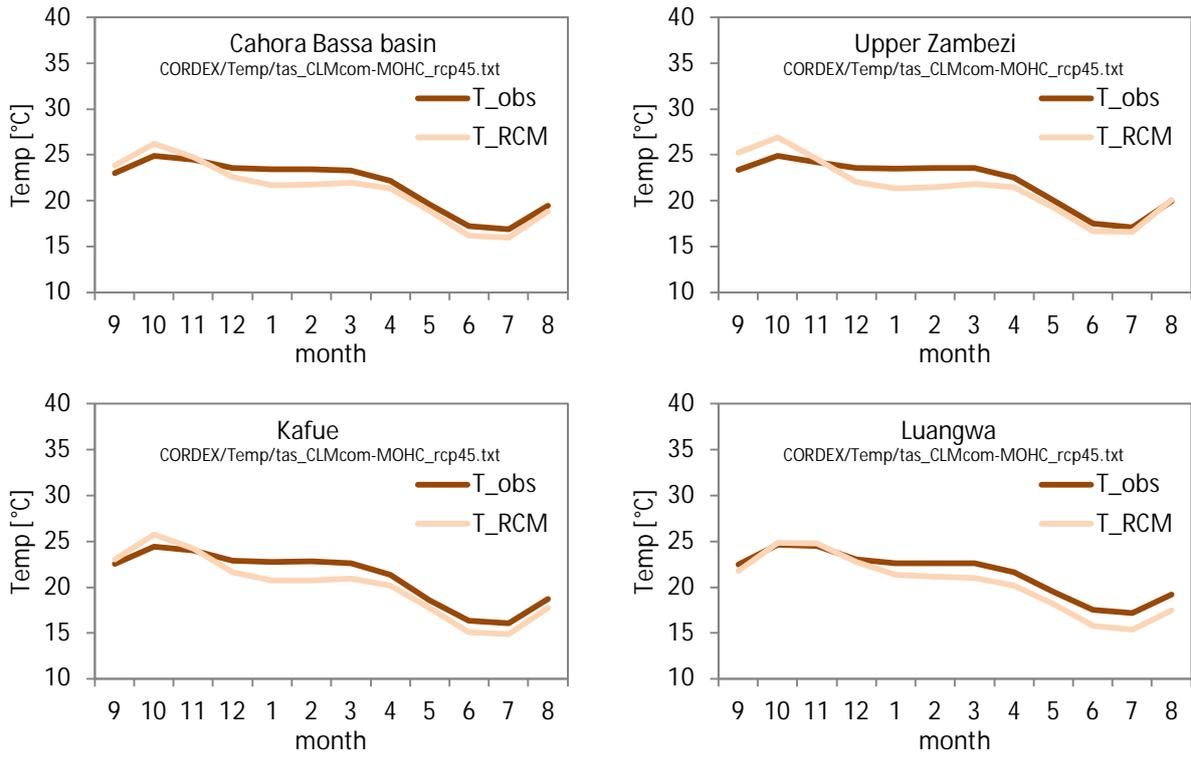
CLMcom-CNRM, 1961-1990



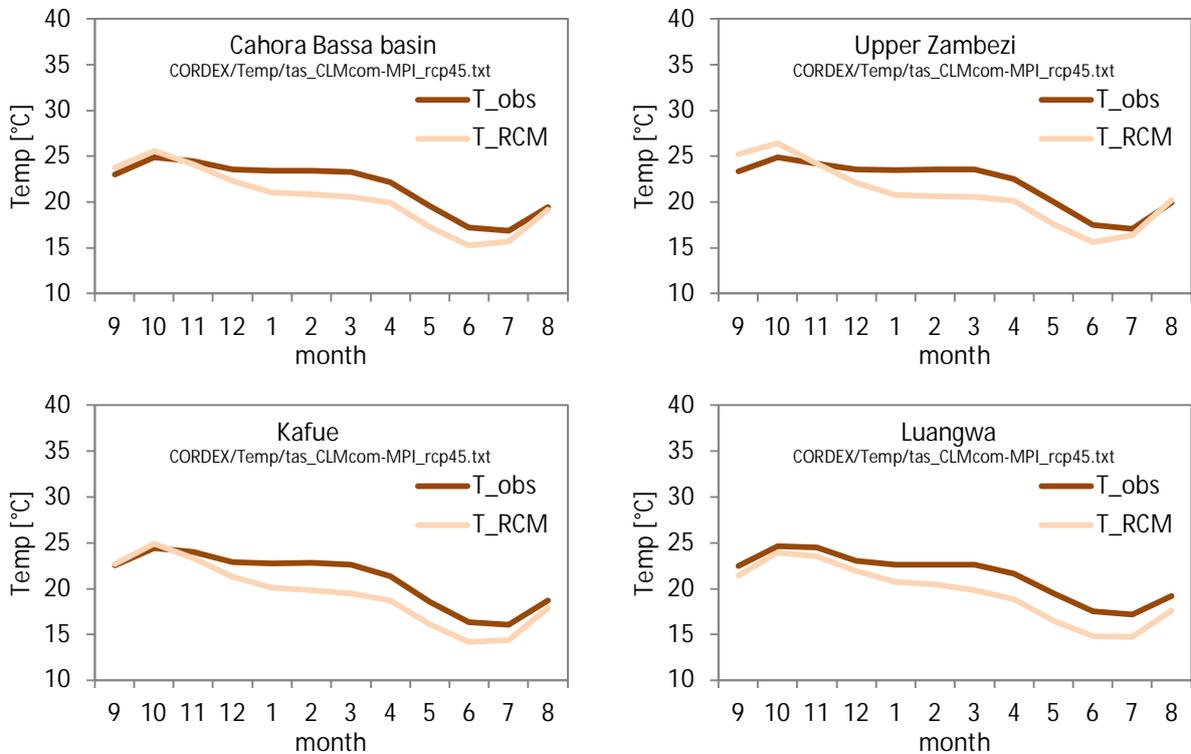
CLMcom-ICHEC, 1961-1990



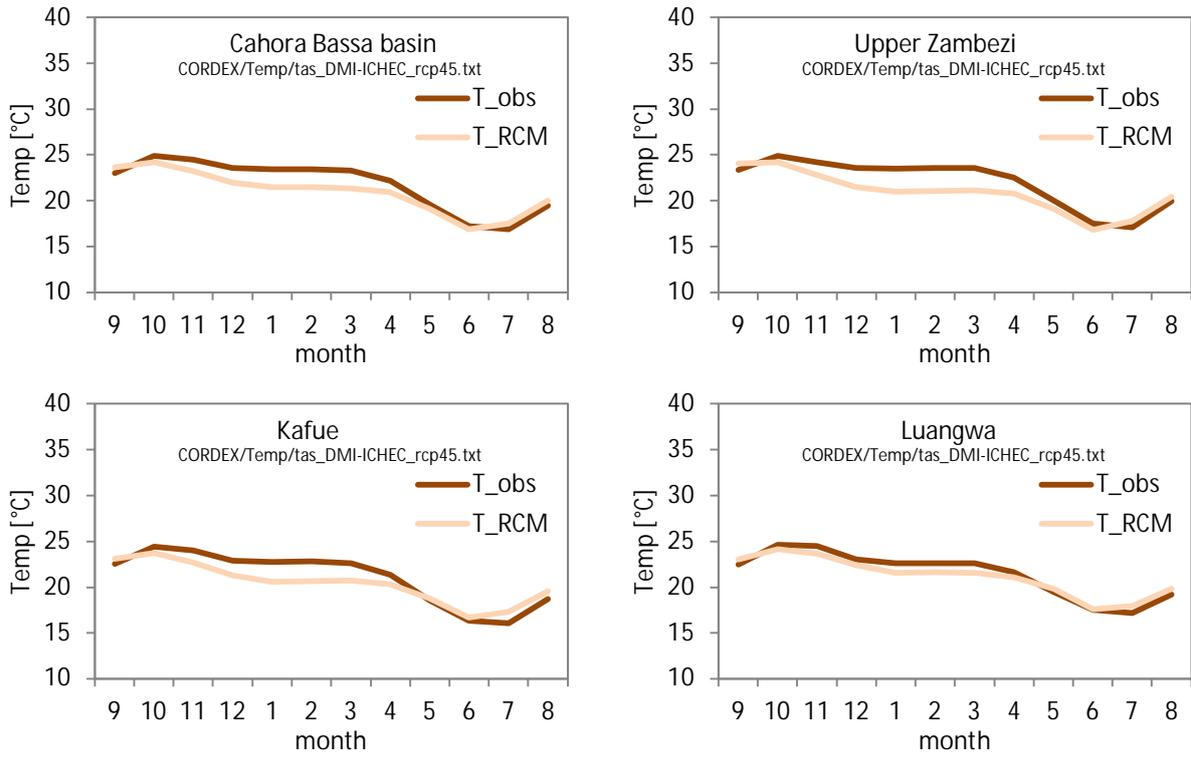
CLMcom-MOHC, 1961-1990



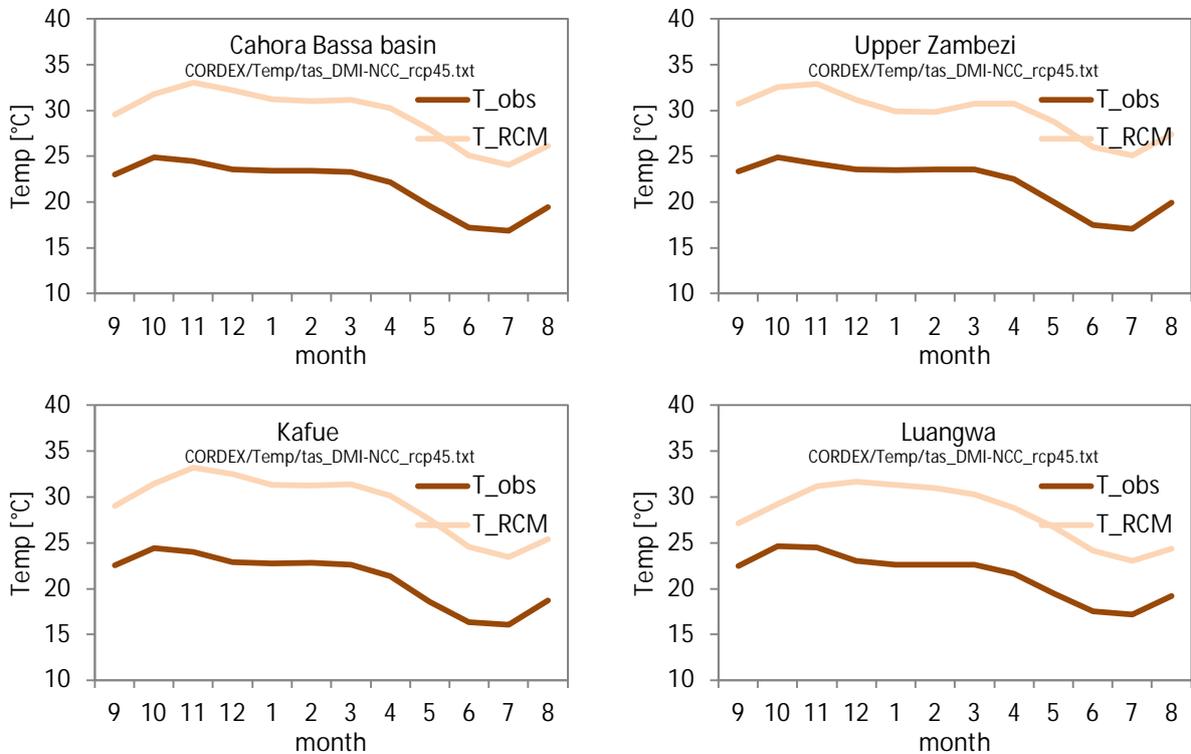
CLMcom-MPI, 1961-1990



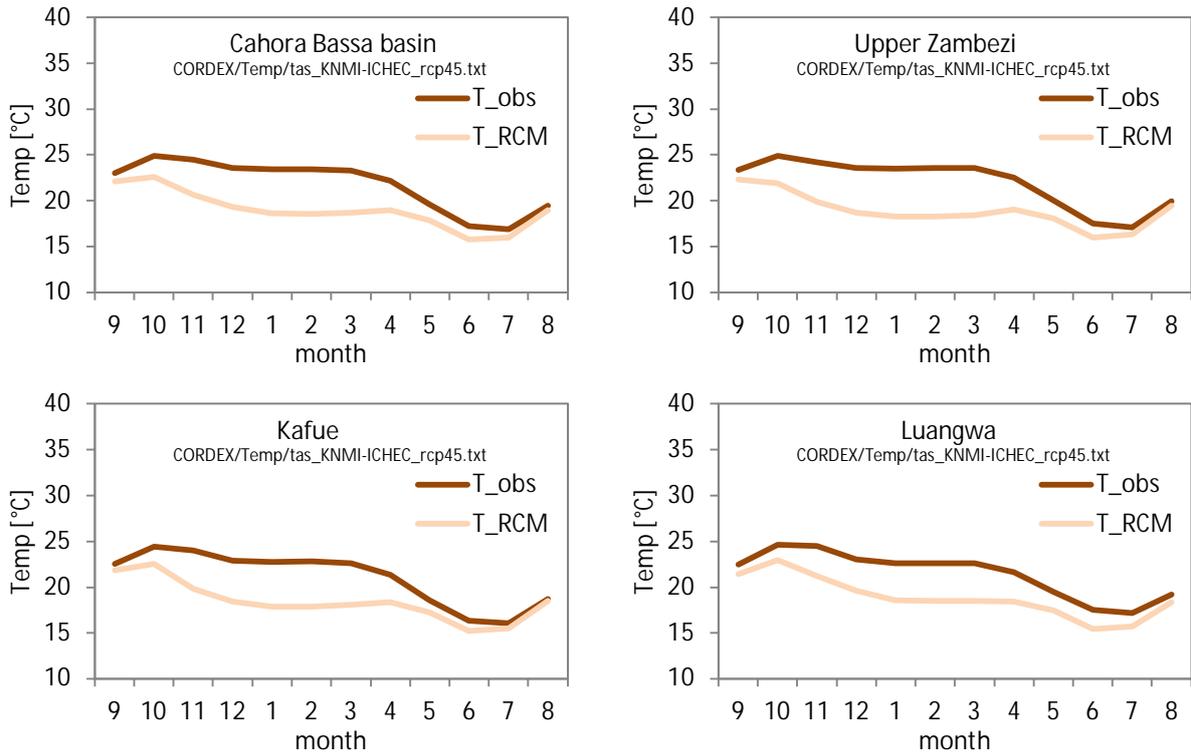
**DMI -ICHEC, 1961-1990**



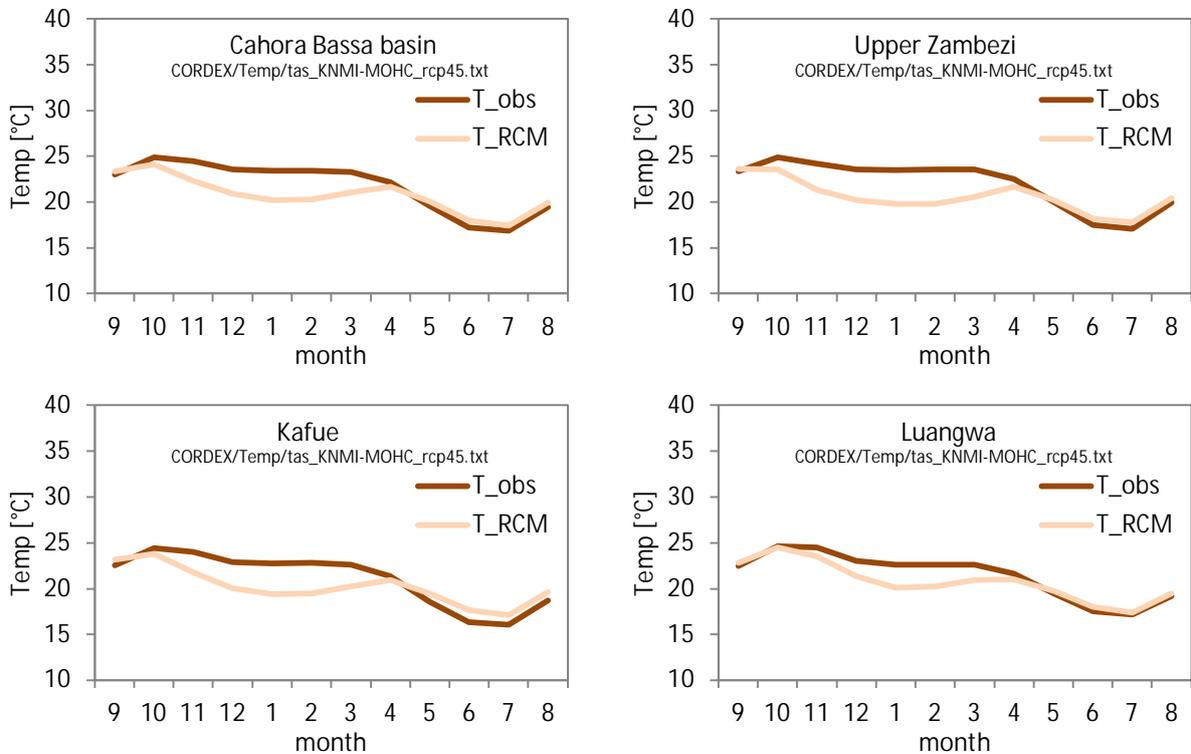
**DMI -NCC, 1961-1990**



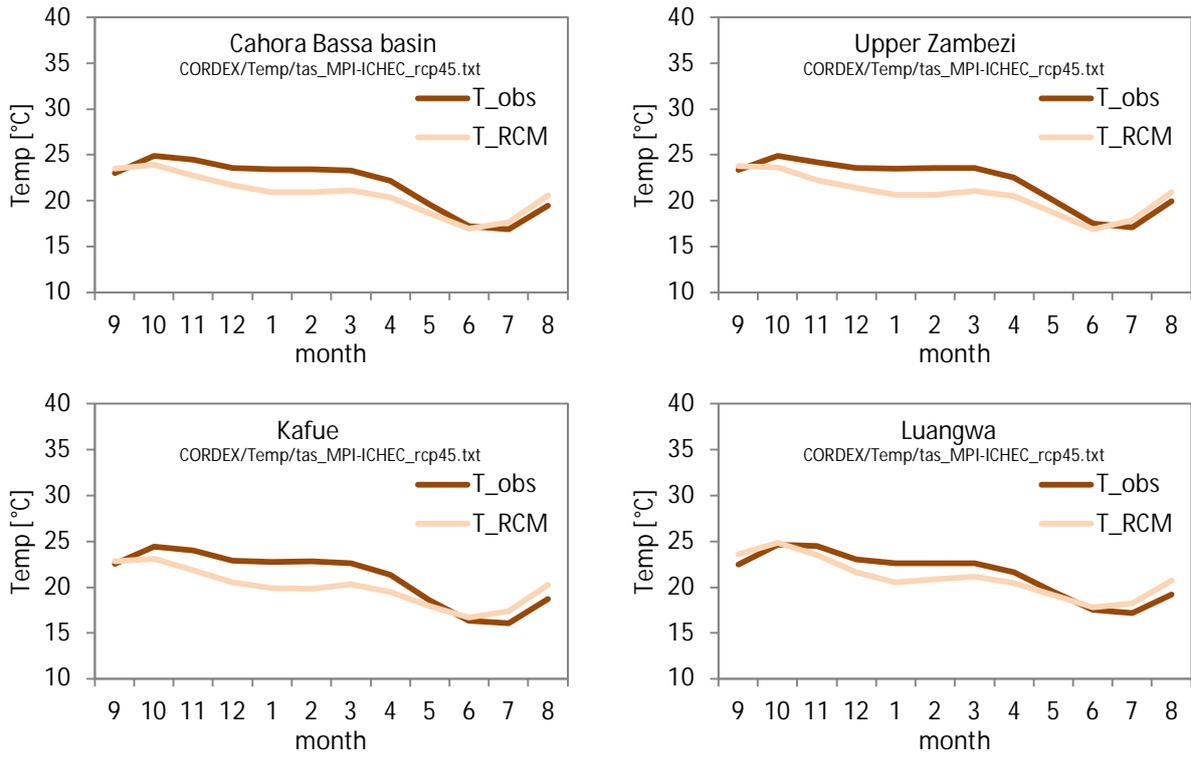
**KNMI -ICHEC, 1961-1990**



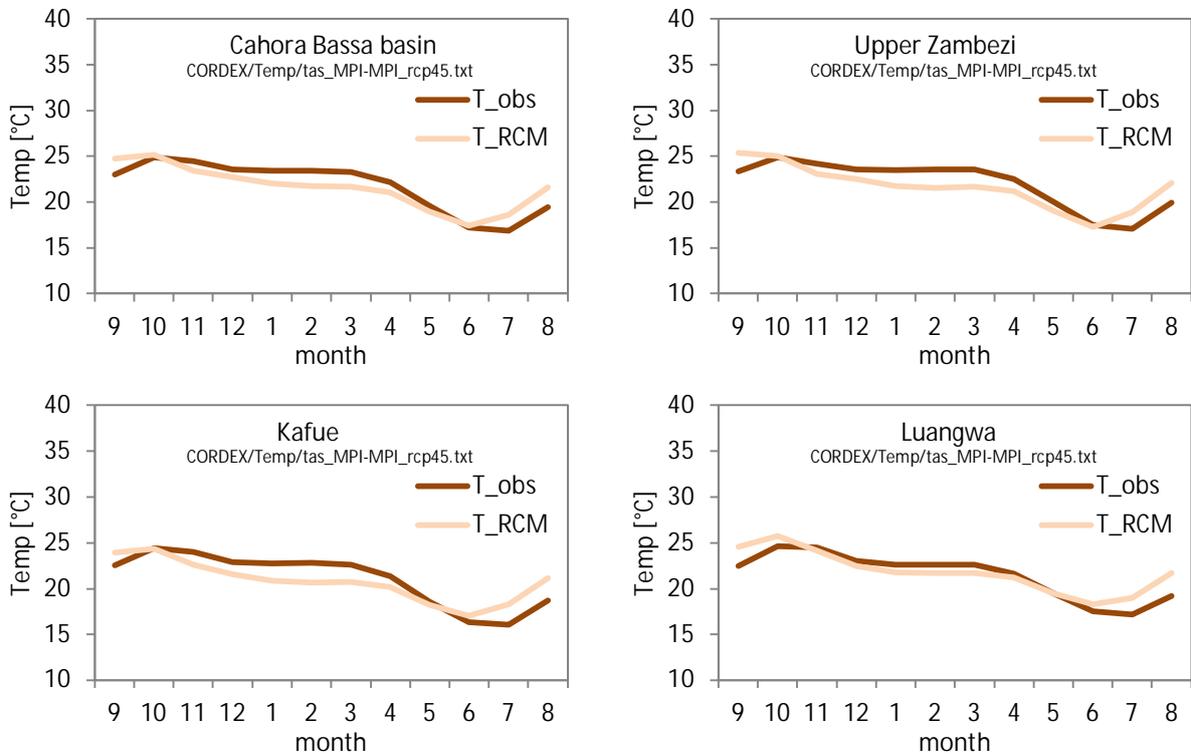
**KNMI -MOHC, 1961-1990**



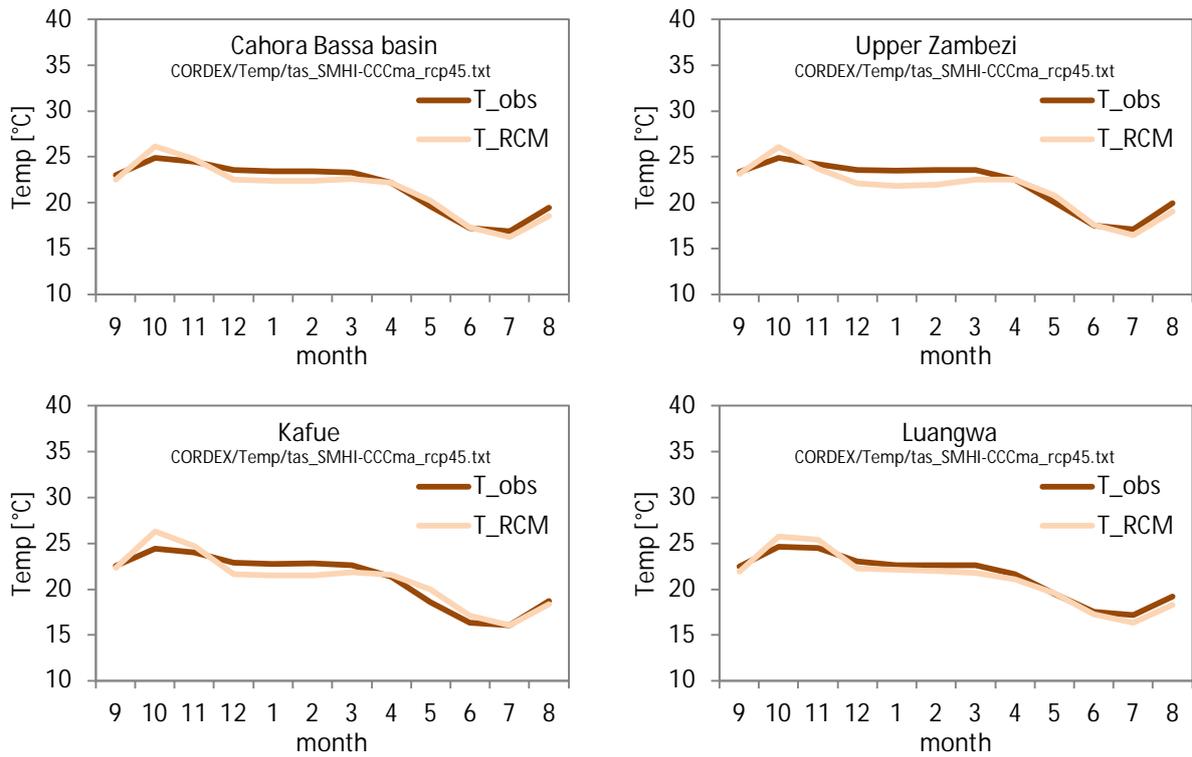
MPI-ICHEC, 1961-1990



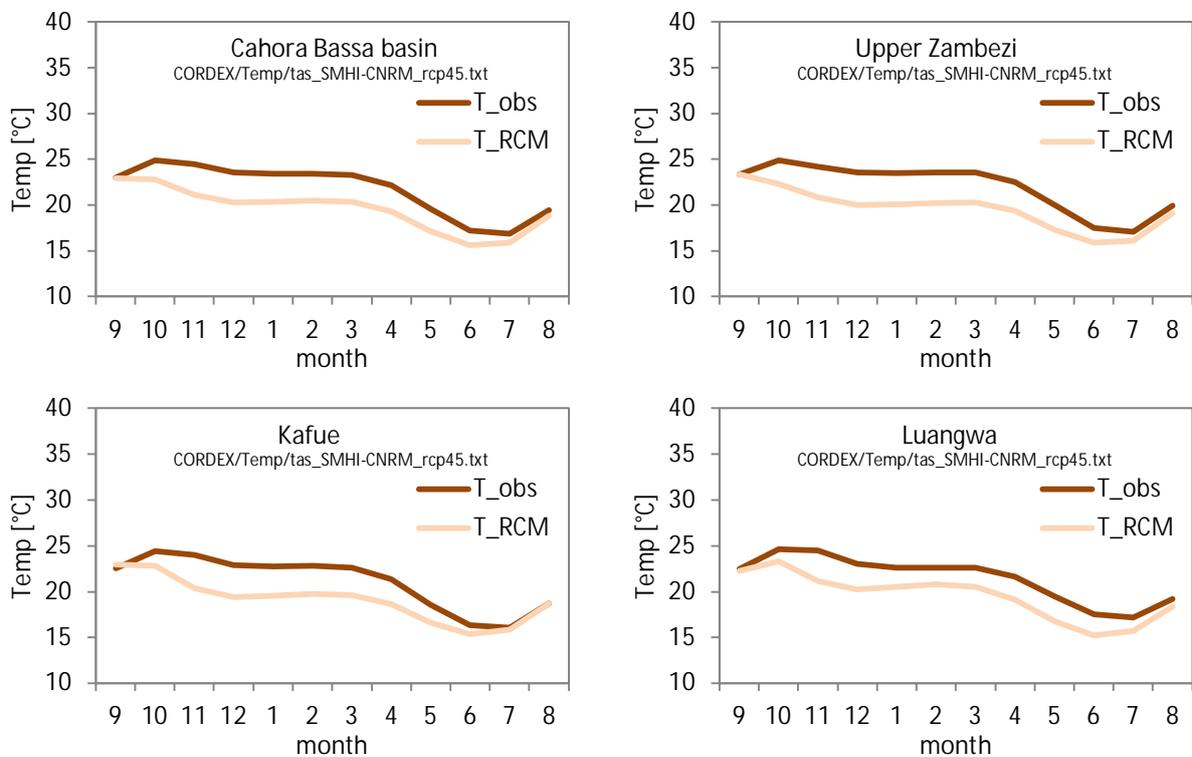
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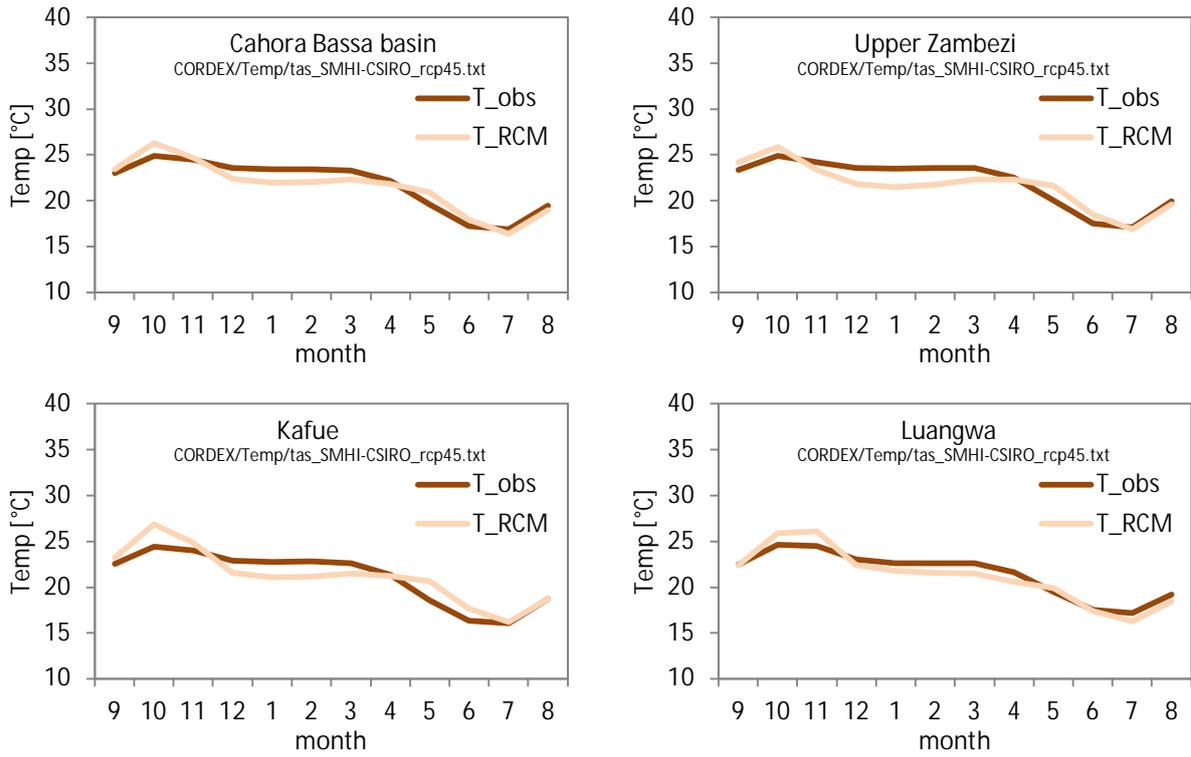
SMHI -CCCma, 1961-1990



