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Impact modelling of water resources development and climate scenarios on Zambezi River discharge

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ABSTRACT

Study region: The Zambezi River basin (1.4×10^6 km^2) in southern Africa, which is shared by eight countries and includes two of the World's largest reservoirs.

Study focus: Impacts on future water resources in the Zambezi basin are studied, based on World Bank projections that include large scale irrigation and new hydropower plants. Also the impacts of climate change scenarios are analysed. Modelling challenges are the large basin area, data scarcity and complex hydrology. We use recent GPCC rainfall data to force a rainfall-runoff model linked to a reservoir model for the Zambezi basin. The simulations are evaluated with 60 years of observed discharge and reservoir water level data and applied to assess the impacts on historical and future discharges.

New hydrological insights for the region: Comparisons between historical and future scenarios show that the biggest changes have already occurred. Construction of Kariba and CahoraBassa dams in the mid 1900s altered the seasonality and flow duration curves. Future irrigation development will cause decreases of a similar magnitude to those caused by current reservoir evaporation losses. The discharge is highly sensitive to small precipitation changes and the two climate models used give different signs for future precipitation change, suggestive of large uncertainty. The river basin model and database are available as anopen-online Decision Support System to facilitate impact assessments of additional climate or development scenarios.

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1. Introduction

"Stationarity is dead" – with this provocative statement Milly et al. (2008) raised a serious discussion for water resources planning in a changing world (see also the criticism by Koutsoyiannis, 2011; Lins and Cohn, 2011; Matalas, 2012). Until recently, a common approach of hydrological engineers for water resources planning was to base the analysis on historic observations, while implicitly assuming that the past conditions are also representative of what to expect in the future. This approach is now more and more critically questioned due to non-stationarity observed in many hydrological variables and the possible impacts of climate change.

In addition to climate change, also development of water resources projects – such as dams for hydro-electric generation or irrigation projects – can have considerable impacts on discharge conditions, as summarized by mean flows, seasonality in flows or flow duration curve. In contrast to climate change – which is expected to be a transition on the time-scale of decades to centuries – development of individual water resources projects can mark an abrupt change for the hydrology in a basin.

In arid regions in Africa – where water is a limited resource – the impacts of climate change and water resources development are of particular concern, especially in international river basins. One example is the Zambezi basin that is shared by eight countries in the southern part of the African continent. Recent institutional strengthening with the establishment of the Zambezi Watercourse Commission (ZAMCOM, which came into force in 2011) aims at efficient and sustainable water resources management in the basin. In contrast to the Nile basin – where water resources are heavily exploited – irrigation projects in the basin are currently of limited importance, but large extensions are planned for the future. Two of the world's largest hydropower reservoirs (Kariba, Cahora Bassa) were already built in the middle of the 20th century at the Zambezi River, providing electricity for the region, but with significant downstream effects on river ecology.

The historic impacts of Kariba and Cahora Bassa dams on Zambezi discharge were analysed by Beilfuss and dos Santos (2001) and Matos et al. (2010) and there have been several studies proposing optimized operation rules to balance energy generation and ecological downstream impacts (e.g. Gandolfi and Salewicz, 1991; Tilmant et al., 2010; Beilfuss, 2010; Mertens et al., 2013). There is concern that future development of large-scale irrigation projects may significantly reduce Zambezi River discharge, with negative impacts on hydropower and ecology (Hoekstra, 2003; World Bank, 2010). On top of this, Zambezi discharge is also susceptible to possible future changes in climate (for a general overview see Beilfuss, 2012).

There are a few modelling studies that analysed future runoff conditions in the Zambezi basin under scenarios of climate change and water demand. This approach requires a fully-fledged hydrological modelling of the water fluxes in the basin and is therefore a considerable task, especially due to the fact that the models are set-up in a large, data-sparse region with a unique hydrology. Harrison and Whittington (2002) studied future energy generation at the proposed Batoka Gorge hydro-power plant at the Zambezi River below Victoria Falls. They modelled significant reductions in future discharge, albeit cautioning that "there is concern regarding the ability of the hydrological model to reproduce the historic flow". Yamba et al. (2011) applied the Pitman water balance model with selected climate scenarios to the full Zambezi basin to assess future energy generation at large hydro-power plants, obtaining results that show gradual reductions in discharge owing to climate change and increasing water demand. They show that their runoff simulations perform well in one tributary (Kabompo River), but do not present evaluations for the Zambezi River or the main tributaries. Beck and Bernauer (2011) modelled the combined changes in water demand and climate in 13 sub-basins of the Zambezi basin and the impact on mean water availability. They conclude that future climate change is of less concern, whereas population and economic growth as well as expansion of irrigated areas are likely to have important transboundary impacts due to significant decrease in water availability. They calibrated their hydrological model on long-term mean monthly discharge data, but do not present an evaluation of their discharge simulations with observed data.

Thus, the existing studies suggest that a reduction in future discharge is likely, but it is not clear how well the applied hydrological models perform for the simulation of Zambezi discharge, which raises questions about the modelling of discharge conditions under future climate change scenarios. Further, results of previous studies are difficult to compare due to different assumptions, models, time-periods and locations of interest. Therefore, the World Bank concluded in a recent study in the Zambezi basin that “additional detailed analysis is needed for assessing the impact of climate change” (World Bank, 2010, vol. 2, p. 83).

The objective of this study was to establish a well-calibrated hydrological model for the Zambezi basin, such that the model can be used with confidence for an assessment of the impacts of water resources development and climate change on Zambezi discharge. An important aspect of our study was a thorough evaluation of the historic simulations, to ensure that the model is capable of realistically representing the main input–output relationships of the system.

For future water resources development in the Zambezi basin we used scenarios of a highly detailed, recently published study (World Bank, 2010). On the other hand, there is a lack of detailed climate modelling for the African continent, where only data of coarse resolution general circulation models – with limited accuracy on the sub-basin scale – were readily available. For illustrative purposes we based our study on downscaled data of two well-known climate models, with contrasting projections about future precipitation.

The paper is structured as follows: After an introduction to the study area the data basis is presented. In the methods section we describe the river basin model, the calibration method and the scenario definitions. The results section includes an evaluation of simulation under historic conditions as well as results for simulation of future scenarios. This is followed by a discussion of results and possible sources of uncertainties. The paper ends with an outlook and conclusions.

2. Study area

This study focuses on the Zambezi basin (Fig. 1), which is the fourth largest river basin in Africa (after Congo, Nile and Niger) and covers 1.4 Mio km^2. 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

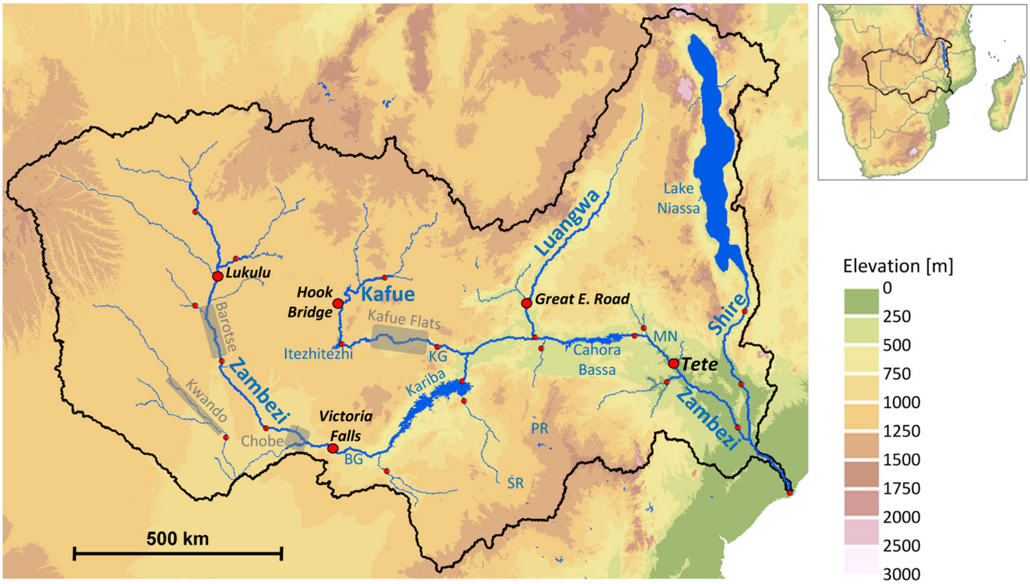

Fig. 1. Zambezi River basin. Basin divides (black) and river-network (blue) derived from HydroSheds data set (Lehner et al., 2008). Names of main rivers in bold. Red circles: outlets of 27 sub-basins, with names of key locations in italic. Shaded boxes: natural floodplains and wetlands. Abbreviations for reservoirs: KG (Kafue Gorge), SR (Sanyati reservoirs), PR (Panhane reservoirs), BG (Batoka Gorge, planned), MN (Mphanda Nkuwa, planned). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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^2. 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^2 surface area). There are also two large artificial reservoirs for hydropower generation at the Zambezi River (Lake Kariba with 5500 km^2 surface area and Lake Cahora Bassa with 2700 km^2). Lake Kariba is actually the world's largest artificial reservoir according to storage capacity (200,000 hm^3, 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^3/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.

Even though in this study the whole Zambezi basin was modelled, in the paper we only report on the results for the Zambezi basin upstream of Tete (covering 1,103,400 km^2). Thereby, the Shire basin – with its specific hydrology due to the large impact of Lake Niassa – is excluded from the analysis.

3. Data basis

Working in a large basin shared by several (eight) countries complicates acquisition of data. Therefore, the aim was to use as much as possible public data sources that are freely available.

Historic monthly climate data from 1901 to 2009 as spatial fields with a half degree (approximately 50 km) resolution were obtained from the following sources:

- Precipitation: Global Precipitation Climatology Centre (GPCC, version 5, published 2011), Deutscher Wetterdienst, Germany.
- Air temperature: Climate Research Unit (CRU, version TS 3.1, published 2011), University of East Anglia, UK.

