HYDROLOGICAL IMPACTS OF CLIMATE CHANGE IN THE
ZAMBEZI RIVER BASIN

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Abstract
Observed hydrological records and climate change projections indicate that freshwater resources are
vulnerable to the impacts of climate change. To assess the impacts of climate change on streamflow in the
Zambezi river basin, the calibrated Pitman model was forced with downscaled and bias corrected GCM
(ECHAM, GFDL and IPSL) data. Calibration and validation results indicate that the modified Pitman model
is capable of reproducing the hydrological response characteristics of the various sub-basins in the Zambezi,
with coefficients of determination and efficiency both above 0.6 in most of the sub-basins. Future (2046-2065)
climate change predictions suggest that conditions in the basin are likely to remain within the ranges of
historically observed variability, with changes in streamflow of ±10%. However there is uncertainty around
the magnitude and direction of change in the basin’s response to future GCM scenarios. The study
recommends that uncertainty should be acknowledged in future water resource management plans.

Keywords: climate change, hydrological modelling, Zambezi basin
1. INTRODUCTION

The availability and accessibility of water is essential for human health and development and for the maintenance of ecosystems. However, water resources are under continuous threats from pollution, increased population growth, development and urbanisation. Added to these threats are the impacts of natural climate variability and anthropogenic climate change. Because of the inherent association between the hydrological cycle and the climate system, hydrological variability is inevitably driven by climatic variability while at the same time variability in climate can be observed through changes in temperature and precipitation (Peel et al., 2002, 2004). The potential threats of a variable and changing climate include alteration of hydrological variables such as precipitation, streamflow, soil moisture, groundwater recharge, evapotranspiration as well as changes to the timing and magnitude of the extreme events (Nijssen et al., 2001; Zhang, 2005; Zhang et al., 2007). Such changes will have varying impacts on societal well-being, ranging from water supply, health, food security, energy and the environment (Xu, 2000). Across Africa, high climatic variability and a high degree of hydrological variability has already imposed immense pressures on the economy, infrastructure, and livelihoods of vulnerable societies (Conway and Hulme, 1996). In addition to the threats of natural climatic variability freshwater resources are also under pressure from a rapidly increasing population and economic development, and as the standard of living improves, the demand for freshwater also increases. The United Nations Population Reference Bureau (UN, 2006) projects a global population of about 8 billion by the year 2025, and the World Bank (2005) estimates that demands for water will exceed supply by 40% by 2030, while two-thirds of the global population could experience water stress by 2025.

Freshwater resources are good indicators of climatic variability and have the potential to be greatly impacted by fluxes of moisture and energy that emanate from changes in atmospheric circulation (Kabat and van Schaik, 2003). As such, most of the impacts of a changing and varying climate will be felt through water resources (Chiew, 2007). The various impacts that occur at the different time scales of variability are a clear indication that water resources can no longer be managed under assumed stationary climatic conditions (Milly et al., 2008), but rather the dynamics of climate change must be considered in order to develop a well-informed water resources management strategy for the future.

There is now compelling evidence that the global climate has become warmer and climate change is rapidly becoming a matter of global concern (IPCC, 2007). Long term records show that the mean global surface temperature increased by 0.6°C in the 20th century (IPCC, 2001; Trenberth et al. 2007). The IPCC (2001) also projects that by the year 2100 the mean temperature will have increased through a range of 1 to 3.5°C, while sea level will rise through a range of 15 to 95cm. At the same time the concentration of atmospheric carbon dioxide (CO2), a major product of burning fossil fuels and a warming agent for atmospheric temperatures is expected to rise to more than double the pre-industrial levels by the end of the 21st century (IPCC, 1996). With the projected changes in global temperatures due to greenhouse gas emissions, there is growing consensus among scientists that the hydrological cycle will intensify and that extreme flood and drought events may become more frequent.