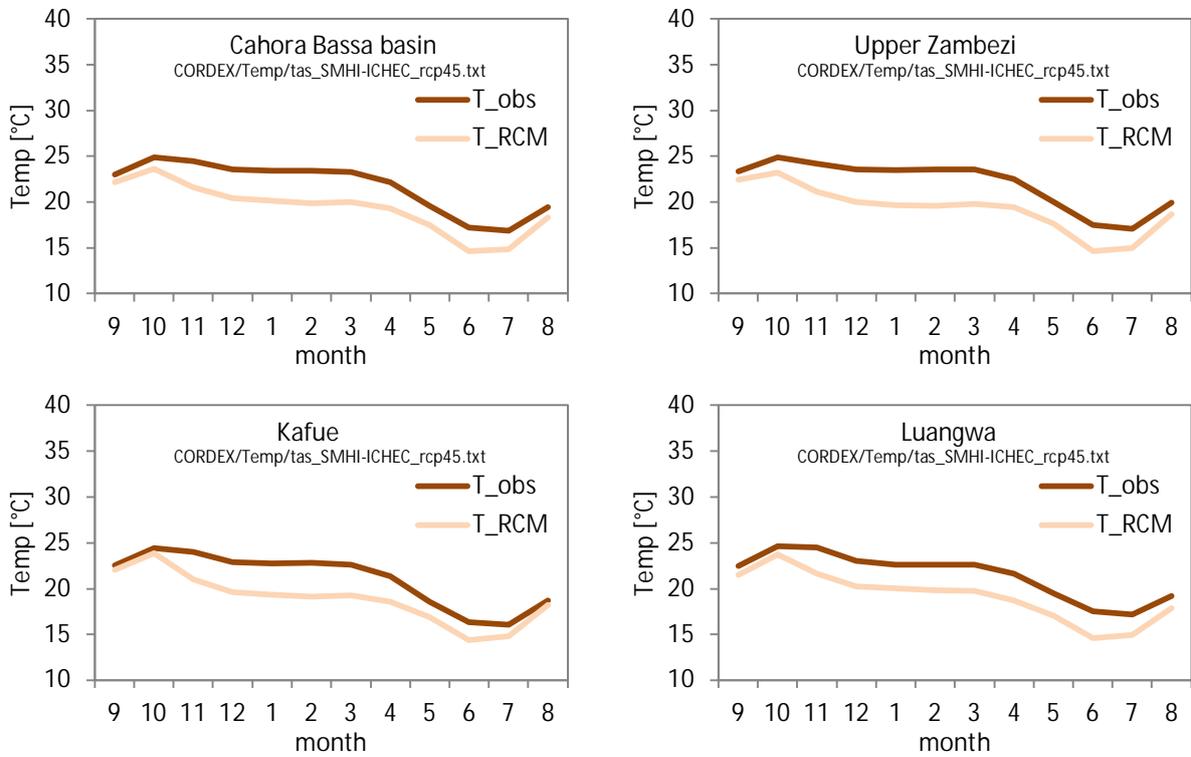
SMHI -CNRM, 1961-1990



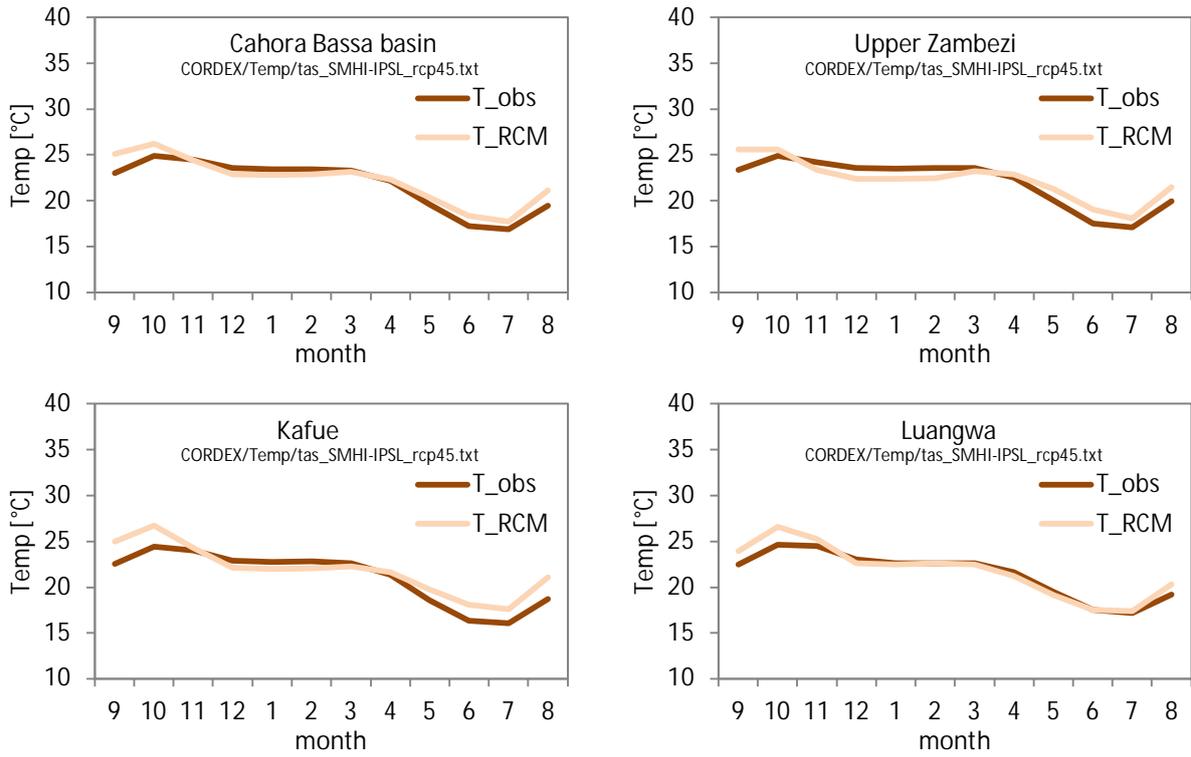
SMHI -CSIRO, 1961-1990



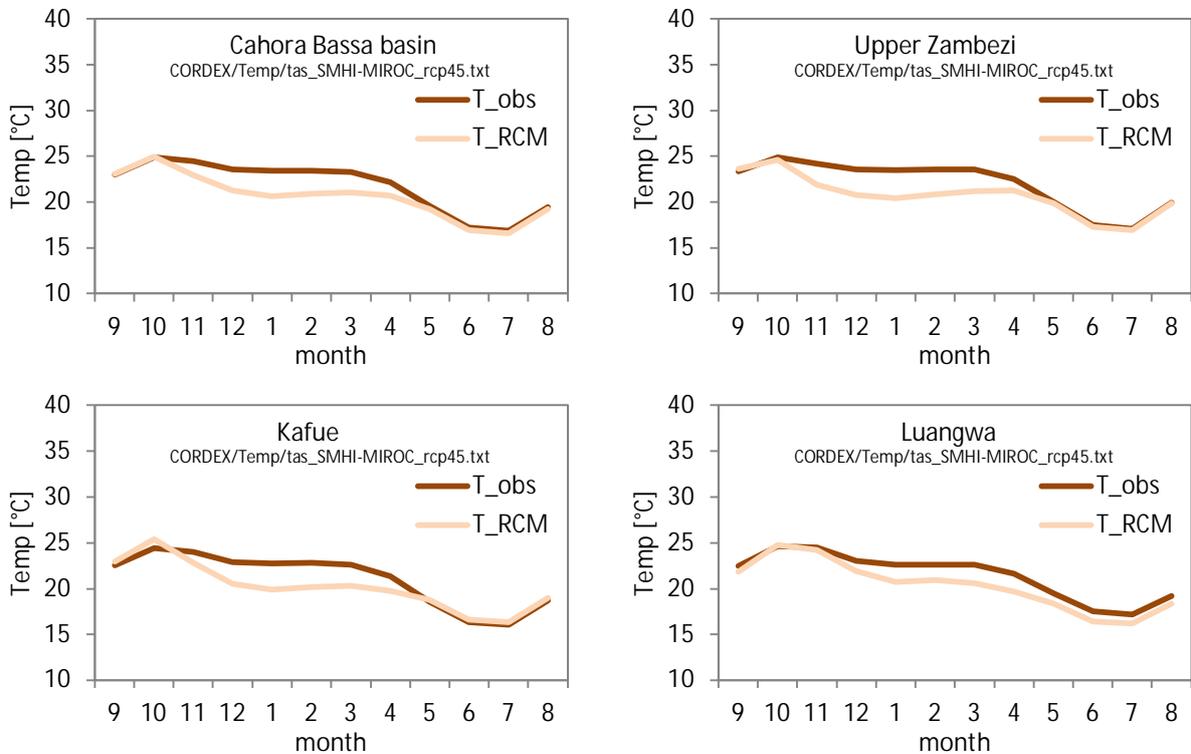
SMHI -ICHEC, 1961-1990



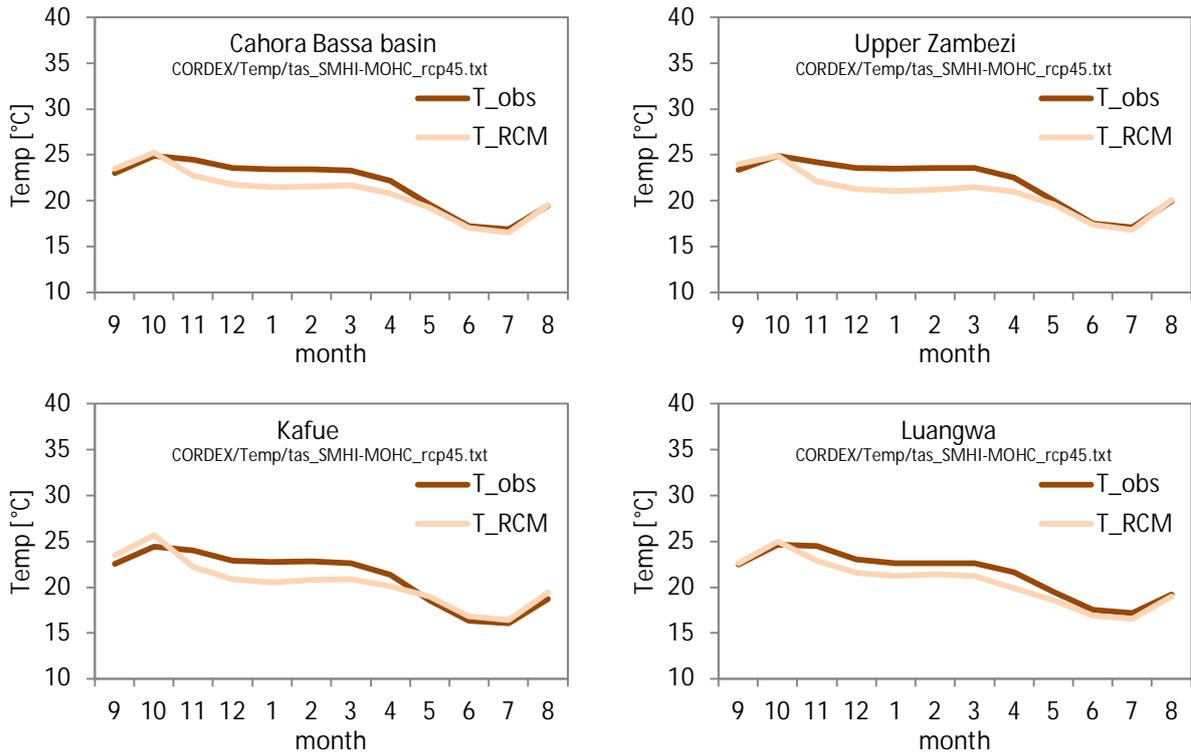
**SMHI-IPSL, 1961-1990**



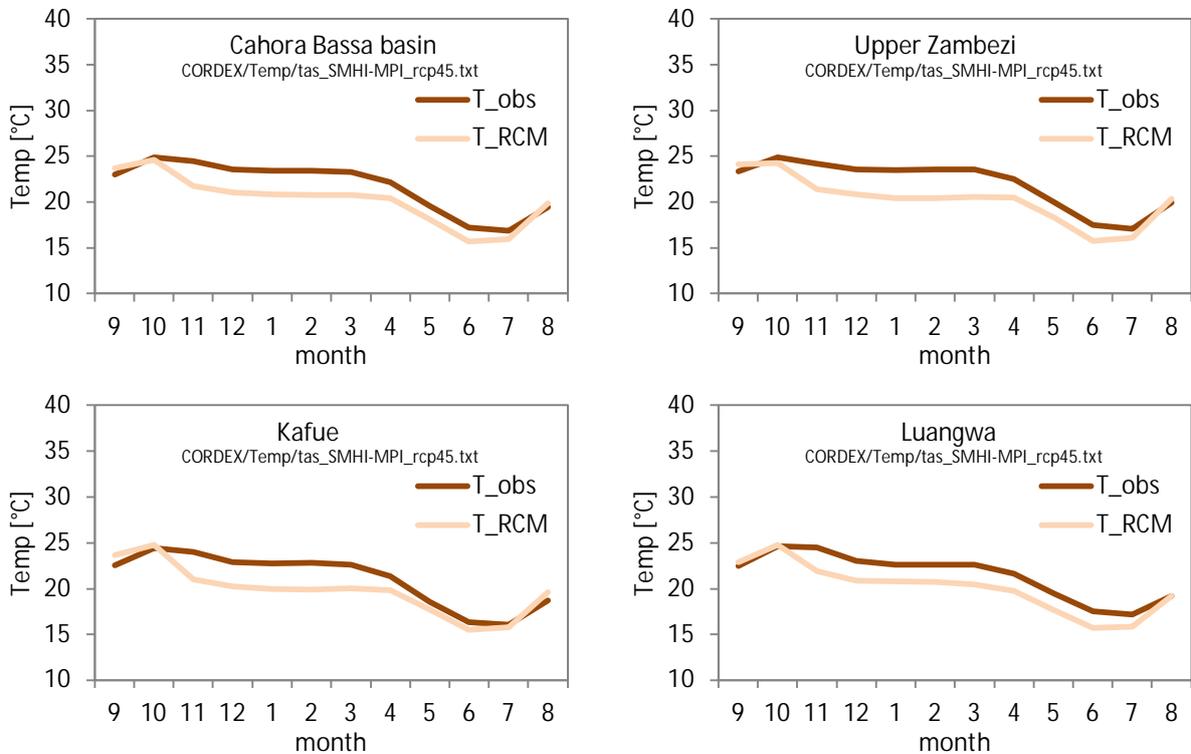
**SMHI-MIROC, 1961-1990**



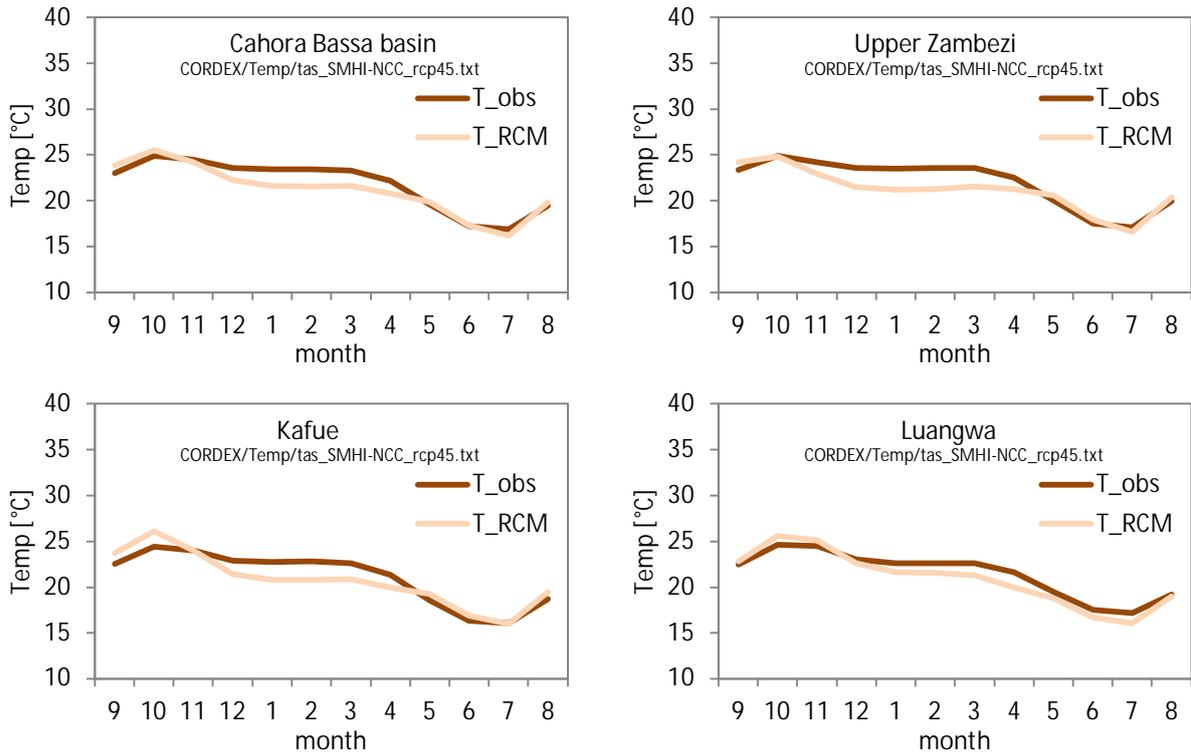
SMHI -MOHC, 1961-1990



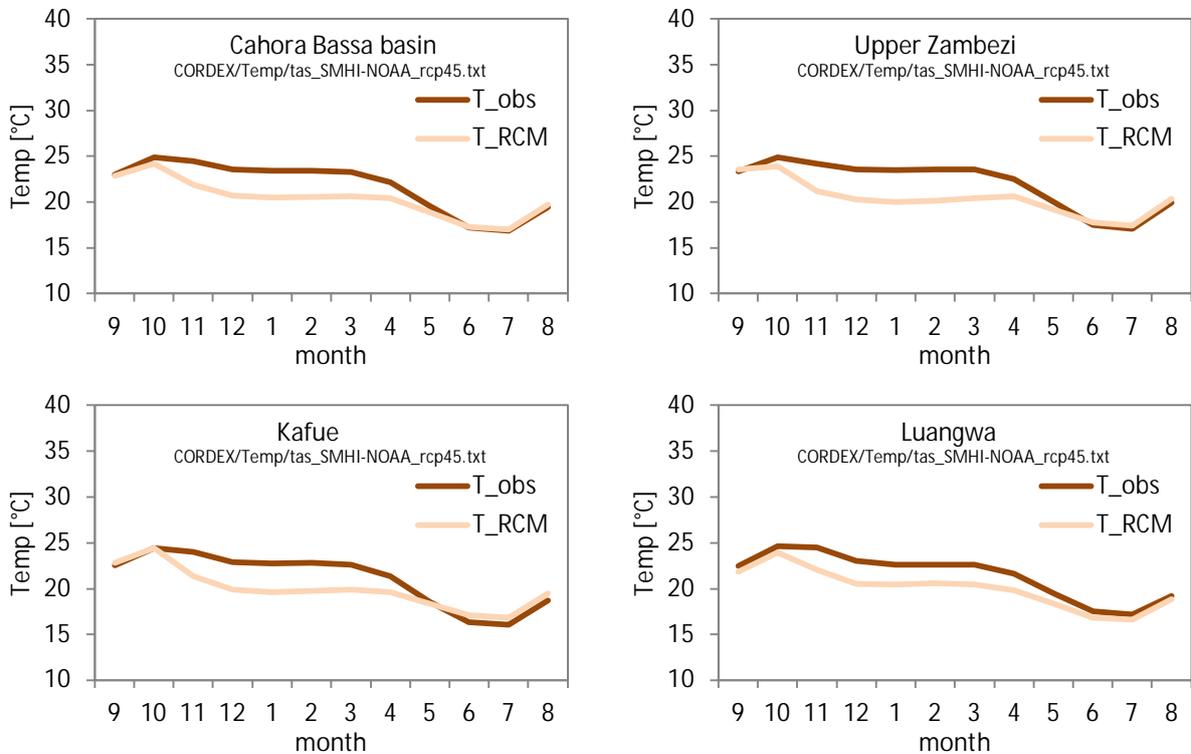
SMHI -MPI, 1961-1990



**SMHI -NCC, 1961-1990**

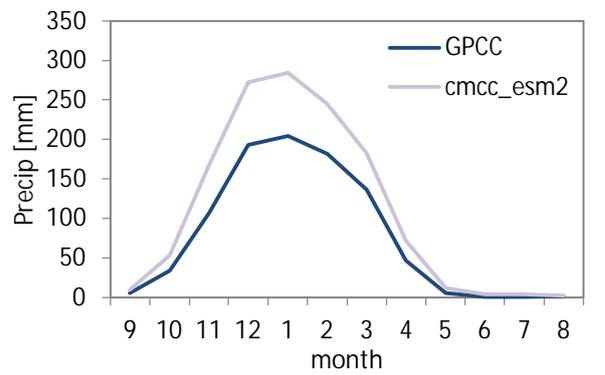
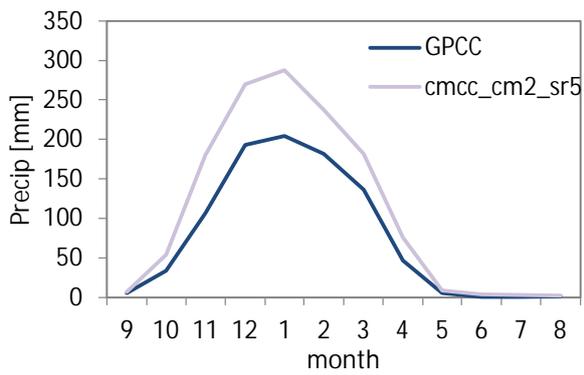
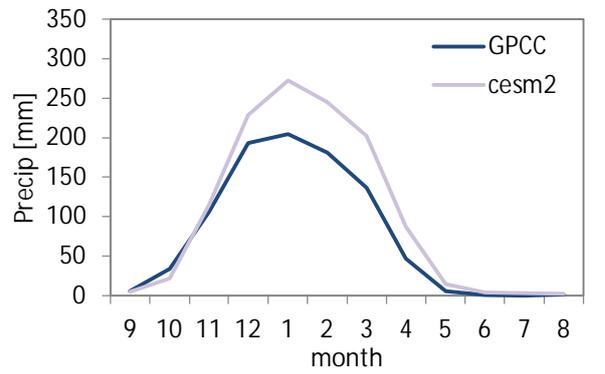
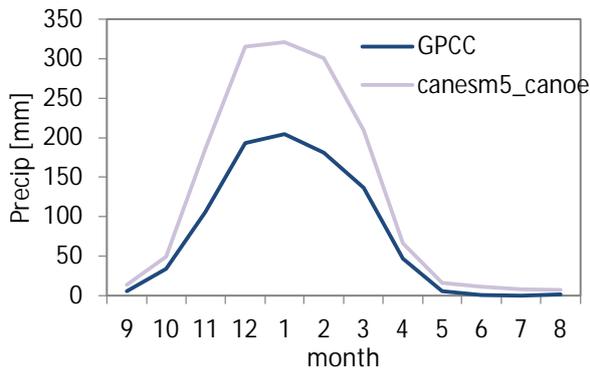
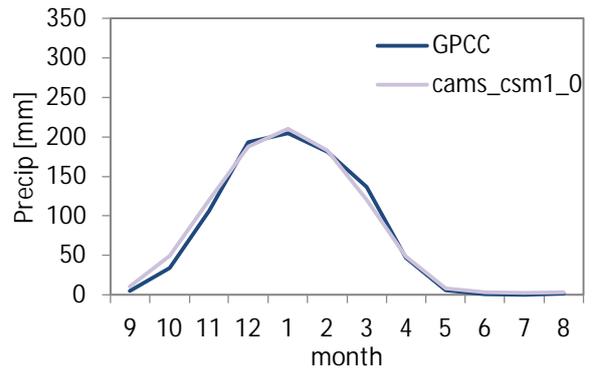
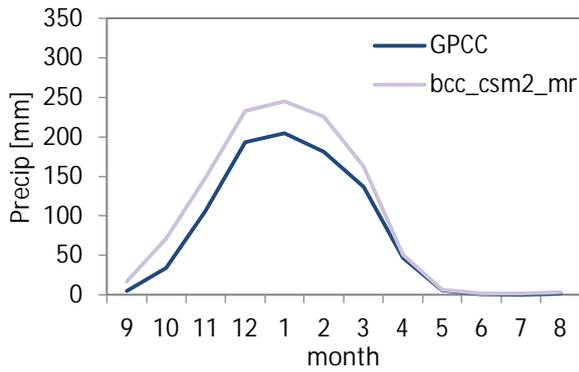