The CRU temperature data in the Zambezi basin are based on interpolation from only few (approximately 10) stations, but in general interpolation of temperature data is assumed to be accurate due to strong correlation with elevation. Of more concern are the precipitation data, due to high spatial variability and the associated problems in interpolation from point measurements (see an assessment for the Zambezi region by Mukosa et al., 1995). In the Zambezi basin upstream Tete, GPCC is based on interpolation from approximately 100 stations during 1961–1990, but considerably fewer stations in other periods, especially after 1990 (Fig. 2). For such a large study area with more than 1 Mio km^2 this is a small number of stations given the high spatial heterogeneity of precipitation. However, the GPCC data set represents the best long-term observational data set available for the region. Note that the precipitation data of CRU – as used by, e.g. Beck and Bernauer (2011) – are based on only approximately half the number of stations as GPCC.

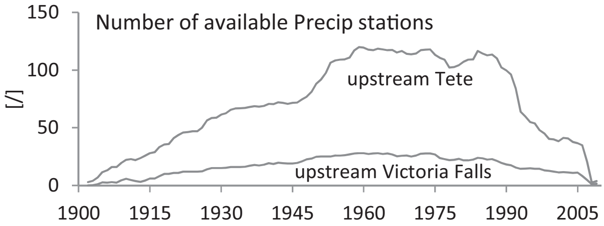

Fig. 2. Availability of precipitation stations. GPCC data set from 1901 to 2009. Upper line: number of stations in the Zambezi basin upstream of Tete. Lower line: number of stations in the Zambezi basin upstream of Victoria Falls.

Long-term mean monthly potential evapotranspiration (mPET) data were obtained from the CLIMWAT data set of FAO for 30 stations in the region. The Penman–Monteith method (Monteith, 1965) was used in the CROPWAT model of FAO to calculate the sensitivity of mPET to changes in temperature. It was found that for an increase in temperature by +1 °C there is an increase in mPET by +2.5%, with insignificant differences in this factor between stations and months. Thus, this relationship is also used for preparing potential evapotranspiration time-series from historic and future (projected) temperature data (see equation in Appendix).

Climate scenario data about future precipitation and temperature were obtained from the recently finished EU WATCH project (WATer and global CHange, published 2011, http://www.eu-watch.org). In the WATCH project, daily data of GCMs (General Circulation Models, or Global Climate Models) were downscaled with quantile mapping with observed data of 1960–2000 (Piani et al., 2010) to a half degree spatial resolution. We applied an additional, small bias correction (linear scaling, see e.g. Lenderink et al., 2007) to aggregated monthly data, such that the GCM data matched the climatology 1961–1990 of the GPCC precipitation data and CRU temperature data. In this paper we report on the results with two climate models for the IPCC A2 emission scenario (high emissions), as summarized in Table 1.

Observed time-series of monthly discharge was obtained for 22 gauges. As Hughes et al. (2010) point out, the discharge measurements and climate data in southern Africa are “subject to unknown errors of varying degrees”. Especially for discharge data plausibility checks (double-mass curves, upstream versus downstream comparisons) yielded ambiguous results. The reliability of discharge data appeared to change significantly over time, with each gauge having its own peculiarities. Therefore, in this paper we only report results for five gauges at key locations:

- Zambezi River at Lukulu (catchment area of 212,600 km^2): Zambezi headwaters, measurements available since 1954.
- Zambezi River at Victoria Falls (519,400 km^2): Upper Zambezi, discharge data of this gauge are assumed to be reliable and are available since 1908.

Table 1
Climate model data of the WATCH project for the Zambezi basin upstream of Tete. A2 emission scenario. P: mean annual precipitation. T: mean annual air temperature. ΔP: change in precipitation relative to 1961–1990. ΔT: change in air temperature relative to 1961–1990.

Institute	GCM	Period	P [mm/a]	T [°C]	ΔP [%]	ΔT [°C]
CNRM[a]	CNRM-CM3	1961–1990	912	21.8	–	–
		2021–2050	967	23.5	+6	+1.7
		2071–2100	980	26.6	+7	+4.8
MPI[b]	ECHAM5/MPIOM	1961–1990	912	21.8	–	–
		2021–2050	892	23.2	−2	+1.4
		2071–2100	862	26.5	−5	+4.7

[a] CNRM: Centre National de Recherches Météorologiques (France).
[b] MPI: Max-Planck-Institut für Meteorologie (Germany).

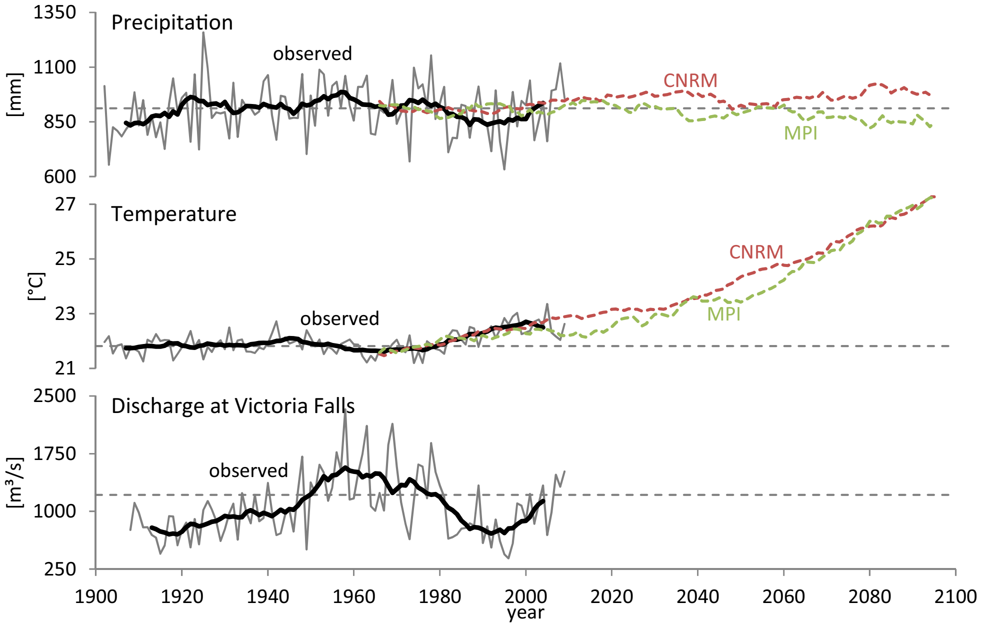

Fig. 3. Long-term climate trends. Annual precipitation amount, mean temperature and mean discharge in the 20th century (observations) and 21st century (climate model projections). Precipitation and temperature data for Zambezi basin upstream Tete. Discharge data for upper Zambezi River at Victoria Falls. Thin black lines: observations in individual years. Bold black lines: 11-year moving average of observations. Dashed horizontal lines: mean of observation 1961–1990. Dashed coloured lines: 11-year moving averages of projections by climate models CNRM and MPI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Kafue River at Kafue Hook Bridge (96,200 km^2): Upper Kafue River, measurements available since 1908. Data of this gauge were obtained at the end of the study for an independent evaluation (not used for calibration).
- Luangwa River at Great East Road (142,000 km^2): Almost full Luangwa basin, measurements available since 1949.
- Zambezi River at Tete (1,103,400 km^2): Lower Zambezi River, measurements available since 1952, but there are implausible differences with nearby gauges. Further, data obtained from different providers for the same location and period frequently differed by up to 100 % (or 600 m^3/s) during low flow conditions.

Fig. 3 gives a summary of the acquired data by showing long-term trends for precipitation, air temperature and discharge. Historic precipitation data before 1930 and after 1990 should be interpreted with caution due to low availability of stations (see Fig. 2). The historic precipitation data show large inter-annual variability, but no clear trend. Climate model data show small trends, but with different signs according to the analysed model. In contrast, the temperature data show a clear warming trend after 1980, which corresponds with the changes on the global scale (IPCC, 2007). The climate model data project that warming continues throughout the 21st century. Annual discharge data of the Upper Zambezi at Victoria Falls exhibit large inter-annual variability – ranging between 400 m^3/s in dry years to 2300 m^3/s in wet years. There is a cyclic behaviour of Zambezi discharge, with above average flows during 1950–1980 (Mazvimavi and Wolski, 2006), which corresponds to small long-term variations in the precipitation data (for a discussion of multi-decadal climate variability in southern Africa see Tyson et al., 2002).

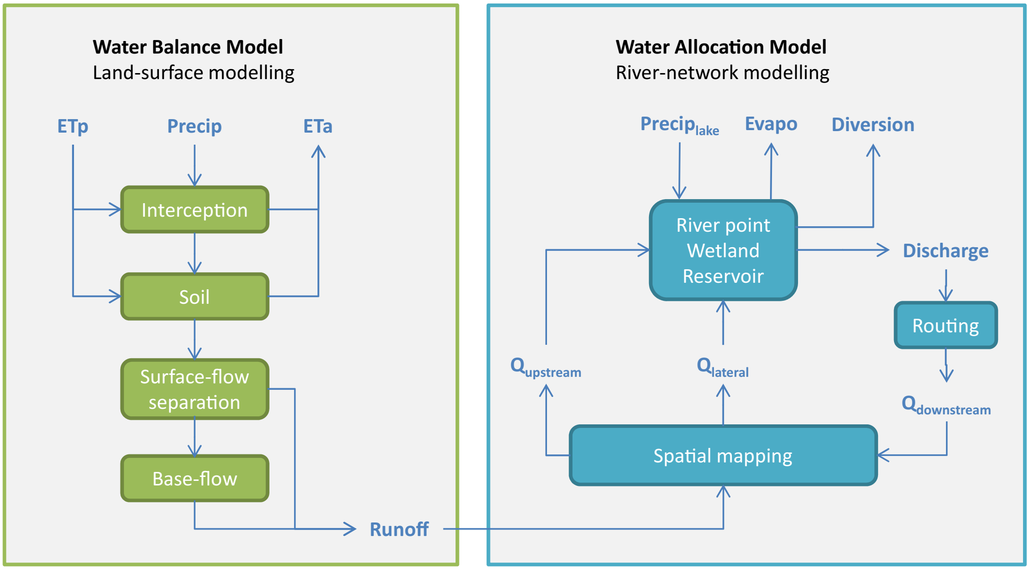

Fig. 4. Conceptual model structure. River basin model consisting of water balance model (left) and water allocation model (right). Precip: precipitation in mm. ETp: potential evapotranspiration in mm. ETa: actual evapotranspiration in mm. Runoff: runoff-depth in mm. $Q_{upstream}$: upstream inflow in m^3/s. $Q_{lateral}$: lateral inflow in m^3/s. $Precip_{lake}$: precipitation on open water body in m^3/s (is zero for River points). Evapo: evaporation from open water body in m^3/s (is zero for River points). Diversion: withdrawal of water in m^3/s. Discharge: river discharge in m^3/s. $Q_{downstream}$: routed downstream discharge in m^3/s.

