Okavango River Basin Transboundary Diagnostic Analysis Technical Report

OKACOM

The Permanent Okavango River Basin Water Commission

Okavango TDA study
Assessment of hydrological effects of climate change in the Okavango Basin

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Okavango TDA study

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Contributions on combined climate change – development impacts by H Beuster

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1 Background and objectives

Consideration whether or not human greenhouse-gas emission-related climate change is happening or will happen in the future, is generally accepted in the mainstream science (IPCC, 2007), and its discussion is well beyond the scope of this report.

The objective of the study reported here is to determine the effects of climate change on the Okavango River flow and flooding in the Okavango Delta, based on methods commensurate with the current state of knowledge and technology in prediction of future global and regional climates and availability of data for the Okavango region. The hydrological focus causes that climatological analyses are simplified, and methodologies concentrate on derivation of inputs for hydrological models (i.e. rainfall and evaporation) that reflect a range of possible future conditions. These are derived from results of General Circulation Models (GCM) and statistical downscaling (SD).

This report is organized as follows:

- introduction gives an overview of methods used in climate change impact studies, in particular addressing uncertainty of the process of derivation of climate change signal
- review section summarized results of earlier work on climate change in the Okavango
- materials and methods section describes available datasets and methods used in the analyses
- exploratory analyses section deals in particular with several issues identified earlier:
    - comparison of various datasets
    - applicability of satellite-derived rainfall for SD
    - analyses of past changes and trends
- results section deals with results of analyses of GCM and SD, as well as results of hydrological models an includes the following:
    - climate change projections based on raw GCM
    - climate change projections based on SD
    - summary of the above – derivation of change signal to be applied in hydrological models
    - results of hydrological modeling
        - present levels of water use in the basin
        - climate change superimposed on future water use projections
- summary and discussion

2 Introduction

Climate projections are generally provided by physically-based Global or General Circulation Models (GCMs). These are computer models that numerically describe physical processes of mass and energy transport in Earth's climate system. State-of-the-art GCMs are coupled atmosphere-ocean models (CGCMs) that simulate both atmospheric and surface and deep ocean circulations, with transfer of energy and water (evaporation and precipitation) and momentum occurring at the sea surface. Space and time is discretized within the GCMs to form distinct computational blocks – i.e. units of space and time, within which properties and fluxes are considered to be uniform. These models are run with observed energy inputs and parameters such as surface albedo or concentration of greenhouse gases and aerosols to reflect past conditions. Projections of greenhouse gas emissions and other factors are then used to simulate future climate.

GCMs are run by several computational centres in the world, and currently there exists over 20 GCMs, output of which is publicly available through World Climate Research Program (WCRP) Climate Model Intercomparison Project (CMIP3) at www-pcmdi.llnl.gov and several other internet data outlets.

GCMs differ in such aspects as size of computational grid and processes that are included in computations and their parametrization. There are therefore differences between climates simulated by various GCMs, and by virtue of GCMs simplicity as compared to the real world, differences between modelled and observed climate. These differences vary in magnitude with spatial and temporal scales, and for various regions and periods. Climate models are based on well-established physical principles and have been demonstrated to reproduce observed features of recent climate and past climate changes. There is considerable confidence that GCMs provide credible quantitative estimates of future climate change, particularly at continental scales and above. Confidence in these estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation) (IPCC, 2007).

Translation of outputs of GCMs to quantitative characteristic of future climate at a given location is affected by a range of uncertainties related to:

- future greenhouse gas emissions and land use changes.
- differences in future climates simulated by various GCMs
- disparity of spatial and temporal scales at which GCMs are working and at which information on changes in climate is needed for impact studies.
- natural climate variability that is not simulated (unresolved) by GCMs

2.1.1 Greenhouse gas emissions

Future conditions of the climate system depend not only of internal processes within that system, but also on anthropogenic emissions of greenhouse gases and aerosols. These relate to the level of population and economic growth and technological development, which in the long term respond to environmental, economic or institutional constraints. Due to their relative unpredictability, in the context of the analyses of climate change these variables are dealt with by emission scenarios – several plausible trajectories of socio-economic and technological development in the future, detailed in the IPCC Special Report on Emission Scenarios (SRES, Nakićenović et al., 2000).

QuickTime™ and a
decompressor
are needed to see this picture.

Fig. 1 Global warming projected under anthropogenic gas emission scenarios (source IPCC, 2007)

Table 1 Summary of greenhouse gas emission scenarios (Nakićenović et al., 2000)

A1 - more integrated world

* Rapid economic growth.
* A global population that reaches 9 billion in 2050 and then gradually declines.
* The quick spread of new and efficient technologies.
* A convergent world - income and way of life converge between regions. Extensive social and cultural interactions worldwide.

A2 - a more divided world.

* A world of independently operating, self-reliant nations.
* Continuously increasing population.
* Regionally oriented economic development.
* Slower and more fragmented technological changes and improvements to per capita income.

B1 - a world more integrated, and more ecologically friendly.

* Rapid economic growth as in A1, but with rapid changes towards a service and information economy.
* Population rising to 9 billion in 2050 and then declining as in A1.
* Reductions in material intensity and the introduction of clean and resource efficient technologies.
* An emphasis on global solutions to economic, social and environmental stability.

B2 - a world more divided, but more ecologically friendly.

* Continuously increasing population, but at a slower rate than in A2.
* Emphasis on local rather than global solutions to economic, social and environmental stability.
* Intermediate levels of economic development.

* Less rapid and more fragmented technological change than in A1 and B1.

GHG scenarios differ considerably in magnitude of projected change in climate, particularly for longer time scales. If treated as equiprobable, they give a large range of possible future climatic conditions, although major differences are noticeable only towards the end of the 21st century.

2.1.2 Differences in climates simulated by various GCMs

It is well recognized that various GCMs differ in how well they simulate past climate, and in magnitude of change they simulate for future (IPCC, 2007; Giorgi and Francisco, 2000). The differences arise because GCMs differ in number of processes they represent, in process parameterization, resolution of spatial grid and initial conditions.

In early climate impact studies, however, outputs of a single, or only a few GCMs were used to determine change signal. This was based on an assumption that the selected model is appropriate for a given location and purpose, but the choice was obviously limited by access to model data. Such an approach was used in earlier climate work in the Okavango region (e.g. Wolski et al., 2002; ODMP, 2006). However, since the advance of Climate Model Intercomparison Project, (CMIP2, Meehl et al., 2000), data from over 20 GCMs are freely available in a uniform format. This has generated a considerable body of work on multi-model ensembles and their use in climate change impact studies.

The multi-model methods are predicated on the fundamental belief that no model is the true model, and there is value in synthesizing projections from an ensemble, even when the individual models seem to disagree with one another. Predictions for the El Nino Southern Oscillation (ENSO) and seasonal forecasts from multi-model ensembles are generally found to be better than single-model forecasts (e.g. Palmer et al., 2005), and allow for formalization of uncertainty related to the modeling errors.

Formalization of range of uncertainty can be done using several methods. The most robust method is to derive a minimum and maximum values of possible future climatic parameteres from the ensemble. However, different models often disagree even on the sign of rainfall changes expected in particular regions (Giorgi and Francisco, 2000), thus simple range information is not particularly useful in impact studies, as, particularly in case of rainfall, it often encompasses both increase and decrease. Determination of consistency between ensemble members in projecting given direction of change (i.e. information on how many models project given direction of change) as in regional climate projections of the 4th IPCC report (IPCC, 2007), provides information on likelihood of that projection.

Other methods are based on model averaging, and provide the most probable scenario with quantified uncertainty range. These methods can either be deterministic or stochastic and treat various GCMs as equiprobable (e.g. Palmer and Räisänen, 2002). More recent approaches take the principle that non-uniform weighting may be more appropriate as models may have unequal skill or simulation capability regional scale temperature change or change in other climatic variables such as precipitation (Allen and Ingram, 2002). Giorgi and Mearns, 2002, developed averaging method based on metrics of model bias and convergence, while Tebaldi et al., 2005 extended it to the Bayesian approach.

The uncertainty across GCMs is generally larger than that across GHG scenarios (e.g. Prudhomme et al., 2003) thus using one GHG scenario and multimodel GCM ensemble will encompass a large proportion of the overall uncertainty

2.1.3 Disparity of spatial and temporal scales

A clear mismatch exists between climate and hydrologic modelling in terms of the spatial and temporal scales, and between GCM accuracy and the hydrological importance of the variables. In spite of computational development since the advance of GCMs in the 1970s they remain relatively coarse in resolution and are unable to resolve significant subgrid scale features such as topography, clouds and land use. For example, the Hadley Centre's HadCM3 model is resolved at a spatial resolution of 2.5° latitude by 3.75° longitude. Impact applications require the equivalent of point climate observations and are usually highly sensitive to fine-scale climate variations that are not explicit in GCMs. Additioanlly, the reproduction of observed spatial patterns of precipitation (Salathe, 2003) and daily precipitation variability (Burger and Chen, 2005) is not sufficient. However improved results can be obtained by the application of even simple downscaling methods (Wilby et al., 1999)

The simplest method is to apply GCM-scale projections in the form of change factors (CFs) – the 'perturbation method' or 'delta-change' approach (Prudhomme et al., 2002). More sophisticated approaches to downscaling of large-scale GCM output to a finer spatial resolution include dynamical and statistical downscaling. The dynamical approach uses a higher- resolution climate model embedded within a GCM. The statistical approach uses statistical methods to establish empirical relationships between GCM-resolution climate variables and local climate.

In the dynamical downscaling, regional climate models (RCMs) use large-scale and lateral boundary conditions from GCMs to produce higher resolution outputs. RCMs are typically resolved at the 0.5 ° latitude and longitude scale and parameterize physical atmospheric processes. Thus, they are able to realistically simulate regional climate features such as orographic precipitation, extreme climate events and regional scale climate anomalies, or non-linear effects, such as those associated with the El Nino Southern Oscillation (Leung et al., 2003). However, model skill depends strongly on biases inherited from the driving GCM and the presence and strength of regional scale forcings such as orography, land-sea contrast and vegetation cover. Variability in internal parameterizations also provides considerable uncertainty.

Statistical downscaling methods rely on the fundamental concept that regional climates are conditioned by two factors: the large-scale atmospheric state and regional/local physiographic features (e.g. topography and land use). This relationship may be expressed as a stochastic and/or deterministic function between large-scale atmospheric variables (predictors) and local or regional climate variables (predictands) that implicitly parameterizes the physiographic features influence on regional/local climate. Predictor variables useful for downscaling typically represent the large-scale circulation, e.g. sea-level pressure and geopotential heights, but can also include measures of humidity and simulated surface climate variables such as GCM precipitation and temperature. After the local climate- large scale atmospheric state relationship is established based on observed data, the large-scale output from GCMs is fed into this statistical model to estimate corresponding local and regional climate characteristics.
Statistical methods are more straightforward than dynamical downscaling but tend to underestimate variance and poorly represent extreme events.

Reviews of methods and applicability of dynamical and statistical downscaling can be found among others in: Fowler et al., 2007; Hewitson and Crane, 1996; IPCC, 2007; Leung et al., 2003; Prudhomme et al., 2002; Wilby et al., 1998; Wilby et al., 2004;)

2.1.4 Natural climate variability

Climatic phenomena are characterized by natural intrinsic variability, that results form nature of processes of turbulent mass and energy transport. The ability to represent these processes and thus the variability in climate models is, obviously, very limited. By they nature (spatial and temporal scales, set of physical processes represented), GCMs are not able to project climatic conditions for any particular year, but are considered appropriate to represent average conditions within a period of time, and 30-year averaging period is usually taken as representative to these prevalent conditions. However, such an assumption does not take into consideration that 30-year climates vary naturally. Such variation can be "random", or forced by internal feedbacks involving processes acting at longer time scales – thermohaline circulation, sea surface temperature anomalies, land use/land cover changes (Ansell et al., 2000; Chelliah and Bell, 2004; Goosse et al., 2005; IPCC, 2007; Meinke et al., 2005; Parker et al., 2007; Power et al., 1999). However, only a few studies of climate change impact formally account for the long-term variation (Arnell, 2003; Hulme et al., 1999, Sorteberg and Kvamstø, 2006). This is either done by derivation of range of natural variability from unforced long runs of climate models under pre-industrial concentrations of GHG (Arnell, 2003; Hulme et al., 1999), or by the analysis of multiple runs of a single GCM with perturbed initial conditions (Sorteberg and Kvamstø, 2006). If range of natural variability is comparable with climate change signal, these might not be distinguishable. This is particularly important in the first part of the 21st century, when climate change signal is not strong.

2.2 Methods of incorporating climate change signal in hydrological projections

The simple perturbation, delta or change factor approach (Prudhomme et al., 2002). for temperature just adds a projected temperature increase to the observed temperature record to obtain a future temperature time series. Precipitation is usually perturbed by a fraction. The use of these simple rules implies that only simple changes in the characteristics of these variables, such as changes in monthly, seasonal or annual means, are taken into account. Changes in the interannual variability, in the number of precipitation days, in the autororrelation and in the correlation between the different variables are usually not considered, although schemes can be appliied that account for changes in some of these characterisics (Lenderink et al., 2005).

The alternative is the "direct" approach, where output of the GCMs, RCMs or SD is used to force the hydrological model (e.g. Elshamy et al., 2009). Because of biases present in output of the climate models, it is usually necessary to perform some corrections prior to feeding the data into hydrological models, what introduces additional uncertainty. Direct approach can represent more complex changes in climate, e.g. correlations between the different climate variables, frequency and persistency of circulation patterns. However, these potential advantages might turn into a disadvantage when the quality of the climate model output is not good, i.e. when it does not adequately represent observed variability in the variables of interest (Diaz-Nieto and Wilby, 2005; Hay et al., 2000; Lenderink et al., 2005).

3 Previous work in the Okavango

Several studies have used predictions of future climate by Global Circulation Models to obtain hydrological and hydro-ecological effects of climate change on the Okavango Delta. The primary focus of these studies, however, seems to be on procedure and indices used for assessing the hydrological or ecological change, and not much attention was put on the actual derivation and uncertainty of climate change signal. To date, no study has used any downscaling procedure to derive change signal for the Okavango system.

Earlier studies differ in the choice of a GCM (or GCMs) on which the prognoses are based. Wolski et al., 2002 and ODMP, 2006 focused on analyses of hydrological effects based on HADCM3 model, which simulates future conditions to be hotter and drier than the past. As a result, a reduction of flows of the Okavango River and flooding in the Okavango Delta are projected. Andersson et al., 2006; Murray-Hudson et al., 2006; Wolski and Murray-Hudson, 2008 and Todd et al., 2008 used output of five GCMs: with two simulating future conditions as wetter, two as drier, and one as similar to conditions observed in the past. Changes in mean annual rainfall ranging from 10% increase to 15% decrease were projected in these studies, associated with increase in termperature in the range of 2.5-3.5 deg C. These changes were projected to result in reduction of Okavango River flows by 20% (for drier scenarios), or incrase by 25%, with marked seasonal differences. However, neither of the analyses revealed significant changes in interannual variability or temporal pattern of the annual flood.
Similar wide range of possible future wetness was obtained by Chiyapo, 2006 who analysed results of eight GCMs and Milzow et al., 2008, who analysed results of five. Obviously, there is a strong divergence between the various GCMs available in terms of magnitude and direction of simulated future rainfall change.

Analyses carried out in the framework of regional assessment for IPCC, 2007 report were not specifically targeting the Okavango. However, that report contains information extracted from the multi-model GCM ensemble for southern Africa. This information suggests lack of consistency between members of the GCM ensemble (21 models) in projecting the direction of change in rainfall in the Okavango, with slightly more models simulating drier than wetter conditions. The balance of the “drier-wetter” models shifts towards domination of wetter models in the northern part of the Okavango catchment. However, maps visualizing results of downscaling analeyeses suggest increase in precipitation over the southern Africa. Temperature projections are more consistent with increase projected in the range of 2-4 deg C.

4 Materials and methods

4.1 General approach

Mean values of rainfall and temperature were determined for a reference period in the 20th century and for a future period in the 21st century, based on SD results analyses. This was done for three equiprobable scenarios capturing the range of climates simulated by an ensemble of models used in SD. Subsequently, a ratio (for rainfall) and a difference (for temperature) of means were calculated for each scenario. These change factors (CF) were used to modify the observed time series of rainfall and temperatures, and the modified series were in turn used to drive a suite of hydrological models. Results of modeling with modified input data series were compared to these obtained with non-modified, observed data series, to assess hydrological effects of considered change, using impact indicators such as flow duration, mean inundation duration and shape of the discharge hydrograph.