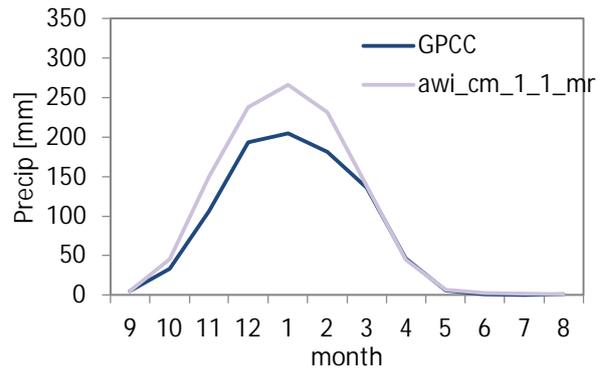
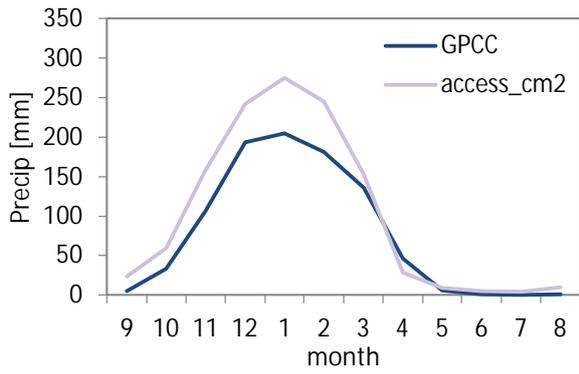


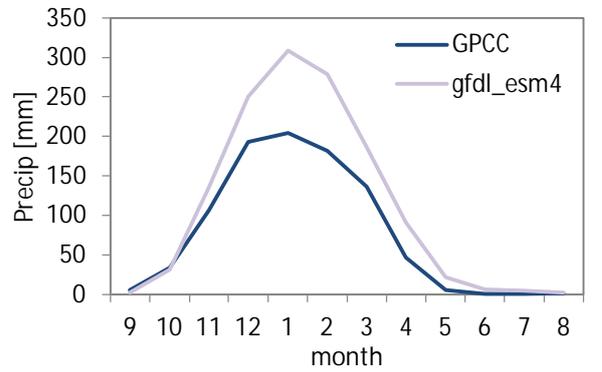
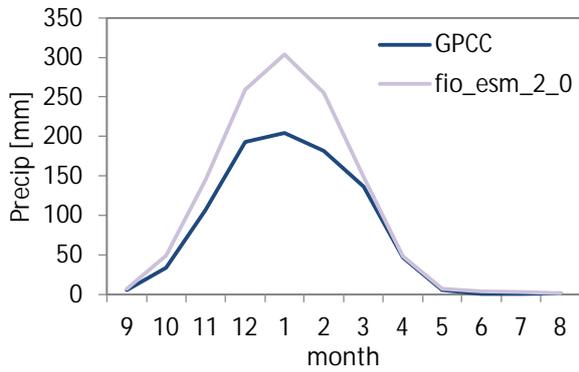
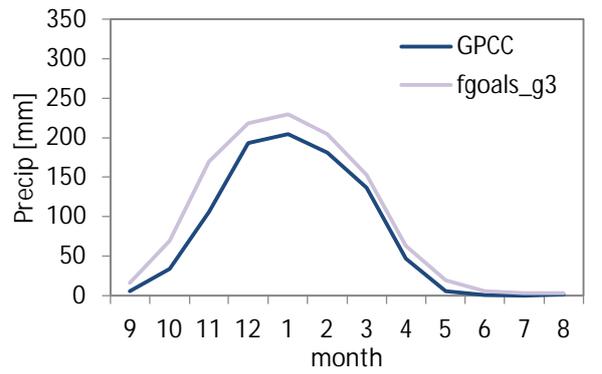
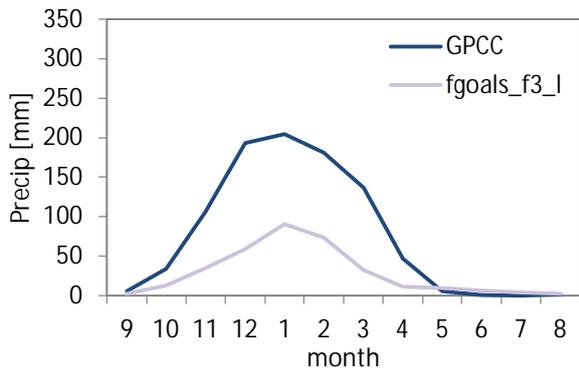
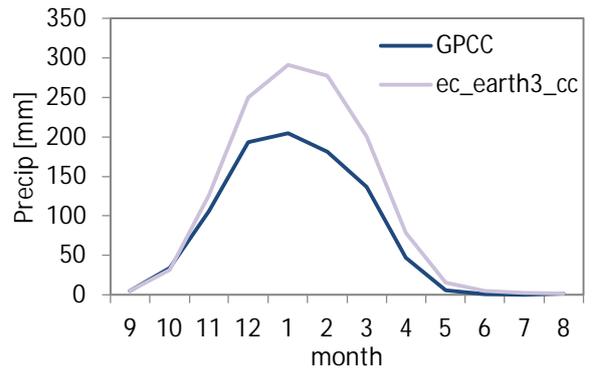
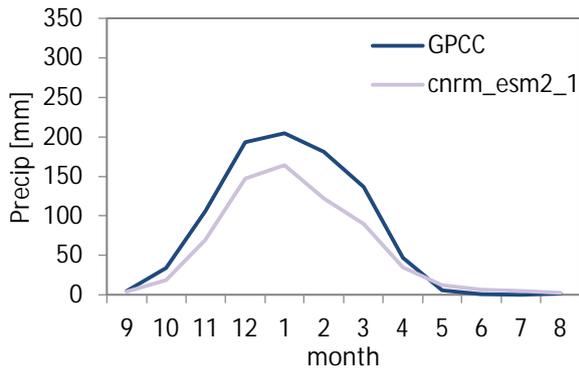
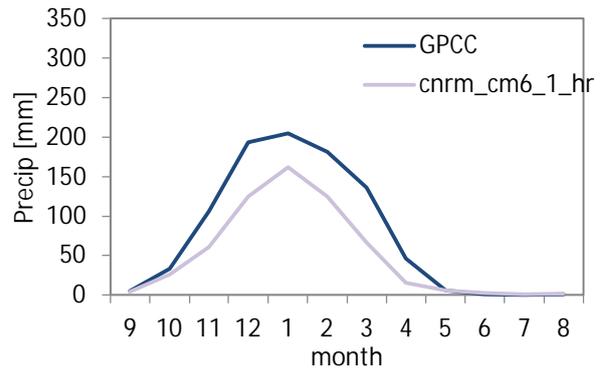
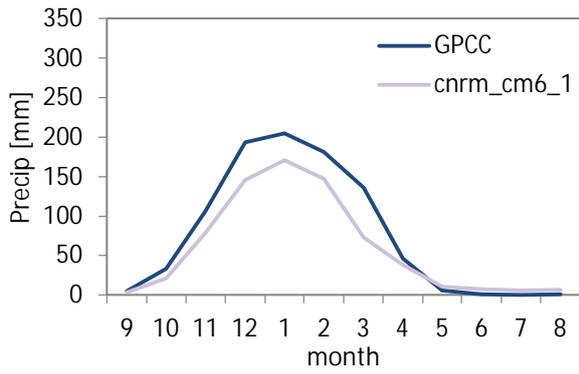
**SMHI -NOAA, 1961-1990**

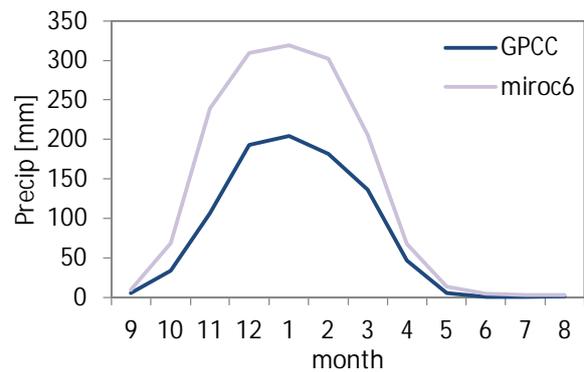
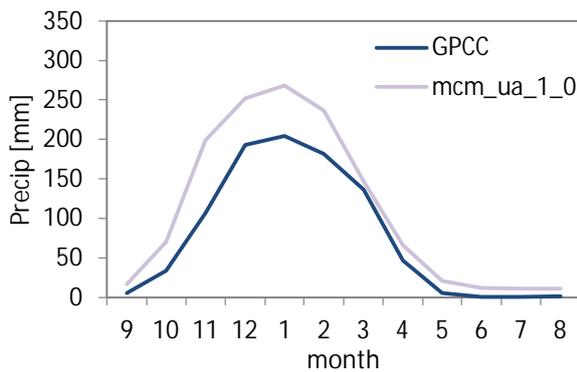
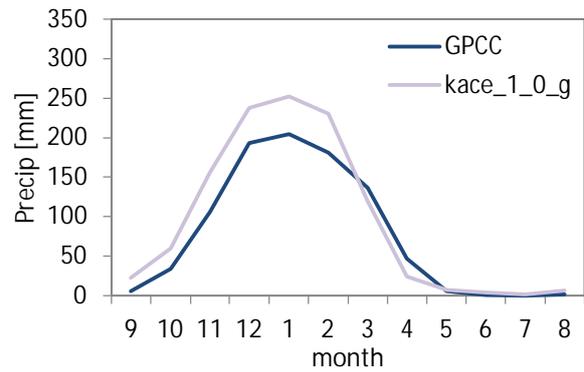
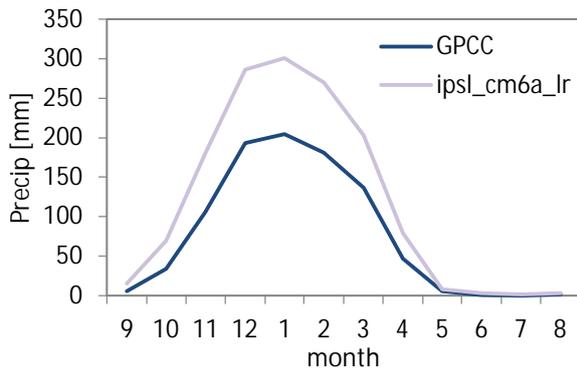
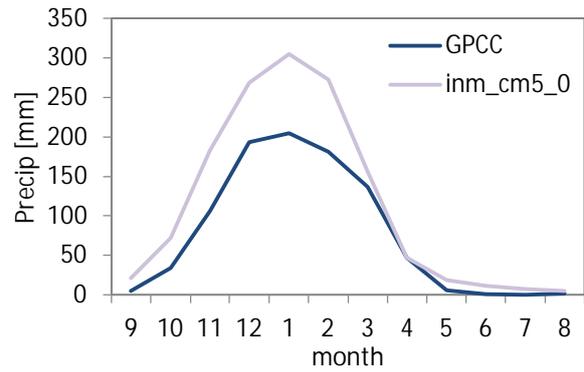
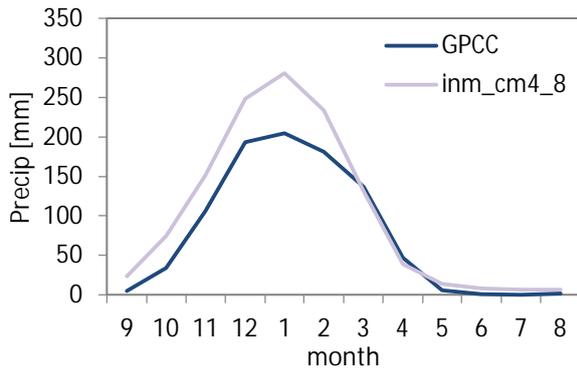
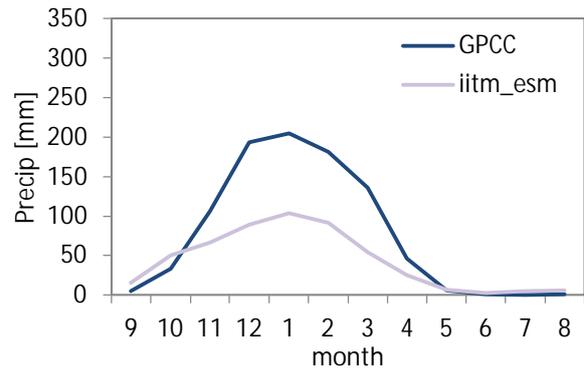
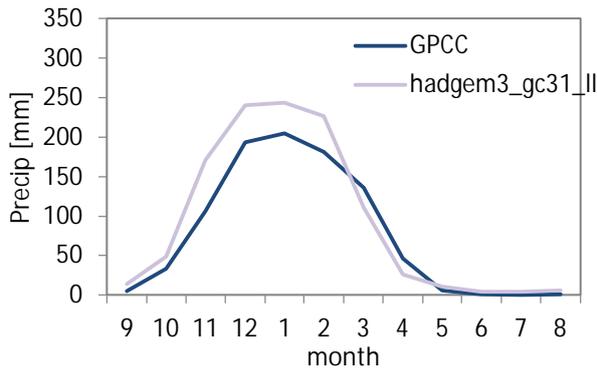