4. Methods

In this study a river basin model – consisting of a water balance model and a water allocation model – was calibrated with historic data. The river basin model was then applied for selected scenarios to analyse the impact of water resources development and climate change on Zambezi River discharge. The following sections describe the water balance model, the water allocation model, the calibration method and the scenario definitions.

4.1. *Water balance model*

The water balance model simulates the precipitation-runoff process in 27 sub-basins of the Zambezi basin. The size of the sub-basins ranges between 10,300 and 132,300 km^2, with a mean size of 50,900 km^2. The sub-basin outlets are depicted in Fig. 1.

In each sub-basin the same model concept is applied (Fig. 4, left). This model was already used in several climate change impact studies in central Europe (e.g. Stanzel and Nachtnebel, 2010; Kling et al., 2012). Similar model structures proved to be successful for the Zambezi (e.g. Winsemius et al., 2008). Inputs are monthly precipitation and potential evapotranspiration. Precipitation can be stored and evaporated from the interception storage. The remaining water falling on the ground is either stored in the soil or generates runoff as an exponential function of soil moisture (HBV-type concept, Bergström, 1995). Evapotranspiration from the soil depends on soil moisture and potential evapotranspiration. Generated runoff is split into a fast component (surface flow) and a slow component representing base flow (simulated as a linear reservoir). In general monthly time-steps are used, but the interception and soil modules internally use descretizations into daily time-steps to account for intra-monthly variability (interception/evaporation of individual rainfall events; inter-dependence of soil moisture, evapotranspiration and runoff generation). The model equations are listed in the Appendix.

Table 2
Reservoirs considered in this study. The last two reservoirs are currently in the planning stage.

Reservoir	Country	Capacity [hm^3]	Water surface [km^2]	Start year
Kariba	Zambia/Zimbabwe	200,000	5500	1959
Cahora Bassa	Mozambique	85,000	2700	1975
Itezhitezhi	Zambia	7000	375	1978
Kafue Gorge	Zambia	950	13	1971
Sanyati reservoirs	Zimbabwe	450	46	1957
Panhane reservoirs	Zimbabwe	1200	125	1976
Batoka Gorge	Zambia/Zimbabwe	1700	26	2024
Mphanda Nkuwa	Mozambique	2300	100	2024

4.2. Water allocation model

The water allocation model aggregates runoff of the water balance model along the river-network to compute discharge and was developed new for this study. Even though the inputs and outputs have a monthly temporal resolution, daily time-steps are used for the internal computations.

The model considers the following elements (Fig. 4, right):

- River points: Used for querying discharge at locations of interest.
- Uncontrolled reservoirs: Wetlands, floodplains, and lakes.
- Controlled reservoirs: Large, artificial reservoirs impounded by dams.
- Diversions: Consumptive use (e.g. withdrawals for irrigation).
- Routing: Simple lag method for discharge routing.

The standard set-up of the water allocation model consists of 38 computation points (see also Fig. 1):

- 27 river points at the sub-basin outlets.
- 5 uncontrolled reservoirs: Barotse Floodplain (3500 km^2), Kwando Floodplain (3000 km^2), Chobe Swamps (2000 km^2), Kafue Flats (1900 km^2) and Lake Niassa (30,000 km^2).
- Controlled reservoirs, as listed in Table 2.

Additional computation points were inserted to query discharge at locations of interest (e.g. Kafue Hook Bridge) and to study the impact of planned reservoirs (Batoka Gorge, Mphanda Nkuwa).

A key characteristic of controlled and uncontrolled reservoirs is the relationship between storage (hm^3), water surface (km^2), water level (m) and release (m^3/s). At uncontrolled reservoirs the release is a direct function of storage. At controlled reservoirs the release depends on a prioritization of water:

1. Environmental flow as a function of month.
2. Diversions (e.g. for irrigation) as a function of month.
3. Desired release (e.g. for hydropower) as a function of water level (reservoir zoning concept).
4. Guide curve operation (e.g. for flood control) as a function of month.

The water surface area may show large seasonal fluctuations especially at natural floodplains, thereby affecting evaporation fluxes. Evaporation is computed as the potential evapotranspiration increased by 5% (according to FAO 56, Allen et al., 1998) and multiplied by the water surface area. Other fluxes at reservoirs include upstream inflows, lateral inflows, and precipitation on the water body. Overall, the model is able to mimic the most important reservoir operation characteristics, as, e.g. also used by the well-known HEC-ResSim model.

4.3. *Model calibration*

The calibration of the river basin model combined methods of a priori estimation (literature review), sensitivity analysis, automatic optimization and manual parameter adjustments with the overall objective to obtain simulations that are consistent with available observations – i.e. observed discharge data measured at gauges and observed water levels in large reservoirs.

The main focus was on calibration of parameters of the water balance model. Initial parameter estimates were based on previous studies that give valuable insights into the hydrological behaviour of the Zambezi basin (Scipal et al., 2005; Winsemius et al., 2006, 2008; Meier et al., 2011). Three parameters were calibrated, whereas the other parameters were manually set to the same values in all sub-basins (see Table 7 in Appendix). Sub-basins with no observed discharge data available for optimization were assigned parameter values of neighbouring sub-basins. The same applied to the downstream sections (e.g. Zambezi at Tete) with no reliable gauge data. The three optimized parameters that vary between (groups of) sub-basins include:

- Soil storage capacity.
- Soil exponent for runoff generation.
- Fraction for separation of surface flow.

The first two parameters affect storage of rainfall in the soil for evapotranspiration and thereby control mean volume of flow. Further, they control how long it takes (up to several months) in the rainy season before the soils are sufficiently wet to enable runoff generation (see also Scipal et al., 2005; Meier et al., 2011). The third parameter defines the fractions of runoff representing surface flow – which leaves the sub-basin within the same month – and base flow with a delayed response controlling dry season discharge.

Observed discharge data of the period 1961–1990 at 14 gauges were used to automatically calibrate these three parameters of the water balance model with the Shuffled Complex Evolution search algorithm (Duan et al., 1992). As objective function we used a slightly modified version of the *KGE*-statistic (Gupta et al., 2009; modified according to Kling et al., 2012):

$$KGE' = 1 - \sqrt{(r-1)^2 + (\beta - 1)^2 + (\gamma - 1)^2} \tag{1}$$

$$\beta = \frac{\mu_s}{\mu_o}$$

$$\gamma = \frac{CV_s}{CV_o} = \frac{\sigma_s/\mu_s}{\sigma_o/\mu_o}$$

where KGE' is the modified version of the *KGE*-statistic (dimensionless), r is the correlation coefficient between simulated and observed discharge (dimensionless), β is the bias ratio (dimensionless), γ is the variability ratio (dimensionless), μ is the mean discharge in m^3/s, CV is the coefficient of variation (dimensionless), σ is the standard deviation of discharge in m^3/s, and the indices s and o represent simulated and observed discharge values, respectively. KGE', r, β and γ have their optimum at unity. For a full discussion of the *KGE*-statistic and its advantages over the often used Nash–Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) or the related mean squared error see Gupta et al. (2009).

The *KGE*-statistic offers interesting diagnostic insights into the model performance because of the decomposition into correlation (r), bias term (β) and variability term (γ). In this paper we use this decomposition of the model performance to report on the evaluation of discharge simulations at five key locations within the Zambezi basin in the calibration period 1961–1990 as well as in the independent evaluation period 1931–1960. Because of the long observed discharge time-series these statistics were also computed at the gauge Kafue Hook Bridge, even though this gauge was not included in the original set-up of the model.

In addition to the parameters of the water balance model, there were also a large number of parameters that had to be specified for the water allocation model. These parameters were not calibrated

Table 3
Overview about scenarios considered in this study, listing mean annual values of Zambezi basin upstream of Tete for precipitation (P), air temperature (T), and irrigation demand (according to World Bank, 2010). Reservoir scenarios include "historic" (considers start year as listed in Table 2 "current" (all reservoirs with start year before 2010), and "future" (also planned reservoirs). Irrigation data also includes withdrawals of 15 m^3/s for water supply of the city Lusaka in Zambia.

Scenario name	Climate scenario				Development scenario	
	Source	Data period	P [mm/a]	T [°C]	Reservoirs	Irrigation [m^3/s]
Historic scenarios						
Calibration	Observed	1961–1990	912	21.8	Historic	15
Evaluation	Observed	1931–1960	933	21.9	Historic	15
Reference scenario						
Baseline	Observed	1961–1990	912	21.8	Current	85
Water resources development scenarios						
Pristine	Observed	1961–1990	912	21.8	None	0
Moderate development	Observed	1961–1990	912	21.8	Future	203
High development	Observed	1961–1990	912	21.8	Future	651
Climate model scenarios						
CNRM near future	CNRM	2021–2050	967	23.5	Current	85
MPI near future	MPI	2021–2050	892	23.2	Current	85
CNRM far future	CNRM	2071–2100	980	26.6	Current	85
MPI far future	MPI	2071–2100	862	26.5	Current	85
Climate sensitivity scenarios						
P −10%	(Observed)	1961–1990	821	21.8	Current	85
P +10%	(Observed)	1961–1990	1003	21.8	Current	85
T +2 °C	(Observed)	1961–1990	912	23.8	Current	85
T +4 °C	(Observed)	1961–1990	912	25.8	Current	85

in a classical sense. Most of them could be estimated a priori using data of reports (reservoir characteristics, reservoir operation rules effective during the 2000s), analysis of spatial data (elevation, vegetation) with Geographic Information System (wetland characteristics), and daily discharge data of upstream versus downstream gauges (lag-parameter for routing). Release rules of reservoirs were further refined by analysis of observed reservoir outflows during dry periods. Storage–discharge relationships of floodplains and wetlands in the upper Zambezi basin were determined manually after sensitivity tests.