The choice of the approach for this study has been constrained by the availability of data, nature of existing hydrological models, and climatic and hydrological variability in the analysed system. Notably:

- work followed the methodology of interval-based change factor. This approach has been selected over the direct methodology due to:
    - the role multidecadal rainfall variability plays in the processes of formation of runoff and flooding in the Okavango system. There is a strong multidecadal variability in the Okavango. It is manifested by sequences of above average or below average rainfall and flows at 40-60 years timescale. Results of SD are available only for two 20-year intervals (2046-2065 and 2081-2100), which is dictated by availability of daily GCM output. Hydrological conditions within such short-term periods would not be directly comparable with past conditions without an explicit selection of analogous period in the past. However, the multidecadal variability, particularly its temporal pattern, is not well represented by GCMs (Wolski, 2009), what makes selection of such an analogous reference period difficult if not impossible.
    - the use of FEWS rainfall dataset for downscaling of GCM output in the Angolan part of the basin. As shown below, the FEWS dataset introduces an error into the results of SD. The error becomes insignificant when relative projections, i.e. projections of change are used instead of direct projections of future conditions.
    - hydrological model of the Okavango catchment utilizing rainfall and potential evaporation data that are a compilation of various data sources. Application of direct method would have to involve reconstruction of the input data and probably recalibration of the model. Considering that the model in its current status has a history of applications, it was considered more appropriate to use it as is, instead of reconstructing it. Additionally, time frame of this project did not allow for the major undertaking of such a reconstruction.
    - hydrological models run on the monthly time step, which cancels the potential direct method's advantage of providing information on change in structure of daily rainfall.
- the work adopted a simple approach of defining “dry”, “moderate” and “wet” climate scenario to characterize ranges of conditions projected by the ensemble of climate models. The scenarios are considered here to be equiprobable. This approach has been selected over a more sophisticated approaches of stochastic or deterministic model averaging and further probabilistic simulations of climate and hydrology for the following reasons:
    - the number of models for which SD output is available is nine. This low number hardly justifies in-depth statistical analyses, particularly because it is

an "opportunistic" rather than a systematic ensemble, i.e. selected based on data availability and not on criterion of systematic representation of factors affecting uncertainty of GCM output.

- The scenarios were defined based on SD results, and not accounted for the range of future climates simulated by raw GCMs. This was done in spite of lack of agreement between raw GCM and SD results in magnitude and direction of change in rainfall. SD method is generally considered to provide results more suitable for hydrological modeling than raw GCM output. SD is calibrated based on observed data and thus more likely to accurately reflect forces driving climate change at a specific location than "generic" GCMs. However, the assessment of which results (raw GCMs or SD) are right or more probable or realistic, is a major research question and well beyond the scope of this report.

- Analyses were done under assumption of static vegetation, i.e. no effects of increased CO_2 and temperature on vegetation type, density and biogeochemistry, and through that on hydrological cycle, are considered.

- In the study, only one greenhouse gas emissions scenario is considered - SRES A2. Discussion of which SRES scenario is more likely is beyond the scope of this report. However, the differences between scenarios are relatively small up to the mid 21st century, which is the main period of interest of this study (Fig. 1). Greenhouse gas scenario used in this study, SRESA2, represents "business-as-usual" conditions. This is the only scenario for which GCM output is currently being downscaled for southern Africa.

4.2 Climate and climate models data

The following datasets were used in the study:
- daily rainfall and temperature data for Maun and Shakawe, obtained from Department of Meteorological Services, Botswana (Table 2).
- Monthly rainfall data for several stations in Angola (Table 2), compiled from various sources by EPSMO project.
- Monthly observed rainfall data from Global Historical Climatology Network, version 2 (GHCNv2) available from http://www.ncdc.noaa.gov (Peterson et al., 1998).
- daily gridded rainfall Famine Early Warning System (FEWS) dataset, obtained from http://www.cpc.noaa.gov. Data covers entire Africa with 0.1 deg resolution, and is composed of two parts, differing in algorithms used to derive rainfall values: RFE1.0 covering the period 1998/01/01 to 1999/12/31 (Herman et al., 1997), and RFE2.0 covering the period 2000/01/01 till 2008/12/31 (based on Xie and Arkin, 1996). For the analyses carried here, both datasets were combined.
- CRU2.0 reanalysis monthly gridded rainfall and temperature data. Data has spatial resolution of 0.1 deg, and covers period Jan 1901- Dec 2000 (Mitchell and Jones, 2005).
- mean monthly values of rainfall, minimum and maximum temperature simulated for 20th century (20C3M) and for 2000-2100 under SRES A2 scenario by 19 GCMs. These data were obtained from World Climate Research Program (WCRP) Climate Model Intercomparison Project (CMIP3) multi-model dataset available from www-pcmdi.llnl.gov. GCMs used are listed in Table 3.
- Results of climate downscaling using Self Organizing Maps (SOM) method for 18 meteorological stations in Botswana, including Maun and Shakawe. Downscaling results were obtained for nine GCMs (Table 3). The results were provided by Climate System Analysis Group, University of Cape Town.

Table 2 Rainfall stations used in the analyses

Station	Source	Long.	Latitude	Period	Type
Botswana					
Maun	DMS			1921-2009	Daily
Shakawe	DMS			1934-2009	Daily
Angola					
Lubango	EPSMO	13.56	-14.90	1961-2002*	Monthly
Huambo	EPSMO	15.45	-12.48	1961-2002*	Monthly
Bie	EPSMO	16.95	-12.38	1961-2002*	Monthly
Moxico	EPSMO	17.70	-14.66	1961-2002*	Monthly
CACONDA	GHCNv2	15.0	-13.2	1950-1974*	Monthly
CHENGA	GHCNv2	15.0	-13.0	1950-1974*	Monthly
CAFU	GHCNv2	15.3	-16.3	1950-1974*	Monthly
CUIMA	GHCNv2	15.5	-13.3	1950-1974*	Monthly
RIO_CHIPIA	GHCNv2	15.5	-12.3	1950-1974*	Monthly
PEREIRA_DECA	GHCNv2	15.7	-17.2	1950-1974*	Monthly
NOVA_LISBOA	GHCNv2	15.7	-12.8	1950-1974*	Monthly
MUPA	GHCNv2	15.8	-16.1	1950-1974*	Monthly
CHIANGA	GHCNv2	15.8	-12.7	1950-1974*	Monthly
CHINGUAR	GHCNv2	16.3	-12.5	1950-1974*	Monthly
CHITEMBO	GHCNv2	16.7	-13.5	1950-1974*	Monthly
CEILUNGA	GHCNv2	16.9	-12.3	1950-1974*	Monthly
SILVA_PORTA	GHCNv2	17.0	-12.4	1950-1974*	Monthly
GENERAL_MACHADO	GHCNv2	17.6	-12.0	1950-1974*	Monthly
SERPA_PINTO/MENONGUE	GHCNv2	17.7	-14.7	1950-1974*	Monthly
COEMBA	GHCNv2	18.0	-12.1	1950-1974*	Monthly
CUANGAR	GHCNv2	18.5	-17.5	1950-1974*	Monthly
CANGAMBA	GHCNv2	19.8	-13.6	1950-1974*	Monthly
GAGO_COUTINHO	GHCNv2	21.4	-14.0	1950-1974*	Monthly

*principal data period, but contains numerous gaps

4.3 Quality control of datasets

Rainfall data were screened for typing errors by visual inspections of rainfall vs. time plots, and identified erroneous values were corrected or replaced with a missing data value. The general approach was to correct only obvious typing errors, such as these identified by values exceptionally deviating from the mean (+-3 standard deviations rule) and for example by the number of significant digits. If error was not obvious, value was left unchanged, but flagged as possibly erroneous. These flags were later used during interpretation of results of analyses. Data for Angolan stations obtained from Angolan Dept of Meteorology, in the period of 1970-1998 often included monthly rainfall values that were in the order of 1-10% of these recorded in 1950-1970s. Such values were considered erroneous. Furthermore, lack of any indications at to number of missing data days in that dataset caused that the whole post 1970 Angolan dataset is considered questionable, even if values seemed realistic.

Systematic analyses of Maun and Shakawe rainfall using double mass plots were carried out in earlier studies (Scudder et al., 1993, SMEC, 1990), and in these studies several correction factors were included to account for small quasi-systematic departures of individual stations from regional trend. This was done in order to tweak performance of hydrological models using rainfall as input. It was later shown (Gieske, 1997; Wolski et al., 2006) that such corrections are not needed for adequate modeling of system's hydrology. It was therefore decided not to correct any rainfall data in this study.

Data from other sources (FEWS, GCM, CRU2.0, GHCNv2) were taken as is, but screened for obvious typing errors, and such were corrected or replaced with missing data value.

4.4 Analyses of consistency of datasets

The issues related to rainfall data availability affect two aspects of this study: analyses of past changes and variability of rainfall, and data needs for the procedure of statistical downscaling of GCM outputs. In both aspects data sources alternative to station data were used and therefore there was a need to assess consistency of available station data and these alternative data sources.

Analyses of past changes and variability of rainfall are relatively straightforward for Botswana data, as long-term rainfall datasets are available and are of good integrity. For Angola, such data are not available. No daily rainfall data for any station were available, precluding analyses of change in daily rainfall. Monthly station data were of questionable quality, and could not be used in change and variability analyses. In view of the above, reanalysis data had be used for such purpose. Consistency between CRU2.0 reanalysis dataset and observed data was assessed though rainfall climatologies. These were obtained directly from observed data (both GHCNv2 and EPSMO). For CRU2.0 gridded dataset, climatologies were calculated based on values for each station's location obtained from bilinear interpolation from grid points.

Due to lack of daily data for Angola, and short overlap between the observed and FEWS datasets, consistency between FEWS rainfall and observed rainfall could be assessed only in terms of monthly climatologies. Rainfall climatologies for observed station data were plotted against FEWS rainfall climatologies calculated based on values for each station's location obtained from bilinear interpolation from grid points.

For Botswana stations, where daily rainfall was available for periods overlapping with FEWS dataset, consistency of FEWS and observed data was analysed in terms of the following indices: mean annual rainfall, number of rain days with > 2mm rainfall (d_2), median daily rainfall (p50), maximum daily rainfall (pd_max), and an index representing timing of rainy season. The last index was taken as number of days since the beginning of climatological year (1 July) when cumulative rainfall exceeded 5% of total for that rainy season. All the indices were calculated for each of years for which data were available. Differences between the datasets were assessed using t-test on mean value of these indices calculated for years overlapping in both datasets.

4.5 Analyses of past change and variability

Past changes and ranges of variability in rainfall and temperatures were assessed through analyses of observed station rainfall data and values obtained from CRU2.0 reanalyses. Data series were tested for linear trend (t-test on significance of trend coefficient), homogeneity (Buishand test, Buishand, 1982) and significance of differences in means (F-test) and variances (Levene's test, Fox, 1997) between three non-overlapping 30-year (or almost-30-year) periods: 1920-1950, 1951-1980 and 1981-2008.

For datasets for which only monthly data were available tests were conducted only on annual means and variances. For daily datasets, the following indices were also assessed: number of rain days with > 2mm rainfall (d_2), median daily rainfall (p50), maximum daily rainfall (pd_max), and an index representing timing of rainy season. The last index was taken as number of days since the beginning of climatological year (1 July) when cumulative rainfall exceeded 5% of total for that rainy season.

4.6 GCM data processing

For the purpose of analyses of GCM climate change signal, each GCM dataset was regridded to a uniform resolution of 0.5 deg, and monthly values were spatially averaged within (rectangular) zones representing Okavango Delta, Lower and Upper catchment of the Okavango River (Table 4), subsequently coded D, L and U.

Means and variances were calculated for rainfall and temperature for each of the zones and for each of the GCMs (or GCM runs if data from more than one run were available) on annual and seasonal basis for reference period (1961-2000) and for "near-future" (2046-2065). Climate change signal was then obtained for each of the GCMs and for each of the zones by calculating differences (for temperature) and ratios (for rainfall and variances) between future and reference period means. If more than one run was available for a model, change signal used in further analyses was calculated by averaging signal obtained from individual runs.

Table 3 Global Climate Models used in the analyses

Modelling centre	Model name	Used in SD
Bjerknes Centre for Climate Research, Norway	BCCR-BCM2.0	
National Center for Atmospheric Research, USA	CCSM3	
Canadian Centre for Climate Modelling & Analysis, Canada	CGCM3.1(T63)	Y
Météo-France / Centre National de Recherches Météorologiques, France	CNRM-CM3	Y
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0 CSIRO-Mk3.5	 Y
Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	Y
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group. Germany/Korea	ECHO-G	Y
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Y
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	
NASA / Goddard Institute for Space Studies, USA	GISS-ER	Y
Instituto Nazionale di Geofisica e Vulcanologia, Italy	INGV-SXG	
Institute for Numerical Mathematics, Russia	INM-CM3.0	
Institut Pierre Simon Laplace, France	IPSL-CM4	Y
Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2(medres)	
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Y
National Center for Atmospheric Research, USA	PCM	
Hadley Centre for Climate Prediction and Research / Met Office, UK	UKMO-HadCM3	
Hadley Centre for Climate Prediction and Research / Met Office, UK	UKMO-HadGEM1	

Table 4 GCM data averaging zones

Block	Latitude	Longitude
Okavango Delta	18.0-20.5 S	21.0-25.0 E
Lower catchment	15.0-18.0 S	16.5-26.0 E
Upper catchment	12.0-15.0 S	16.5-26.0 E

4.7 Statistical downscaling of rainfall and temperature data

Statistical downscaling (SD) of rainfall and temperature data was obtained using the method developed at Climate System Analysis Group, University of Cape Town, described in details by Hewitson and Crane, 2006b. In the method, unique combinations of wind vectors, specific and relative humidities, and surface temperature are determined for a localized domain surrounding each location of interest on the basis of NCEP 6-hourly reanalysis data from 1979 to 2007. This is done with the Self Organizing Maps clustering technique. Importantly, the clustering takes into account not only values of variables, but also their spatial (circulation) pattern. For each unique atmospheric state, precipitation and temperature probability density functions (PDF) are derived based on observed precipitation and temperature data. Future climate states are derived from GCM data and temperature and precipitation values are drawn at random from the associated respective PDFs to produce downscaled series at given location.

SD has been done using synoptic variables derived from nine GCMs (Table 3). SD results are obtained in the form of daily rainfall series for reference period (1979-2000) and for "near-future" period (2046-2065) for each downscaled station/location.

The downscaling procedure requires at least 10-year long sequence of daily rainfall and temperature measurements overlapping with the period for which observed (NCEP reanalysis) synoptic variables are available, i.e. 1979-2007. Such data are available for Maun and Shakawe (and for several other stations in Botswana), but are not available for Angola. In order to derive rainfall change signal for Angola, FEWS rainfall series has been used.

As for change in temperature, analyses for Maun and Shakawe (and other Botswana stations) show that downscaling procedure gives results that are not significantly different from results derived from raw GCM output. Station observed temperature data are not available for Angola, however, it was considered unnecessary to attempt to substitute these data with an alternative dataset. Instead, temperature change in the Angolan part of the system was derived from raw GCM output.

Downscaling of GCM rainfall projections was done for locations corresponding to centroids of subcatchments used in hydrological modeling of the Okavango catchment. Since the hydrological model treats each of the subcatchments as lumped (i.e. no within-unit spatial heterogeneity is introduced in inputs and processes), this allows for straightforward implementation of results of climate change analyses into hydrological modeling. Rainfall data for each of considered locations have been derived from FEWS dataset and used as input to downscaling procedure.

4.7.1 Analyses of applicability of FEWS rainfall as input to statistical downscaling

Due to unavailability of observed daily rainfall time series for Angolan part of the Okavango catchment, FEWS rainfall dataset was used in the downscaling procedure. FEWS rainfall carries systematic and non-systematic biases compared to observed station rainfall.

Potential errors involved in using FEWS data instead of observed station data as input to downscaling procedure have been assessed by comparing results of downscaling for Maun and Shakawe (and other stations in Botswana) based both on station data and FEWS data. That comparison was carried out through:
a) analyses of differences in downscaled future rainfall indices between FEWS-derived and observed station-derived downscaled rainfall and
b) analyses of differences in relative change (ratio of future to past) in rainfall indices between FEWS-derived and observed station-derived downscaled rainfall.

The t-test on means has been used to assess statistical significance of these differences.

4.8 Hydrological modeling

Assessment of hydrological effects of change in climate characteristics was done using two hydrological models, each simulating a separate part of the Okavango system.

4.8.1 Okavango catchment

The Okavango catchment upstream of Mohembo was simulated using Pitman model embedded in SPATSIM modeling engine, developed by Institute for Water Research (IWR), Rhodes University, South Africa. It is a semi-distributed model that represents subcatchments as s set of storages linked by functions designed to represent the main hydrological processes: interception, evaporation, infiltration, surface runoff, groundwater recharge and discharge and flow attenuation in river channels. The model runs on a monthly time-step. A detailed description of the model can be found in Hughes et al., 2006 and Hughes, 2004.

Hydrological conditions under projected climate were simulated by modifying monthly rainfall and evaporation values used in the reference run (1960-2003) for each of the subcatchments. The modifications were applied separately to each of the subcatchments and seasons: Dec-Feb (DJF), Mar-May (MAM), Jun-Aug (JJA) and Sep-Nov (SON). In case of rainfall, change factor was derived directly as a ratio of future to reference period rainfall. In case of evaporation, change factor was derived as difference of future and reference period temperatures, separately for minimum and maximum temperatures. The observed (CRU2.0) temperatures were then modified (location-wise and seasonally) and used for calculating potential evaporation from Hargreaves (Hargreaves and Samani, 1985) formula. The modified time series of potential evaporation was used as input to the catchment model.

4.8.2 Okavango Delta

Okavango Delta and Boteti were simulated with a hybrid linear reservoir-GIS model developed at Harry Oppenheimer Okavango Research Centre, University of Botswana. The reservoir model is a monthly semi-conceptual, semi-distributed model, where Okavango Delta is represented by nine large units. Within each of the units a monthly water balance is calculated accounting for upstream inflow, rainfall, evaporation, surface water-groundwater interactions and downstream outflow. GIS model allows inundated area obtained as a lumped value for each of the units of the reservoir model to be represented in the form of a distributed inundation map. The GIS model is based on the analysis of the time series of satellite-derived flood maps in a probabilistic setting. Details of the models are presented in Wolski et al., 2006.