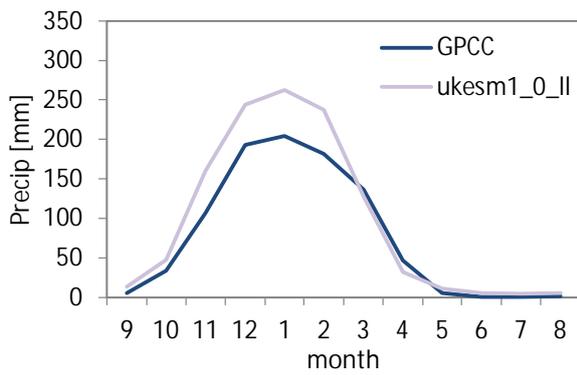
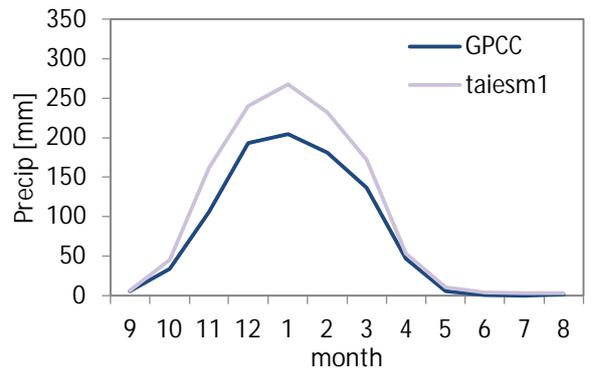
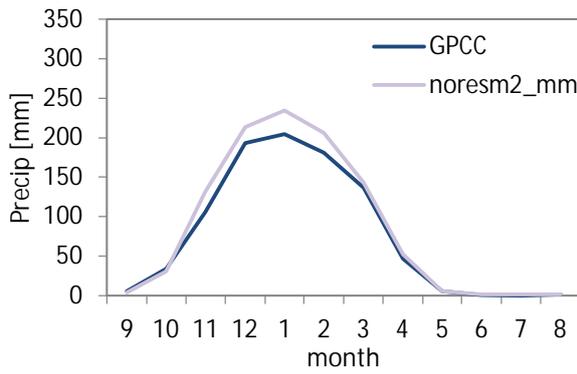
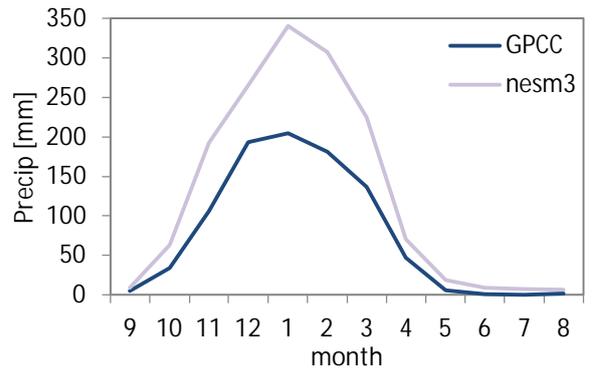
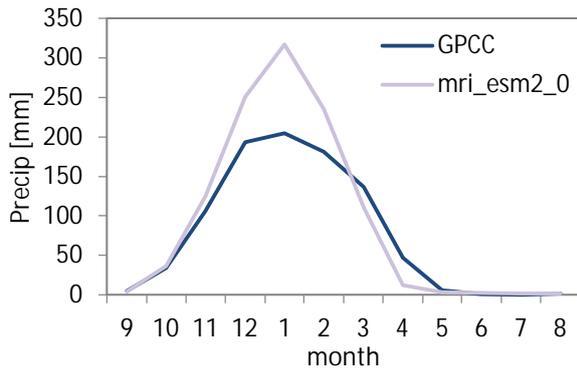
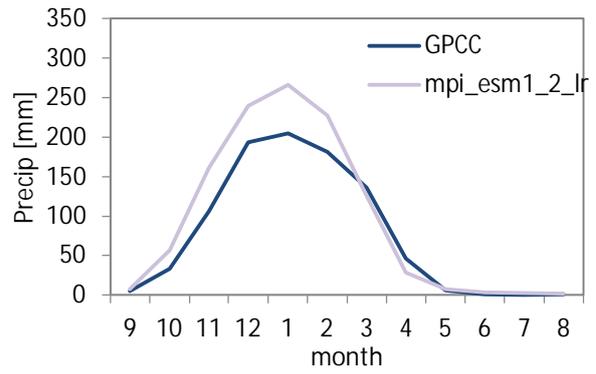
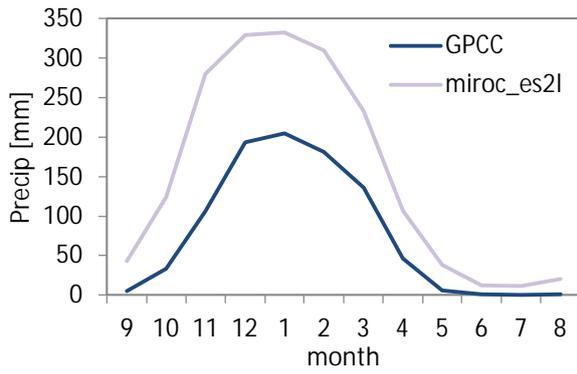
## 9.5 Appendix: CMIP6 climate model data

The following graphs show a comparison of observed (GPCC) versus simulated (GCM) mean monthly precipitation in the period 1961-1990. Spatial average for the Zambezi basin upstream of Cahora Bassa.









## 9.6 Appendix: Evaluation of simulated and observed flow

The following sections show a comparison of simulated (Zambezi DSS) versus observed flow at key gauges and reservoirs in the Zambezi basin. In the graphs observed values are displayed in black and simulated values are displayed in red colour. The simulation results are for the “historic” scenario, where the commissioning year (start year of operation) is considered for each reservoir, which includes the simulated filling of the reservoir (and reduced downstream flow during filling).

In general the simulated flow and the available flow records agree sufficiently well. The model performance is higher for flow gauges than for observed reservoir outflow. This is due to the fact that the model uses fixed operation rules (representative as of the year 2022), whereas the actual operations were also impacted by ad-hoc release decision and other effects (e.g. the transmission lines were not available for Cahora Bassa during the 1980s).

### 9.6.1 Model performance statistics

The model performance statistics in the table below include:

- Avg: long-term average flow
- StdDev: standard deviation of monthly flow
- correl: correlation between simulated and observed monthly flow
- beta: bias ratio between mean simulated and observed flow
- gamma: variability ratio between simulated and observed flow
- NSE: Nash-Sutcliffe Efficiency
- KGE': Kling-Gupta Efficiency (modified version of Kling et al. 2012)

For the definition and a discussion of these model performance statistics see Gupta et al. (2009) and Kling et al. (2012):

Gupta HV, Kling H, Yilmaz KK, Martinez GF (2009): '*Decomposition of the Mean Squared Error and NSE performance criteria: Implications for improving hydrological modelling*' Journal of Hydrology (377): 80-91

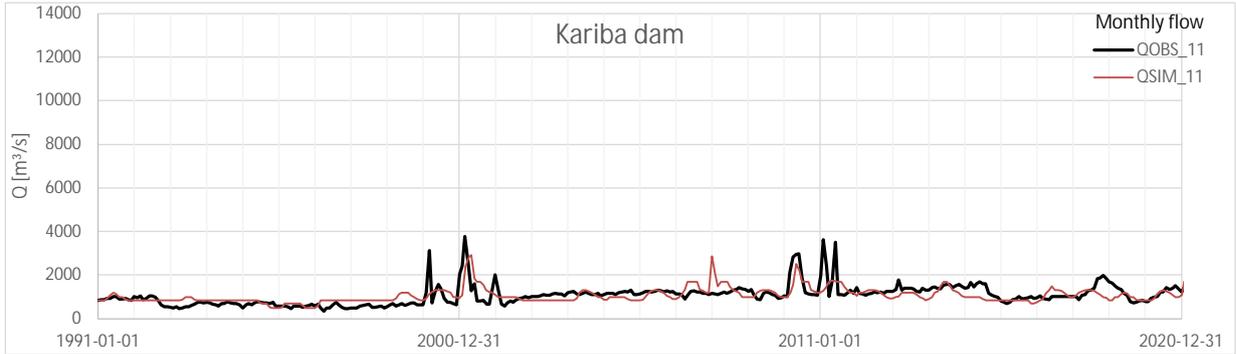
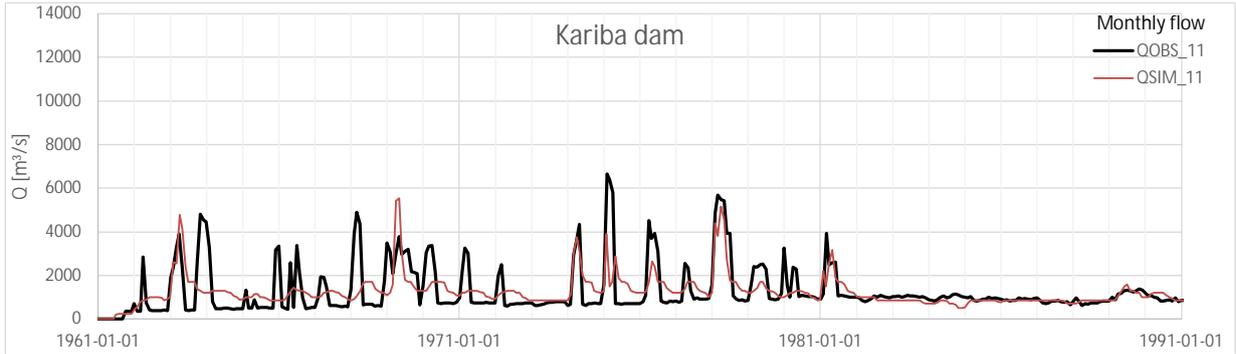
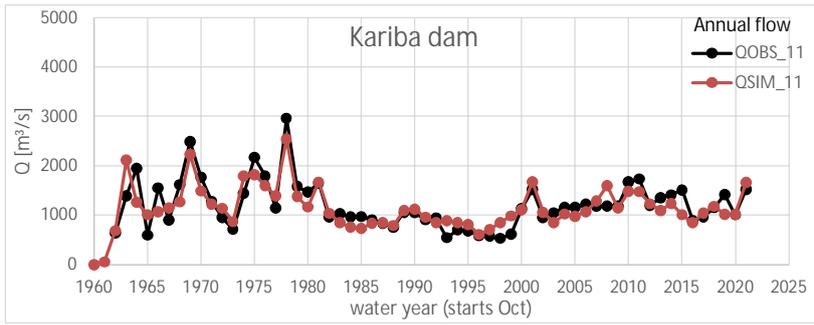
Kling H, Fuchs M, Paulin M (2012): '*Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios*' Journal of Hydrology (424-425): 264-277

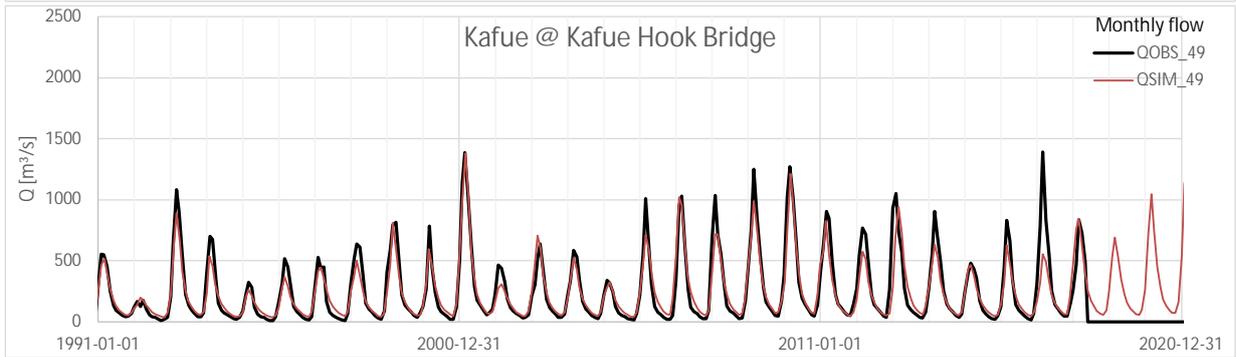
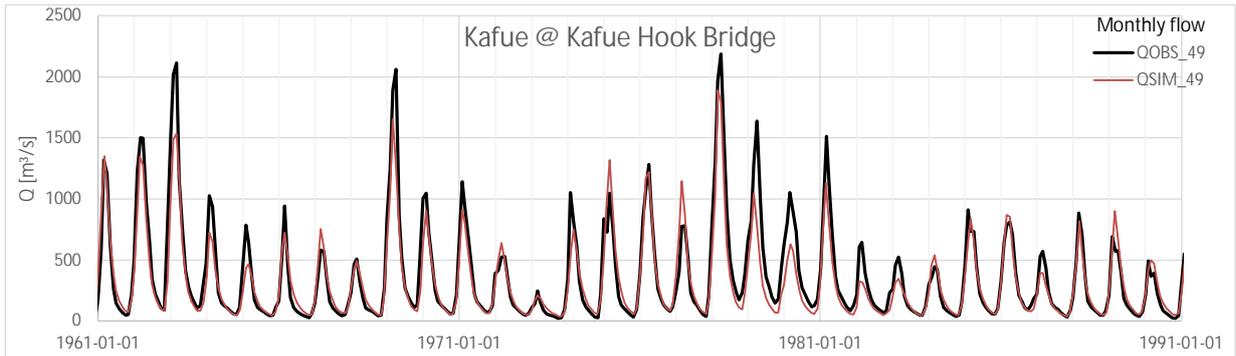
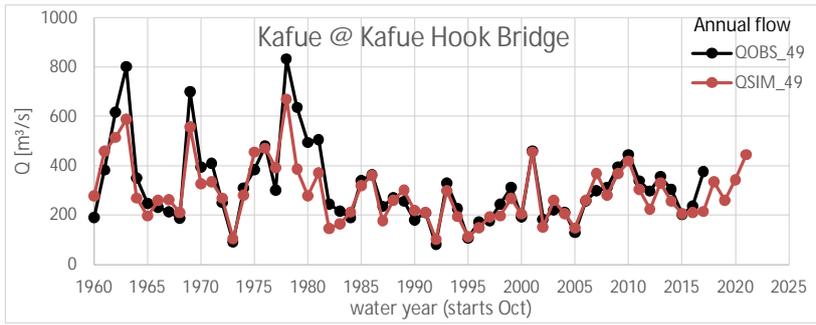
Model performance for flow simulation (historic conditions)										
		[m <sup>3</sup> /s]	[m <sup>3</sup> /s]	[m <sup>3</sup> /s]	[m <sup>3</sup> /s]	[/]	[/]	[/]	[/]	[/]
location	eval period	Avg obs	Avg sim	StdDev obs	StdDev sim	correl	beta	gamma	NSE	KGE'
Zambezi @ Victoria Falls	1961-1990	1259.2	1234.5	1206.0	1201.2	0.94	0.98	1.02	0.875	0.933
Zambezi @ Victoria Falls	1991-2020	1073.2	1033.9	1037.9	949.2	0.91	0.96	0.95	0.819	0.887
Kariba dam	1961-1990	1329.5	1272.3	1138.7	716.7	0.57	0.96	0.66	0.323	0.451
Kariba dam	1991-2020	1077.9	1067.3	474.3	332.4	0.53	0.99	0.71	0.244	0.442
Kafue @ Hook Bridge	1961-1990	371.1	327.5	404.9	331.9	0.94	0.88	0.93	0.862	0.851
Kafue @ Hook Bridge	1991-2020	267.5	250.8	291.8	234.7	0.94	0.94	0.86	0.857	0.832
Itezhtezhi dam	1961-1990	339.6	352.6	344.3	340.2	0.91	1.04	0.95	0.817	0.890
Itezhtezhi dam	1991-2020	259.7	263.9	196.7	178.3	0.79	1.02	0.89	0.605	0.761
Kafue Gorge dam	1961-1990	340.4	346.1	306.0	268.0	0.87	1.02	0.86	0.758	0.810
Kafue Gorge dam	1991-2020	238.1	234.1	144.0	143.0	0.84	0.98	1.01	0.687	0.842
Luangwa @ Gt East Road	1961-1990	600.4	596.5	708.4	707.3	0.93	0.99	1.00	0.865	0.932
Luangwa @ Gt East Road	1991-2020	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Cahora Bassa inflow	1961-1990	2329.6	2409.2	1973.3	1613.8	0.90	1.03	0.79	0.803	0.766
Cahora Bassa inflow	1991-2020	1765.9	1839.3	1176.2	946.2	0.90	1.04	0.77	0.791	0.746
Cahora Bassa dam	1961-1990	2258.8	2267.6	1537.3	1166.2	0.61	1.00	0.76	0.351	0.540
Cahora Bassa dam	1991-2020	1737.0	1772.3	780.9	662.7	0.78	1.02	0.83	0.607	0.725
Zambezi @ Tete	1961-1990	2417.1	2636.5	1639.2	1661.9	0.75	1.09	0.93	0.484	0.729
Zambezi @ Tete	1991-2020	1974.8	2061.3	723.6	894.3	0.77	1.04	1.18	0.369	0.705

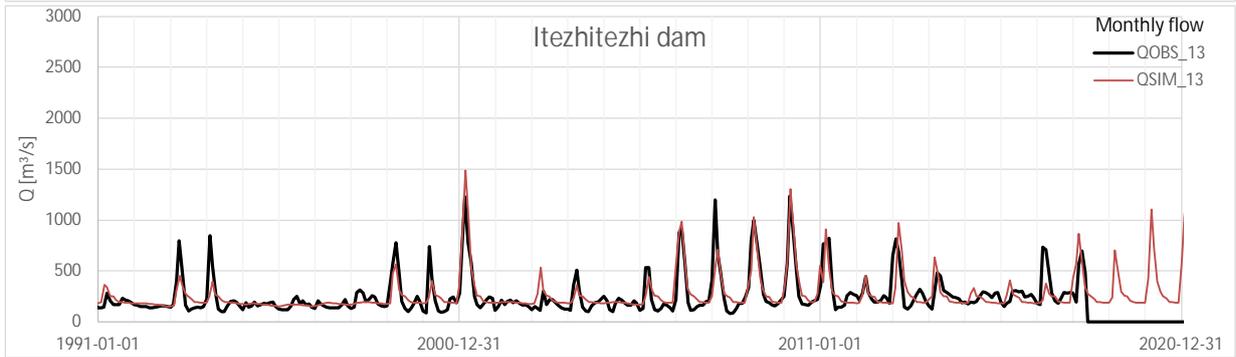
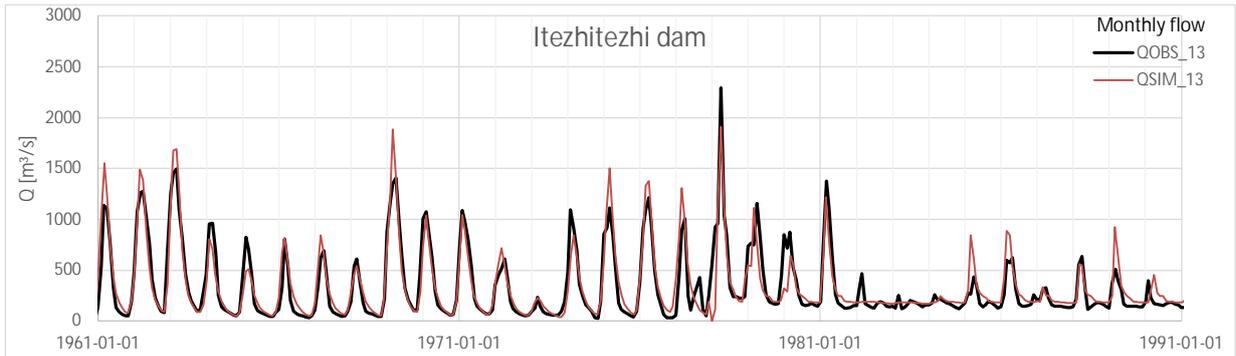
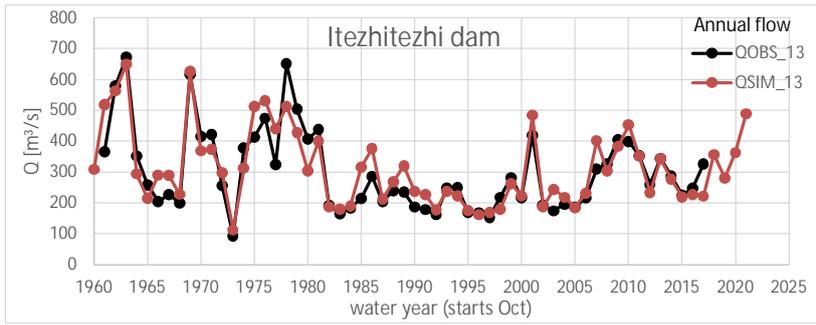
### 9.6.2 Annual and monthly flows

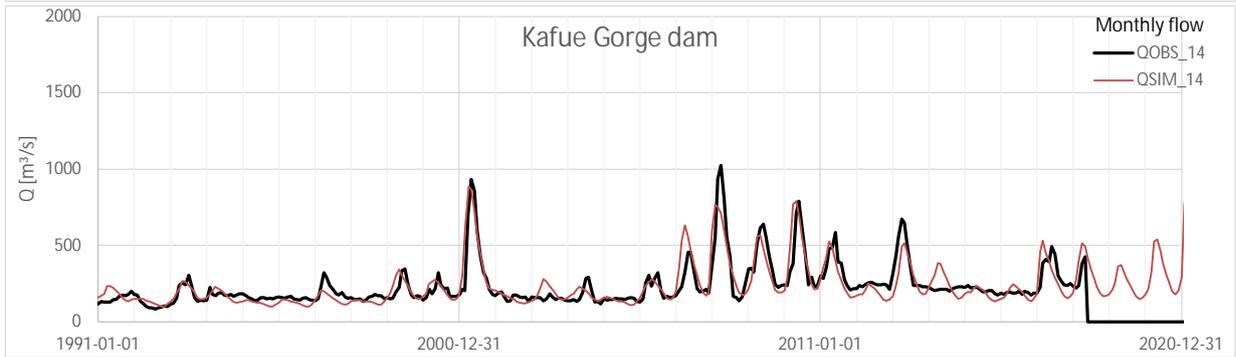
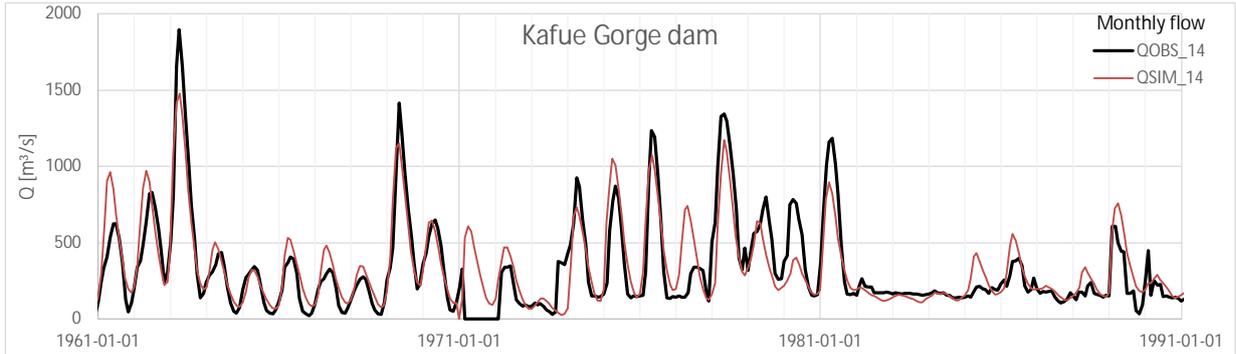
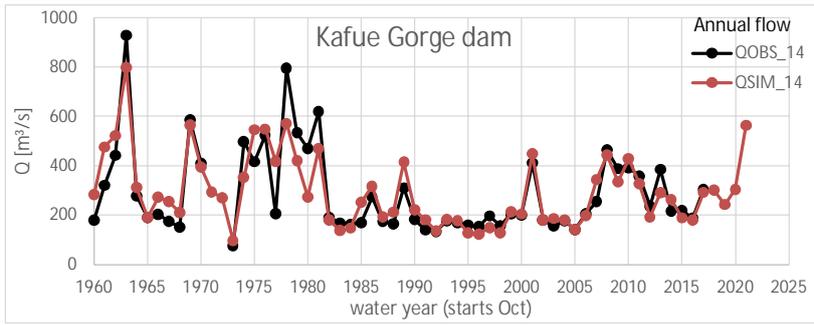
In the figures below the top graph shows annual flow, the middle graph monthly flow 1961-1990, and the bottom graph monthly flow 1991-2020.