4.4. Scenario definition

We used the scenarios listed in Table 3 to separately assess the impact of water resources development and climate change on discharge in the Zambezi basin. Such a scenario approach required to first define a baseline scenario, for comparison against all the other scenarios. In the case of the Zambezi basin, the simulation of historic conditions – as in the calibration and evaluation periods – was not suitable for such a baseline scenario, due to abrupt changes in discharge conditions caused by the building of large dams and the subsequent filling of the reservoirs over several years, which temporarily reduced downstream discharge significantly. Therefore, a separate "Baseline" scenario was defined using observed climate data of the period 1961–1990 but including all existing large reservoirs as of year 2010 (Table 2). For this scenario the reservoirs are always under operation, regardless of commissioning date. Further, this scenario also includes existing irrigation withdrawals according to World Bank (2010), where for each sub-basin, a mean monthly irrigation demand was available. These irrigation withdrawals were not included in the "Calibration" and "Evaluation" scenarios because of lack of information about start years of individual irrigation withdrawals and generally low irrigation levels.

Three different development scenarios were considered for water resources management. The "Pristine" development scenario includes neither reservoirs nor diversions, thus representing undisturbed conditions in the Zambezi basin. The "Moderate" and "High" development scenarios represent different levels of irrigation according to World Bank. For each scenario the corresponding mean monthly irrigation diversions are applied to the 38 computation points of the model. Moderate development includes identified irrigation projects that may be realized within the next decades, whereas High development includes all theoretically possible irrigation projects. For both scenarios the planned reservoirs Batoka Gorge and Mphanda Nkuwa were considered to be under operation. Several other, smaller planned reservoirs were not considered. For all three development scenarios the observed climate data of the period 1961–1990 were used.

Four climate scenarios were considered based on data of two climate models (CNRM, MPI) and two time periods. "Near future" was defined as 2021–2050 and "far future" was defined as 2071–2100. For these scenarios the same development scenario was specified as for the Baseline scenario.

In addition to the climate scenarios based on GCM data, further scenarios were defined for climate sensitivity analysis. Observed climate data of the period 1961–1990 were modified by increasing/decreasing precipitation by 10%, as well as increasing temperature by +2 °C and +4 °C. Again the same development as in the Baseline scenario was used.

For the sake of brevity and clarity we do not present scenarios that are combinations of different levels of development and climate projections. One obvious combination would be to assess the impact of Moderate development in conjunction with climate model projections for the near future. However, the current climate model projections are highly uncertain which we show in the results section. Therefore, little could be learned from additional scenario combinations.

5. Results

First we report on the simulation results for discharge under historic conditions and the related performance of the river basin model. Subsequently, results of the scenario simulations for the predefined development and climate change scenarios are presented.

5.1. Simulation of historic conditions

This section gives insights into the historical hydrological conditions of the period 1961–1990 in the Zambezi basin, as observed and modelled.

Fig. 5 shows a comparison of simulated and observed monthly hydrographs for the Upper Zambezi River at Victoria Falls and the Zambezi River at Tete. With the exception of a few years, the simulated

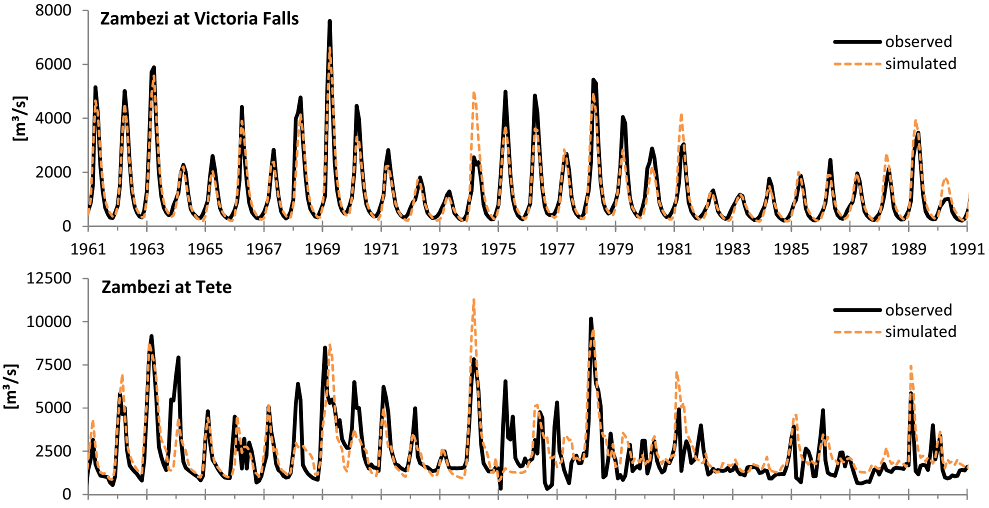

Fig. 5. Evaluation with discharge data. Simulated and observed monthly hydrographs 1961–1990. Top: upper Zambezi River at Victoria Falls. Bottom: Zambezi River at Tete.

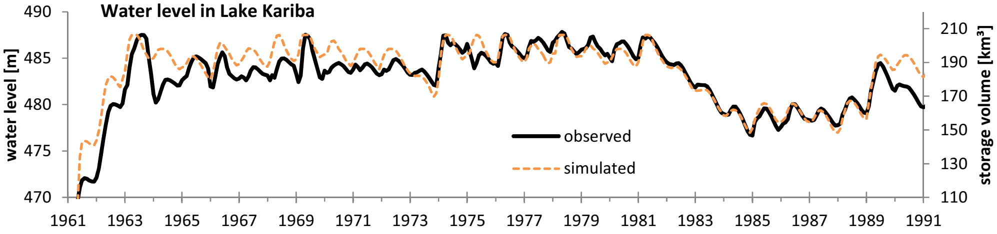

Fig. 6. Evaluation with water level data. Simulated and observed monthly water levels in Kariba reservoir. Period 1961–1990.

discharge closely matches the observed discharge at Victoria Falls. The differences are larger for the simulation of discharge at Tete, but still the general characteristics are simulated well. From Fig. 5 it is clear that the hydrograph at Victoria Falls represents undisturbed river flows with typical seasonality, whereas the hydrograph at Tete is impacted by the operation of the large Kariba and Cahora Bassa reservoirs. For example, during the 1980s there was no typical seasonality in discharge due to constant releases from Kariba reservoir in dry periods and flood attenuation in wet periods. From 1975 to 1977 the simulations deviate considerably from the observed discharge. During this period Cahora Bassa reservoir was first filled and the operation rules imposed on the model do not reflect the actual operations in this period well. During the 1980s water levels in Cahora Bassa reservoir were affected by the armed conflict in Mozambique. The reservoir was not run with normal operations from 1981 to 1998 because transmission lines from the hydropower plant were destroyed.

The simulation of the operation of Kariba reservoir – which is the largest reservoir in the basin and twice as large as Cahora Bassa – is evaluated next. Fig. 6 shows a comparison of simulated and observed water levels. Kariba dam was completed in 1959 and the filling of the reservoir lasted until 1963, which is simulated well (Fig. 6, left side). In the two-year period from the middle of 1961 to the middle of 1963 the volume of water stored in the reservoir increased by 100 km^3, resulting in an average reduction of downstream discharge of approximately 1600 m^3/s (= 100 km^3/2 years). After this first complete filling of the reservoir the water level was held at a lower level from 1964 to 1973 than in later periods. Release decisions were also affected by electricity generation, where the installed capacity of turbines increased over time. From 1974 onwards the simulated water levels closely match the observed water levels. From 1981 to 1984 the water level dropped because of low inflows but constant, higher releases. During this four-year period the volume of stored water decreased by 60 km^3, thereby increasing downstream discharge by an average of approximately 500 m^3/s. In the last two years of Fig. 6 (1989 and 1990) water levels are over-estimated because of too high simulated inflows (see discharge simulation at Victoria Falls in Fig. 5). Overall, the general impact of reservoir operation is simulated sufficiently well, even though there may be deviations in individual years.

In addition to the reservoir simulation discussed above, of key interest is also the simulation of undisturbed discharge conditions at the three main tributaries: Upper Zambezi River, Kafue River, and Luangwa River. Fig. 7 shows that both the seasonality in discharge and the overall distribution of discharge (monthly flow duration curve) are simulated well. Mean annual discharge of the Upper Zambezi is with 1200 m^3/s much larger than for the Kafue River (370 m^3/s) and Luangwa River (600 m^3/s). A separate evaluation in the ten wettest and ten driest years of 1961–1990 for the Upper Zambezi River shows that the model accurately simulates the different discharge conditions in wet and dry years (Fig. 8). Mean annual discharge in wet years is with 1700 m^3/s more than twice as large as in dry years (800 m^3/s), even though differences in annual precipitation are not as pronounced with values of 1060 mm/a in the 10 wettest years versus 820 mm/a in the 10 driest years. This means that the percentage change between wet and dry years is for discharge approximately four times larger than for precipitation, highlighting the high sensitivity of discharge to precipitation.

To better understand the processes governing the generation of discharge Fig. 9 shows the simulated seasonal water balance averaged over the land-surface of the Zambezi basin upstream of Tete (water bodies of wetlands and reservoirs, as well as the effect of routing, are excluded from this

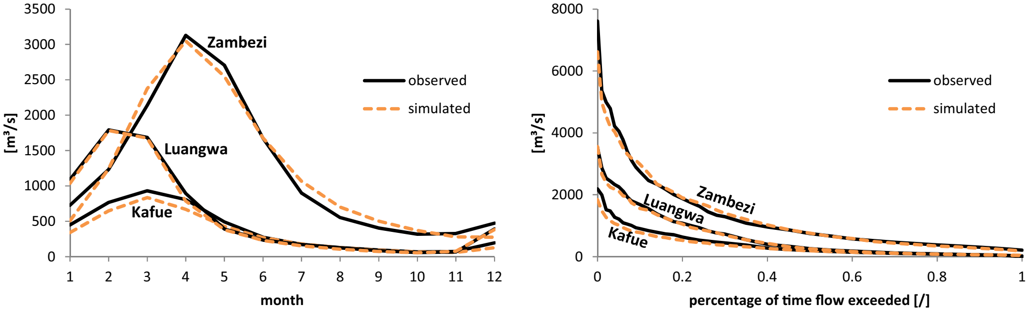

Fig. 7. Simulated and observed discharge conditions of key tributaries. Zambezi: upper Zambezi River at Victoria Falls. Luangwa: Luangwa River at Great East Road. Kafue: Kafue River at Kafue Hook Bridge. Period 1961–1990. Left: seasonality in discharge. Right: monthly flow duration curve.