Hydrological conditions in the Okavango Delta under projected climate were simulated using the output form the catchment model and rainfall and potential evaporation data modified in a similar way to these for the Okavango River catchment.

5 Exploratory analyses

5.1 Comparison of rainfall datasets

For stations in Angola there is a relatively good consistency between the observed and reanalysis data. CRU2.0 dataset has no systematic biases compared to GHCNv2 dataset in terms of mean monthly rainfall, although there occur non-systematic differences in minimum and maximum monthly rainfall (Fig. 2 and Fig. 3). For FEWS rainfall dataset mean monthly rainfall generally agree with observations. However, this dataset seems to underestimate maximum monthly rainfall, and overestimate minimum monthly rainfall. Part of the differences can, however, result from the fact that comparison presented in Fig. 4 contains data from non-overlapping periods. FEWS dataset is known to be systematically biased, and methods are available for unbiasing it (). The standard method, however, reduces systematic bias in overall climatology and does not allow for selective correction of lower and higher than average values. Lack of overlapping observed dataset from Angola, prevents development of a tailored unbiasing algorithm.

For stations in Botswana part of the system, differences were assessed in terms of indices derived from daily rainfall (Table 5) obtained from observed and FEWS dataset for identical period. Although biases do exist, these are mostly statistically insignificant considering variability of data. The only significant difference is that in terms of number of rain days for Shakawe station. Since such a difference occurs only in 2 out of 18 Botswana stations (data not presented), it does not seem to indicate a systematic bias that would require correction.

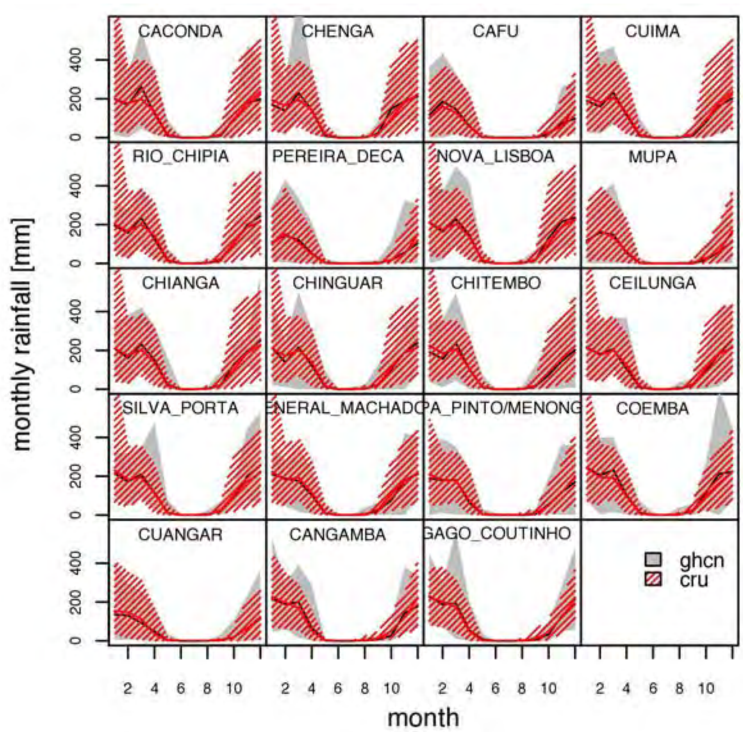


Fig. 2 Monthly rainfall climatologies derived from CRU2.0 and GHCNv2 datasets for stations in Angola for 1950-1974 period.

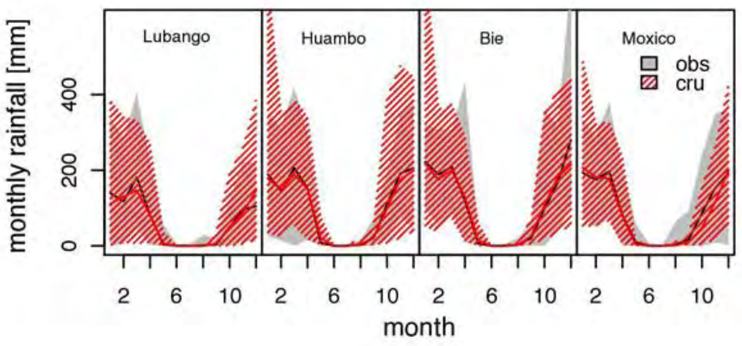


Fig. 3 Monthly rainfall climatologies derived from observed data (EPSMO dataset) and CRU2.0 dataset for stations in Angola (overlapping years in 1961-1999 period)

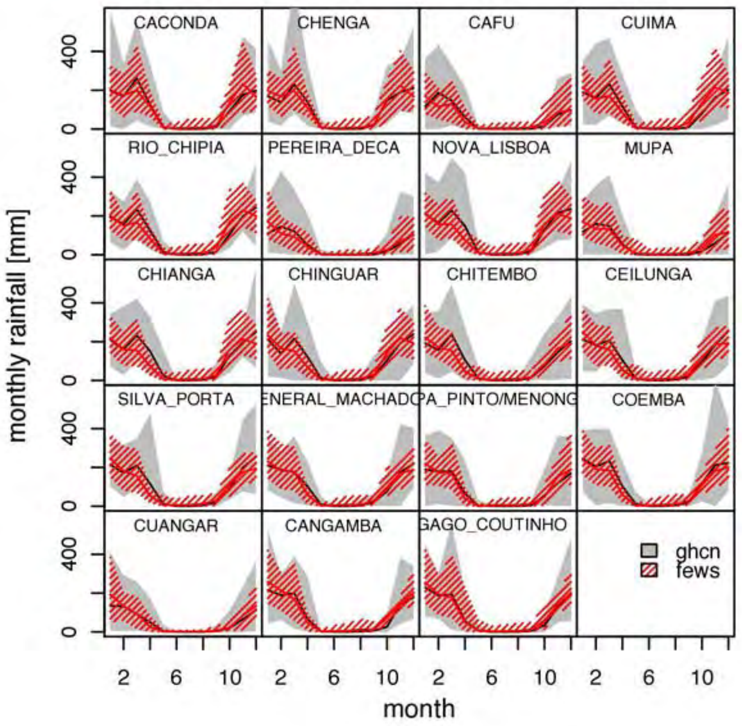


Fig. 4 Comparison of monthly rainfall climatologies derived from FEWS (1998-2007) and GHCN (observed, 1950-1974) datasets for stations in Angola

Table 5 Differences between mean values for rainfall indices calculated based on observed and FEWS data (period of overlap 1998-2007). P-values of t-test in brackets

	Annual total	Days>2mm	Median daily	Max daily	Onset of rains
Maun	-121 (0.21)	-5 (0.28)	0.63 (0.25)	-7 (0.47)	0.9 (0.91)
Shakawe	-122 (0.35)	-20(<0.01)	0.14 (0.49)	-0.08 (0.99)	3.9 (0.64)

5.2 *Change and variability in the past climate*

5.2.1 Temperatures

Since no consistent time series of temperature measurements were available that would allow for assessment of 20th century changes and variability, reanalysis data is used instead. These data indicate that mean 30-year temperature fluctuated in the 20th century within +-0.2 deg C of the long-term mean, and that there was no clear overall trend (Fig. 1Fig. 5). There is an increase in temperature recorded since 1960s that could be attributed to changing climate. However, a similar increase is present during the period of 1920-1940, although both the rate of increase and range were smaller than within the post 1960 period. Pattern of variability is similar in the three regions of the Okavango system.

Statistical analyses of homogeneity of temperature time series show that although there is no significant overall trend, the series is non-homogeneous in mean and variance (Table 6). This suggests that factors other than natural short-term variability influenced long-term characteristics of temperatures in the Okavango region. Determination of causes of this long-term variability is beyond the scope of this report.

Table 6 Results of analyses of trend and homogeneity of time series of mean annual temperature (CRU2.0 reanalysis) for the three regions of the Okavango system

	Delta	Lower Okavango	Upper Okavango
Mean value	295.8	295.3	294.1
Standard deviation	0.46	0.34	0.33
Trend coefficient (per year)	0.006	0.005	0.004
Trend significance (p-value)	0.87	0.89	0.90
Homog. in mean Buishand test (p-value)	<0.01	<0.01	<0.01
Homog. in variance Levene test* (p-value)	<0.01	<0.01	<0.01
Homog. in mean, (AOV) F-test* (p-value)	<0.01	0.02	0.04

*test performed splitting the series into three independent groups: 1921-1950, 1951-1980, 1981-2008

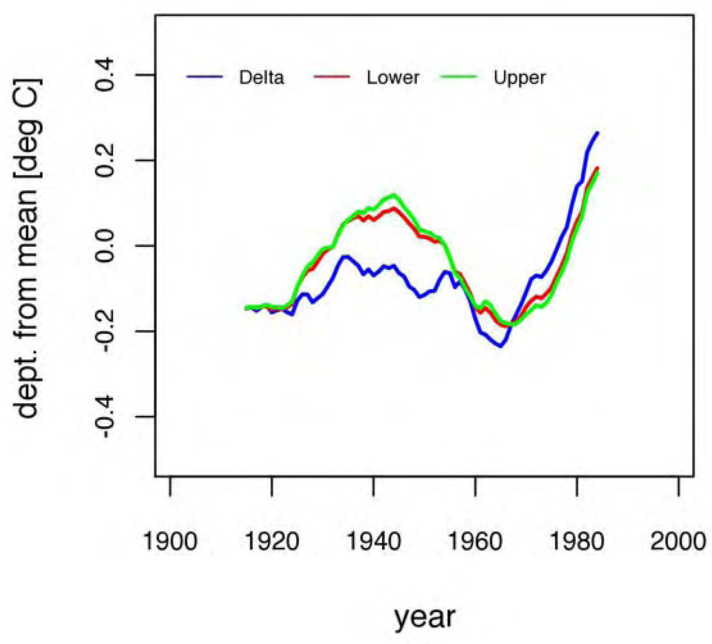


Fig. 5 30-year moving average of mean annual air temperature for the three regions of the Okavango system, CRU2.0 reanalysis data

5.2.2 Rainfall

The general characteristics of Okavango river runoff time series during the period of record (1920-onward) is such that the first part of the 20th century is relatively dry, mid-century years are relatively wet, and last years of the century are relatively dry again (Wolski et al., 2002, Mazvimavi and Wolski, 2006, McCarthy et al., 2000). Similar pattern in observed in annual rainfall (Fig. 6). A consequence of such variability is that it is erroneous to analyse past climatic changes from data sets starting in mid 20th century. Such analyses would reveal trends that do not reflect long-term conditions in the system. When the entire available series is analysed, no significant (linear) trends are revealed in neither of the analysed indices (Table 7). The indices mostly appear to be homogeneous in means and variances, and the only statistically significant departure from homogeneity is revealed for median daily rainfall for Shakawe. The differences in rainfall indices between various periods of the 20th century can, therefore, result purely from short-term variability. Temporal patterns of the indices are not consistent, and do not suggest presence of systematic trends (Fig. 7, Fig. 8). As a consequence, there is no basis for stating that changes in rainfall observed since mid 20th century are an expression of anthropogenic change in climate.

Table 7 Results of analysis of trend and homogeneity of various indices of Maun (upper value in each table row) and Shakawe (lower value in each table row) rainfall series (1922-2008)

	Total annual rainfall [mm/year]	Number of rain days >2mm [days]	Median daily rainfall [mm/day]	Maximum daily rainfall [mm/day]	Onset of rainy season [day after 1 July]

Mean value	448.6 522.2	36 38	5.4 5.8	54.1 57.4	102 101
Standard deviation	168.6 205.2	10 12	2.1 2.1	25.7 19.9	16 25.9
Trend coefficient (per year)	-0.3 0.85	-0.008 0.1	-0.02 -0.01	-0.13 -0.14	-0.05 0.36
Trend significance (p-value)	0.70 0.43	0.97 0.69	0.86 0.91	0.93 0.67	0.85 0.37
Homog. in mean Buishand test (p-value)	>0.1 >0.1	>0.1 0.01	>0.1 0.02	>0.1 0.07	>0.1 >0.1
Homog. in variance Levene test* (p-value)	0.32 0.36	0.15 0.41	0.48 0.05	0.80 0.72	0.54 0.67
Homog. in mean, (AOV) F-test* (p-value)	0.41 0.73	0.78 0.44	0.05 0.001	0.89 0.08	0.43 0.67

*test performed by splitting the series into three independent groups: 1921-1950, 1951-1980, 1981-2008

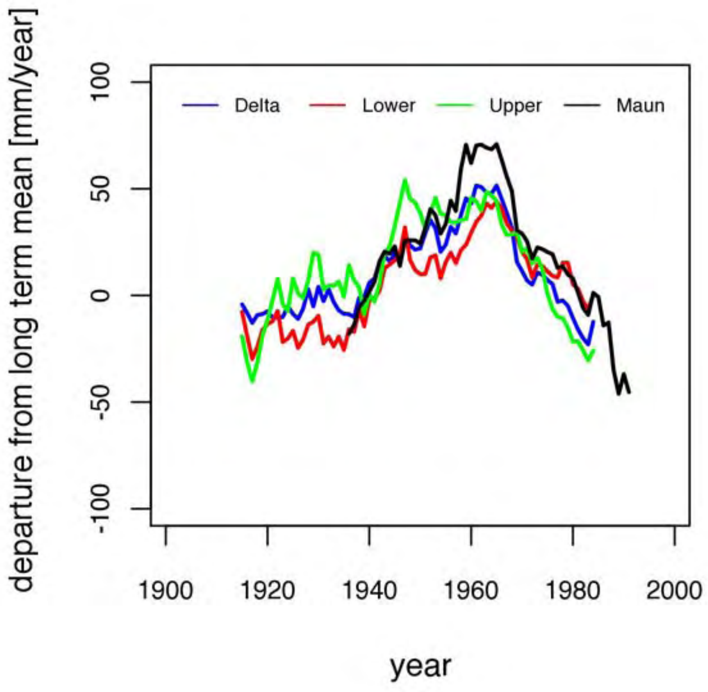


Fig. 6 30-year moving average of mean annual precipitation for three regions of the Okavango system (CRU2.0 reanalysis data) and observed rainfall at Maun.

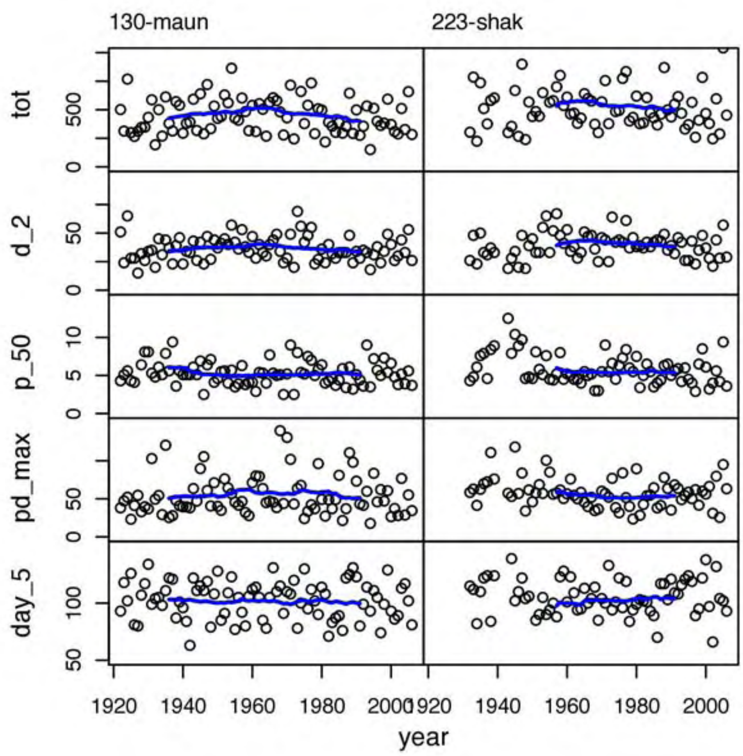


Fig. 7 Annual values and 30-year moving average (blue line) of rainfall indices for Maun and Shakawe (tot – total annual rainfall [mm], d_2 – number of rain days with rain>2 mm/day, p_50 – median daily rainfall [mm], pd_max – maximum daily rainfall [mm], day_5 – day after 1 July when 5% of given year's rainfall has fallen)

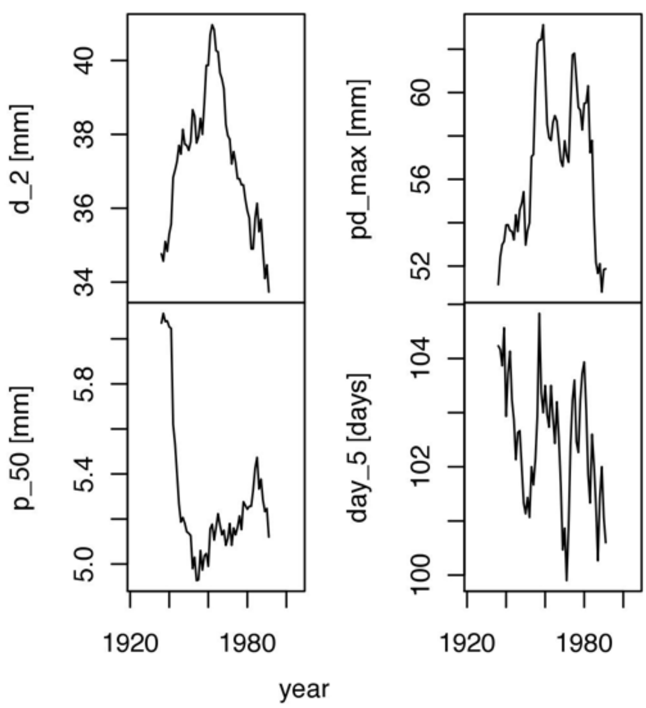


Fig. 8 30-year moving averages of rainfall indices (d_2 – number of raindays with rainfall>2 mm, pd_max – maximum daily rainfall, p_50 – median daily rainfall, day_5 – day when 5% of annual total has fallen) for Maun

5.3 Analysis of applicability of FEWS daily rainfall dataset for statistical downscaling

In order to assess errors involved in the use of FEWS rainfall dataset in the downscaling procedure, downscaling was done using observed data and FEWS data for the same locations.

