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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