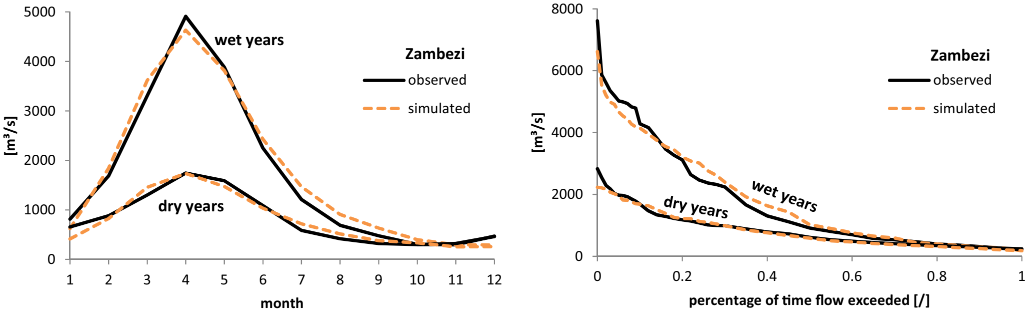

Fig. 8. Simulated and observed discharge conditions in wet and dry years. Upper Zambezi River at Victoria Falls. Separate evaluation in 10 driest and 10 wettest years according to precipitation data of the period 1961–1990. Left: seasonality in discharge. Right: monthly flow duration curve.

analysis). Runoff-depth is only a small fraction in relation to the other components of precipitation, actual evapotranspiration and storage change (which gives the cumulative changes of water stored as soil-moisture and ground-water). In the first months of the rainy season (October–December) no runoff is generated because all of the precipitation is either stored in the ground – indicated by positive

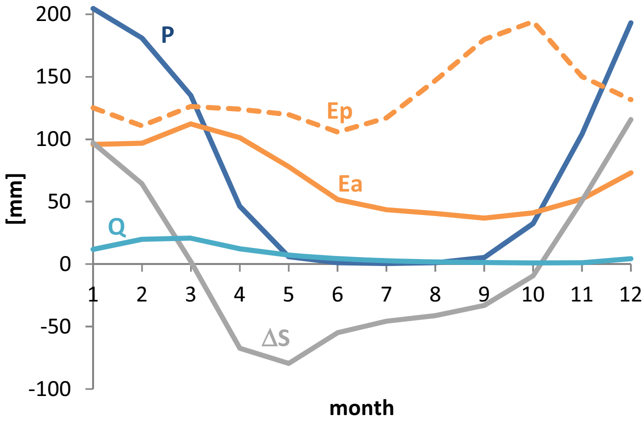

Fig. 9. Simulated seasonal water balance of the Zambezi basin upstream of Tete. Variables represent mean monthly amounts of the period 1961–1990. P: precipitation. Ep: potential evapotranspiration. Ea: actual evapotranspiration. Q: runoff-depth (does not include the impact of routing, wetlands, reservoirs, diversions). ΔS: storage change. Water balance equation: $P = \mathrm{Ea} + Q + \Delta S$.

Table 4
Model performance for monthly discharge simulation at key locations in the Zambezi basin. Years: number of years with available discharge observations. *KGE′*: modified *KGE*-statistic (see Eq. (1)). *r*: correlation coefficient. β: bias ratio. γ: variability ratio. NSE: Nash–Sutcliffe Efficiency. All performance statistics are dimensionless.

River	Gauge	Calibration period 1961–1990						Evaluation period 1931–1960					
		Years	*KGE′*	*r*	β	γ	NSE	Years	*KGE′*	*r*	β	γ	NSE
Zambezi	Lukulu	29	0.90	0.93	1.00	1.08	0.85	7	0.87	0.97	1.10	0.92	0.92
Zambezi	Victoria Falls	30	0.92	0.94	1.00	0.96	0.88	30	0.79	0.91	1.19	0.99	0.73
Kafue	Hook Bridge	30	0.83	0.94	0.86	0.92	0.85	29	0.81	0.92	1.01	0.83	0.84
Luangwa	Great E. Road	28	0.93	0.94	0.97	0.99	0.88	11	0.84	0.93	1.07	0.87	0.86
Zambezi	Tete[a]	30	0.71	0.74	1.08	0.90	0.48	9	0.70	0.95	1.28	1.10	0.63

[a] Zambezi discharge data at Tete are not reliable, and in addition are affected by changing operation rules at upstream reservoirs.

values of storage change – or lost via actual evapotranspiration. Actual evapotranspiration is however considerably smaller than potential evapotranspiration due to dry soils. This changes towards the end of the rainy season (February, March) when soils become wet and actual evapotranspiration is similar to potential evapotranspiration. During this period with wet soils runoff is eventually generated from precipitation, but the overall amounts of runoff are still an order of magnitude smaller than the other water balance components. After the end of the rainy season in April runoff is still significant due to base flow. Actual evapotranspiration becomes larger than precipitation – which is basically zero during the dry season from May to September – resulting in drying up of soils indicated by negative storage change. The peak in potential evapotranspiration in September and October – caused by hot, dry and windy conditions – has no direct impact on actual evapotranspiration due to lack of water.

5.2. Model performance statistics

In addition to the evaluation based on visual comparisons presented in the previous section, we also report on the model performance statistics for the calibration period (1961–1990) and the independent evaluation period (1931–1960).

Table 4 lists the performance statistics for discharge simulation at key locations. At some gauges data are available only in a limited number of years during the evaluation period, but time-series are mostly complete in the calibration period. In general the model performance is high in both periods, with a few exceptions as discussed further below. In most cases the correlation is above 0.90 and the Nash–Sutcliffe efficiency is above 0.80. This applies for the calibration period as well as the independent evaluation period.

Even though performance statistics in Table 4 are also listed for the gauge Tete, it has to be considered that the reported observed discharge data for this gauge are of limited accuracy. This mainly affects the computed bias ratio (β), but not so much temporal dynamics as measured by the computed correlation (r). In the calibration period the correlation is low ($r = 0.74$) because operation rules imposed on the model reflect the current situation (as effective during the 2000s), whereas the actual historic operation of Kariba and Cahora Bassa reservoirs changed over time (see discussion in previous section). In contrast to the calibration period, the correlation between simulated and observed discharge is high ($r = 0.95$) in the independent evaluation period, with observed data at Tete available from 1952 to 1960. The first seven years represent undisturbed (pristine) conditions, whereas the last two years are affected by the filling of Kariba reservoir.

Of greater interest than the poor bias ratio and correlation at Tete is the model performance for simulation of Zambezi discharge at Victoria Falls. Discharge data measured at this gauge are considered to be accurate – and are not affected by upstream reservoir operations. Model performance during the calibration period is high, but the bias ratio becomes significant ($\beta = 1.19$) in the evaluation period. The most likely source for this bias is that the precipitation inputs are already biased. From the calibration to the evaluation periods mean annual precipitation increased by +3%, but observed discharge decreased by −4%. Even though these are small changes, it is counter-intuitive that discharge decreases when precipitation increases. Here, the low density of precipitation stations has to be considered in the

Table 5
Mean annual scenario simulation results for the Zambezi basin upstream of Tete.

Scenario	[m^3/s] Discharge	[%] ΔQ to baseline	Evaporation [m^3/s] Wetlands	Evaporation [m^3/s] Reservoirs	[m^3/s] Diversions
Historic scenarios					
Calibration	2514	−3	311	368	15
Evaluation	3042	+17	333	7	15
Reference scenario					
Baseline	2597	–	311	437	74
Water resources development scenarios					
Pristine	2956	+14	311	0	0
Moderate development	2498	−4	310	440	179
High development	2137	−18	308	424	564
Climate model scenarios					
CNRM near future	2846	+10	343	465	75
MPI near future	2241	−14	289	447	73
CNRM far future	2965	+14	324	499	76
MPI far future	2127	−18	267	469	70
Climate sensitivity scenarios					
P −10%	1754	−32	243	418	71
P +10%	3725	+43	364	447	76
T +2 °C	2375	−9	304	455	73
T +4 °C	2176	−16	295	473	72

upper Zambezi basin, which is on average approximately one station per 21,000 km^2 in the calibration period, but even lower during the evaluation period (see Fig. 2). An under-estimation of discharge in the evaluation period is also obtained at the upstream gauge Lukulu, albeit the period with available data is only 7 years.

The under-estimation of Kafue River discharge at the gauge Kafue Hook Bridge during the calibration period is the result of a large negative bias (−34%) during a 5-year period (1978–1982), which coincides with the start of operation of nearby Itezhitezhi reservoir. The source of this bias is not clear, but it could be related to the accuracy of the precipitation data or the discharge data. Outside this 5-year period the simulation shows only a small bias – this also applies to the independent evaluation period.

5.3. *Scenario simulation*

The calibrated model was applied for simulation of a number of pre-defined scenarios (see Table 3). The scenario simulations are always compared against the “Baseline” scenario representing current water resources management (reservoirs, operation rules, irrigation withdrawals) in the basin but using historic climate of the period 1961–1990. The analysis focuses on Zambezi River discharge at Tete in Mozambique.

Table 5 lists mean annual scenario results. Mean annual discharge in the Baseline scenario amounts to approximately 2600 m^3/s, with values ranging from around 1750 m^3/s to 3700 m^3/s in the scenario simulations.

Total evaporation losses from reservoirs amount to 437 m^3/s in the Baseline scenario. This value ranges from 418 to 499 m^3/s in the other scenarios. The differences are caused by:

- Different number of reservoirs (Batoka Gorge and Mphanda Nkuwa are included in the Moderate and High development scenarios).
- Increase in temperature causes higher evaporation rates.
- Variations in inflow (due to changes in precipitation, evapotranspiration, diversions) affect reservoir water levels. For example, lower inflows can result in lower water levels, thereby decreasing evaporation losses due to smaller surface area of the water body.

More than 90% of the total reservoir evaporation occurs from Kariba and Cahora Bassa reservoirs. These are significant losses of water and the main reason that under the Pristine scenario (with no reservoirs) discharge is considerably larger than in the other scenarios.

In addition to the reservoirs, water also evaporates from the natural wetlands and floodplains – with mean annual evaporation losses ranging from 243 to 364 m^3/s between the scenarios. The contribution to total evaporation from the individual wetlands is roughly 40% from Kafue Flats, 25% from Barotse Floodplain, 25% from Chobe Swamps, and 10% from Kwando Floodplain. The sum of evaporation losses from reservoirs and wetlands amounts to approximately 750 m^3/s, which is more than 20% of the runoff that enters the river network.