Future rainfall obtained from the downscaling procedure based on FEWS data does not correspond to that obtained from downscaling based on observed data (Fig. 9). Significant differences (p-values of t-test predominantly lower than 0.05) were obtained for each analysed index (Fig. 9). Additionally, the differences are systematic, and their magnitude changes for various locations (nine left-hand side points in each panel in Fig. 9 are for Maun, nine right-hand side points are for Shakawe)

Relative change (future-past) obtained from downscaling appears to be more robust with respect to the input data. Differences between change factors for various indices obtained from the downscaling procedure based on FEWS and these obtained from downscaling based on observed data are still present (Fig. 10). However, these differences appear to low compared to the natural variability, and thus have low statistical significance (p-values in the order of 0.1 to 1 for most of the cases). Additionally, the differences are not systematic – i.e. there is no consistent over- or underestimation of change factors when FEWS data are used instead of observed data. Similar results were obtained for 16 stations in Botswana (data not presented here).

In view of the above, the application of FEWS dataset in downscaling is possible, however only when relative change in rainfall is derived. If future rainfall obtained based on FEWS dataset were to be used directly - it is likely that such rainfall would contain errors that would hinder detection/estimation of climate change effects.

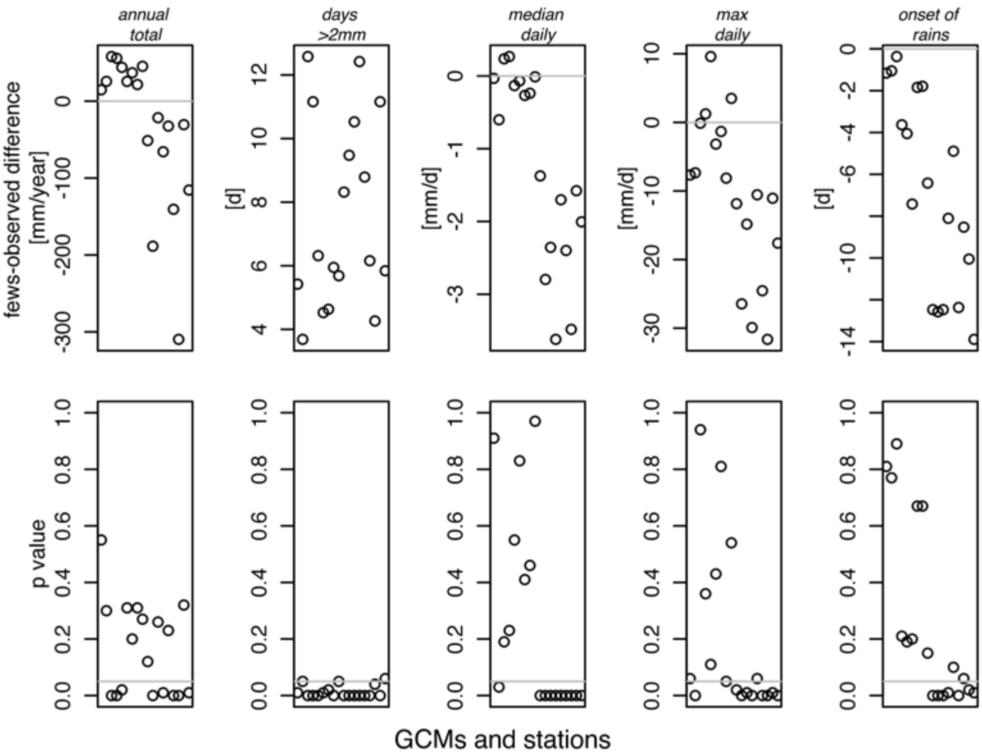


Fig. 9 Differences between indices of future rainfall obtained from downscaling based on observed data and FEWS data, and their statistical significance. Results of downscaling nine GCMs based on Maun and Shakawe data.

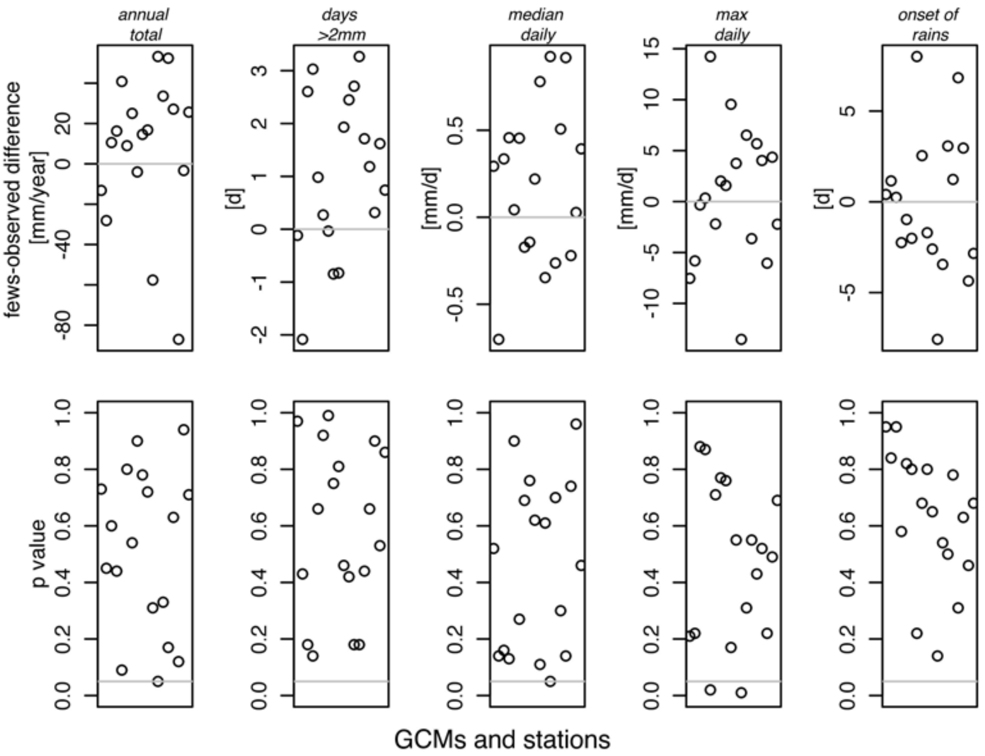


Fig. 10 Differences between change factors obtained from downscaled rainfall based on observed data and FEWS data, and their statistical significance (p-values of t-test). Results of downscaling nine GCMs based on Maun and Shakawe data.

5.4 Biases of raw GCMs and SD

The performance of the downscaling procedure was assessed by comparing observed rainfall with that generated by SD based on the observed synoptic variables. Statistically insignificant differences suggest good skill of SD method, i.e. that the main large-scale drivers of local rainfall have been incorporated into the SD procedure. Results of such an analysis carried out for data from 18 stations in Botswana show that SD reproduces relatively well timing of rainy season (day_5), number of rain days and median daily rainfall (Fig. 11). Maximum daily rainfall and total annual rainfall are not well reproduced – downscaling with synoptic variables used during training, produces significantly different annual total and maximum daily rainfall values than the observed ones. However, the SD procedure gives lower biases than these present in raw GCMs (Fig. 12).

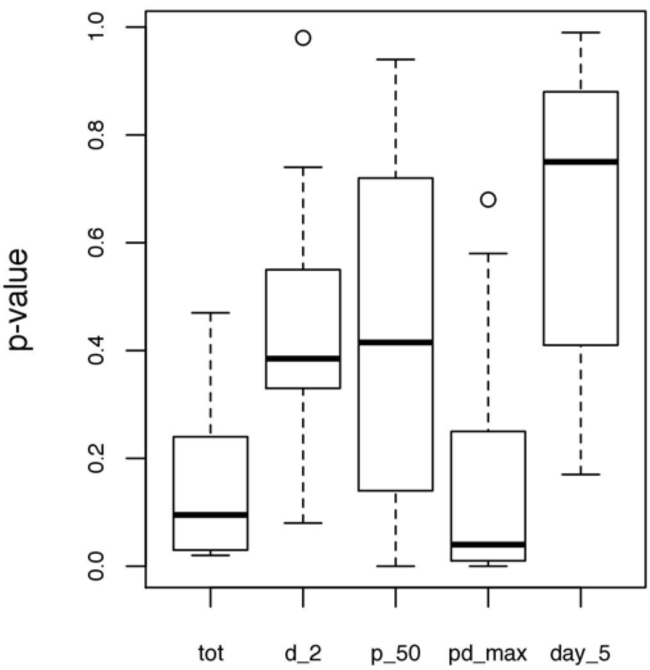


Fig. 11 Skill of statistical downscaling in replicating rainfall indices. Boxplots show p-values of t-test performed on mean rainfall indices (tot-total annual rainfall, d_2 – number of days with >2mm.day, p_50 – median daily rainfall, pd_max – maximum daily rainfall, day_5 – day when 5% of annual total is exceeded) calculated from observed data and from rainfall data obtained from downscaling of NCEP synoptics. 1979-2007 period, data for 18 stations in Botswana.

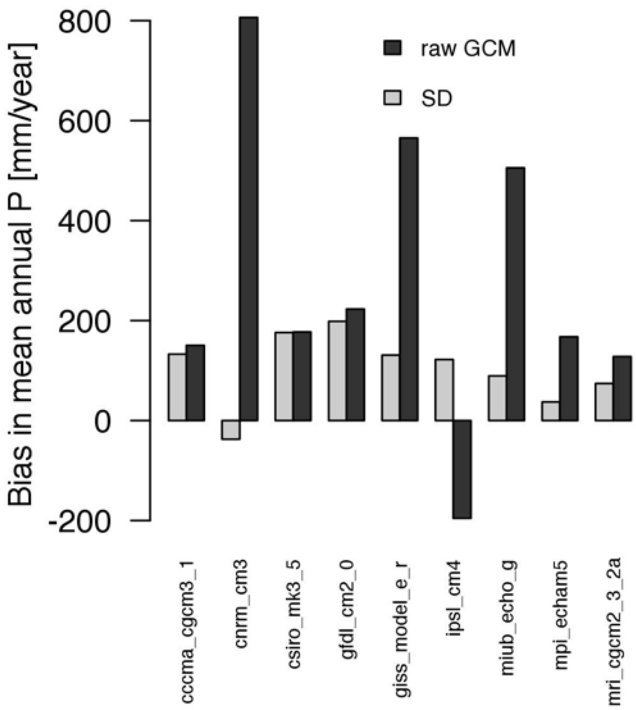


Fig. 12 Biases in mean annual rainfall for SD (1979-2007, Maun, relative to observed rainfall) and raw GCM (1961-1999, Delta region, relative to CRU2.0)

6 Results

6.1 Climate change signal from GCM ensemble

Rainfall

GCM-based projections of change in mean rainfall vary broadly within -25% to + 15 % range, depending on a GCM and season (Fig. 13).

In general there is a tendency of members of the GCM ensemble to project decrease in total annual rainfall – majority of models give change factor smaller than one.

In terms of differences between various parts of the Okavango system, there seems to be a slight tendency towards “less drying” conditions towards the north – i.e. the number of models projecting decrease in rainfall reduces towards the north.

There is again a lack of consistency between members of the GCM ensemble in terms of changes in interannual variability of rainfall (taken as changes in standard deviations of annual or seasonal totals) (Fig. 14).

These results are broadly consistent with the regional-scale assessment presented in IPCC 2007 report (IPCC, 2007). Fig. 11.2 of that report suggests that there is a lack of consistency in between ensemble GCMs in terms of projected direction of change in the northern part of the Okavango basin, while in the southern part of the basin, majority of GC models project decrease in rainfall.

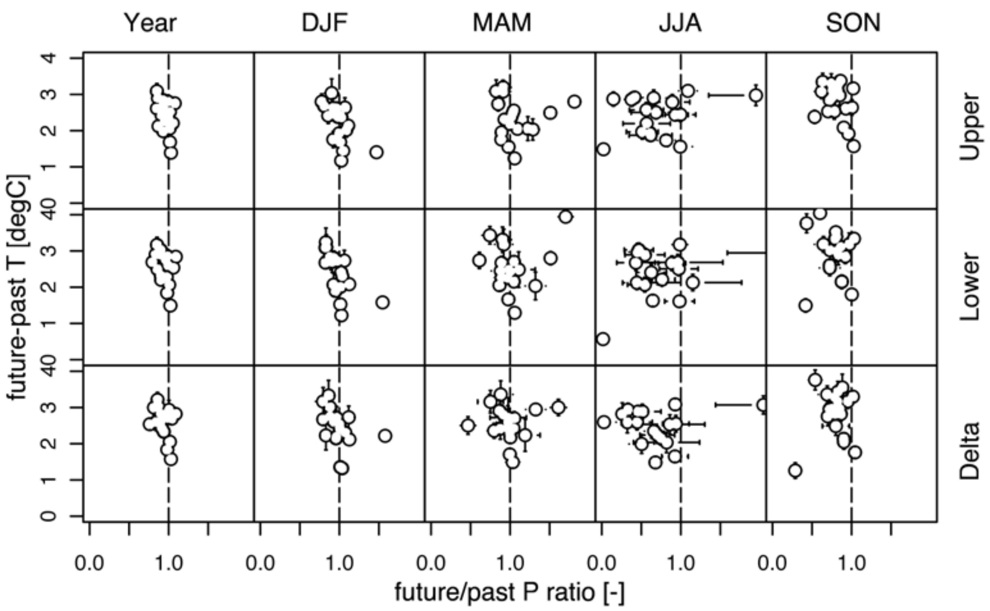


Fig. 13 Change (2046-2065 as compared to 1960-1990) in mean temperature and mean rainfall for three basin zones, on annual and seasonal basis, determined from 21 GCMs. SRES A2 scenario. Bars denote +/- 1 standard error of difference or ratio of means.

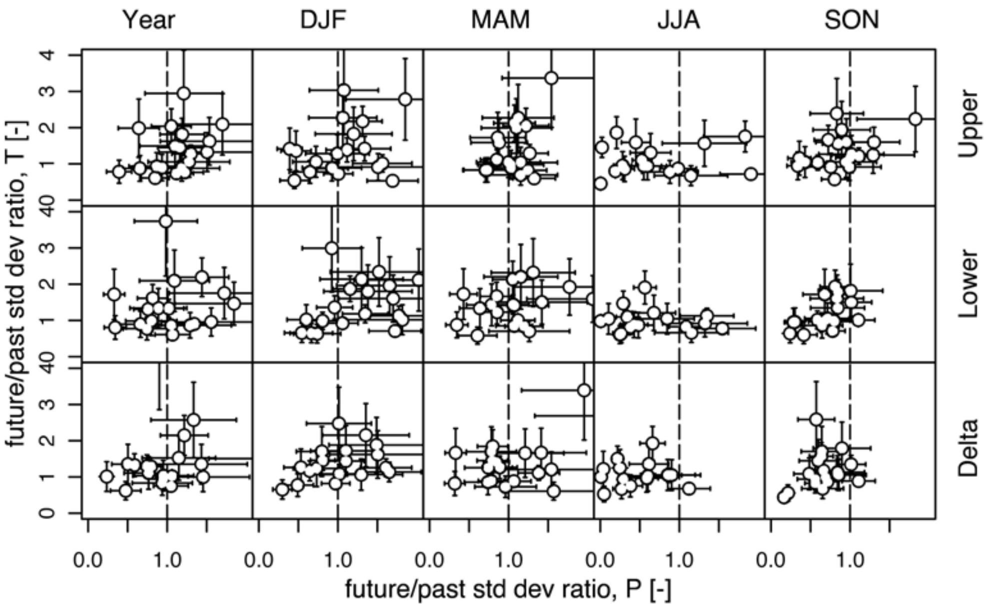


Fig. 14 Change (2046-2065 as compared to 1960-1990) in standard deviation of monthly temperature and rainfall for three basin zones, on annual and seasonal basis, determined from 21 GCMs. SRES A2 scenario. Bars denote +/-1 standard error.

Temperature

There is a relative consistency in between members of the GCM ensemble in terms of projections of future temperatures (Fig. 13). Projected is an increase by 1.1-3.5 deg C in average annual temperatures. Mean seasonal temperatures are projected to increase within the same range and differences between seasons are minor. Importantly, there is relatively little spatial variation – i.e. projected change in northern part of the basin is similar to that in the southern part.

There is a consistent increase in standard deviation of annual and seasonal mean temperature (Fig. 14). This, however, probably reflects an increase in range of temperatures in the future resulting from systematic trend within the averaging period rather than an increase in year-to-year variability.

6.2 Climate change signal from the SD ensemble

Statistical downscaling has been done for Maun and Shakawe stations based on observed daily rainfall and temperatures. As mentioned in earlier, daily rainfall data were not available for any station in Angolan part of the Okavango system. Daily rainfall derived from FEWS dataset has been used instead, and downscaling has been done for locations corresponding to centroids of subcatchments used in the hydrological model of the catchment.