A wealth of literature is available justifying the need to undertake investigations on the impacts of changing climates on water resources. Quantifying the hydrological impacts of climate change and knowledge of the vulnerabilities to climate variability as well as appropriate response strategies will enable the formulation of
adaptation options that are based on the most appropriate design and implementation techniques (Zhang et al., 2007; Ziervogel et al., 2010). Kundzewicz (1997) advocates the incorporation of the current climate variability into water-related management as this would make adaptation to future climate change easier. Zhang et al. (2007) state that quantifying the hydrological impacts of climate change will assist in understanding the potential climate-related water problems and to make better planning decisions. Bardossy (2007) and Jacob and van den Hurk (2009) concur that understanding the potential impacts of a changing climate on streamflow is vital for design and management of water resources and that it can be explored through the use of complex numerical models, including the hydrological models (e.g. Knutti, 2008).

There is high uncertainty as to how climate change will manifest itself and about how the climate system will respond to external forces including anthropogenic influences such as land use changes, development and population expansion and greenhouse gas emissions. Uncertainty in climate predictions will continue to undermine the efforts being put towards promoting human social and economic development as well as safeguarding the environment (Todd et al., 2011). Despite the uncertainties, the imminent threats of climate change must still be acknowledged alongside the threats of climate variability and development impacts so that appropriate strategies may be developed to deal with the risks in the management of water resources. It is therefore necessary to quantify the responses of the global climate system to future development scenarios. Because of the complexity of the climate system, it is prudent to use physically based climate models to simulate the flow of energy between the land surface, atmosphere and oceans and to date Global Circulation models (GCMs) have been used for this purpose. Hydrological models have also enjoyed wide use in quantifying water resources worldwide.

The overall goal of this study was to quantify the hydrological impacts of climate change in the Zambezi River basin. The modified Pitman hydrological model was calibrated after which future streamflow was predicted by forcing the model with downscaled future rainfall and temperature data generated under future climate change scenarios.

2. MATERIALS AND METHODS

2.1 Study area
Covering an area of about 1 360 000 km² and located between latitudes 8°S-20°S and longitudes 16.5°E-36°E (Figure 1), the Zambezi is the fourth largest river basin in Africa. About 30 million people reside in the basin with most of the livelihoods largely dependent on rainfed agriculture. The Zambezi River runs for a total length of 2 750 km from source to its mouth in the Indian Ocean. Much of the basin’s drainage area is within south-central Africa and there are eight countries riparian to the basin namely; Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe.

The arid to semi-arid climate of the Zambezi basin is influenced by the Congo air masses and prevailing wind systems, including tropical cyclones from the Indian Ocean. High temperatures are the main cause of the variable and elevated evaporation rates across the basin. The actual evaporation amounts are variable across the basin and range from average annual amounts of 1 600 mm to 2 500 mm based on the class A evaporation pans and using a standard coefficient of 0.9 (Beilfuss and dos Santos, 2001). Rainfall in the basin is largely influenced by the Inter Tropical Convergence Zone (ITCZ) which moves over the basin from October until...
April (Chenje, 2000), thereby concentrating the rainfall during the months of December to March. The mean annual rainfall in the basin is about 950mm but with a very high degree of spatial variability across the basin. Less rainfall is received in the south while the northern areas receive more rainfall.

About 15.4% of the basin area is under agriculture of which about 71% is open land on which shifting cultivation occasionally takes place. Forests take up about 5.6% of the basin area whilst about 7.7% of the area includes water bodies of various forms (Chenje, 2000). The predominant natural vegetation type in the basin is Savanna while dense forests and woody Savannas are common in the north-western part of the basin. Large areas of cropland are present particularly in the middle and in some lower areas of the basin. A number of floodplains and swamps exist in the basin and these mainly act as evaporating pans resulting in substantial loss of the basin’s annual precipitation. About 65% of the total annual precipitation is lost to evaporation over the Barotse and Chobe flood plains before passing over Victoria Falls (Salecwicz, 1996).