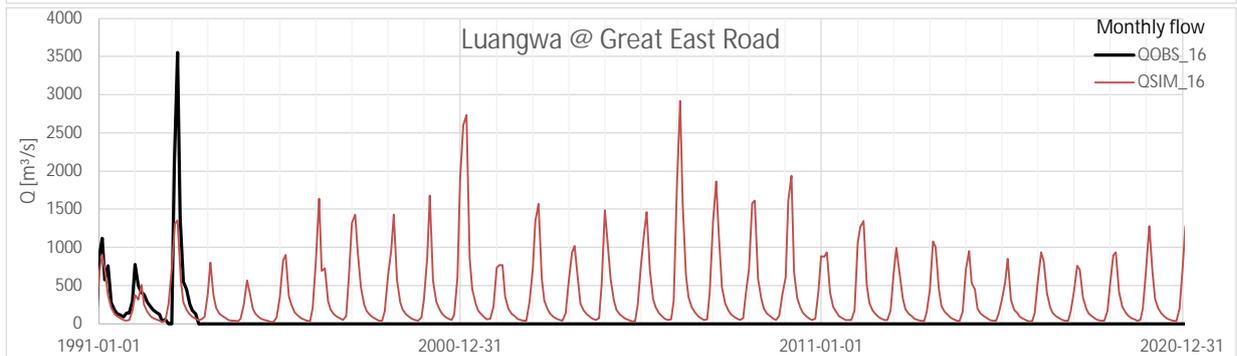
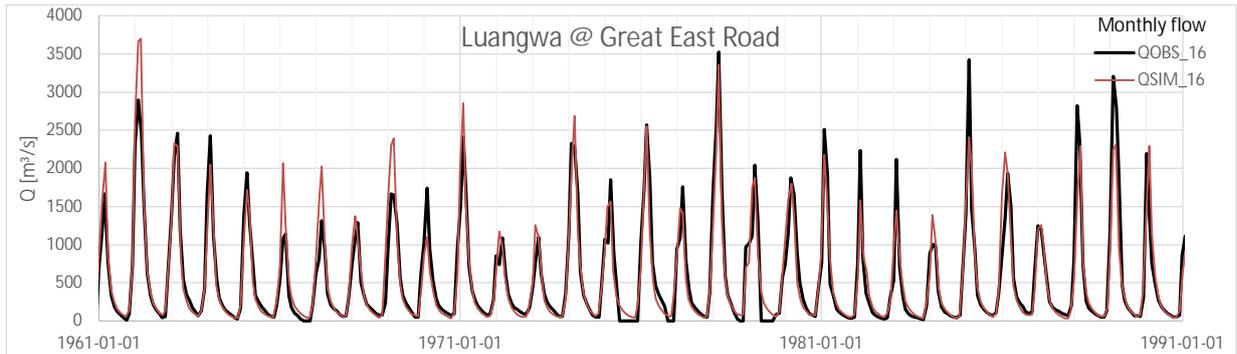
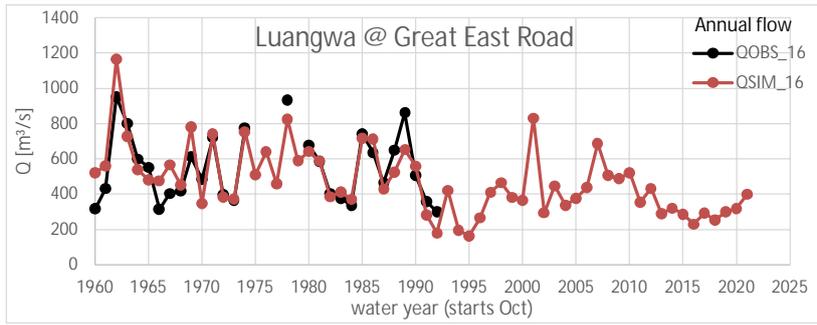


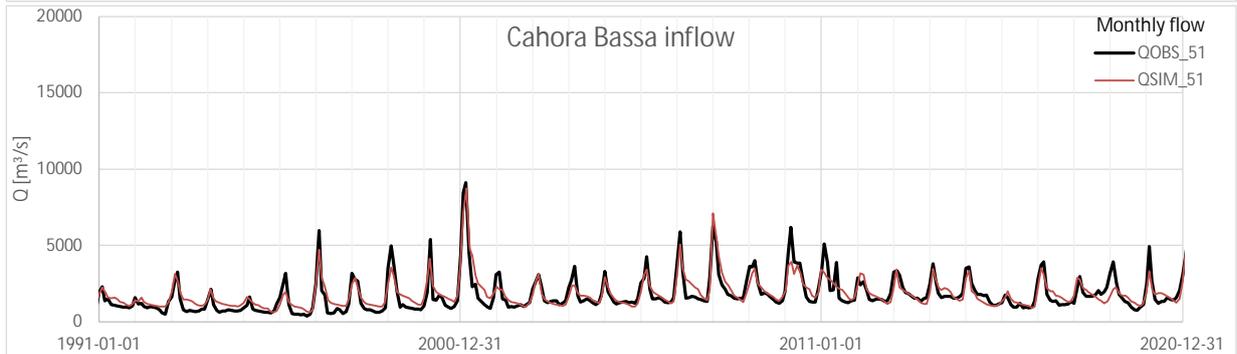
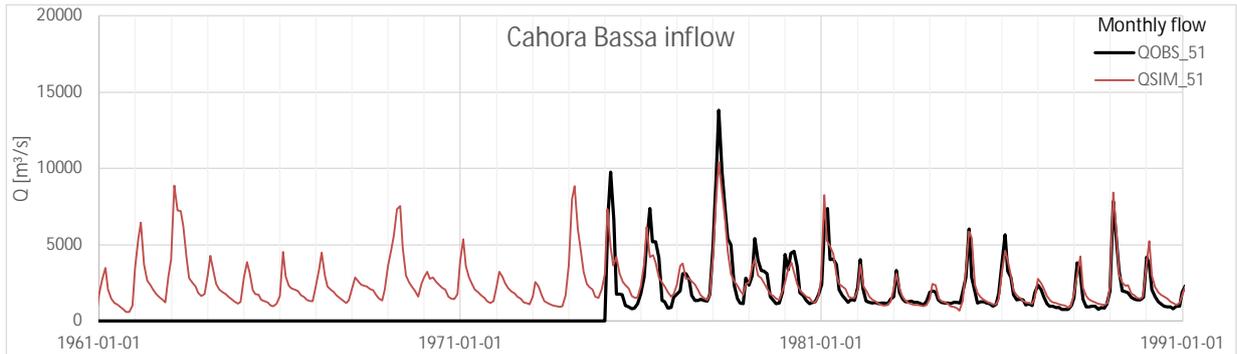
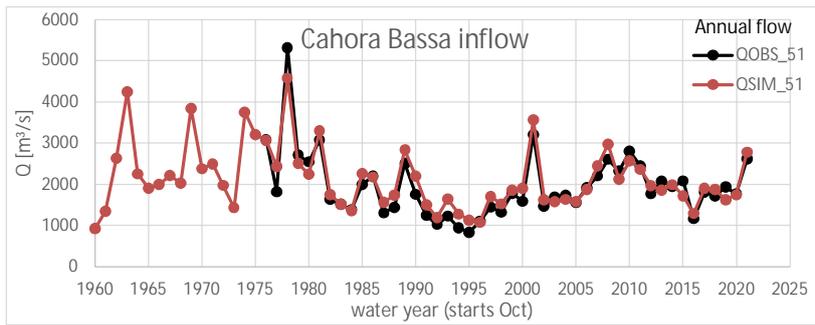


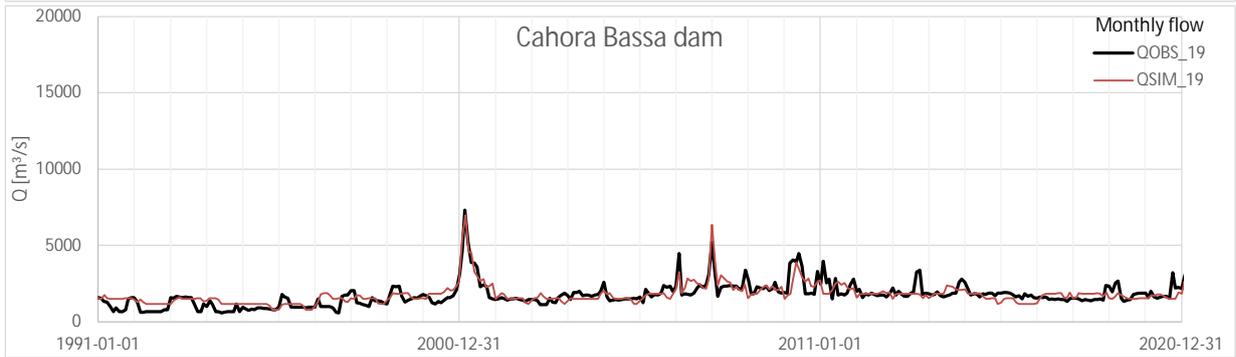
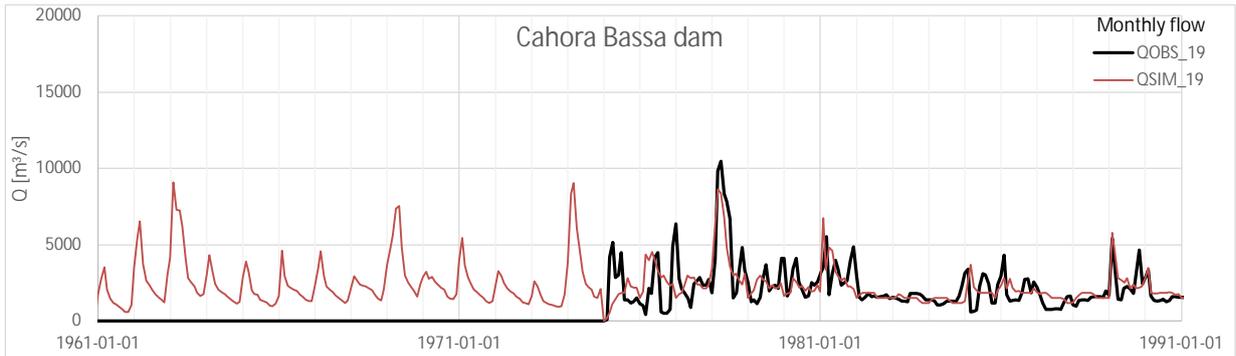
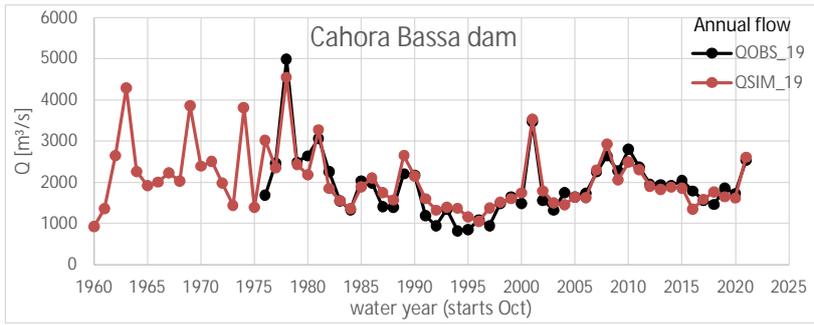


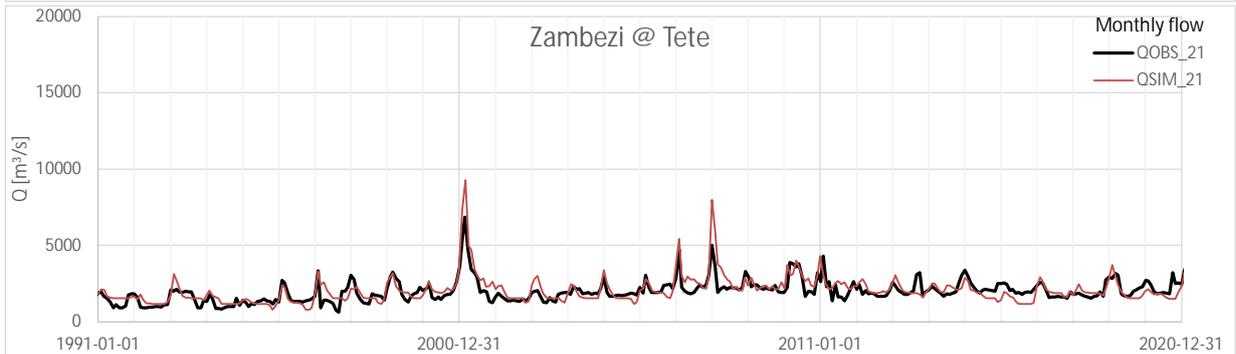
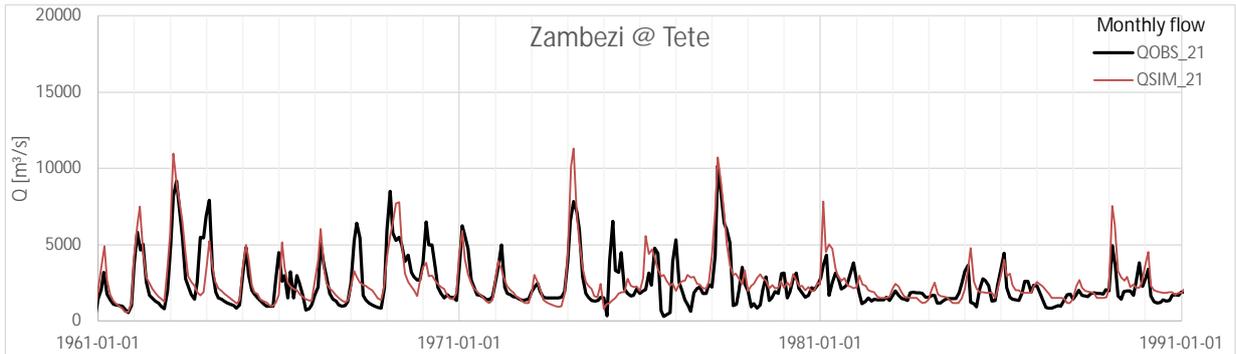
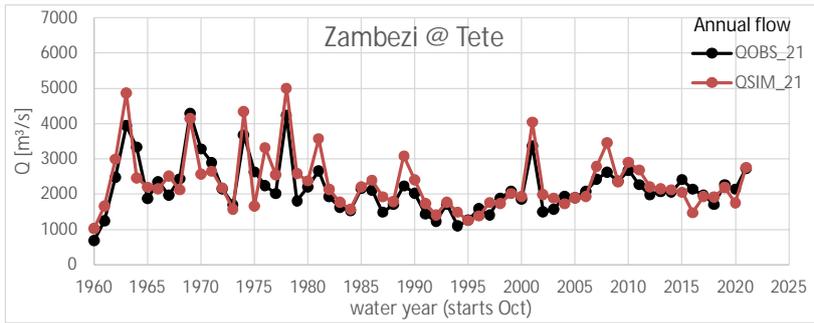












The following graphs show the simulation results 1991-2020 for smaller catchments in the vicinity of Cahora Bassa. All these river catchments show very high variability in flow, with zero flow in the dry season and in some years zero flow even in the rainy season (in dry years). There is a rapid response of the (monthly) hydrograph if rainfall is sufficient.