6.2.1 Okavango Delta

Rainfall

The results obtained for Maun and Shakawe indicate that the majority of SD ensemble members project an increase in mean annual rainfall (Fig. 15). There is a marked difference between seasons. Projections of the ensemble appear to be centered on zero for DJF and SON, while there is a consistent increase in MAM and JJA. The change in JJA, although relatively strong, is of little absolute significance because total rainfall during that period is minimal.

Change in interannual variability of rainfall is not consistent between the members of the ensemble (Fig. 16). Additionally, the changes are of little or no statistical significance (p-values of F test on difference in variances are in the range of 0.2-1.0, with only 2 out of 18 cases (nine models and two stations) having p-value of less than 0.05).

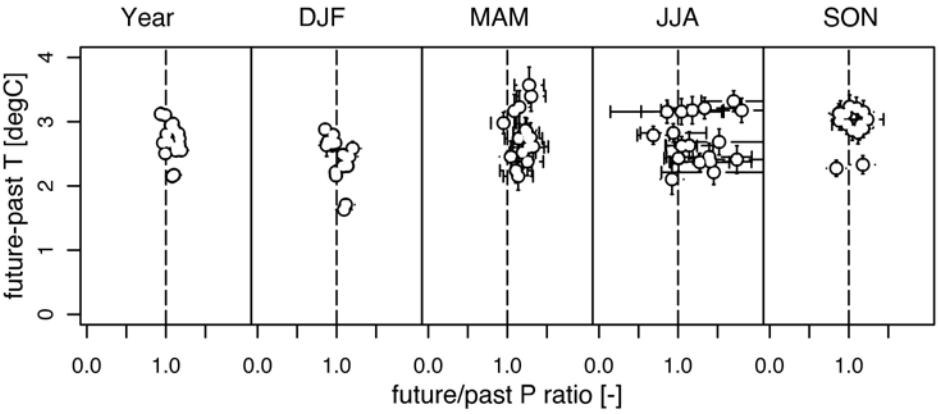


Fig. 15 Change (2046-2065 as compared to 1960-1990) in mean temperature and mean rainfall for Maun and Shakawe, on annual and seasonal basis, determined from downscaled climate. SRES A2 scenario. Bars denote +/- 1 standard error of difference or ratio of means.

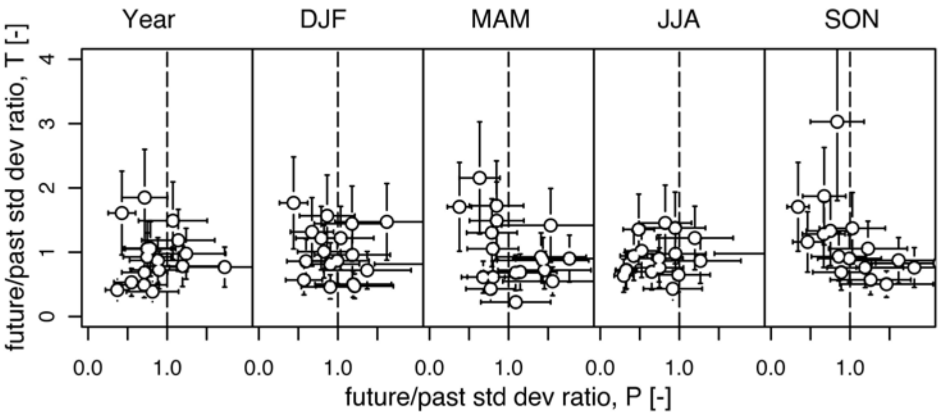


Fig. 16 Change (2046-2065 as compared to 1960-1990) in standard deviation of temperature and rainfall for Maun and Shakawe, on annual and seasonal basis, determined from SD, SRES A2 scenario. Bars denote +/- 1 standard error.

SD projects consistently an increase in number of rain days, but projections of changes of other indices, including total annual rainfall, are not consistent between models, and the changes are not significant (Fig. 17).

Rainfall projections obtained here from SD are broadly consistent with these presented in the IPCC 2007 report (IPCC, 2007). Fig. 11.3 of that report shows that downscaled GCMs project increase in rainfall in southern Africa in general and in northern Botswana in particular.

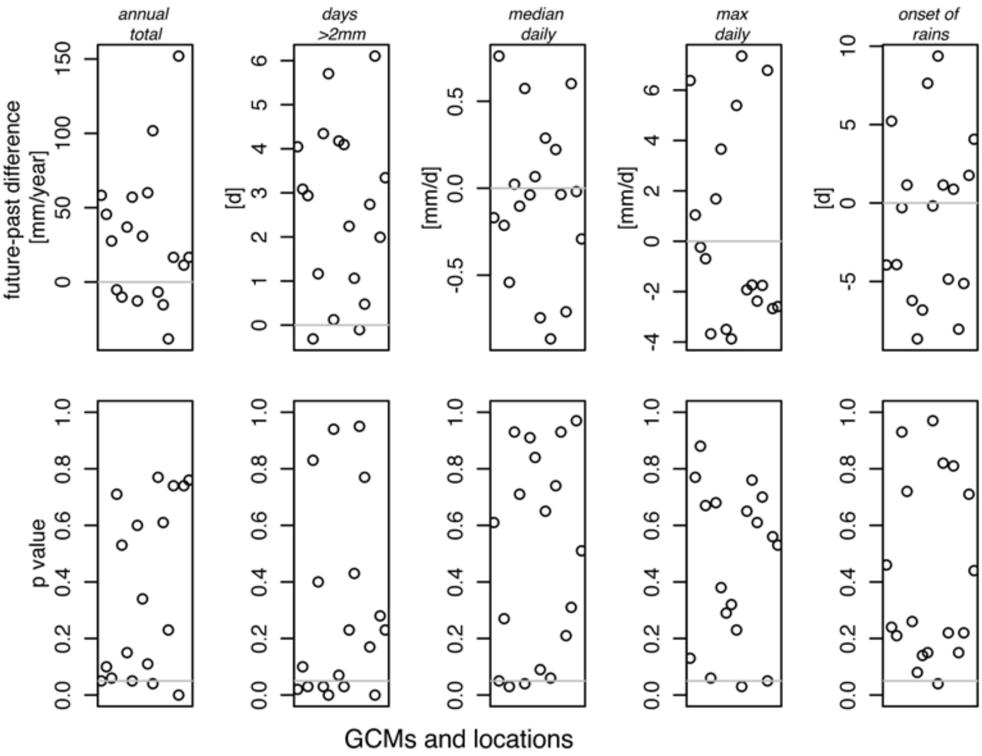


Fig. 17 Changes in rainfall indices (future-past) derived from SD for Maun and Shakawe, and their statistical significance.

Temperatures

Changes in mean annual temperature projected by members of the SD ensemble for Maun and Shakawe fall within the range of 2-3.2 deg C, and there is a difference between seasons – with DJF projected to have increases between 1.5 and 2.8 deg C, while MAM is projected to have an increase between 2 and 3.5 deg C (Fig. 15).

There is a consistent increase in standard deviation of annual and seasonal means (Fig. 16). Similarly to the signal obtained from the GCM ensemble, this seems to signify an increase in range of temperatures related to the trend rather than year-to-year variability.

6.2.2 Okavango Catchment

Rainfall

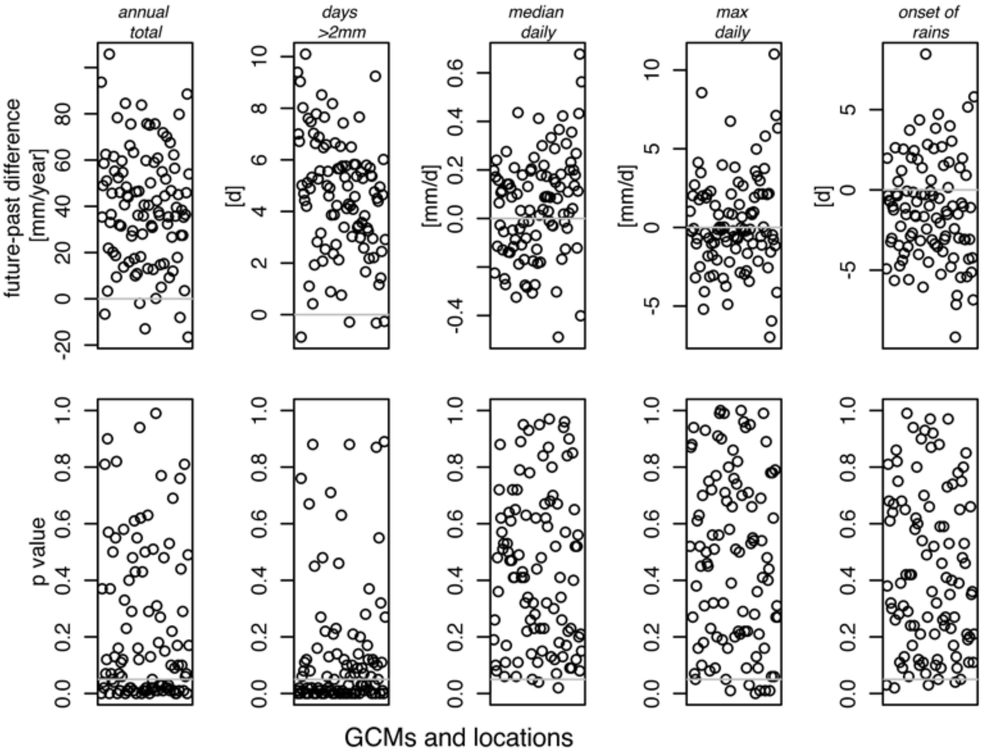


Fig. 18 Changes in rainfall indices derived from SD for locations within lower Okavango catchment (lat: 15-18 S), and their statistical significance.

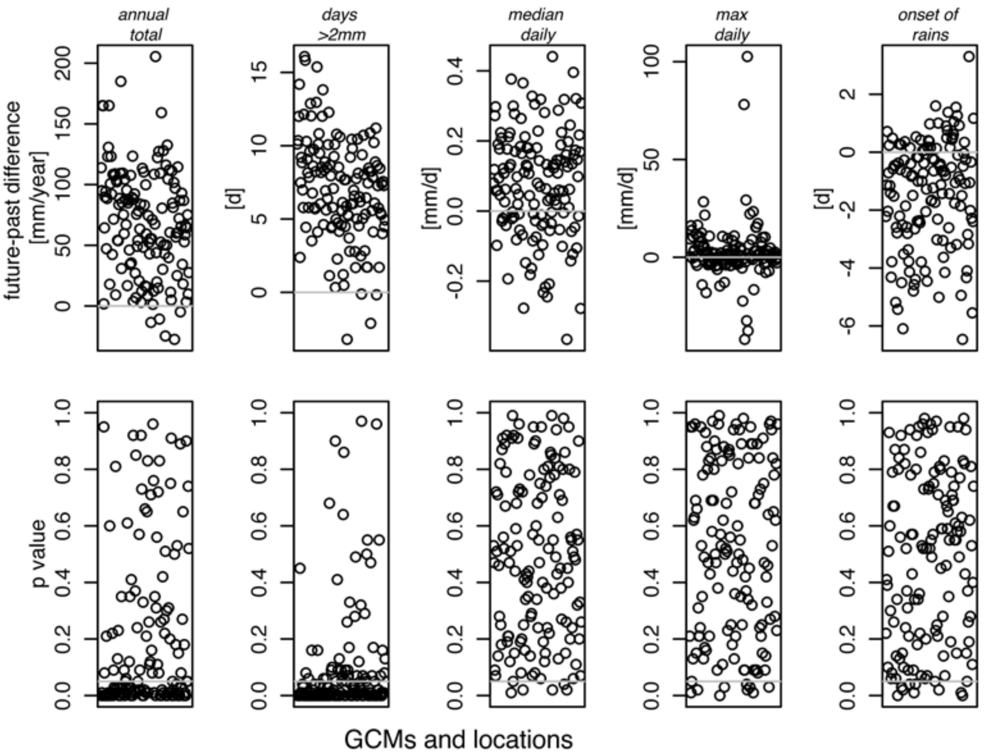


Fig. 19 Changes in rainfall indices derived from SD for locations within upper Okavango catchment (lat: 12-15 S), and their statistical significance.

Downscaling results for the Okavango catchment indicate statistically significant increase in mean annual rainfall (Fig. 18 and Fig. 19) Larger increases are projected to take place in the north. This increase is projected to be due to increase in number of rain events, change of which is also statistically significant. Projections of change in other indices are not consistent in direction and between locations and models, and are not statistically significant.

Temperature

Due to lack of consistent time series of observed daily temperatures for locations in the Okavango catchment, no downscaling of temperature signal for that region has been attempted. However, as comparison of differences between temperature signal derived from SD and from raw GCM data shows these differences are minimal (Fig. 20). Thus, for the purpose of hydrological modeling it was decided to use in the temperature change signal derived directly from GCM data.

6.3 Derivation of change signal to use in hydrological modeling – envelope of change

6.3.1 Comparison between GCM-derived and SD-derived change signal

To avoid possible misinterpretation of possible artifacts resulting from the use of FEWS dataset in downscaling procedure, only downscaling results based on observed data for Maun and Shakawe is interpreted here. There are rather strong differences between projections of change in rainfall between GCMs and SD methods (Fig. 20, Fig. 21, Fig. 22). Projections of change in temperatures are, however, similar between methods (Fig. 20, Fig. 21, Fig. 23). Similar results are obtained for 16 stations in Botswana (data not presented here).

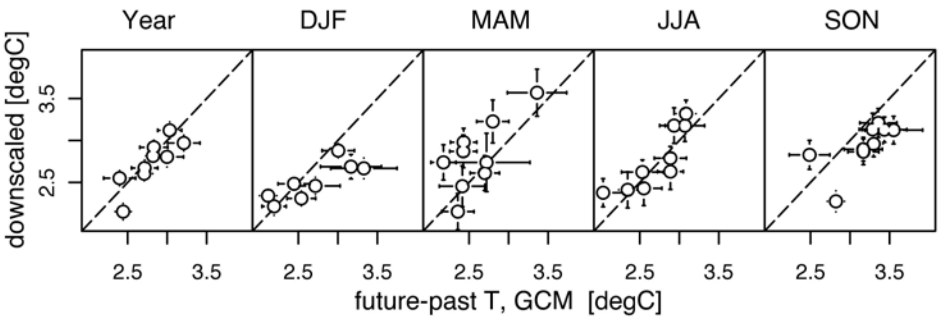


Fig. 20 Comparison of GCM-derived and SD-derived change signal for mean temperature on annual and seasonal basis. GCM data are for Delta region, SD data are for Maun only. GCM data only for models used in SD.

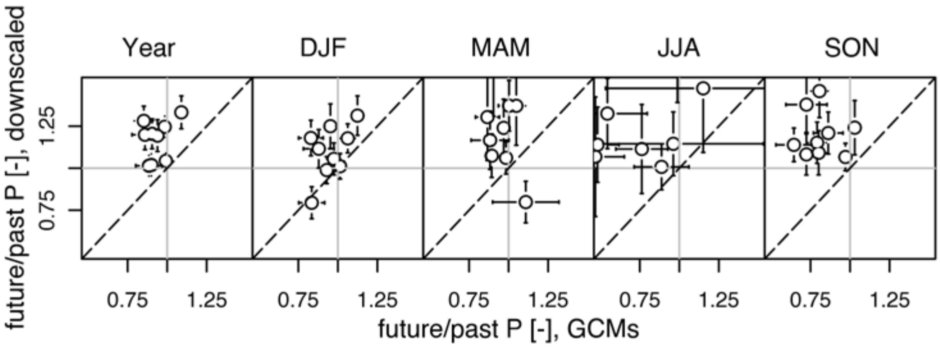


Fig. 21 Comparison of GCM-derived and SD-derived change signal for mean annual and seasonal rainfall. GCM data are for Delta region, SD data are for Maun only. GCM data only for models used in SD.