Diversions amount to 74 m^3/s in the Baseline scenario, which is small compared to the evaporation losses from reservoirs and wetlands. However, diversions increase to 179 m^3/s in the Moderate development scenario, and to 564 m^3/s in the High development scenario. This means that irrigation levels under the High development scenario have a similar magnitude as evaporation losses that are already occurring from existing reservoirs. Under this scenario mean annual discharge decreases by −18% as compared to the Baseline scenario. 87% of the irrigation demand (Table 3) can be met by the simulated diversions (Table 5). Similar percentages are obtained in the Moderate development and Baseline scenarios – albeit with much lower diversion amounts. Shortages for meeting irrigation demand occur when reservoir water levels fall below minimum operation levels. This situation occurs at Zimbabwean tributaries under all scenarios, but also in dry years at Kariba reservoir under the High development scenario.

It is clear that an implementation of irrigation projects will cause a decrease in discharge due to increased diversions. The impact of future climate is less clear, though. Contrasting results are obtained for the scenarios based on climate data of GCMs. For the near future (2021–2050) the scenario based on CNRM climate data projects an increase in discharge of +10%, whereas MPI projects a decrease of −14%. These differences are even larger for the far future (2071–2100), with projected changes of +14% versus −18%.

To disentangle the effects of changes in precipitation and temperature the last four scenarios listed in Table 5 present assessments for changes super-imposed on historic climate (delta-change approach). If temperature increases by +4 °C then discharge decreases by −16%. An even larger decrease in discharge of −32% is obtained for a reduction of precipitation by −10%. An increase in precipitation by +10% results in an increase of discharge by +43%.

The percentage changes in mean annual discharge are not evenly distributed during a year, as evident in an analysis of seasonality in discharge (Fig. 10, top left). By far the largest differences to the Baseline scenario are obtained with the Pristine scenario, with a more pronounced seasonality. The main reason is that the Pristine scenario does not include any reservoirs. The reservoir operation results in a strong attenuation of the seasonal flood peak and an increase of discharge during the dry period. This is even clearer when analysing the distribution of flows (Fig. 10, top right). In the Pristine scenario high flows are increased, but low flows are much lower, even though the mean annual discharge is larger.

For the High development scenario the magnitude of changes in seasonality and distribution of discharge are considerably smaller than for the Pristine scenario (Fig. 10, top) – and the changes are insignificant for the Moderate development scenario. In the High development scenario a relatively constant decrease is obtained for the seasonality in discharge (Fig. 10, top left), which is the result of the interplay of seasonality in irrigation demand and reservoir operation. For the distribution of flows (Fig. 10, top right) there are significant decreases for higher flows, but almost no decreases for low flows. This is caused by constant releases of reservoirs during dry periods.

Fig. 10 (middle) shows the changes in seasonality and distribution of discharge in the scenarios based on future projections of climate models. The differences between the climate models are large, whereas the time period (near versus far future) is of limited importance. This reflects the lower sensitivity to temperature – which is different in the two time periods – and the higher sensitivity to precipitation – which is different in the two climate models. For the far future scenario with MPI climate data the low flows decrease more than in other scenarios. This is caused by lack of precipitation, which cannot be fully compensated by reservoir operation during dry periods.

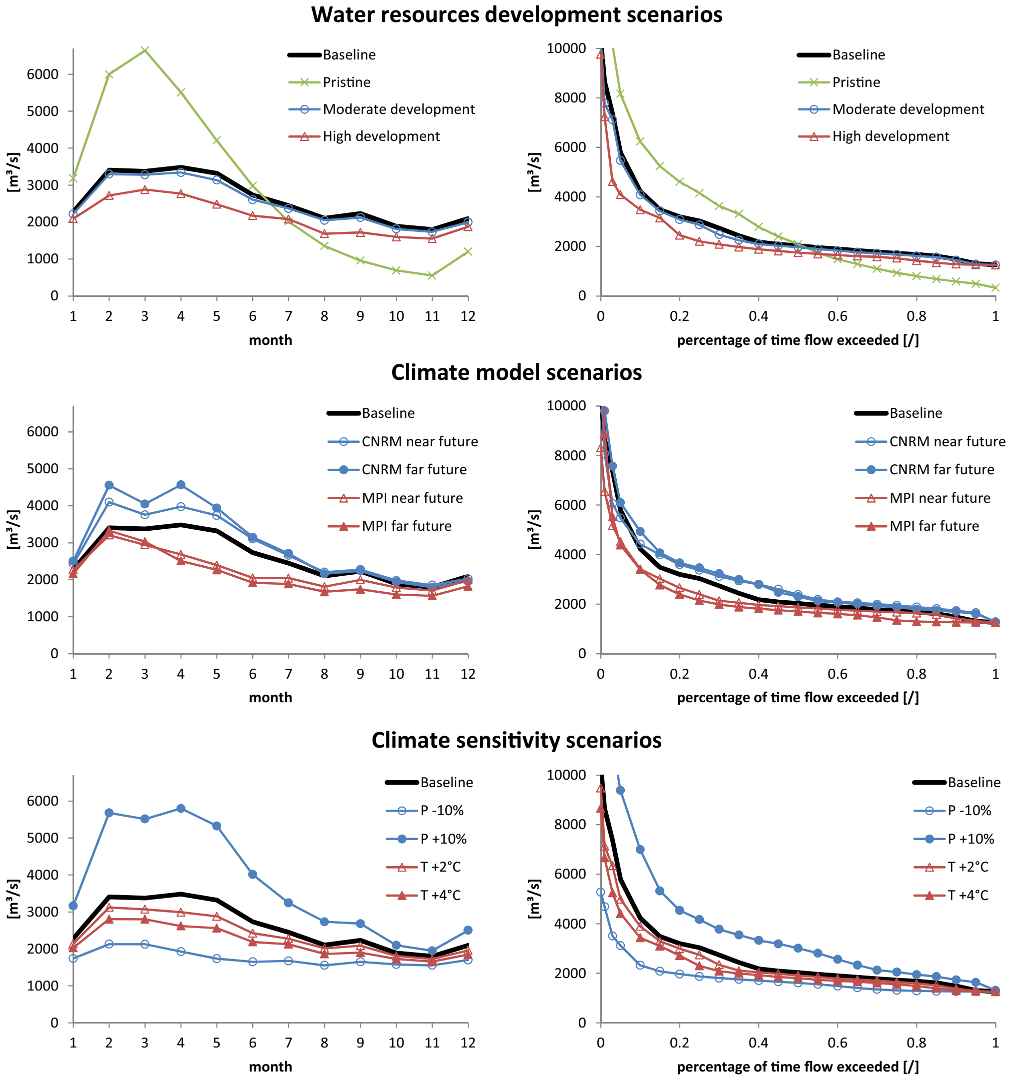

Fig. 10. Simulated discharge conditions of Zambezi River at Tete under various scenarios. Top: water resources development scenarios. Middle: climate scenarios. Bottom: climate sensitivity tests. Left: seasonality in discharge. Right: monthly flow duration curve.

The results for the climate sensitivity scenarios are shown in Fig. 10 (bottom). In the scenario with +10% increase in precipitation there is a pronounced seasonality in discharge, whereas for −10% decrease in precipitation seasonality almost completely disappears (Fig. 10, bottom left). For this scenario, 90% of the time discharge is almost constant at approximately 2000 m^3/s (Fig. 10, bottom right).

The monthly flow duration curves shown in Fig. 10 suggest that there will not be severe changes for low flows in the future. As Fig. 11 shows, annual discharge of individual years will also not change significantly in the future for the driest years. Interestingly, the lowest annual discharge was simulated for the Pristine scenario, with no reservoirs to sustain minimum flow in very dry periods. In contrast, there are significant differences in the annual discharge in the wettest years. The scenarios based

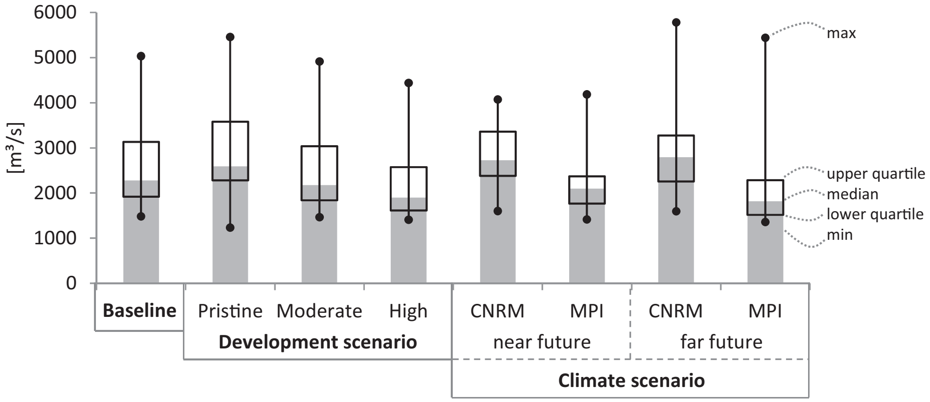

Fig. 11. Distribution of annual discharge. Box-plots show the annual discharge of individual years simulated under various scenarios. Zambezi River at Tete simulated for 30-year periods. Comparison of baseline scenario to water resources development scenarios and climate scenarios.

on climate model data project that the highest annual discharge will be significantly larger in the far future than in the near future. These changes are independent from the changes in mean annual discharge. However, any interpretation of extreme events based on climate model data should be cautious (Kundzewicz and Stakhiv, 2010; Wilby, 2010; Blöschl and Montanari, 2010).

6. Discussion

In this section we discuss the simulation results and also give a brief overview about possible sources of uncertainties in the impact modelling.

6.1. Simulation results

The model simulations obtained for historic conditions are consistent with available observations. This applies for a visual comparison of simulated and observed discharge and reservoir water level data, as well as performance statistics in the calibration and independent evaluation periods.

The performance statistics are higher than in previous studies. For example, for the discharge simulation at Victoria Falls during calibration period Harrison and Whittington (2002) obtained a correlation coefficient R^2 of 0.61, which is lower than the results presented here with R^2 of 0.88. Similarly, Winsemius et al. (2006) report for their two models a Nash–Sutcliffe Efficiency NSE of 0.72 and 0.82 respectively, whereas we obtained a slightly higher performance with NSE of 0.88. Note that Winsemius et al. did only apply their model to the upper Zambezi and did not focus on impact modelling. Unfortunately, the other impact modelling studies of the whole Zambezi basin (Hoekstra, 2003; Yamba et al., 2011; Beck and Bernauer, 2011) do not report performance statistics. However, we believe that the model simulations presented here are among the most accurate – if not best – models for simulation of Zambezi discharge currently available.