2.2 The Pitman Model

The Pitman model (Pitman, 1973) is a conceptual semi-distributed monthly time-step rainfall runoff model. The model consists of conceptual tank type storages; interception, soil moisture and groundwater that are linked by functions to represent hydrological processes at the catchment scale. The main inputs to the model are a time series of monthly rainfall and monthly distributions of potential evaporation. Catchment area is also a necessary requirement for the model. Originally developed by Pitman (1973), the model has since undergone some modifications that are meant to account for challenges in data availability and to better quantify hydrological processes at the catchment level. The modified version of the Pitman model (Hughes et al., 2006) was used for this study. The new version still maintains a large part of the original model structure as developed by Pitman (1973) but with additions of other components and functionalities. A more explicit representation of the ground water and surface water interactions as well as reservoir and wetland water balance functions have also been added (Hughes 1997, 2004). Because of its ability to represent real catchment responses to runoff in southern Africa, the model has been widely applied to water resources assessment in the region (e.g. Hughes, 1997; Hughes et al., 2006; Kapangaziwiri and Hughes, 2008; Ndiritu, 2009).

The Pitman model for the Zambezi River basin was set up in SPATSIM; a Spatial Time Series and Information Modelling software (Hughes and Forsyth, 2006). The software is intended to provide tools for managing and manipulating data, setting up and running hydrological models, as well as analysing and interpreting data. SPATSIM has a GIS spatial interface linked to a flexible database of attribute information and supported by a comprehensive range of data display and analysis facilities. Model set up in SPATSIM includes creating the necessary features by loading shapefiles of all the relevant spatial elements which consist of the sub catchment polygons, raingauge and streamflow gauging station points and rivers (lines). Necessary attribute information is linked to a run of the model for a group of sub-catchments. This is done by creating sub-catchment linkages in the ‘downstream area’ attribute where, for an active sub-catchment the name of the downstream sub-catchment is entered. The full time series of simulated flows are stored within the SPATSIM database and can be examined in detail using the inbuilt SPATSIM utilities. A text file which consists of all the parameter values and some summary statistics, including mean monthly flow, mean monthly recharge and the flows for three % points (10, 50 and 90) of the simulated flow duration curves. A set of objective functions are included for each simulation. These are the percentage bias between the mean monthly flows (observed and simulated) and the Nash-Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970) based on the normal
and transformed values. The transformed values are used to eliminate the large influence of high flows and to emphasise the role of low flows.

Figure 2 represents the schematic used in calibrating the Pitman model. The initial step involved an exploration of the physical basin property data necessary to inform the initial ranges (minimum and maximum) of model parameters across the sub-basins. Based on some of the established calibration principles for the Pitman model (Hughes, 1997), the conceptual understanding of the model parameters and a qualitative interpretation of the physical basin characteristics, it was possible to derive the initial ranges of the model parameters. The length of observed streamflow records varied between the different gauging stations hence there was no common simulation period but the simulations were based on a reasonably long time series (> 10 years). Due to the problem of ungauged catchments and issues of data paucity, the Pitman model was calibrated for the Zambezi River basin only at those sub-basins (Figure 3) that are gauged and whose data was of reasonably long time series and with a few missing gaps. These sub-basins are mainly on the mainstream of the Zambezi River as well as at the outlet of the Luangwa sub-basin.

2.3 Scenarios for climate change
To evaluate the climate change impacts on water resources in the Zambezi basin, three GCM model outputs (ECHAM, GFDL and IPSL) under the A2 emissions scenario (Nakicenovic et al., 2000) were obtained from the Climate Systems Analysis Group (CSAG) at the University of Cape Town. The A2 scenario describes a world of high population growth and less rapid economic development which is characteristic of many developing countries. These GCMs are a subset of the CMIP3 (Coupled Model Inter-comparison Project) multi-model dataset that was used as input to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007). The GCMs were empirically downscaled (Hewitson and Crane, 2006) to 0.25° resolution using artificial neural networks. Unlike the traditional empirical downscaling methods that rely on statistical relationships between the global circulations and the local climate characteristics and thus being constrained by the assumptions of the statistical model, the artificial neural networks method removes the constraints by deriving direct mathematical relationships between the global circulations and the local climate characteristics. In addition this method is able to capture some of the non-linear relationships that exist between the global and local climates. The impacts of future (2046-2065) climate change were assessed in relation to the baseline historical period of 1960-1990. The points for which the downscaled GCM data are available are shown in Figure 4.