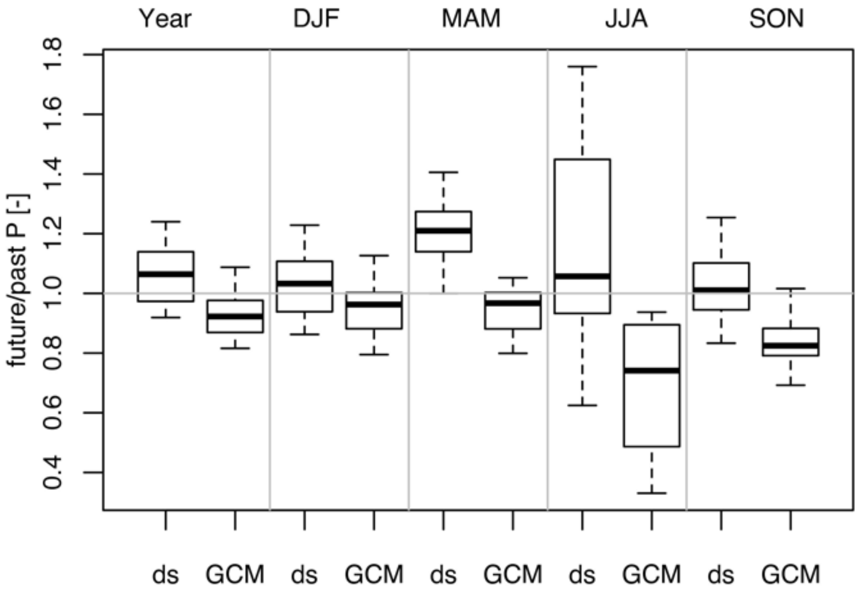


Fig. 22 Boxplots of annual and seasonal change in rainfall obtained from GCMs and SD (9 models) for Maun and Shakawe

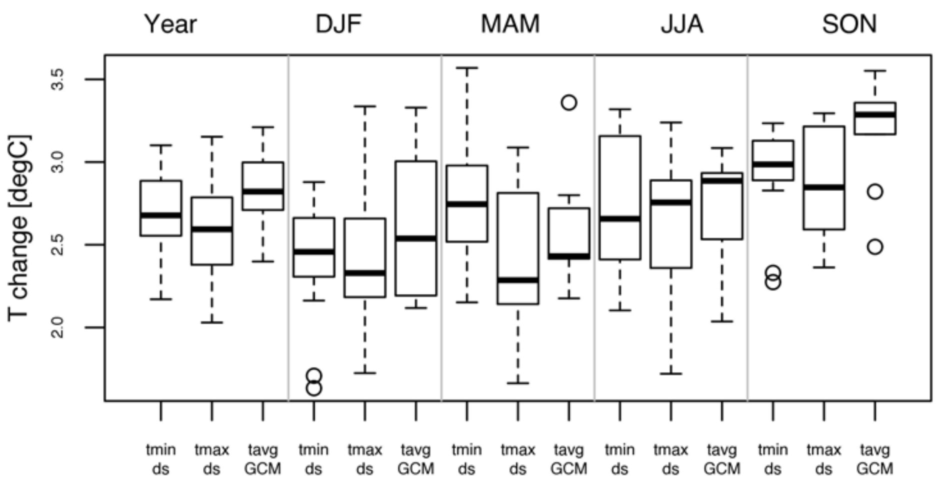


Fig. 23 Boxplots of annual and seasonal change in temperatures obtained from GCMs and SD (9 models) for Maun and Shakawe

In general, while GCMs project general decrease in rainfall, SD produces an increase in rainfall. This is a surprising result as SD procedure is "nested" within the respective GCM. The set of boundary characteristics of the atmosphere that drives generation of rainfall in GCMs and in SD are, therefore, identical. Preliminary work suggests, however, that there are some differences in the set of synoptic variables that GCMs and SD rainfall respond to, what would explain the discrepancy in direction and magnitude of change. Similar discrepancy has been obtained in earlier work for South Africa (Hewitson and Crane, 2006a), and in the regional-scale assessment presented in IPCC 2007 report (IPCC, 2007).

SD is one of the accepted methods to derive local-scale responses from GCMs. The SD method used here is a well-established one and has been applied for climate change assessment in southern Africa (Hewitson and Crane, 2006a; Schulze, 2005). It has been therefore decided to base assessment of future climatic and hydrological conditions in the Okavango system on results of SD method.

6.3.2 Climate scenarios for hydrological modelling

Considering the above, it was decided to derive three basic scenarios:

- "dry" - that corresponds to driest conditions (i.e. bottom of the envelope of change in rainfall and top of the envelope of change in temperature) projected by SD
- "moderate" – that corresponds to median conditions (median change in rainfall and tmedian increase in temperatures) projected by SD
- "wet" – that corresponds to wettest conditions (top of the envelope of change in rainfall and minimum of the envelope of change in temperatures) projected by SD

In further assessment it has been decided to use 25th and 75th percentiles of ensemble values to define top and bottom of the change envelopes. Considering that SD dataset comprises results based on nine GCMs, this effectively screens out two lowest and two highest projections. In this way, both spread and consistency of projections from various models are taken into account, and the final results are not affected by extreme projections from a single model. Boxplots showing ranges of change factors for rainfall and temperature for the three blocks/zones of the Okavango system are presented in Fig. 24 and Fig. 25.

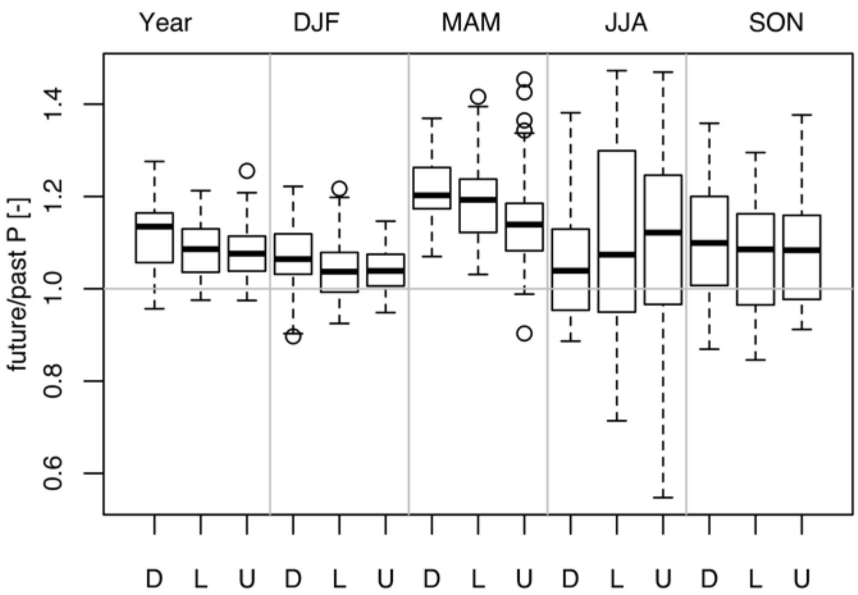


Fig. 24 Boxplots of annual and seasonal change in rainfall for Delta (D), lower Okavango catchment (L) and upper Okavango catchment (U), SD results, 9 models. Data include downscaled rainfall for all locations within each zone.

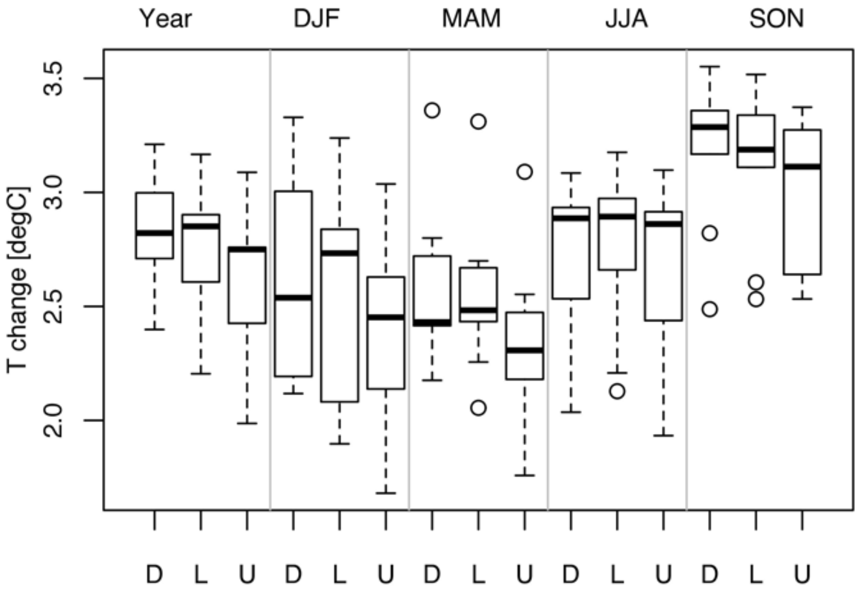


Fig. 25 Boxplots of annual and seasonal change in temperatures for Delta (D), Lower catchment (L) and upper catchment (U), GCM results, 21 models

Change in temperatures was recalculated into change in potential evaporation using Hargreaves (Hargreaves and Samani, 1985) formula. This formula was used because it was used earlier in the Okavango Delta and the Okavango catchment models to derive potential evaporation values. Additionally, this formula does not require any other climate data apart from temperatures to derive potential evaporation. Its application is, therefore, straightforward. Because of its empirical nature, the formula should implicitly take into account changes in other climatic factors that are associated with temperature, such as humidity. Comparison was carried out between the PET increase rate obtained from Hargreaves formula and from Penman (Doorenbos and Pruitt, 1977) and Penman-Monteith (Allen et al., 1998) formulas. The two latter ones incorporated changes in relative humidity, incoming solar radiation, and wind speed, derived from GCMs. The comparison was carried out only for five GCMs for which the above mentioned variables were available from PCMDI. Results indicate that Hargreaves formula gives a slight underestimation (in the order of 0.5% per 1 deg increase in temperature) of potential evaporation compared to the Penman and Penman-Monteith methods (Fig. 26). Considering data requirements for the two latter methods, it was decided to use the Hargreaves method.

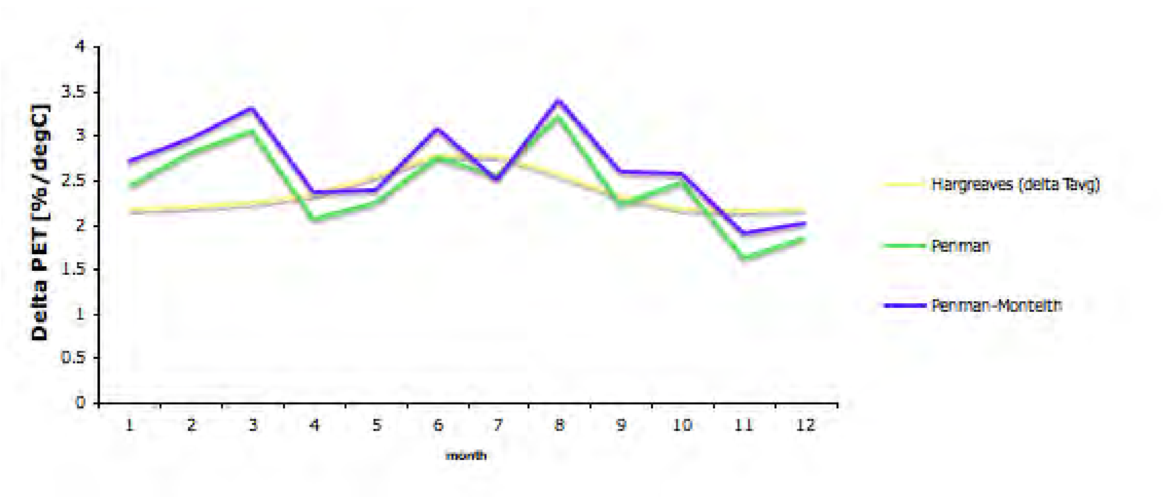


Fig. 26 Increase in PET per 1 deg C increase in temperature, obtained using various ET calculation methods with temperature, humidity, wind and radiation data from seven GCMs.

6.4 Results of Okavango catchment modelling

Results of modeling of the Okavango catchment with the Pitman model under climate scenarios are summarized in Fig. 27 (flow hydrograph), Fig. 28 (flow duration curves) and Fig. 29 (mean monthly hydrograph). "Dry" climate scenario results in minimal changes to the Okavango River discharges – notably, a slight increase in peak flows. Obviously, change (increase) in evaporation considered in this scenario is compensated by change (increase) in rainfall. Under "wet" and "moderate" climate scenarios, discharges of the Okavango River increase throughout the whole range – i.e. both low flows and peak flows are increased. There are no noticeable effects on timing of flood hydrograph.

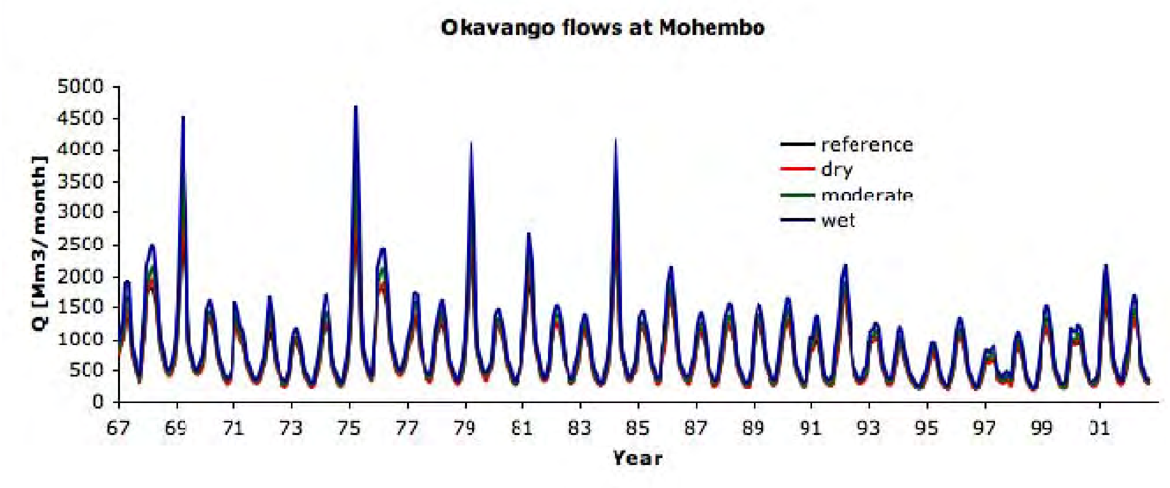


Fig. 27 Okavango flow hydrograph, reference run, "dry", "moderate" and "wet" climate scenarios

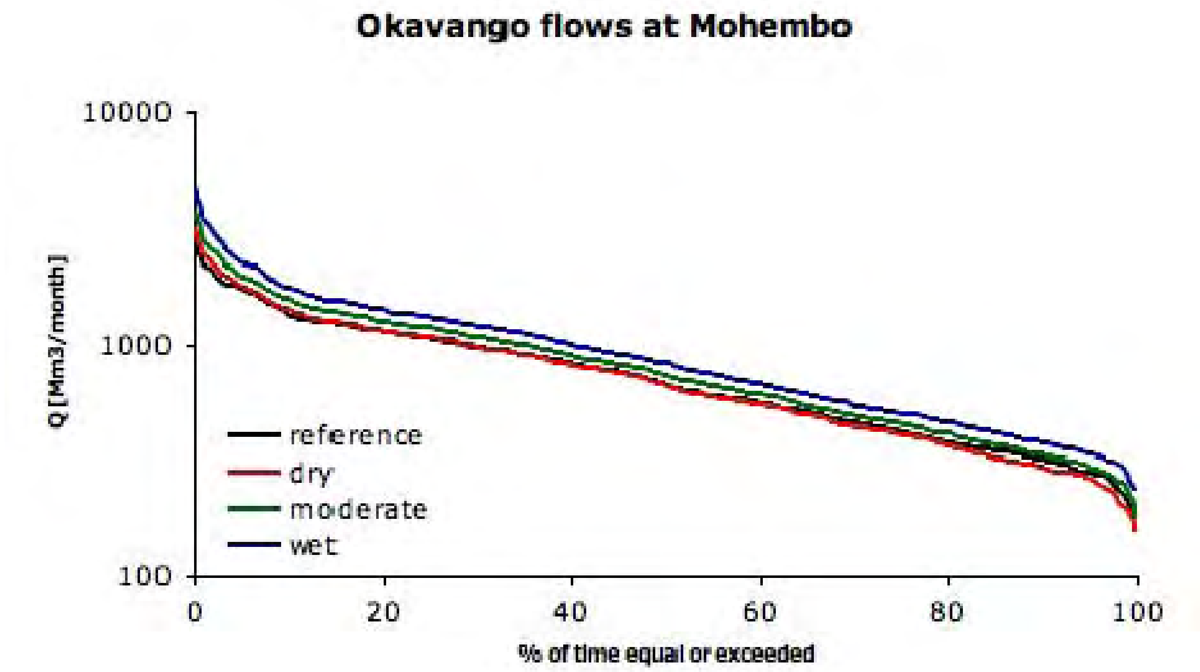


Fig. 28 Flow duration curves of Okavango River at Mohembo, reference, "dry", "moderate" and "wet" climate scenarios.

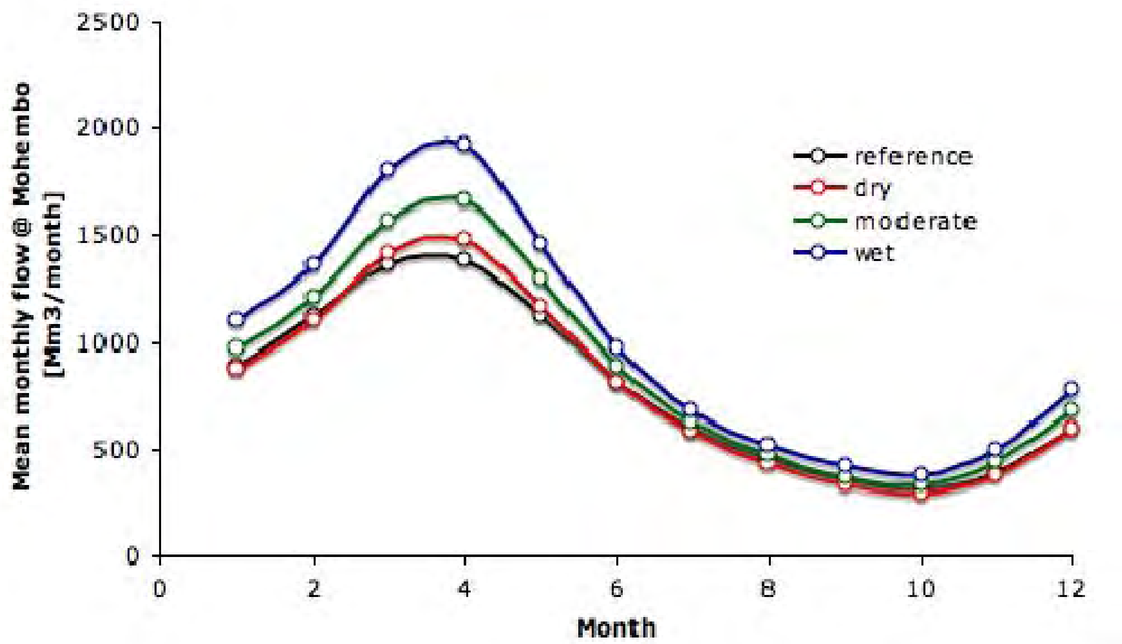


Fig. 29 Mean monthly flows of the Okavango River at Mohembo under reference conditions and climate scenarios.