The exact reason for the higher model performance as compared to previous studies remains unclear. It may be related to improved input data (GPCC), calibration method, consideration of wetlands and river routing. The latter two are important for simulation of timing of Zambezi discharge (Cohen-Liechti et al., 2014) and would cause serious modelling problems if not explicitly considered, with the risk of corrupting parameter values to obtain simulations that are “right for the wrong reason” (Refsgaard and Henriksen, 2004). The higher performance is most likely not related to the structure of the water balance model (see Fig. 4, left), as here the applied models are all very similar in the various studies.

The evaluation of historic discharge conditions (see Figs. 5 and 6) also shows the considerable impact of the large reservoirs and the problem of reservoir operation; where (ad hoc?) release decisions at upstream reservoirs complicate simulation of downstream discharge. Different sets of operation rules would have to be applied to different time periods, but instead fixed operation rules – as effective during the 2000s – were imposed on the model. Therefore, simulations in the downstream sections (e.g. at Tete) frequently show deviations to observations.

Due to the above mentioned peculiarities of Zambezi discharge in downstream sections, we focussed on the simulation results averaged over the land-surface – thereby excluding the confounding impacts of reservoirs – to learn more about the hydrology in the context of the seasonal water balance (see Fig. 9). The hydrology in the Zambezi basin is characterized by representing a water limited system – as opposed to energy limited. Already under historic climate the potential evapotranspiration cannot be met by the actual evapotranspiration (see Fig. 9), simply because there is not enough water stored in the soil due to insufficient annual precipitation amounts. Therefore, any increases in temperature – and consequently increases in potential evapotranspiration – have a small impact on discharge. In contrast, small changes in precipitation have large impacts on discharge. This was already observed in the past, where discharge is considerably larger in wet years than in dry years and the model simulations are well in line with this observation (see Fig. 8). Under such conditions any projections with climate models have to be interpreted with caution – only small variations (increases/decreases) in precipitation projections cause large differences in the impact on discharge. This was also confirmed by the sensitivity tests (see Table 5 and Fig. 10, bottom) – where a decrease of precipitation by −10% caused a decrease in discharge by almost −850 m^3/s, or −32%. Note that this high sensitivity of discharge to precipitation contrasts the conclusions of Beck and Bernauer (2011) that climate has relatively small effects on water availability in the Zambezi basin, which may be related to their approach of calibration to long-term average conditions.

Our simulations under climate change scenarios show a range of −14% to +10% for mean annual Zambezi discharge at Tete in the near future (2021–2050 as compared to Baseline simulation 1961–1990). These results (and the large uncertainty) have to be interpreted within the context of the results of previous studies. Harrison and Whittington (2002) focussed on the upper Zambezi River at Victoria Falls. For the 2080s their three climate scenarios show a warming of about +5 °C and a reduction in rainfall between −2% and −18%, which results in a reduction in runoff by −10% to −36%. In a preliminary analysis the World Bank (2010) used GCM data (A1B emission scenario) for the whole Zambezi region. For 2030 they estimate a change in runoff between −13% and −34% (depending on the sub-region). Beilfuss (2012) summarized existing climate change assessments for the Zambezi and concludes that by 2050 runoff is likely to decrease by −26% to −40% if the reduction in rainfall lies between −10% and −15%. This corresponds well to our climate sensitivity tests where for a reduction of −10% in rainfall the simulation shows a reduction of −32% in discharge. However, apart from these dramatic projections with reduction in flows we also have to acknowledge that rainfall may actually increase in the future, highlighting the uncertainty in the climate model scenarios.

In addition to climate change, also future development of large-scale irrigation is expected to have a considerable impact on Zambezi discharge. For the high-level irrigation development the simulations show a decrease of mean annual Zambezi discharge at Tete by −460 m^3/s (−18%). This is similar in magnitude as the reduction caused by evaporation from existing reservoirs (437 m^3/s). Overall, the impact of the existing reservoirs is much larger than just reducing mean annual discharge, because in addition they also affect the discharge conditions. The construction of Kariba and Cahora Bassa dams and the reservoir operation policies have led to a strong alteration of the natural seasonality and distribution of discharge (flow duration curve). This became evident in a comparison between Baseline and Pristine scenarios (see Fig. 10). No such significant changes were found in the other analysed scenarios representing possible future conditions. This means that – and we believe this is a significant finding – the biggest changes for Zambezi discharge have already occurred in the past.

Apart from the Pristine scenario, in all other scenarios studied, no pronounced changes were obtained for neither monthly low flows (see monthly flow duration curves in Fig. 10) nor annual discharge in the overall driest years (see Fig. 11). The reason is that Kariba and Cahora Bassa reservoirs are sufficiently large to support low flows in dry periods by drawing down the water levels. However, if more extreme (i.e. drier) climate scenarios were included, then the reservoirs would reach their minimum operation levels and discharge would drastically decrease in dry years.

The impact of the reservoirs becomes larger for scenarios with drier conditions. For example, if precipitation decreased by −10%, this would result in almost constant flows without any seasonal fluctuations (Fig. 10, bottom). This would have dramatic consequences for downstream ecology. Under such conditions reservoir operation rules should be refined to impose seasonal fluctuations on the reservoir releases (Beilfuss, 2010).

This large impact of the reservoir operation enables water resources managers to actively control the downstream discharge conditions. Poor planning or lack of co-operation obviously can lead to negative impacts, but on the other hand good planning can have many positive impacts. Therefore, balanced solutions are required considering flood safety, hydropower generation, irrigated agriculture and ecological aspects.

6.2. Sources of uncertainties

The hydrological impact modelling in this study is affected by several uncertainties. Exact quantification of these uncertainties would significantly increase the scope of this study and is left for future work. However, it is still worthwhile to discuss where these uncertainties may arise from for the hydrological model and future scenarios.

The main sources of uncertainty for the hydrological model set-up are listed below:

- Observed discharge data: Measurement errors due to inaccurate rating curves.
- Historic climate data: Poor precipitation station density.
- Water balance model: Model structure, model parameters.
- Water allocation model: Reservoir operation rules.

Of the uncertainties listed above it is deemed that the observed discharge data are most important. As the model is calibrated to closely match these data, any systematic biases in the observed data would also affect the simulations. Before calibration, plausibility checks (double-mass plots, upstream–downstream comparisons) resulted in rejection of discharge data from a number of gauges, to avoid an over-fitting of the model to biased data. However, also the remaining gauges may be – and most likely are – affected by biases, affecting computation of mean flows, but not so much the temporal dynamics of flows. In summary, even though the accuracy of discharge observations is to some degree questionable, the data of the used gauges are the best information available.

For the historic climate data the poor precipitation station density is a concern especially in the upper Zambezi basin – with approximately one station per 21,000 km^2. The station density is highest – and uncertainty is lowest – during the period 1961–1990, which was also used for calibration and for the Baseline scenario. The used precipitation data set (GPCC) is currently the best available long-term, observational data set in the Zambezi basin. The number of stations included is almost twice as high as in the well-known data set of CRU. Other interesting data sources would include satellite-based data such as TRMM (Tropical Rainfall Measurement Mission of NASA, Huffman et al., 2007), albeit TRMM data are only available since 1998. A comparison of these data-sets could be an attempt to quantify the uncertainty in the historic precipitation model inputs, but faces the obstacle of lack of overlapping time-period with good quality ground-based data (Cohen-Liechti et al., 2012).

Uncertainties in model structure and parameters have received considerable attention in the scientific literature, and there are also a few examples of such studies in southern Africa (e.g. Winsemius et al., 2006, 2009; Hughes et al., 2010). These studies give interesting insights into model behaviour and performance of alternative models. However, we believe that a well calibrated model, with high performance and thorough evaluation – including for example separate evaluation in wet and dry years – increases the confidence also for simulation under various scenarios. An important assumption here is that parameter values obtained from calibration to historic conditions are also applicable for simulation under future conditions, thereby ignoring possible impacts of land-use change and dependence of calibrated model parameters on climate characteristics (Singh et al., 2013). An inter-comparison

Table 6
Climate model data of the ENSEMBLES project for the Zambezi catchment upstream of Tete. A1B emission scenario. Spatial resolution of RCMs is approximately half degree. Raw (uncorrected) RCM data. P: mean annual precipitation, T: mean annual air temperature, ΔP: change in precipitation relative to 1990–2010, ΔT: change in air temperature relative to 1990–2010.

Institute	GCM/RCM	Period	P [mm/a]	T [°C]	ΔP [%]	ΔT [°C]
DMI[a]	ECHAM5-r3/HIRHAM5	1990–2010	770	24.3	–	–
		2021–2050	724	25.5	−6	1.2
		2071–2100	n/a	n/a	n/a	n/a
ICTP[b]	ECHAM5-r3/RegCM3	1990–2010	808	22.3	–	–
		2021–2050	780	23.4	−3	1.1
		2071–2100	660	26.7	−18	4.4
INM[c]	HadCM3Q0/RCA3	1990–2010	994	22.0	–	–
		2021–2050	989	23.4	−1	1.4
		2071–2100	901	25.5	−9	3.5

[a] DMI: Danmarks Meteorologiske Institut, Denmark.
[b] ICTP: International Centre for Theoretical Physics, Italy.
[c] INM: Instituto Nacional de Meteorología, Spain.

study – juxtaposing results of different modelling approaches – would be required to quantify the hydrological model uncertainty.

Simulations under future development and climate scenarios strictly have to be interpreted as What-if analyses, as opposed to deterministic forecasts. No likelihoods are attached to these scenarios. Future development of irrigation and dam projects in the basin depends on political decisions, economic development, population growth, and sound water resources planning. Climate model projections are affected by emission scenarios, natural climate variability, climate model errors, downscaling technique and bias correction. All these aspects result in a large range of uncertainty. Within the scenarios, there are different sensitivities of the results. For the development scenarios, the impact of future irrigation projects is more important than future dam projects. For the climate scenarios, higher temperatures cause gradual decrease in discharge, but results are more (highly) sensitive to precipitation. Here, the two climate models used do not agree on the sign in the change of future precipitation.