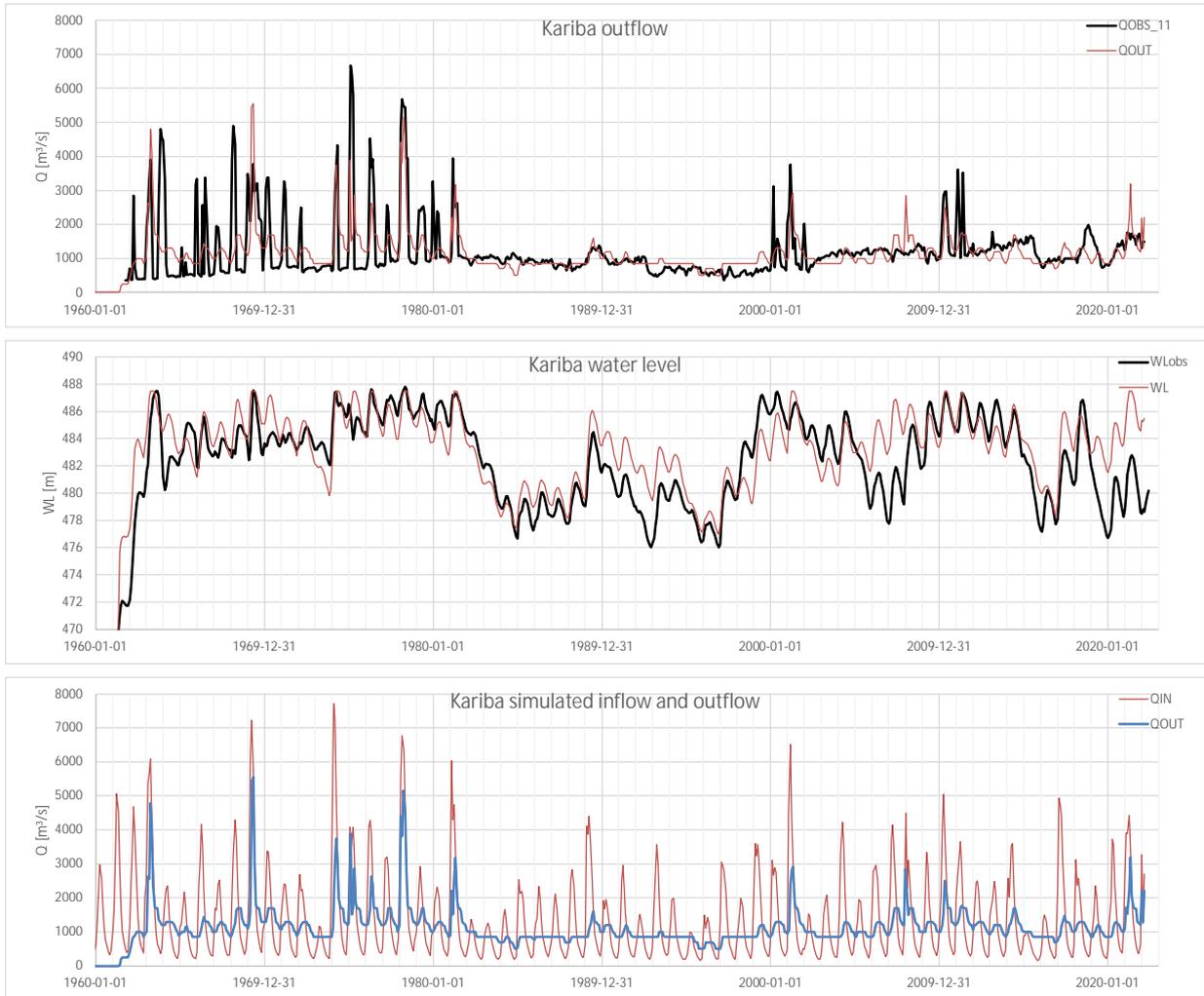


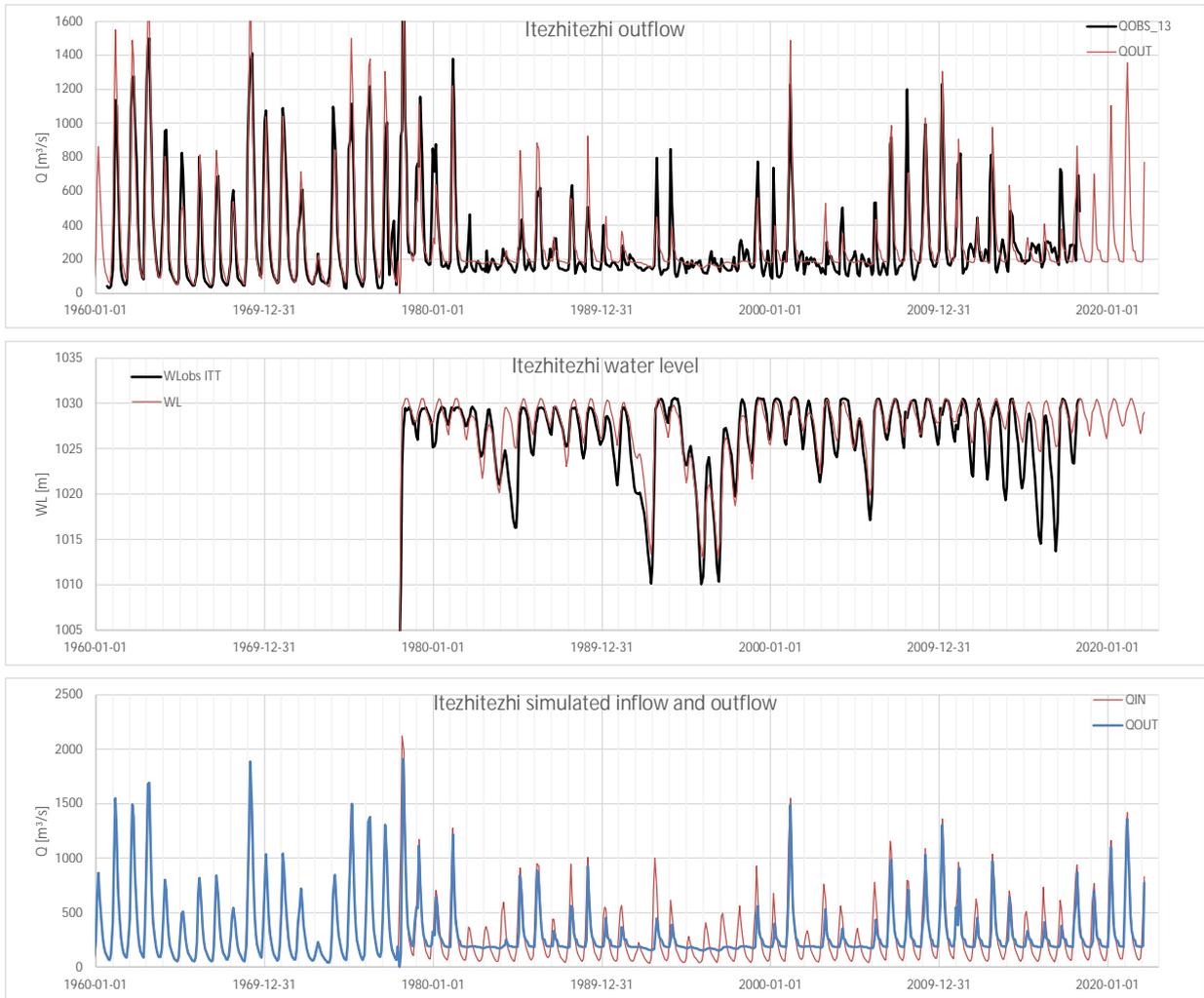
### 9.6.3 Reservoir simulation

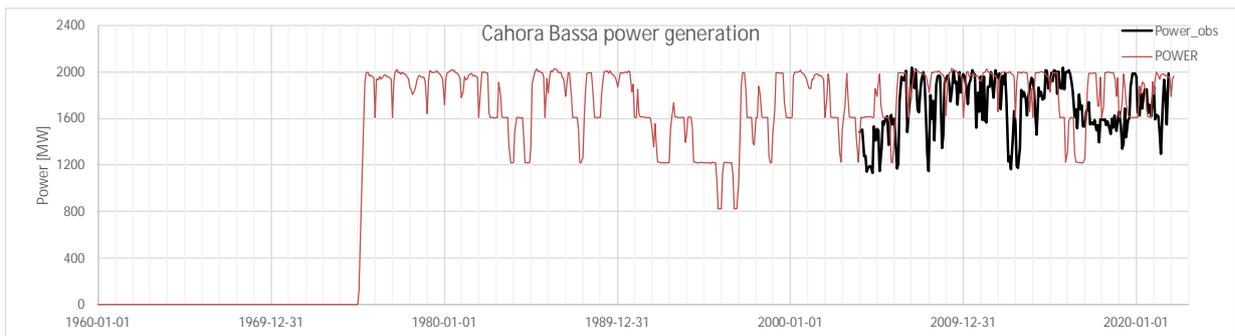
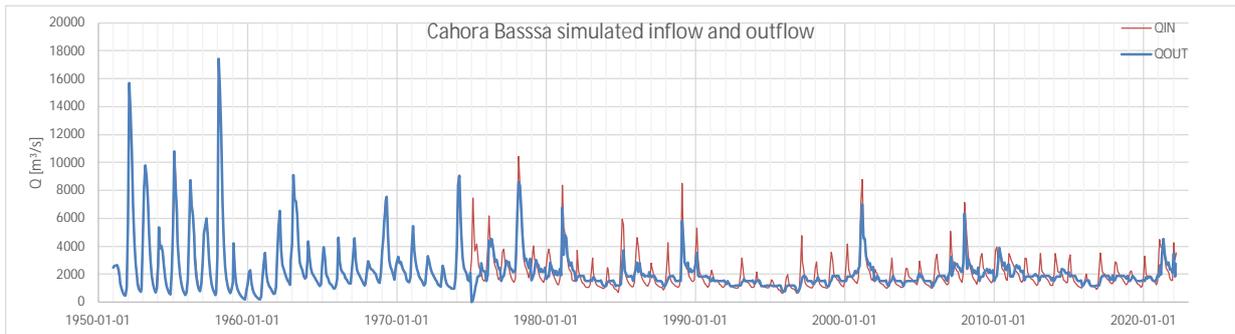
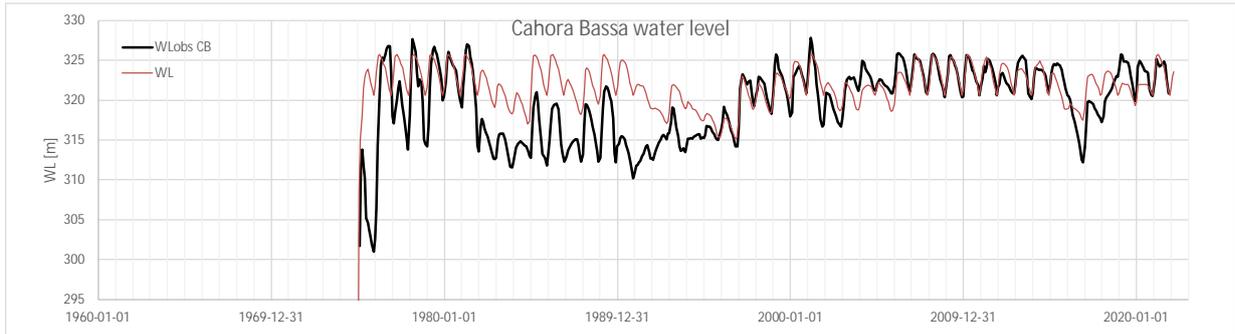
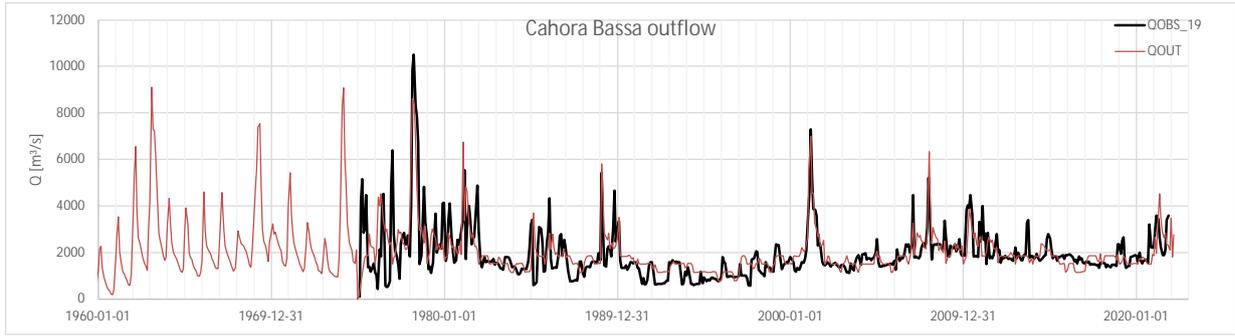
The following graphs show the reservoir simulation for Kariba, Itzehitezhi and Cahora Bassa for historic conditions (includes initial filling) in the period 1960-2022.

Black: observed data

Red and blue: simulated variables



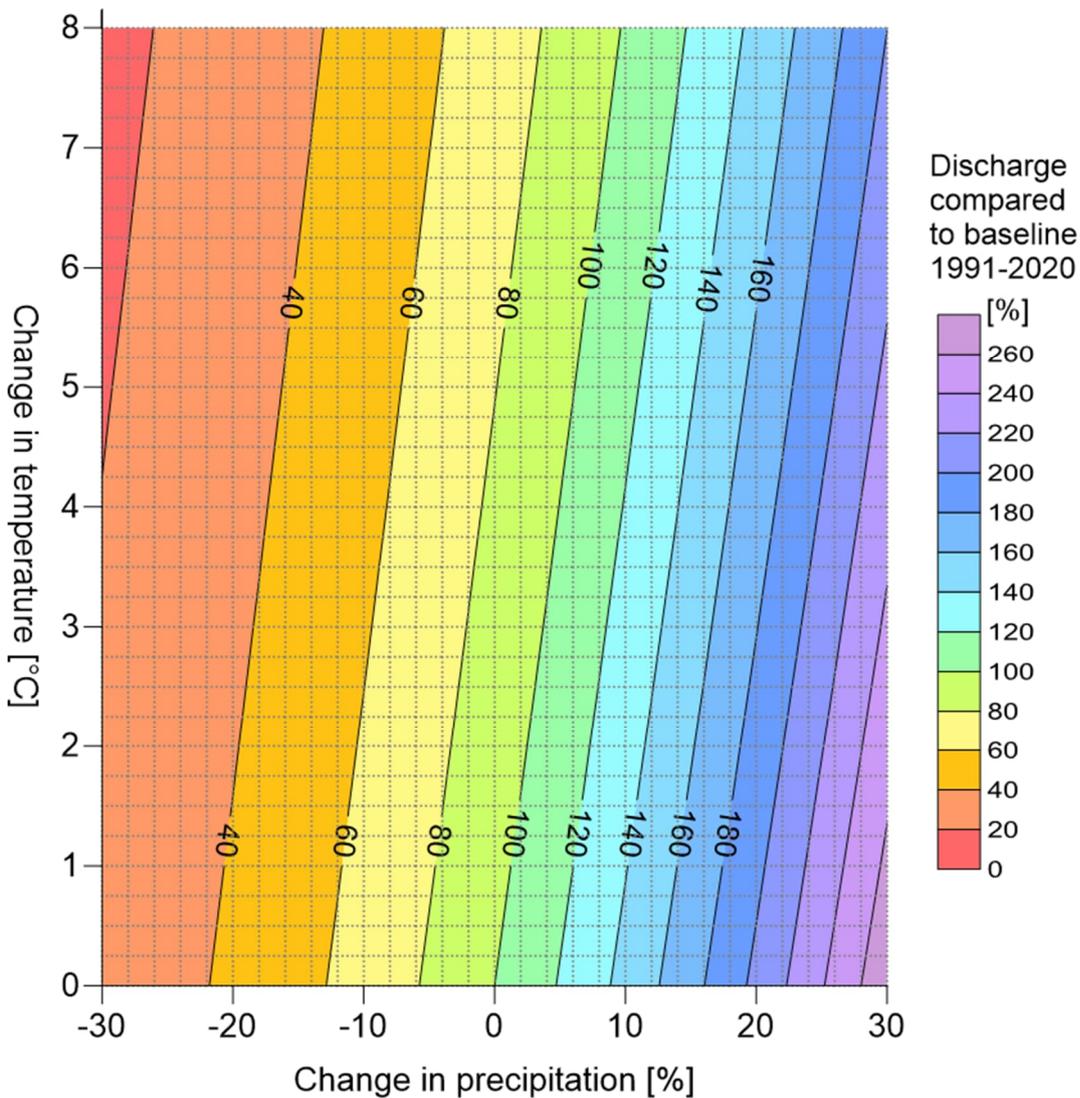


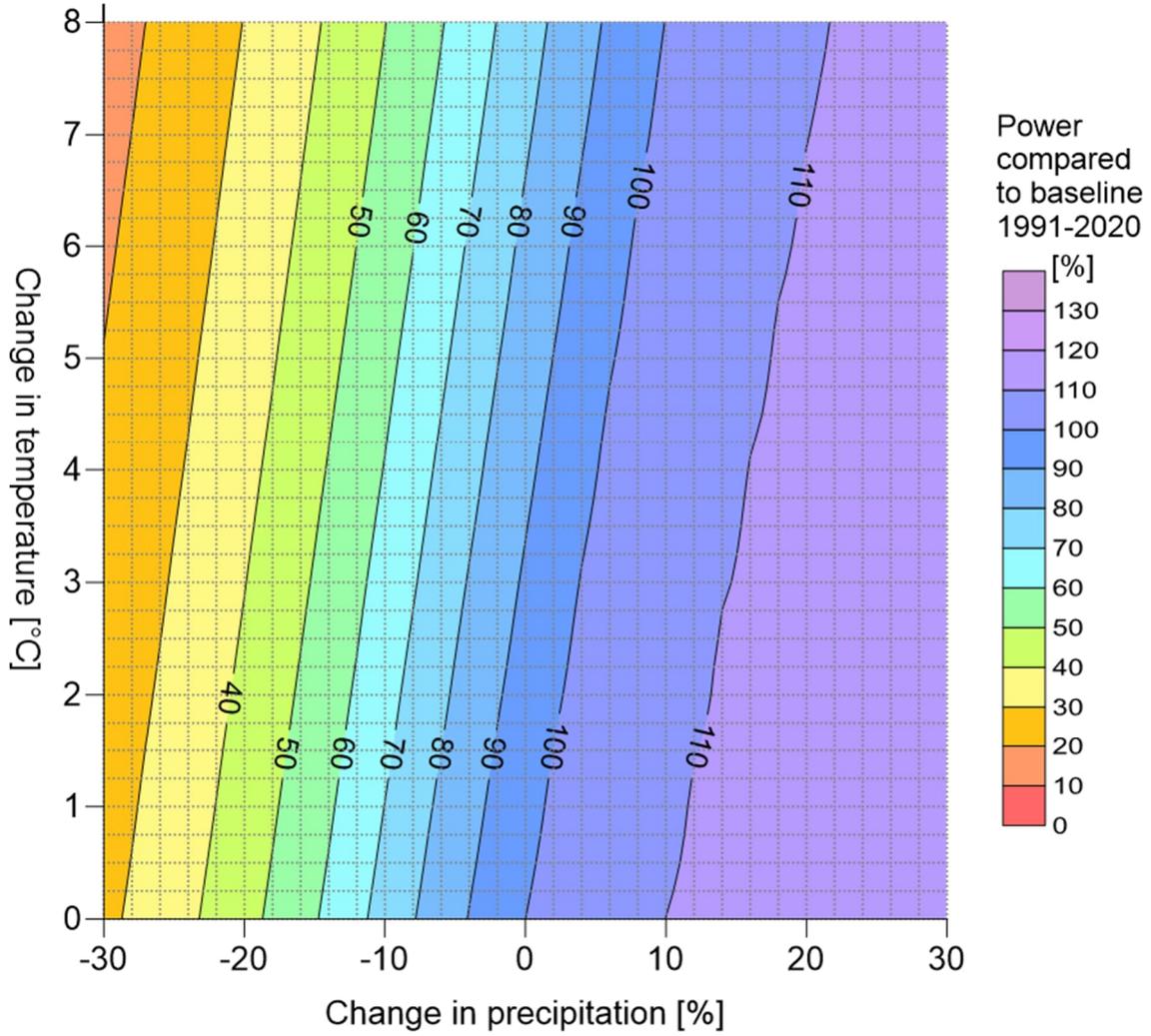


### 9.7 Appendix: Sensitivity analysis

The results of the sensitivity analysis of joint changes in air temperature and precipitation and the corresponding mean annual simulated outflow and power generation at Cahora Bassa are shown as three-dimensional surfaces in Figure 44 and Figure 45 (chapter 5.3).

In addition, the same results are also presented in plan view in the figures below. The grey gridlines indicate the overall 1023 scenarios of joint changes in air temperature and precipitation (at each gridline intersection the model was run for this scenario). The contour lines and colour areas were interpolated from the simulation results.



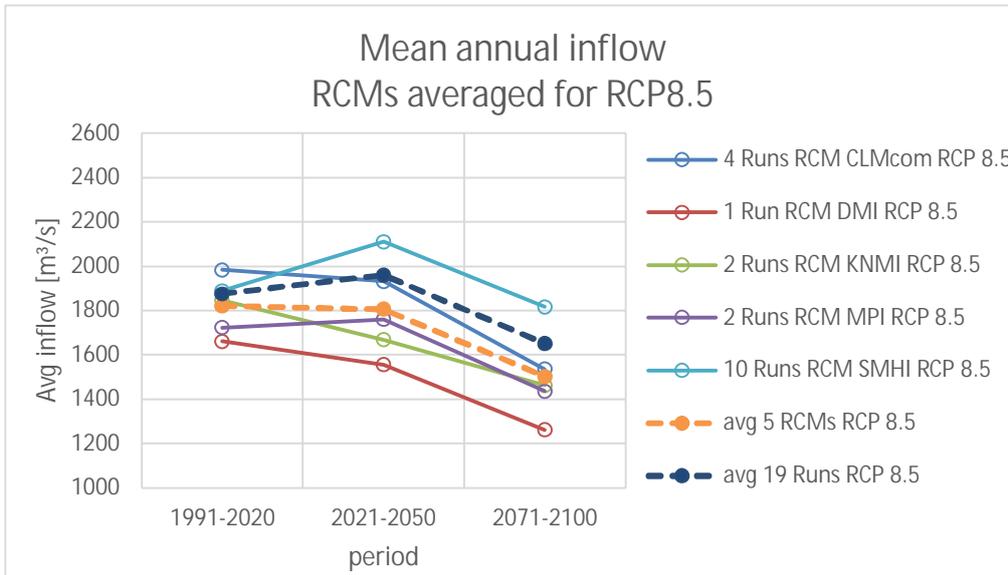
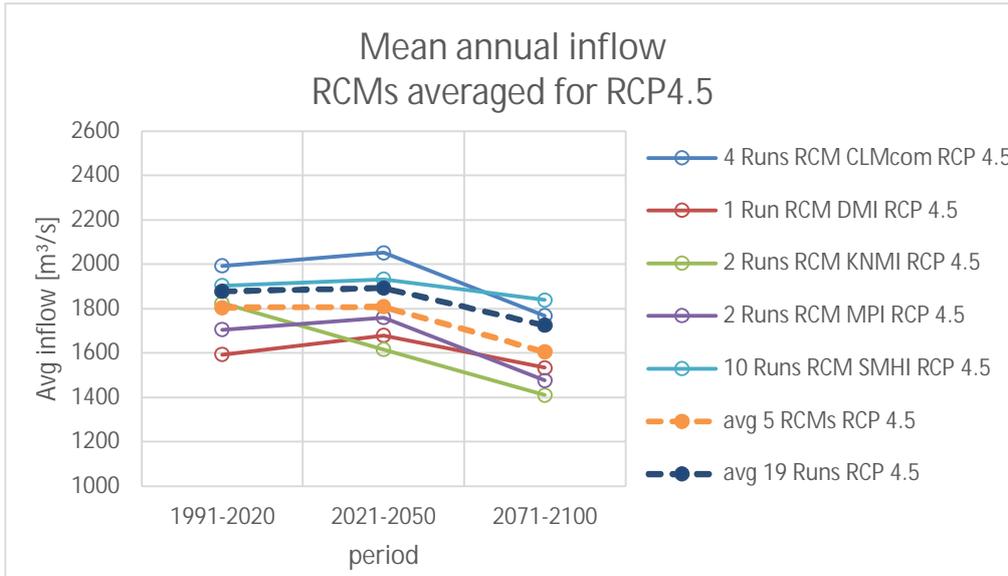


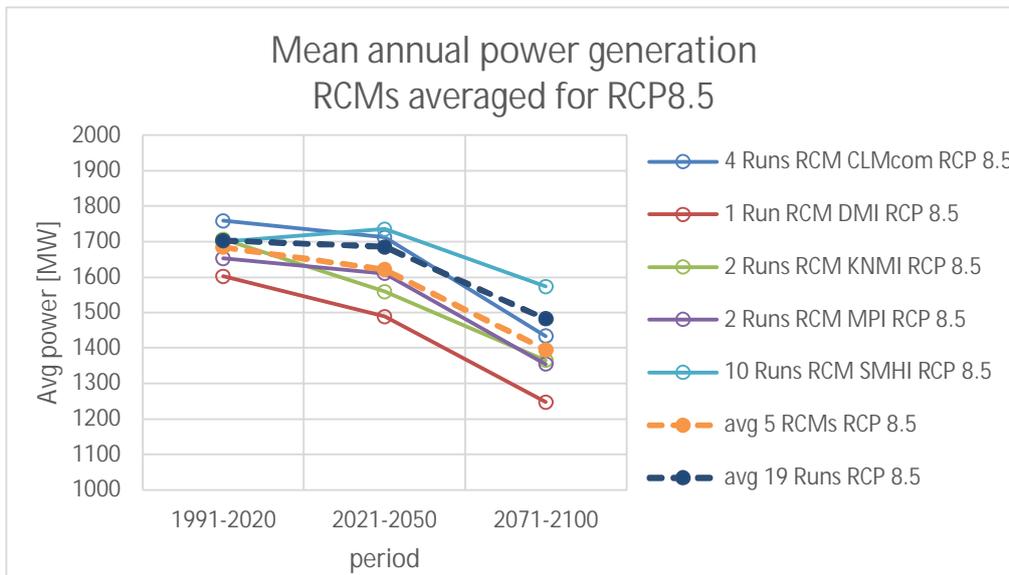
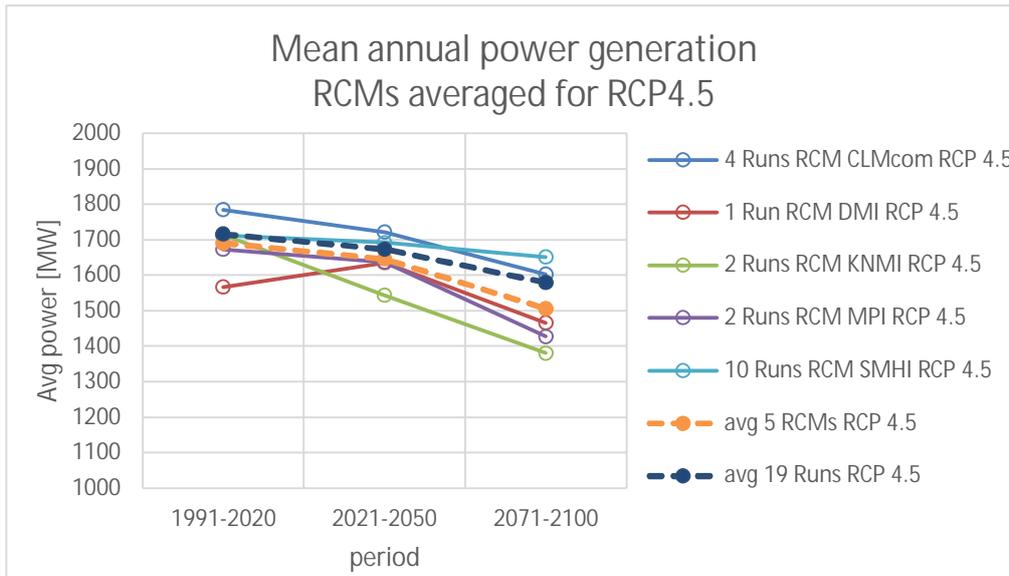
## 9.8 Appendix: Averaging of CORDEX RCMs

The CORDEX ensemble is not distributed equally among RCMs. More than half (i.e. 10) of the overall 19 climate projections are based on the RCM of SMHI. In comparison with the other RCMs the results of SMHI show a wetter future climate. Therefore, averaging over all RCM runs (i.e. 19) may skew the overall interpretation of results, as the weight of SMHI results may be overly emphasized. Therefore, it was tested to compute the average with two different methods:

- Standard method: Based on the overall ensemble of 19 runs, where each run is treated equally and has the same weight.
- Alternative method: Computing, first, the average for each of the 5 RCMs, and then computing the average over the 5 RCMs. This approach eliminates the high weight of SMHI results.