6.5 Results of Okavango Delta modeling

Results of modeling of the Okavango Delta under climate scenarios are summarized in Fig. 31 through to Fig. 33. “Dry” scenario results in a reduction in average duration of inundation in the mid and distal parts of the Okavango Delta. This is also associated with a small reduction in frequency of inundation. Permanently inundated zone reduces and so does the area subject to seasonal and occasional inundation. These generally drier than reference conditions occur in spite of a slight increase in inflow and rainfall. In the evaporation-dominated Delta, unlike in the catchment, the increase in inflow and rainfall does not compensate for the increase in evaporation, and this results in drier conditions.

Under “moderate” and “wet” increases of inflow and rainfall exceed increase in evaporation, thus, ultimately, conditions that are wetter than reference occur. Under these scenarios expansion of the permanently inundated areas and areas subject to long inundation is observed. There is a relative reduction in areas subject to short inundation.

Thamalakane flows reduce under “dry” climate with no-flow conditions increasing from 29% of time (under reference conditions) to 39 % of time, but peak flows remain relatively unaffected. Under “wet” climate, both peak flows and low flows increase, and no-flow conditions reduce to approximately 13% of time.

There is no change in temporal distribution of Thamalakane flows.

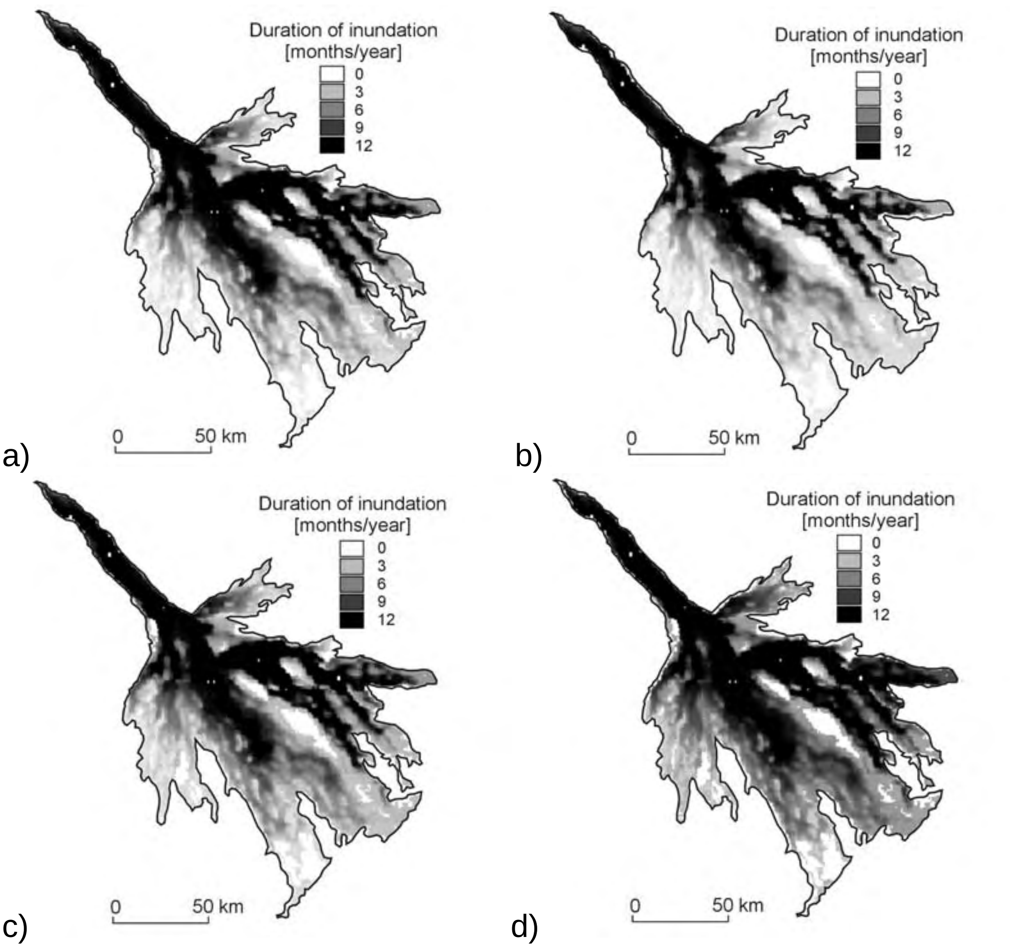


Fig. 30 Average duration of inundation in the Okavango Delta under a) reference conditions, b) "dry", c)"moderate" and d) "wet" climate change scenarios

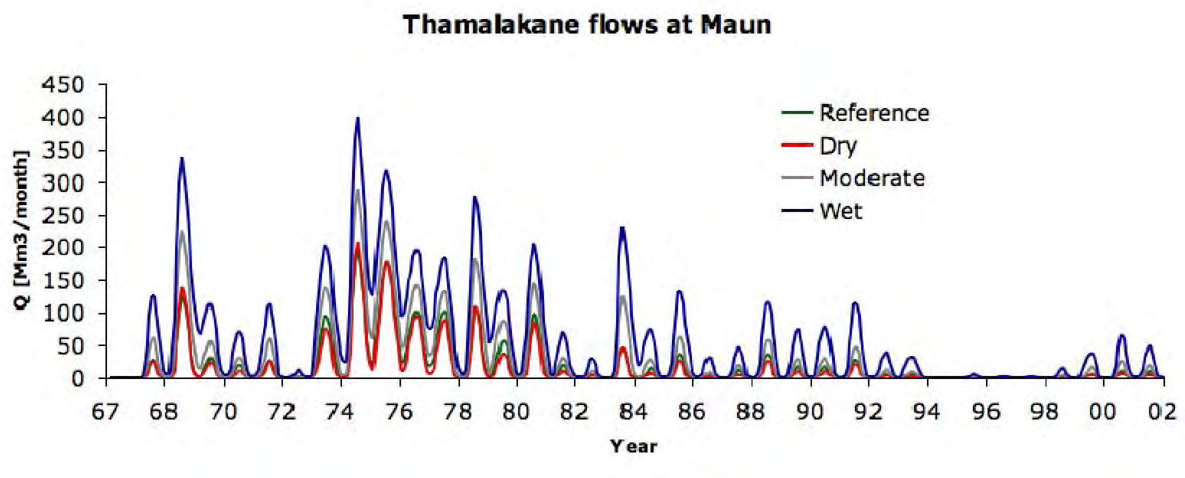


Fig. 31 Thamalakane flows under reference, "dry", "moderate" and "wet" climate scenarios

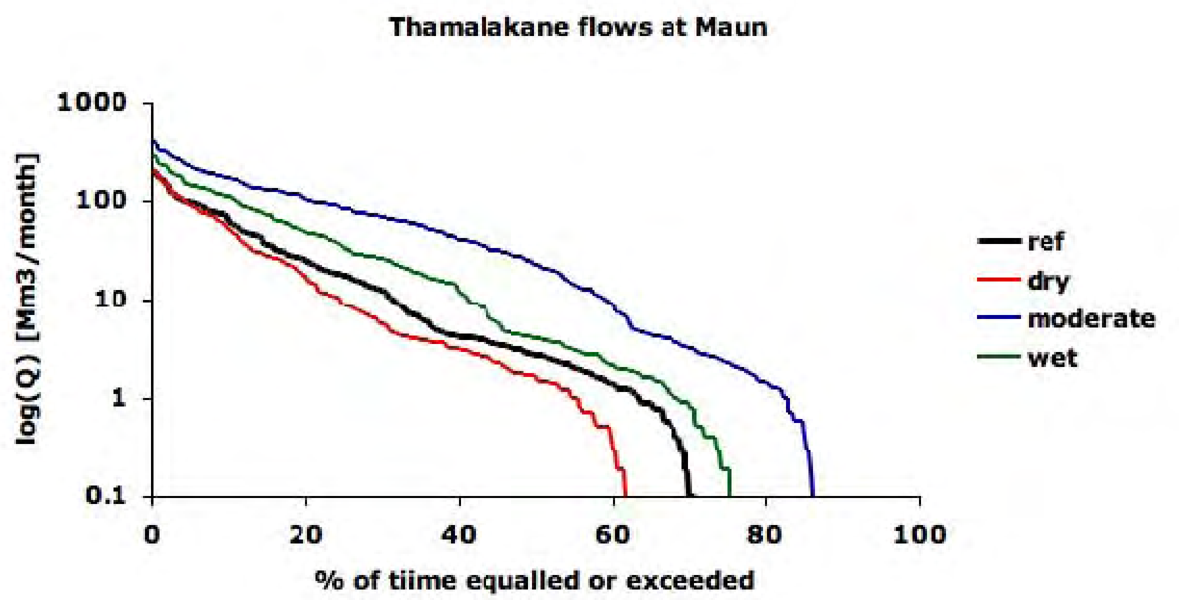


Fig. 32 Thamalakane flow duration curves under reference, "dry", "moderate" and "wet" climate scenarios

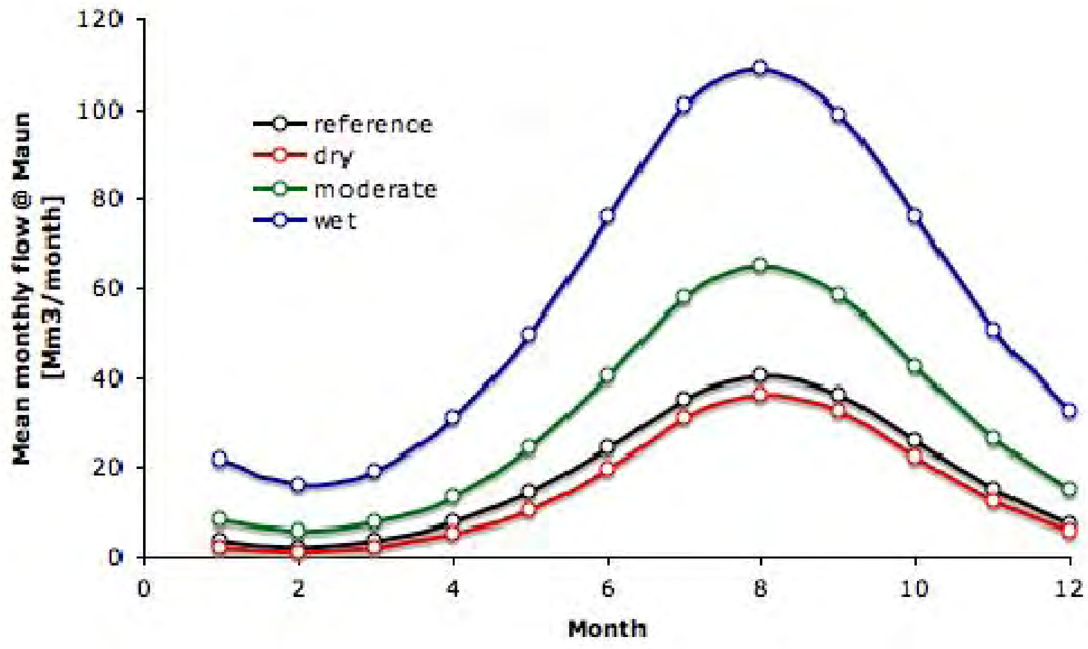


Fig. 33 Mean monthly flows of Thamalakane River at Maun, under reference, “dry”, “moderate” and “wet” climate scenarios

7 Combined climate-development scenarios

7.1 *Superimposition of Climate Change Scenarios on Development Scenarios*

The preceding analyses have shown that, subject to present levels of water use in the Okavango catchment, the projected increase in rainfall overcompensates for the projected increase in evaporation caused by higher temperatures. As a result, an increase in runoff is projected. In the Delta, for “dry” scenarios, the increase in evaporation and transpiration may exceed the increase in local rainfall and inflow from the catchment, with an overall decrease in system’s wetness. However, for “wetter” scenarios, overall increase in system’s wetness is projected. These projected changes will only hold if current levels of water resource development and water use continue into the future. To assess the situation under likely future water use conditions, the climate modified runoff sequences produced by the Pitman catchment model were configured in the WEAP systems model to assess the combined effects of water resource development and climate change futures on the water resources of the Okavango system.

The water resource development scenarios that were considered include a limited number of dams, irrigation and hydropower schemes and a low increase in urban and other water demands in a **Low Scenario**, approximately representing the present 5-7 year plans of the three governments. All of these interventions, plus more that represented possible 10-15 year plans were included in the **Medium Scenario**. The **High Scenario** added a further layer of interventions, some of which are probably not realistic. The main purpose of this final scenario was to ‘push’ the ecosystem as far as possible in terms of development interventions, to assess if there would be significant ecological and social impacts.

The development scenarios are summarised as follows:

- The Present Day scenario includes all existing water resource developments, notably:
    - About 2 700 ha of irrigation in Namibia
    - The urban water demands of Menongue and Cuito Cuanavale (Angola), Rundu (Namibia), and Maun (Botswana)
- A low water use scenario which is based on the continuation of historical growth in water demands in the three countries. Growth rates in Angola reflect the recent acceleration associated with resettlement in de-mined areas. Increased water consumption is mainly due to growth in urban and rural domestic, livestock and irrigation water demands. The largest water demands are represented by:
    - About 3 100 ha of irrigation in Namibia
    - About 18 000 ha of irrigation along the Cuebe River in Angola
    - One storage based and three run-of-river hydropower stations in Angola
- A medium scenario which includes
    - About 8 400 ha of irrigation in Namibia
    - Development of a first phase of the Eastern National Carrier (17 Mm^3/a) for water supply from the Kavango to Grootfontein and Windhoek,
    - About 198 000 ha of irrigation at various locations in Angola
    - One storage based and four run-of-river hydropower stations in Angola
- A high scenario which includes:
    - About 15 000 ha of irrigation in Namibia
    - About 338 000 ha of irrigation at various locations in Angola
    - Completion of all planned hydropower stations in Angola, i.e. one storage based and nine run-of-river hydropower stations in Angola ,

- Completion of a second phase of the Eastern National Carrier (total capacity 100 Mm3/a),
- Development of a storage based water supply scheme for urban and industrial water supply from a dam in the Boteti River to Maun.
- At these levels of demand, it was necessary to introduce a hypothetical dam in the upper basin (Cuchi River) with a capacity of about 500 million m^3 to provide for shortfalls in irrigation water supply and inter-basin transfers.

As can be seen from the above, there are many possible combinations climate-development water futures. For this assessment, the unlikely High water use scenario and the Moderate climate change scenarios were not considered. In total, seven combinations of climate change and water resource development scenarios were assessed. These are shown in Table 8.

Table 8 : Matrix of Climate Change and Development Scenarios

		WATER FUTURES			
Water Use	*High Water Use*				
	Medium water use (M)		**MD**		**MW**
	Low water use (L)		**LD**		**LW**
	Reference (R)	**RR**			
		Reference (R)	*Dryer (D)*	*Moderate (M)*	*Wetter (W)*
		Climate Change			

7.2 Results of Okavango Catchment Modeling

The WEAP modelling system was used to simulate the combined effects of future water resource developments and climate futures on flow sequences at points of interest in the Okavango catchment upstream of Mohembo. WEAP operates on a monthly time step, and is capable of simulating the operation of water resource developments such as irrigation scheme and urban abstractions, in channel dams for irrigation water supply, inter-basin transfers, run-of-river and storage based hydropower schemes. Naturalised (undeveloped) runoff sequences resulting from climate modified rainfall and temperature were exported from the Pitman catchment model and used as inflow time series in the WEAP model.

Present day (reference) and future water resource developments (Low and Medium water use scenarios) were then configured in the WEAP model for use in the scenario simulations.

Results of modeling of the Okavango catchment under combined climate-development scenarios at Mohembo are summarized in Table 9 (flow changes[1]), Fig. 2734 (flow hydrograph), Fig. 28 (flow duration curves) and Fig. 29 (mean monthly hydrograph).

In summary, climate change under the driest scenario reverses the loss of mean annual runoff brought about by the Low and Medium water use scenarios and under the wettest scenario increases mean annual runoff by up to 20% above present day levels even under the Medium water use scenario.

The flood season starts about the same time with climate change, except in the Cuito[2] where it is up to two months earlier. It also lasts up to three months longer, with the most extreme case again being the Cuito. At Mohembo there is a 12-16% reduction in peak under the driest scenario and a very low increase under the wettest. Flood volumes move back toward present day values in the driest scenario, ameliorating development, and greatly exceed present day by up to 50% in the wettest. The overall picture is of the flood season starting a little earlier, lasting longer, having higher flood peaks and providing more water than present day, particularly in the wettest scenario and the upper basin. The Cuito shows the most extreme response, with flooding starting up to two months earlier, peaks up to 20% higher, flood volumes up to 75% higher and the flood season being up to 62% longer.