This uncertainty in future precipitation is the most important source of uncertainty for future Zambezi discharge. As a logical next step, the analysis should be expanded by using a whole ensemble of climate models, as shown, e.g. by Kling et al. (2012) for the upper Danube basin. Ideally, the climate data should be based on regional climate models (RCMs) that are currently applied in on-going research projects for the African continent. RCMs have a much finer spatial resolution and are deemed to be superior to GCM projections (as used in this study), especially regarding the simulation of the seasonal shift of the Inter-Tropical Convergence Zone (ITCZ), which controls precipitation.

Table 6 lists a first analysis of climate projections for the Zambezi basin simulated by three RCMs in the recently finished ENSEMBLES project (Paeth et al., 2011). All three analysed RCMs project a decrease in precipitation for the Zambezi basin – with projections for 2071–2100 of −9% by INM and −18% by ICTP. These decreases are significantly larger than the decrease in the analysed GCM data of this study – with a maximum decrease of −5% projected by MPI for 2071–2100 (see Table 1). Decreases in precipitation by −10% and more would have dramatic impacts on discharge in the Zambezi River, where from the sensitivity analyses presented here it is expected that annual discharge would decrease by more than −30% (see Table 5). Therefore, we recommend focusing future work on assessing the impact of an ensemble of regional climate model projections, which will be made available via the Coordinated Regional Climate Downscaling Experiment for Africa (CORDEX-Africa, see e.g. Nikulin and Jones, 2011; Kalognomou et al., 2013).

7. Outlook

This study is embedded in a broad scale initiative to assess – and prepare for – climate change impacts in Mozambique (INGC, 2009). The modelling tools and databases of this study have been implemented in a web-based, interactive Decision Support System (DSS, online access at http://zdss.ingc.gov.mz/[1]). Thereby, the whole database used in this study is readily available to the general public. In addition to data export, the DSS allows editing and creating development and climate scenarios, as well as inserting computation points to query discharge simulations at points of interest along the river network. Mozambican analysts have been trained on the DSS, such that further work can focus on:

- Studies for individual Mozambican tributaries of the Zambezi.
- Adapting operation rules of existing large reservoirs.
- Impact assessment of planned water resources projects including dams, irrigation projects as well as inter-basin transfers (e.g. upper Zambezi water diversion to Botswana/South Africa).
- Assessments for new climate scenarios (CORDEX).
- Combined assessment of climate and development scenarios.
- Teaching of students at university.

In a recent update, the DSS has been extended to include simulation of energy generation at hydropower plants, discharge simulation in daily time-steps, and coupling with flood mapping in the lower reaches of the Zambezi. The training on – and the work with – the DSS is one building block for capacity increase in Mozambique. Thereby, this will foster awareness and preparedness for possible future impacts of water resources development and climate change in the Zambezi basin.

8. Conclusions

This study focussed on the hydrological impact modelling of water resources development and climate change scenarios on discharge conditions in the Zambezi basin. A river basin model was calibrated with historic data, before being applied for a number of scenarios.

A specific objective of this study was a thorough evaluation of the model simulations, as there has been a lack thereof in previous impact assessment studies. Our simulations of historic conditions are consistent with available observations. This applies for simulation of river discharge as well as reservoir water levels. The model performance statistics do not drop significantly when moving from the calibration period to an independent evaluation period. Overall, the performance statistics are superior to previous studies. The accurate discharge simulations thereby increase the confidence in the impact assessment.

The simulation of historic conditions enables the following conclusions:

- There are large inter-annual variations in discharge. Discharge in wet years is more than twice as large as discharge in dry years, which is related to small variations in precipitation. This high sensitivity of discharge to precipitation was not fully appraised in previous impact modelling studies.
- Runoff is only a small component of the water balance and shows a strong seasonality due to distinctive rainy/dry seasons. Most of the rainfall is lost via evapotranspiration, with the actual evapotranspiration rates considerably lower than the potential ones throughout most of the year. Here, changes in soil moisture play a key role for the seasonal water balance.
- Natural wetlands and operation of large reservoirs have a large impact on discharge. This has to be explicitly included when building hydrological models of the Zambezi River basin.

Several scenarios were defined considering future developments for irrigation withdrawals and dams as well as climate change scenarios, with the following main findings:

- The biggest changes in the Zambezi basin have already occurred in the past. The construction of large reservoirs caused a decrease in discharge by evaporation and significantly altered the discharge conditions by reservoir operation. Low flows have been increased and high flows decreased.

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[1] Back-up server available at http://hydro.poyry.at/zambezi/.

- The simulated decrease of −18% in mean annual discharge due to possible future high-level irrigation development is of similar magnitude as the total evaporation from existing reservoirs. Moderate irrigation development and planned new dams have only minor impacts on Zambezi River discharge. The projected irrigation demand in both future scenarios can be met to a similar degree (almost 90%) as the current demand (when climate change is not considered).
- Future climate causes large uncertainties in future discharge. This is caused by the high sensitivity of discharge to precipitation, but the analysed climate models do not agree on the sign of future changes in precipitation.
- Even though mean discharge is strongly affected by any changes in precipitation, the low flows remain almost unchanged due to constant releases from reservoirs during dry periods. Low flows may be drastically reduced if analysing scenarios with more than −10% change in future precipitation.
- Future warming will cause higher actual evapotranspiration and therefore lower discharge. A warming of +4 °C has a similar impact as high-level irrigation development.

These scenarios show that the impact on future Zambezi River discharge can be quite large. At the same time, the human-induced changes in the past may have been larger than the changes in the future. This also means that human management – if adapted well to the changing conditions – can contribute substantially to mitigating negative effects of a changing climate. Here, the largest uncertainty relates to future precipitation. Current, on-going research efforts with regional climate models applied to Africa should enable more detailed assessments within an ensemble modelling framework.

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Appendix A.

When a fine temporal discretization (e.g. $\Delta t = 24$ h) is used, then the water balance model can be formulated with the simple equations given below. To overcome numerical artefacts that arise with such a discrete numerical formulation, the actual model code uses (1) an internal adaptive temporal discretization for the soil module and (2) the analytical solution of the differential equation that gives the exact result for $\Delta t \rightarrow 0$ for the base flow module. The interception module uses daily time-steps with alternating wet and dry days for precipitation within a month. The parameters of the model are listed in Table 7 and the variables are listed in Table 8. Δt is in the units of h. The index t identifies the time-step and the index i identifies the month (January–December). To improve readability, the index for identifying the sub-basin is omitted for all parameters and variables. Each sub-basin is treated lumped (i.e. no spatial variability within sub-basin).

Table 7
Parameters of the water balance model. Range specifies the parameter bounds during calibration. A single value is given if the parameter is not calibrated.

Parameter	Units	Range	Description
$mETP$	mm/d	–	Long-term mean monthly potential evapotranspiration in reference period.
mT	$^\circ$C	–	Long-term mean monthly air temperature in reference period.
F	$^\circ$C^{-1}	0.025	Empirical factor obtained from sensitivity tests with Penman-Monteith.
TF	–	0.5	Through-fall fraction for interception of precipitation.
SI_{max}	mm	2	Interception storage capacity.
$S1_{max}$	mm	100–2000	Soil storage capacity.
$S1_{crit}$	–	0.5	Critical soil moisture below which evapotranspiration is reduced.
$Beta$	–	1–10	Soil exponent for runoff generation.
$K2$	–	0–1	Fraction for separation of surface flow.
$K3$	h	1000	Base flow recession coefficient.

Table 8
Variables of the water balance model. Flux variables represent sums over the time-step. State variables give the water storage at the end of the time-step.

Variable	Units	Type	Description
P	mm	Input	Precipitation sum over time-step.
T	$^\circ$C	Input	Mean air temperature within time-step.
ETP	mm	Flux	Potential evapotranspiration.
$ETPI$	mm	Flux	Available potential evapotranspiration for interception.
$ETAI$	mm	Flux	Actual evaporation from interception storage.
$ETPR$	mm	Flux	Remaining potential evapotranspiration after interception.
SI	mm	State	Water stored in interception storage.
$PNET$	mm	Flux	Net-precipitation after interception.
$S1$	mm	State	Water stored in soil storage.
$ETAG$	mm	Flux	Actual evapotranspiration from soil storage.
ETA	mm	Flux	Total actual evapotranspiration.
$Q0$	mm	Flux	Runoff generation.
$Q1$	mm	Flux	Surface flow.
$Q2$	mm	Flux	Percolation to base flow storage.
$S3$	mm	State	Water stored in base flow storage.
$Q3$	mm	Flux	Base flow.
$QSIM$	mm	Flux	Runoff.
$X1$ to $X3$	mm	–	Temporary variables for interception module.

Potential evapotranspiration

$$ETP_t = mETP_i \cdot [(T_t - mT_i) \cdot F + 1] \cdot \Delta t/24$$

Interception module

$$X1 = SI_{t-1} + (1 - TF) \cdot P_t$$

$$X2 = \max\{0, X1 - SI_{max}\}$$

$$X3 = X1 - X2$$

$$ETPI_t = ETP_t \cdot \frac{1.5 \cdot SI_{max}}{1.5 \cdot SI_{max} + 1}$$

$$ETAI_t = \min\left\{ETPI_t, X3\right\}$$

$$ETPR_t = ETP_t - ETAI_t$$

$$SI_t = X3 - ETAI_t$$

$$PNET_t = X2 + TF \cdot P_t$$

Soil module

if $S1_{t-1} < S1_{crit} \cdot S1_{\max}$:

$$ETAG_t = ETPR_t \cdot S1_{t-1}/(S1_{crit} \cdot S1_{\max})$$

if $S1_{t-1} \geq S1_{crit} \cdot S1_{\max}$:

$$ETAG_t = ETPR_t$$

$$ETA_t = ETAI_t + ETAG_t$$

$$Q0_t = PNET_t \cdot (S1_{t-1}/S1_{\max})^{Beta}$$

$$S1_t = S1_{t-1} + PNET_t - ETAG_t - Q0_t$$

Surface flow module

$$Q1_t = K2 \cdot Q0_t$$

$$Q2_t = (1 - K2) \cdot Q0_t$$

Base flow module

$$Q3_t = \Delta t \cdot S3_{t-1}/K3$$

$$S3_t = S3_{t-1} + Q2_t - Q3_t$$

Runoff

$$QSIM_t = Q1_t + Q3_t$$

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