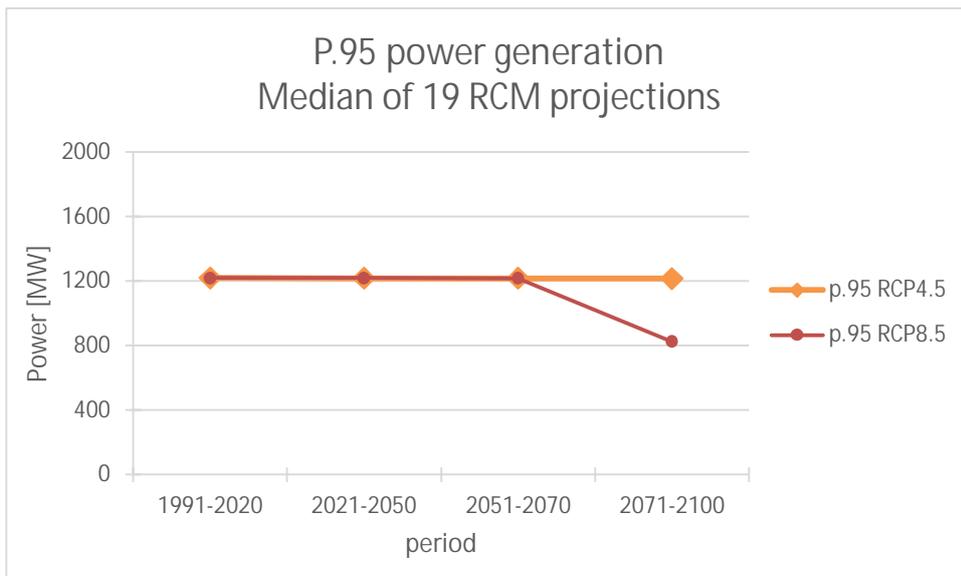
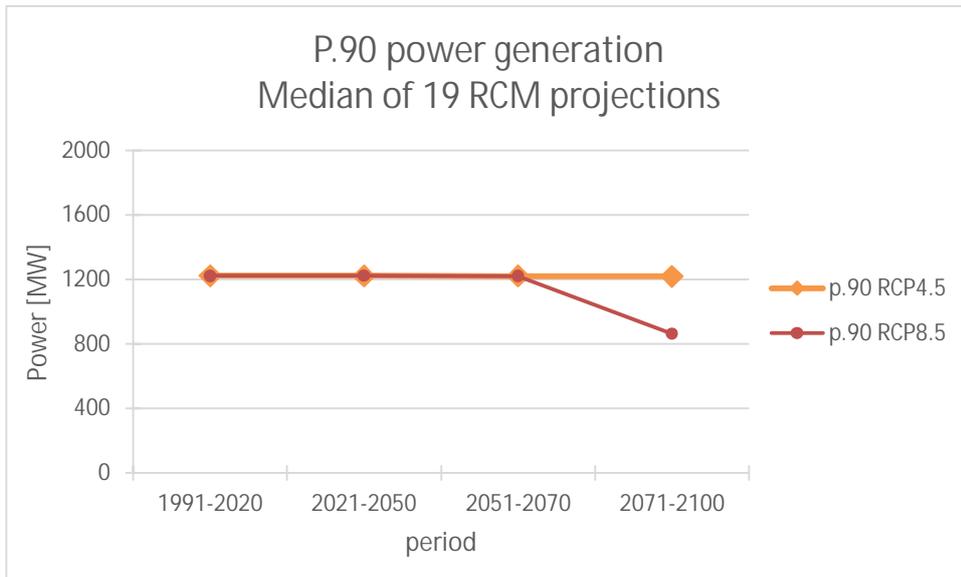
The results with the two methods are shown in the figures below for mean annual inflow and mean annual power generation at Cahora Bassa. Indeed, the results with the standard method show higher inflow and power generation compared to the alternative method. However, the overall conclusions still remain valid, with no pronounced changes in the near future, but considerable decrease in the far future.

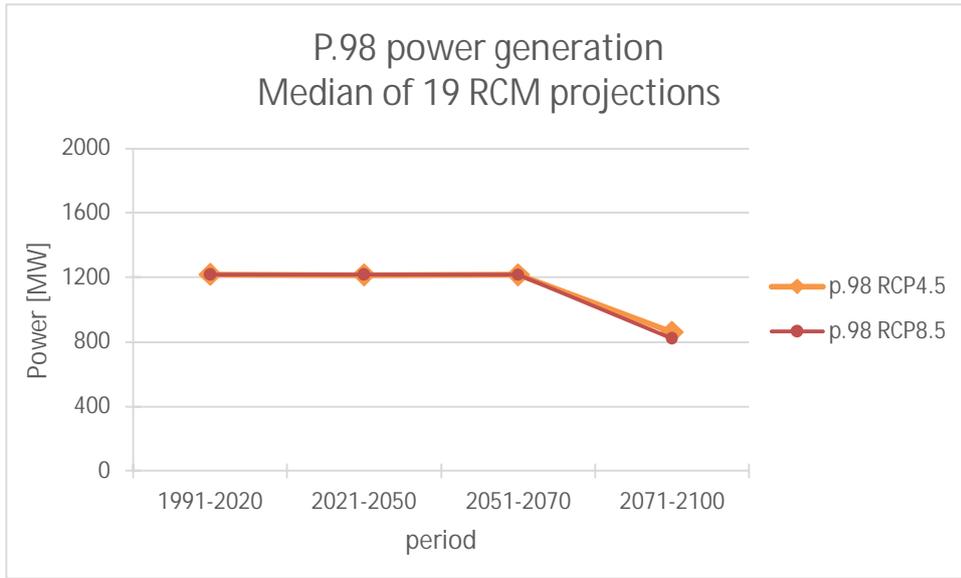




### 9.9 Appendix: Baseload generation for different percentiles

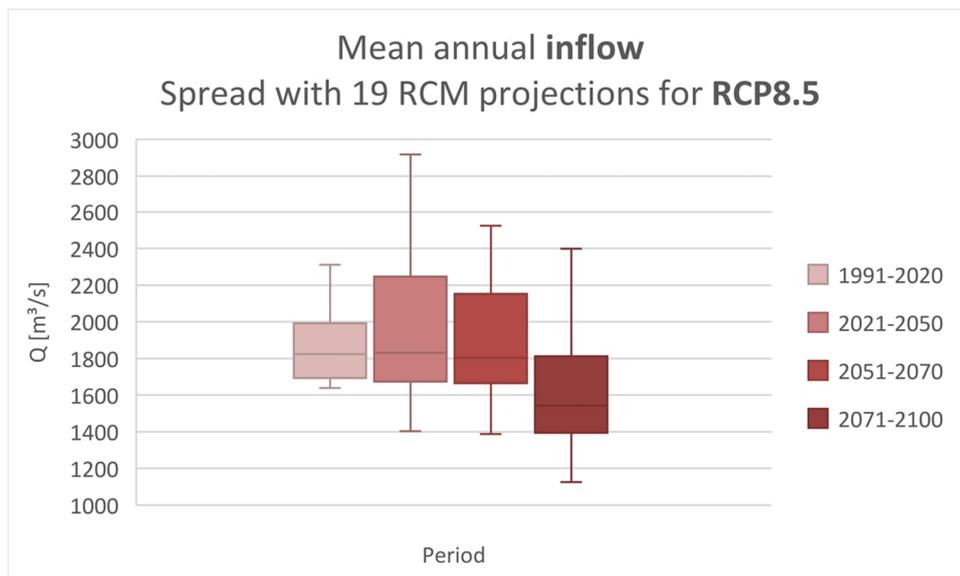
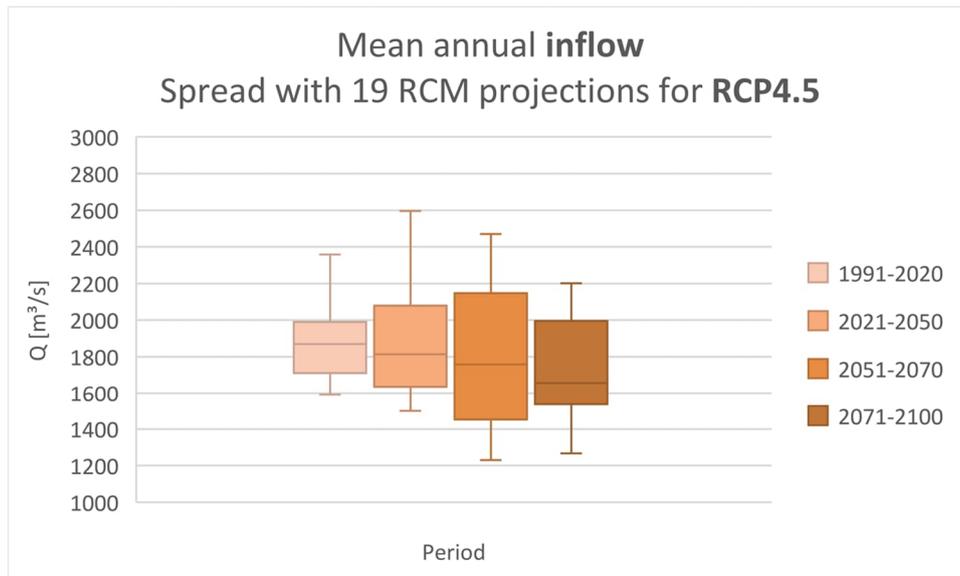
Cahora Bassa baseload power generation that is exceeded 95% of the time (p.95), as well as for p.90 and p.98, is shown in the figures below. Note that the values are clustered in about 400 MW steps, as this relates to the operation rule of operating either 1, 2, 3, 4 or 5 units. Therefore, the p.95 value of 1200 MW shows little variation between periods, as this is equivalent of 3 units running. Only in the far future period under high emission scenario RCP8.5 this is reduced to about 800 MW (i.e. 2 units running) due to the considerably reduced inflow.

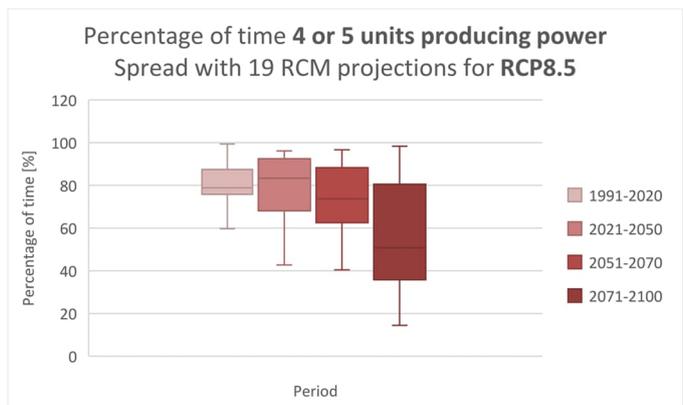
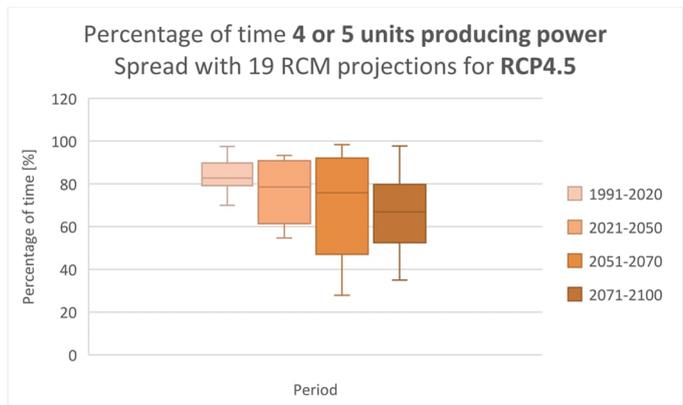
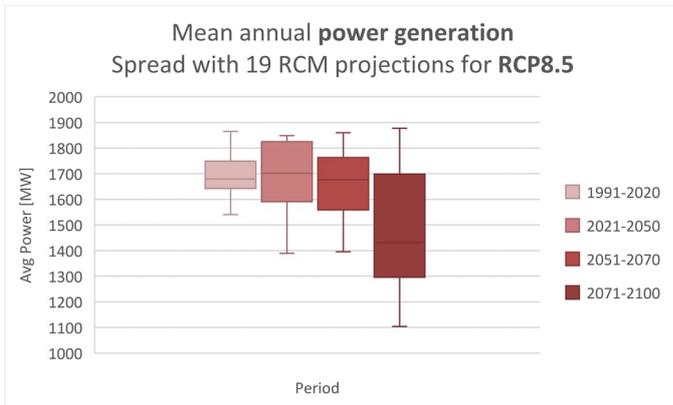
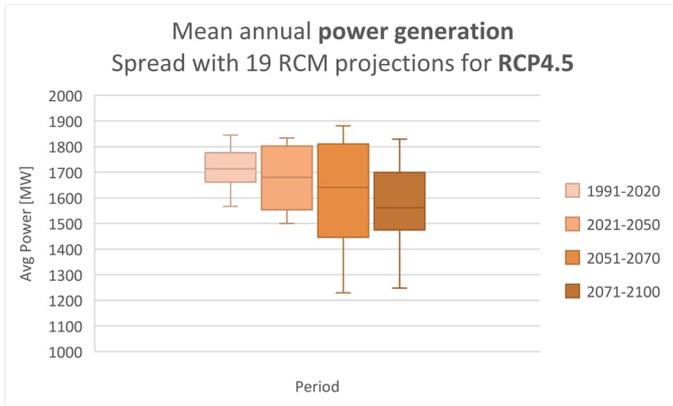




### 9.10 Appendix: Results for the intermediate future period

The results for the intermediate future period 2051-2070 are presented in the graphs below. The results for the intermediate future period are consistent with the results for the near future period 2021-2050 and far future period 2071-2100 and show a gradual transition of Cahora Bassa inflow and power generation between future periods.

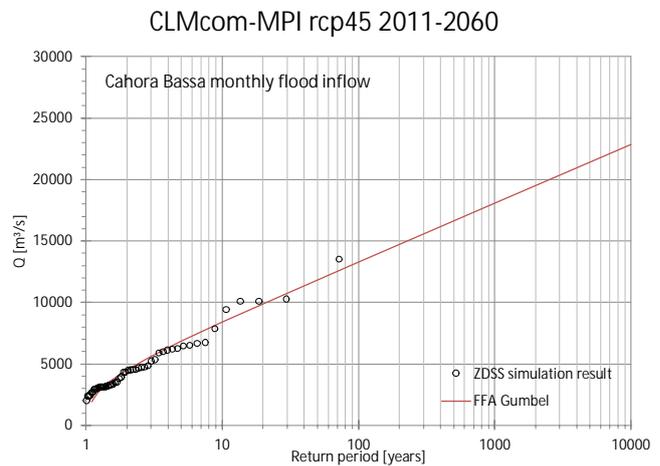
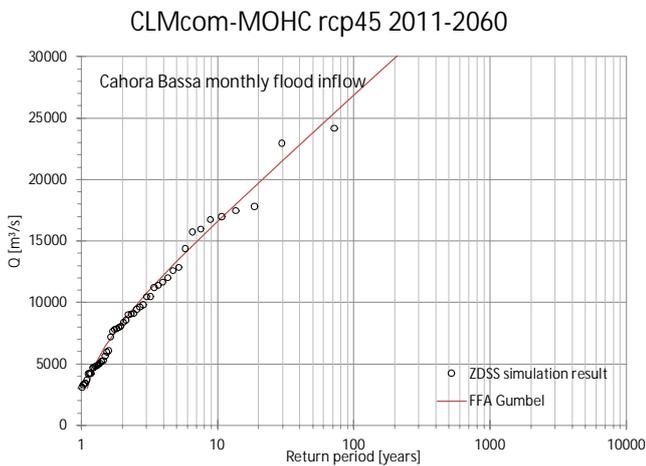
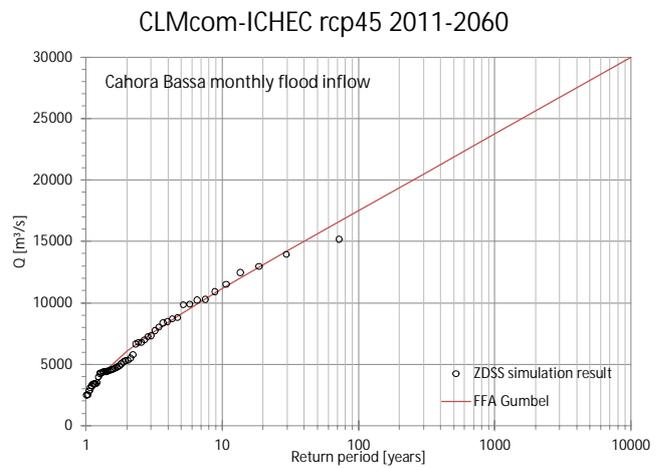
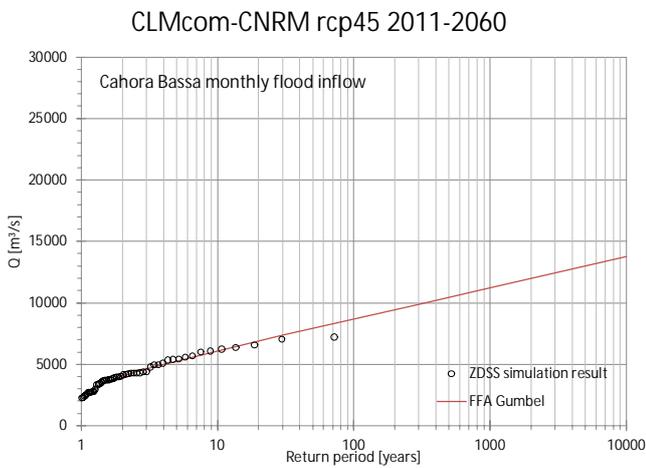




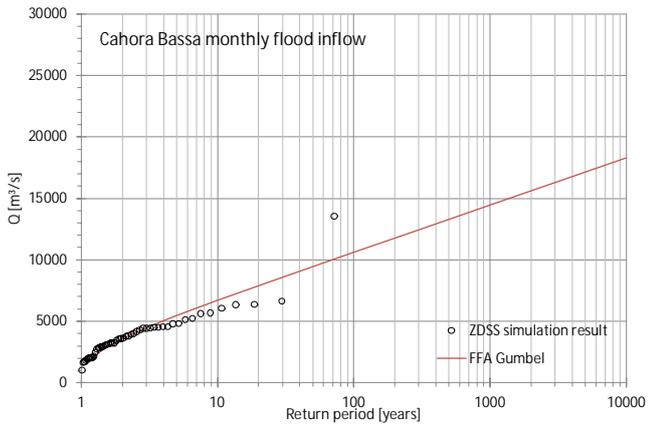
## 9.11 Appendix: Flood Frequency Analysis under climate change

The Gumbel distribution was used for the flood frequency analysis of Cahora Bassa monthly inflow simulated by the Zambezi DSS (ZDSS) under climate change scenarios. As an example, the results for the period 2011-2060 and the emission scenario RCP4.5 are shown below for all 19 RCM projections. The black dots represent annual monthly maxima simulated by ZDSS. The red line shows the fitted Gumbel distribution.

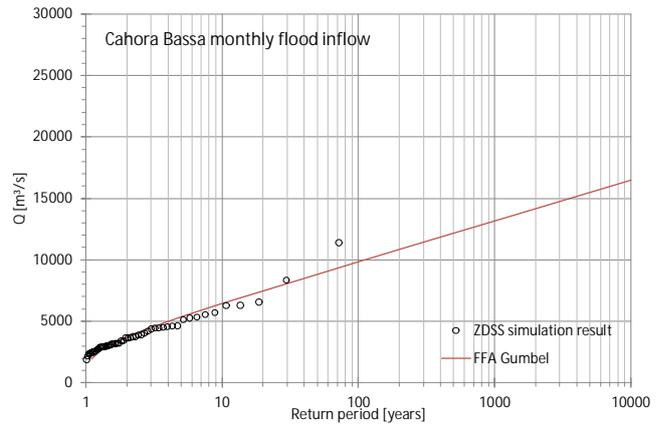
In most cases the Gumbel distribution fits reasonably well to the simulation results of ZDSS. Thus, it is concluded that the Gumbel distribution can be used for extrapolation to higher flood values (with a high return period).