3. RESULTS AND DISCUSSION

3.1 Pitman Model Calibration and Validation
Model calibration results for selected sub-basins of the Zambezi are presented in Table 1 and Figure 5. Calibration and validation results indicate that the modified Pitman model is capable of reproducing the hydrological response characteristics of the various sub-basins in the Zambezi, with coefficients of determination and efficiency both ranging between 0.66 and 0.83 in most of the sub-basins and from 0.6 to 0.84 for the calibration and validation (Table 2) respectively.
3.2 Future climate change
The near future period of 2046-2065 is considered relative to the historical baseline period of 1960-2000. To simulate the basin’s response to future climate change three GCM model outputs for the A2 emissions scenario consisting of ECHAM, GFDL and IPSL were used as input to the Pitman rainfall runoff model which was calibrated for the Zambezi basin. This study focuses on the changes in streamflow as a result of climate change.

In addition to precipitation, estimates of potential evapotranspiration are also required as input to the Pitman model. Instead of evaporation data, the CSAG data sets provide minimum and maximum temperature data for the baseline and future climates. These temperature data are first converted to potential evapotranspiration using the Hargreaves approach (Allen et al., 1998). In general the three GCMs predict accelerated potential evapotranspiration rates (Table 3) which are expected to change through a range of 4% to 20% across the entire basin; a consequence of basin warming in the future.

Bias-corrected GCM as well as the historical mean monthly rainfall distributions for selected sub-basins in the Zambezi are presented in Figure 6. The results show that seasonality is largely preserved and there are no indications of a shift to an earlier or later wet season. Comparing the three GCMs, the IPSL model predicts large changes in the peak rainfall distribution amounts. Basinwide the seasonal changes in precipitation are more pronounced for the wet season months of December to April and there is almost no notable change throughout the dry season (May to September). The changes in magnitude and frequency of occurrence of rainfall in response to climate change and with respect to the historical rainfall are reported in Figure 7. All three GCMs predict no substantial changes in the near future rainfall. In general the predicted changes deviate from the mean monthly historical rainfall by amounts in the range of -2 to 12%.

3.3 Impacts of climate change (2046-2065) on streamflow
The predicted changes in the magnitude, duration and frequency in streamflows for the near future period for using example sub-basins of the Zambezi are illustrated in Figure 8. Overall there are some notable changes in the high flow events while the low flow events are expected to be less impacted by the changes in climate. In most of the cases the low flows are very similar in magnitude to the historical flow conditions. In general the patterns of change observed for the near future streamflows follow closely the pattern of change of rainfall where there is a distinct variation in the high rainfall events between the historical and the near while no clear distinction can be made for the low rainfall events. This pattern suggests that rainfall has a major influence on the streamflows and the water balance in general.

Changes in the monthly streamflow distribution amounts relative to the historical streamflows are shown in Figure 9. The changes are calculated as percent deviations of the long term mean monthly streamflow values of the future climate from the historical means. Mixed changes in seasonal streamflow distributions are observed for the three GCM scenarios. In general and for all the GCMs no considerable (≤10%) changes in the mean annual streamflow are anticipated by the 2050s. The fact that all models show predominantly reduced or stable near future streamflow conditions may be due to the magnitude of projected increases in potential evapotranspiration that tend to exceed the predicted increases in precipitation. Although the absolute percentage increase in the dry season flows is predicted to be quite high compared to the change in wet season
flows the change can be considered to be insignificant in relative terms since in arid areas the base-flows are low and they do not contribute much to the total annual flow.

4. CONCLUSION
This study gives insight into the hydrological responses of the Zambezi basin to future changes in climate. The Pitman model was successfully calibrated for the Zambezi basin. Climate change scenarios for the near future period of 2046-2065 were used to assess the future climate and hydrological conditions of the Zambezi basin. Outputs of three global climate models (ECHAM, GFDL and IPSL) were used as inputs to the Pitman rainfall-runoff model which had been calibrated for the Zambezi River basin. The future changes were evaluated against historical climate of 1961-2000 and quantified by taking the percentage deviation of the mean future conditions from the mean historical conditions. There is no consensus among the GCMs on the direction and magnitude of change of precipitation and streamflow. With a few exceptions, all the GCMs predict changes in total annual precipitation in the range of ±20% and -3% to 12% for the average monthly distributions. The wet season rainfall is expected to increase by varying degrees between the different months of the season and across the various GCMs while the dry season rainfall conditions will remain almost the same.

The three GCMs predict a warming basin in the future resulting in accelerated potential evapotranspiration rates which are expected to change through a range of 5% to 20%. Unlike the mixed direction of change in rainfall predictions of the different GCMs, unidirectional increases in potential evapotranspiration are predicted in the entire basin and these changes are of a similar range of magnitude for all the GCMs. Judging from the close similarity in potential evapotranspiration changes predicted by the three GCMs it can be assumed that GCMs are better at simulating temperature than rainfall.

All the GCMs predicted a general but marginal increase (≤10%) in the high flow components of the flow duration curves, while the dry season flows are simulated to decrease slightly or to remain relatively stable. Although it was observed that the absolute percentage increase in the dry season flows was quite high compared to the change in wet season flows the change was considered to be insignificant in relative terms since in arid areas the base-flows are low and they do not contribute much to the total annual flow. Predictions for the seasonal streamflows are mixed in direction but overall the near future streamflow conditions are expected to change slightly or to remain almost the same as the historical streamflow. It is possible that when there is no change in rainfall or when the changes are minimal the increases in potential evapotranspiration may result in increased actual evapotranspiration thereby reducing the runoff.

This study has therefore generated some preliminary estimates of the effects of future climate change on water resources in the Zambezi basin. Overall the research findings indicate a warmer basin climate and a generally increasing trend in precipitation but only with slight changes in the basin streamflows by the 2050s. Although the predicted changes in precipitation and streamflow are not of the same magnitude, the patterns of streamflow change closely follow those of the change in precipitation. There is, however, a large range of uncertainty in the quantitative prediction of the basin’s hydrological responses. It is concluded in general that the predicted impacts of climate change will be minimal in the near future and that the hydrological conditions
are likely to remain within the historical range of variability. It is also recommended that water resource planners should acknowledge uncertainty when assessing the hydrological impacts of climate change.

REFERENCES


Figure 1: Location of the Zambezi River basin. Boundaries-sub-basins
Figure 2: Schematic for calibration with Pitman model

Figure 3: Flow gauging stations used to calibrate the Zambezi River basin
Figure 4: Downscaled GCM grid points for the Zambezi River basin

Table 1: Objective performance statistics for calibration in selected sub-basins

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<tr>
<th>Sub-basin</th>
<th>Station</th>
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<th>$R^2$</th>
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<th>% error</th>
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Figure 5: Observed and simulated monthly streamflows for selected sub-basins

Table 2: Objective performance statistics for validation in selected sub-basins

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<th>Sub-basin</th>
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Figure 6: Seasonal distributions of monthly rainfall for the historical (1961-2000) and bias corrected near future (2046-2065) rainfall

Table 3: Mean monthly potential evapotranspiration changes in the future example sub-basins

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<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
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<th>Jun</th>
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Figure 7: Future (2046-2065) changes in mean monthly rainfall relative to the historical rainfall (1961-2000)

Figure 8: Flow duration curves for the historical and near future streamflows
Figure 9: Future changes in streamflow relative to the historical flow