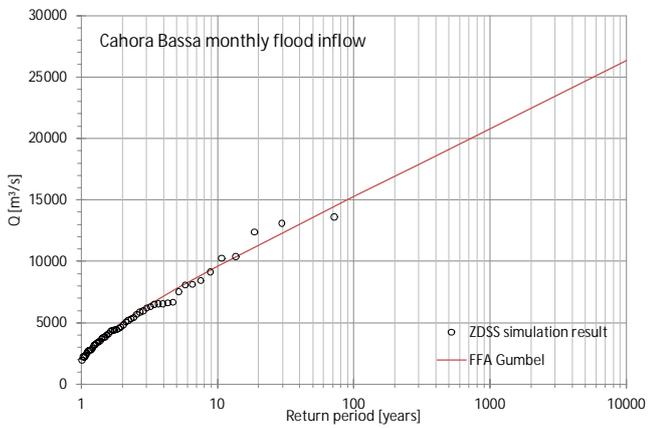
DMI-ICHEC rcp45 2011-2060



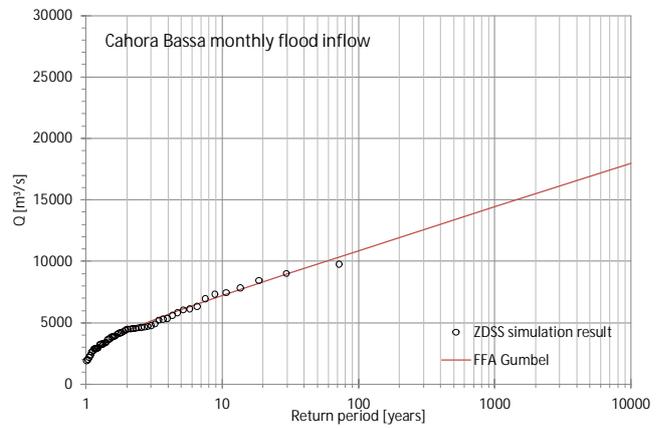
KNMI-ICHEC rcp45 2011-2060



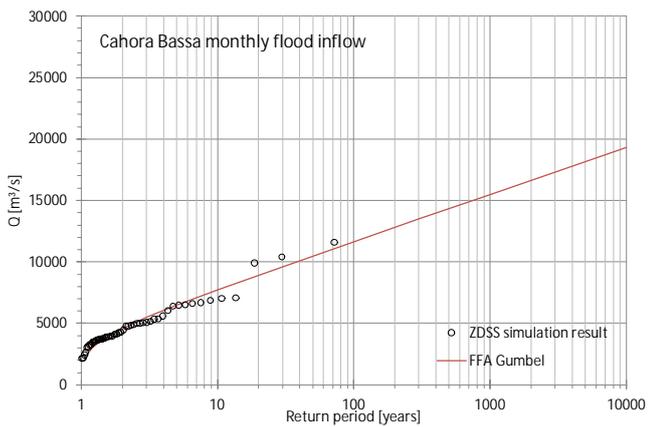
KNMI-MOHC rcp45 2011-2060



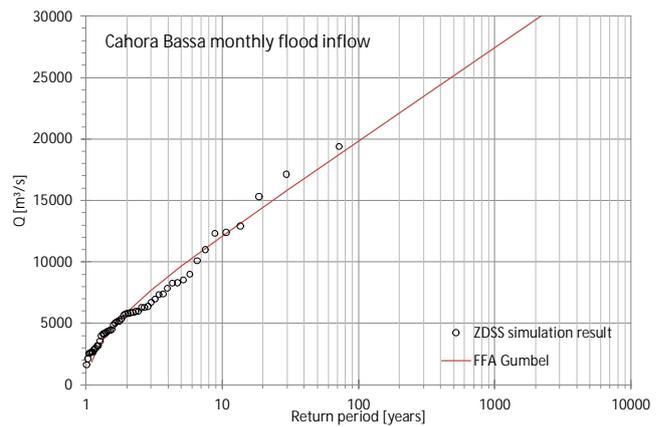
MPI-ICHEC rcp45 2011-2060



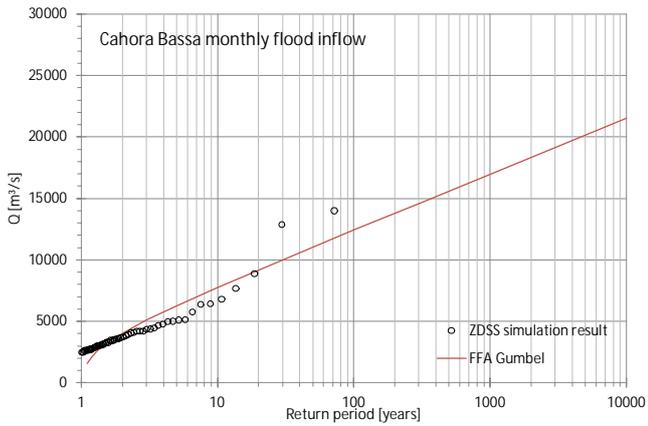
MPI-MPI rcp45 2011-2060



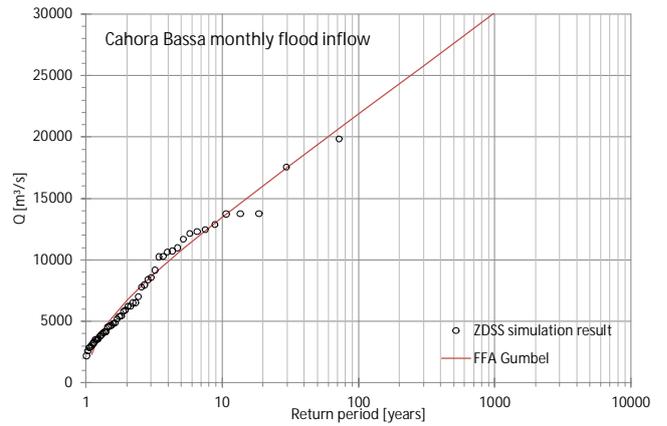
SMHI-CCCma rcp45 2011-2060



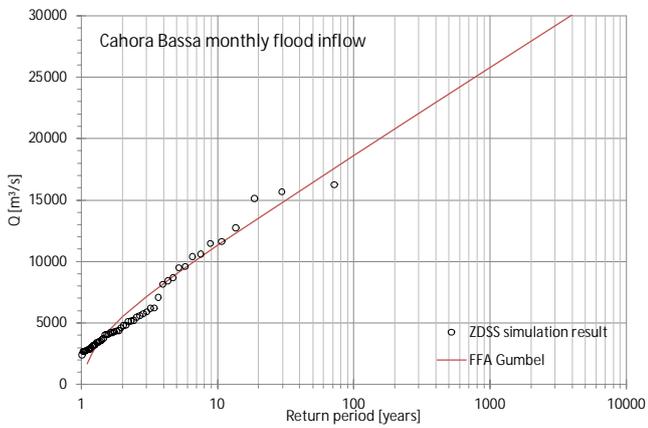
SMHI-CNRM rcp45 2011-2060



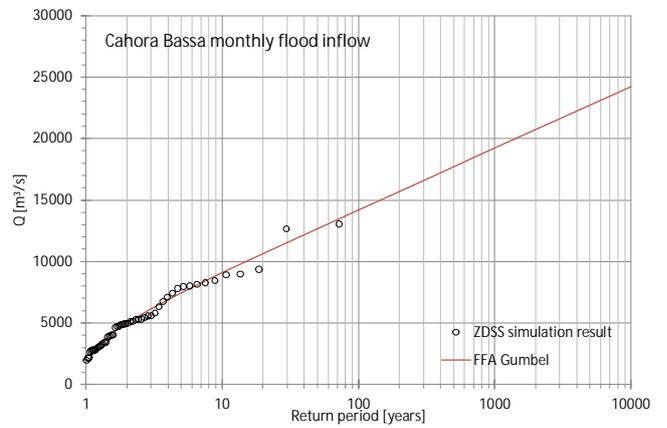
SMHI-CSIRO rcp45 2011-2060



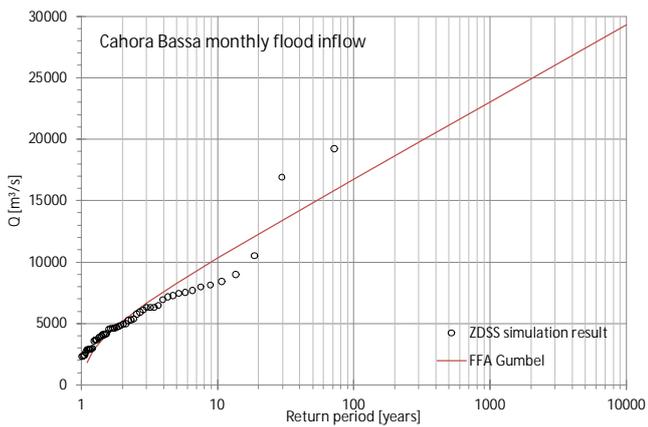
SMHI-ICHEC rcp45 2011-2060



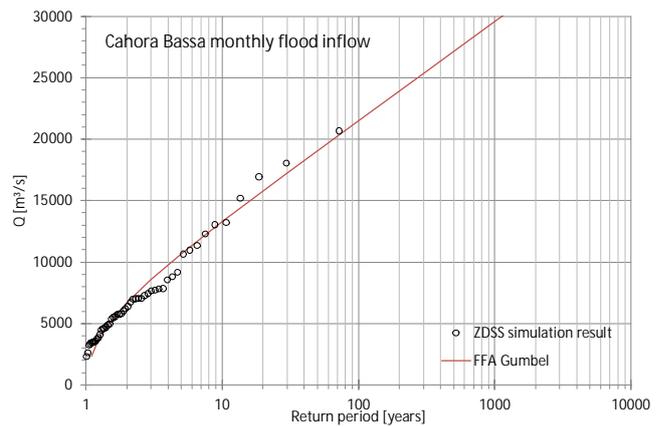
SMHI-IPSL rcp45 2011-2060



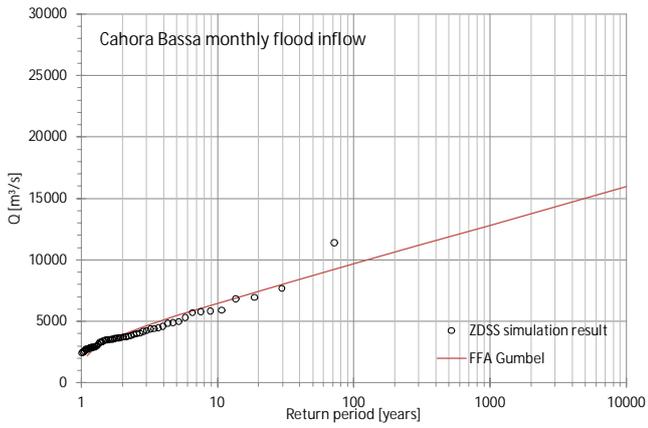
SMHI-MIROC rcp45 2011-2060



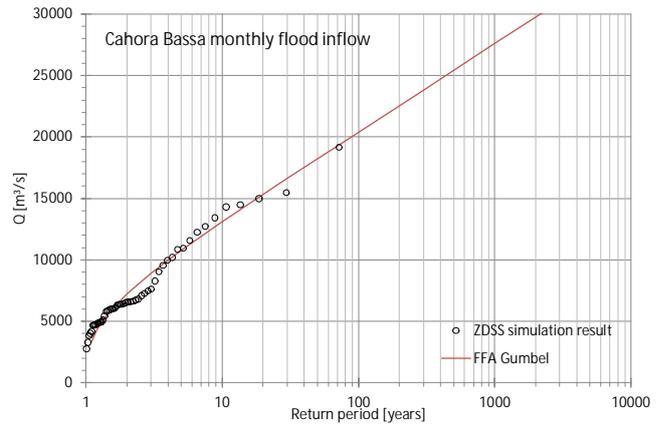
SMHI-MOHC rcp45 2011-2060



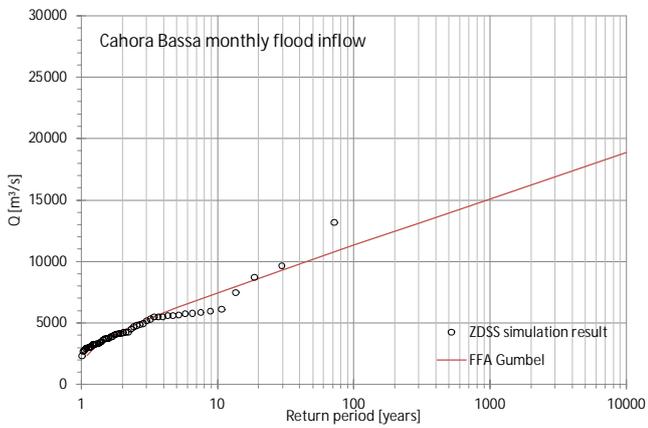
SMHI-MPI rcp45 2011-2060



SMHI-NCC rcp45 2011-2060



SMHI-NOAA rcp45 2011-2060



## 9.12 Appendix: Classification levels for risks and opportunities

The following tables provide a verbal description of the classification levels for (a) risks and opportunities, (b) likelihood, and (c) potential gains and losses.

	Level	Code	Description
Opportunities	Large	O4	Great opportunity
	Major	O3	True opportunity
	Moderate	O2	Potential opportunity
	Minor	O1	Small opportunity
	Negligible	O0	No or negligible opportunity
No impact	None	N0	No impact
Risks	Negligible	R0	No or negligible risk, no action required
	Low	R1	Action in specific cases might be required; risk could also be acceptable
	Medium	R2	Action/mitigation measures required
	High	R3	Immediate action/mitigation measures required
	Very high	R4	Immediate action/mitigation measures required

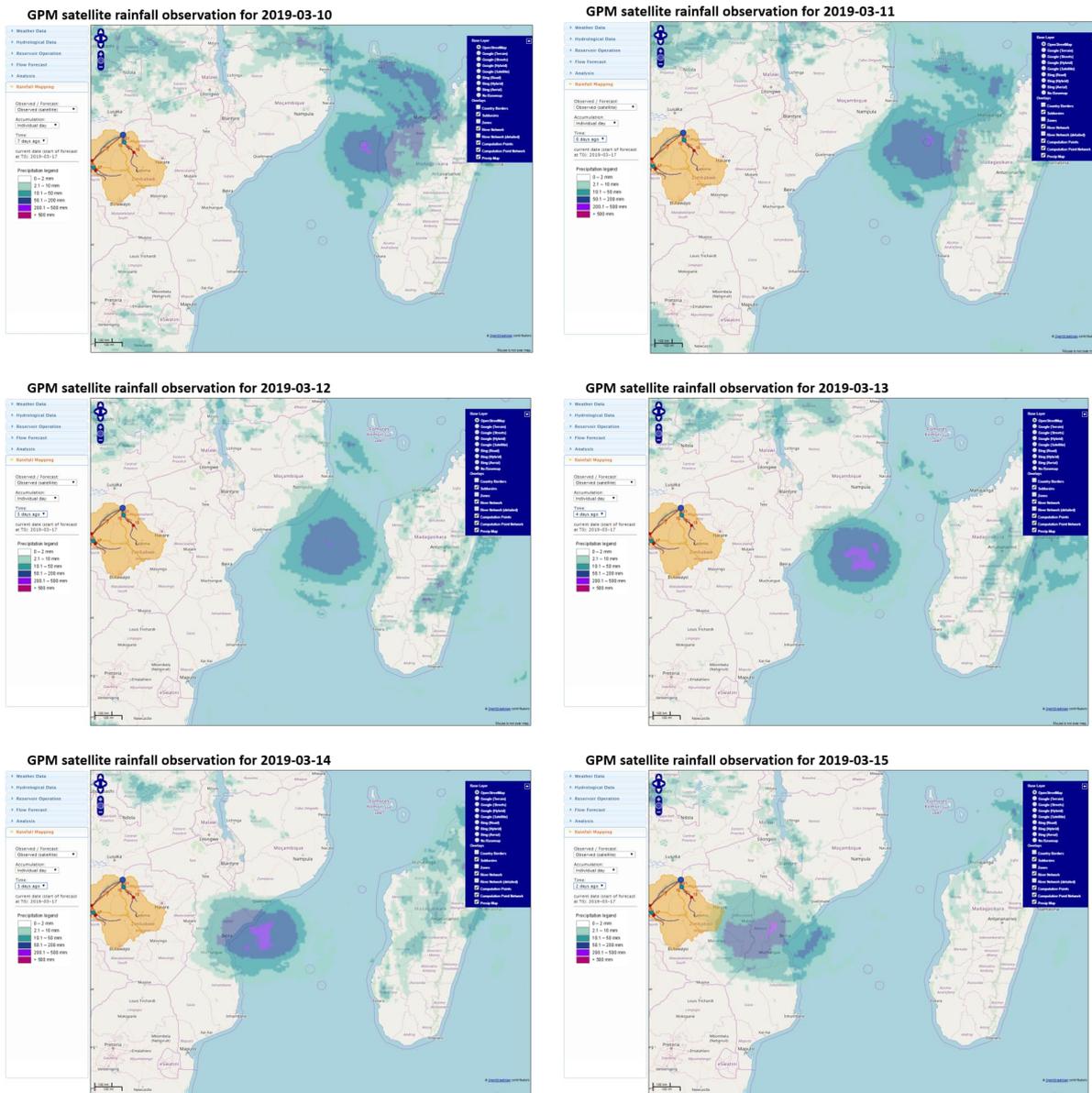
Likelihood	Level	Description
Unlikely	1	Unlikely, bot possible to happen
Possible	2	Possible, happens sometimes
Likely	3	Likely, may happen several times

		Potential gain			Potential loss		
		High	Medium	Low	Low	Medium	High
Generation performance	Mean annual generation	G3	G2	G1	L1	L2	L3
	Mean monthly generation	increase > 15%	increase 5-15%	increase 0-5%	decrease 0-5%	decrease 5-15%	decrease > 15%
	Baseload generation	increase in all months provided > 95% of time	increase in most months provided 90-95% of time	increase in some months provided 85-90% of time	decrease in some months provided 75-80% of time	decrease in most months provided 65-75% of time	decrease in all months provided < 65% of time
Flood safety performance	Extreme flood inflow 10,000 year flood	Extreme inflow < 14,000 m³/s	Extreme inflow 14-16,000 m³/s	Extreme inflow 16-18,000 m³/s	Extreme inflow 18-20,000 m³/s	Extreme inflow 20-22,000 m³/s	Extreme inflow > 22,000 m³/s
	Description	Extreme inflow lower than spillway capacity would increase flood safety and would allow higher reservoir water levels (and thus increased hydraulic head).	With the existing spillway capacity the current rule curve (drawdown before flood season) ensures safe reservoir operation during extreme flood inflow.	Given timely inflow forecasts and proactive flood management there should be no damages to the structures during extreme flood inflow.	Some minor damages might occur due to extreme flood inflow. Repairs within maintenance costs; hydropower operations not affected.	Moderate to significant damages may occur due to extreme flood inflow. Required repairs exceed planned maintenance costs; hydropower operations negatively affected.	Serious damage or destruction may occur due to extreme flood inflow and overtopping of dam. Very high repair costs; hydropower operations no longer possible over an extended period of time.
Flood warning level at Tete	Flood warning level at Tete	n/a	n/a	Exceeded < 1% of time	Exceeded 1-10% of time	Exceeded > 10% of time	n/a
	Description			Reduced flood warnings for Tete. Cahora Bassa operations could fully focus on hydropower generation, not impacted by downstream flood concerns.	Increased flood warnings for Tete. This probably will increase pressure to operate Cahora Bassa at lower reservoir water levels (reduced hydraulic head) to avoid downstream flooding.	Regular flood warnings at Tete would require infrastructure adaptation in the city, as well as a revision of the current rule curve (with considerably lower water levels) and reduced hydraulic head at Cahora Bassa.	

### 9.13 Appendix: Monitoring of tropical storm tracks

The following screenshots of AFRY’s operational Kariba Inflow Forecasting System used by the Zambezi River Authority show an example of the timely, near real-time monitoring of the track of the tropical storm Idai in March 2019 (GPM satellite observation). The storm did not reach Cahora Bassa but crossed the transmission lines and caused devastating losses in the region of Beira.

The storm track and intensity were correctly forecasted by GFS with a lead-time of about three days.



## 9.14 Appendix: Terms and definitions for climate risk management

Important terms and definitions related to climate risk management are given below.

### Weather

According to the definition of the World Meteorological Organization (WMO, 1966) Weather, is the state of the atmosphere at a particular time, as defined by the various meteorological elements.

The meteorological elements include different variables describing the state of the atmosphere, such as air temperature, air pressure, wind speed, precipitation, solar radiation and many others. Meteorological elements also include weather phenomena such as thunderstorms and snowstorms.

### Climate

Climate is the synthesis of the weather conditions in a given area, characterized by long-term statistics (mean values, variances, probabilities of extreme values, etc.) of the meteorological elements in that area. (WMO, 1966).

The classical period for calculation of the long-term statistics is 30 years, as defined by the World Meteorological Organization for Climate Normals (e.g. WMO, 2017).

In order to reflect the dynamics of climate change it is now also commonly accepted to use shorter averaging periods, e.g. 20 years. This allows for a more accurate description of the climate observed in the last decades or projected for a certain sub-period of the 21st century.

### Climate Variability

Climate variability as defined by the Intergovernmental Panel on Climate Change (IPCC, 2013) refers to variations in the mean state and other statistics (such as the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

### Climate Change

Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2013)

The United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in

addition to natural climate variability observed over comparable time periods. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

### Reference Periods and Time Horizons of Climate Change

As described above, climate change and climate variability are assessed based on long-term statistics, which have to be calculated for certain periods.

In this CRA the following 30-year periods are applied to describe the historical and future climate conditions:

- Historical reference period: 1961-1990 (WMO standard period)
- Baseline period: 1991-2020 (WMO standard period)
- Near future: 2021-2050
- Intermediate future: 2051-2070 (only 20 years)
- Far future: 2071-2100

Using WMO standard periods as a reference or baseline for assessment of changes in climatological and hydrological conditions has become a common approach in climate science. These periods can be considered representative for characterization of climate conditions. It is therefore considered a good reference/baseline period for comparing future climate with the climate that was experienced in the last decades.

### Climate Stressor

In this document the term Climate Stressor is used for a (changed) climate condition that imposes a threat on a hydropower asset or - more generally – that causes stress for the operations of an electricity generator and electricity supplier.

### Climate Threats and Prospects

Climate Threats (and Prospects) describe how a change in the climate conditions negatively (or positively) affects the assets and operations of an electricity generator and electricity supplier. For a negative affect also the term Stress is used.

Different from the terms Loss (and Gain) and Risk (and Opportunity), which describe the effect in a quantitative and probabilistic way, the term Threat (and Prospect) only refers to a qualitative description.

### Climate Resilience

Following the definition used in the Hydropower Sector Climate Resilience Guidelines, Climate Resilience is the capacity of a system (e.g. a certain hydropower asset or the whole operations of an electricity generator and supplier) to absorb the stresses imposed by climate change, and in the process to evolve into greater robustness.

## Climate Risks and Climate Opportunities

In this document the term Climate Risk is based on a probabilistic definition of risk, as used in classical engineering and financial risk assessment. In this approach Risk is defined as the product of a Potential Loss and the Likelihood that this loss will occur.

$$\text{Risk} = \text{Potential Loss} \times \text{Likelihood}$$

Potential losses and Likelihoods are described in a semi-quantitative way with categories of potential losses and categories of likelihood, resulting in several categories of Risk. Opportunities are treated in a similar manner.

### Direct and Indirect Climate Risks

In the CRA also a distinction between direct and indirect Climate Risks is made.

Direct Climate Risks are risks which are caused by a Climate Stressor directly affecting the assets or operations of the electricity generator, e.g. a projected decrease in precipitation resulting in a potential decrease in inflow and generation

Indirect Climate Risks are risks imposed by climate stress on the market environment, which causes changes in the market conditions affecting also the operations of the electricity generator. An example would be an increase of the winter temperatures, resulting in a reduction of electricity demand for heating and in a decrease of the electricity prices during the winter months.

### Direct and Indirect Climate Opportunities

Direct Climate Opportunities are opportunities which are caused by a change in the climate conditions directly affecting the assets or operations of the electricity generator, e.g. a projected increase in precipitation resulting in a potential increase in inflow and generation.

Indirect Climate Opportunities are opportunities imposed by climate stress on the market environment, which causes changes in the market conditions affecting also the operations of the electricity generator. An example would be an increase of the summer temperatures, resulting in an increased electricity demand for cooling and in an increase of the electricity prices during the summer months.