The dry season is predicted to begin at about the same time as present day or slightly later and to become shorter. Climate change partially or completely returns minimum flows to present day levels even under Medium development. Again, the most dramatic changes are for the Cuito, where the dry season could be up to 19 weeks shorter with minimum flows up to 18% higher.

[1] A detailed description of the ecological relevance and selection of the flow change indicators is given in EPSMO/Biokavango Report Number 2; *Process Report*.

[2] Flow change indicators for the IFA sites upstream of Mohembo are provided in EPSMO/Biokavango Report Number 8; *Final IFA Project Report*.

Table 9 Median values of the ecologically-relevant summary statistics for each climate-change scenario at Mohembo. PD = Present Day. CC = climate change. CCD = driest climate change prediction. CCW = wettest climate change prediction.

Flow Change	PD	Low			Medium			Comment
		No CC	CCD	CCW	No CC	CCD	CCW	
Mean Annual Runoff (Mcm)	270	261	287	341	245	270	324	CCD mitigates development and CCW goes further, increasing MAR to 20-26% more than PD
Dry season onset	Aug	July	Aug	Aug	July	July	Aug	CC mitigates development, with onset as PD.
Dry season duration (days)	115	130	110	71	145	133	92	CCD partially (Medium) or completely (Low) mitigates development and CCW goes further, shortening the dry season by up to 38% of PD
Dry season minimum flow (m^3s^{-1})	114	101	113	125	93	107	122	CCD and CCW partially or completely mitigate development
Flood season onset	Jan	Jan	Jan	Dec	Jan	Jan	Jan	No change.
Flood season peak (m^3s^{-1})	620	618	528	649	611	519	635	Reduction to 84% of PD in CCD and increase by up to 4% in CCW.
Flood season volume (Mcm)	5269	4980	5587	7882	4450	5038	7236	Under CCD volume moves back toward or just above PD, and in CCW show a large increase to 37-50% above PD
Flood season duration (days)	150	143	158	190	129	141	178	Under CCD duration moves back toward or slightly longer than PD, and in CCW is longer than PD by 19-27%

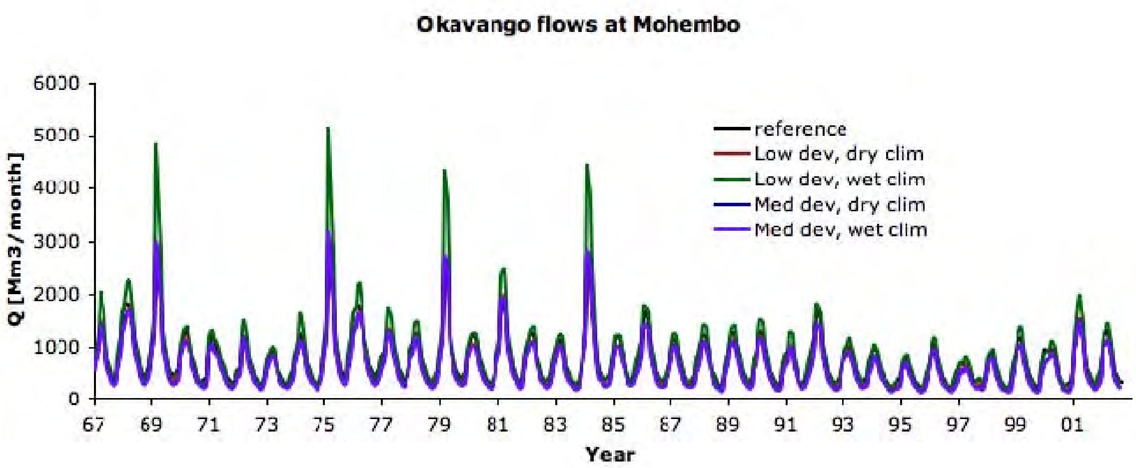


Fig. 34 Mohembo flows under reference conditions and four combined climate change and development scenarios

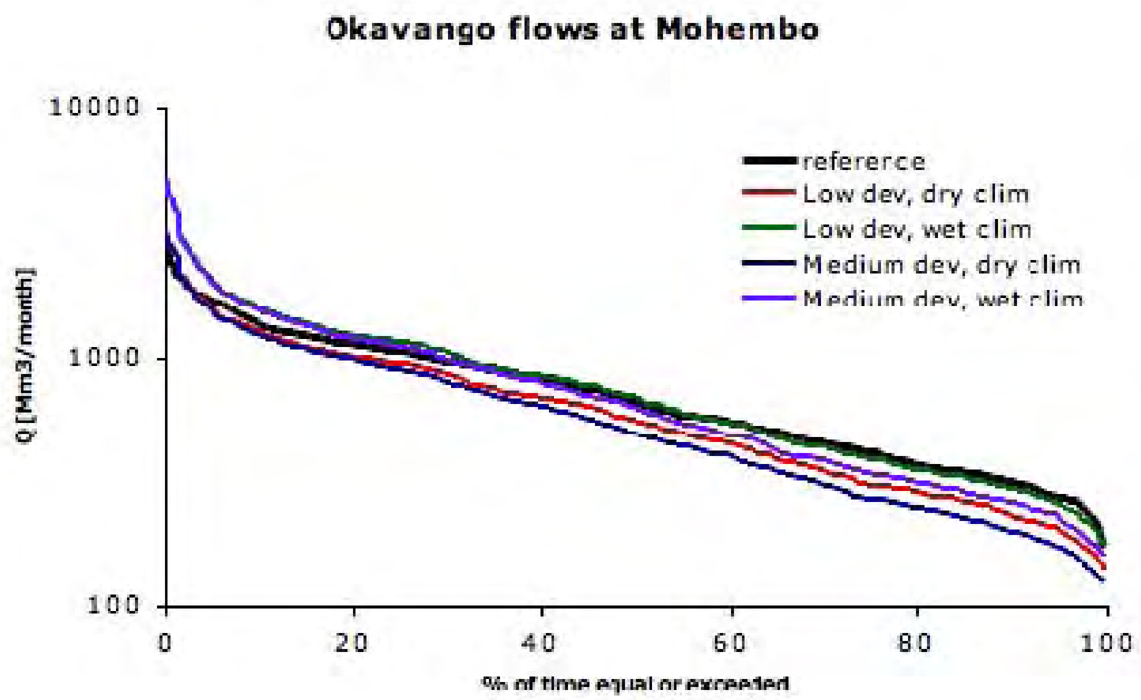


Fig. 35 Flow duration curves for the Okavango River at Mohembo, under reference and four combined climate change and development scenarios.

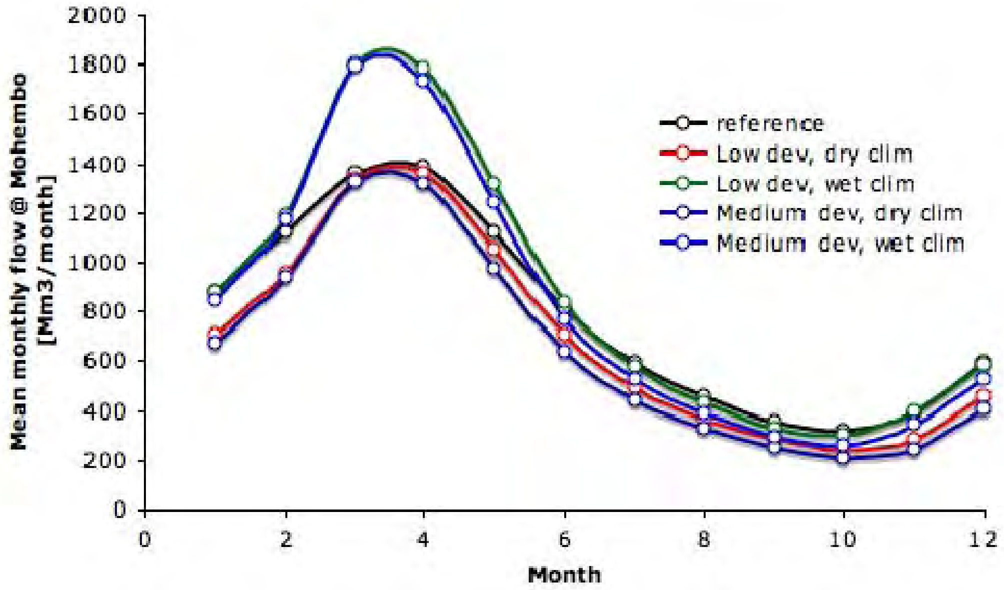


Fig. 36 Mean monthly hydrograph for the Okavango River at Mohembo, under reference and four combined climate change and development scenarios

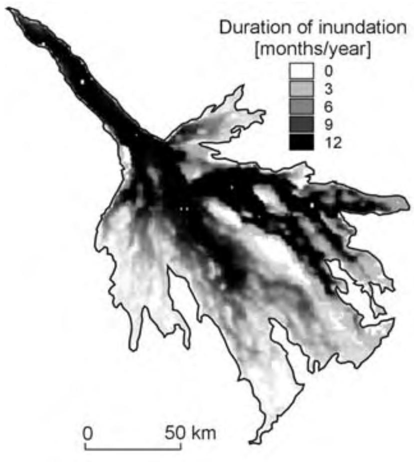
7.3 Results of Okavango Delta Modeling

Results of modeling of the Okavango Delta under combined climate-development scenarios are summarized in Fig. 31 through to Fig. 33.

Under the wet climate change and low water use scenario, inundation patterns revert back to present day levels, with an increase in the average duration of inundation in the mid and distal parts of the Delta. If the medium water use scenario is superimposed on wet climate change, the effects of a wetter climate compensate for increased water use, and inundation patterns closely resemble those associated with present day conditions.

Under the dry climate change scenarios, the drying out of the Delta is exacerbated by increasing levels of water use, with a moderate shift from permanent swamps to seasonal swamps and savanna under the Low CC Scenario and a more severe shift under the Medium CC Scenario to the same conditions predicted for the original High Scenario with no climate change. The impact on the permanent swamps is limited to some extent by the location of future water use developments, which are mostly located in the Cubango sub-basin. Were there to be a shift of development into the Cuito sub-basin (as is the case for the High water use scenario) which provides the bulk of dry-season inflows into the Delta, the impact on the permanent swamps would be much more pronounced.

Under the wet climate change scenario, some of the impacts of development on Thamalakane flows are reversed. Under these climate conditions, flow conditions resemble the present day situation even with Low and Medium development included. Under the drier conditions, drying out of the Delta has a corresponding impact of outflows into the Boteti/Thamalakane system. In the outflow system, the low water use / dry climate change scenario would resemble the medium water use with no climate change, while the medium water use / dry climate change represent a condition half way between the medium and high water use scenarios with no climate change.



a)

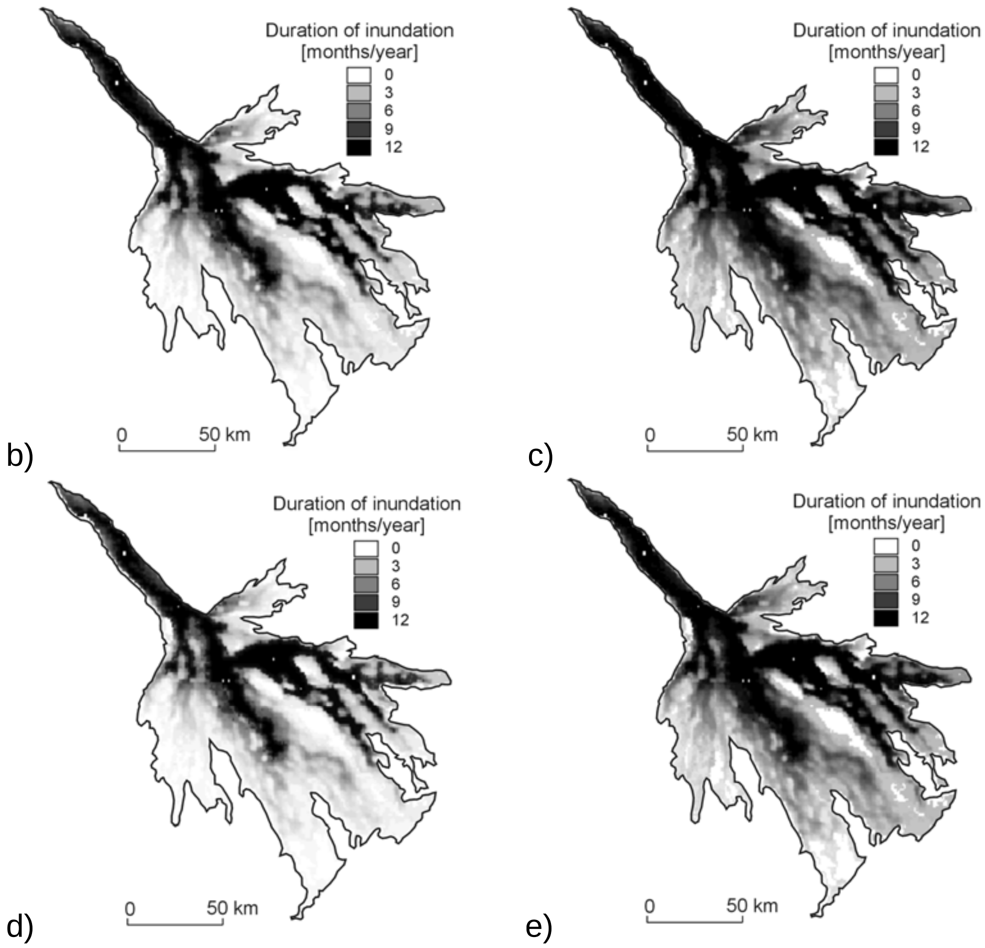


Fig. 37 Average duration of inundation under a) reference, b) low development, dry climate, c) low development, wet climate, d) medium development, dry climate and e) medium development, wet climate scenarios.

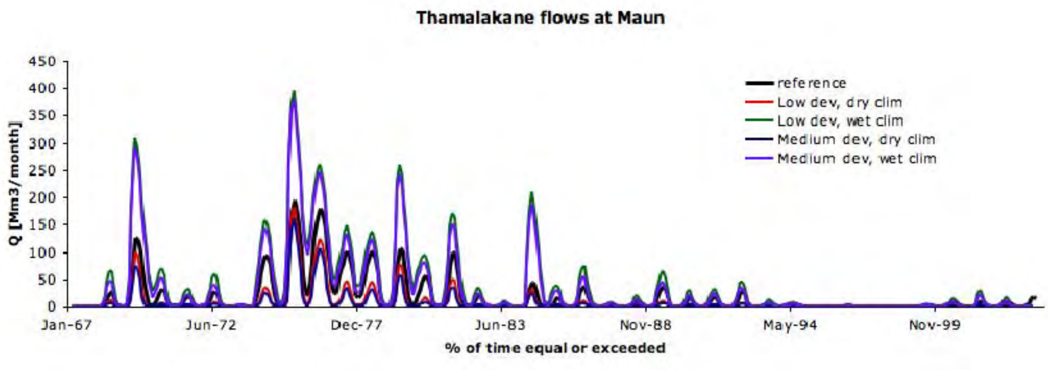


Fig. 38 Thamalakane River flows under reference conditions and four combined climate change and development scenarios

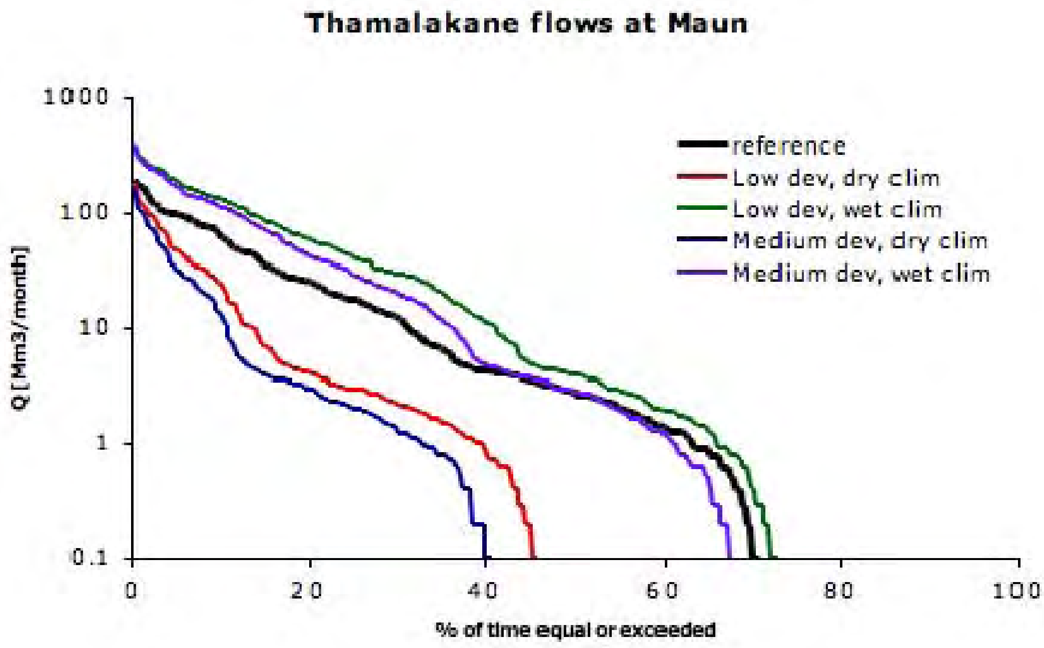


Fig. 39 Flow duration curves of Thamalakane River under reference conditions and four combined climate change and development scenarios

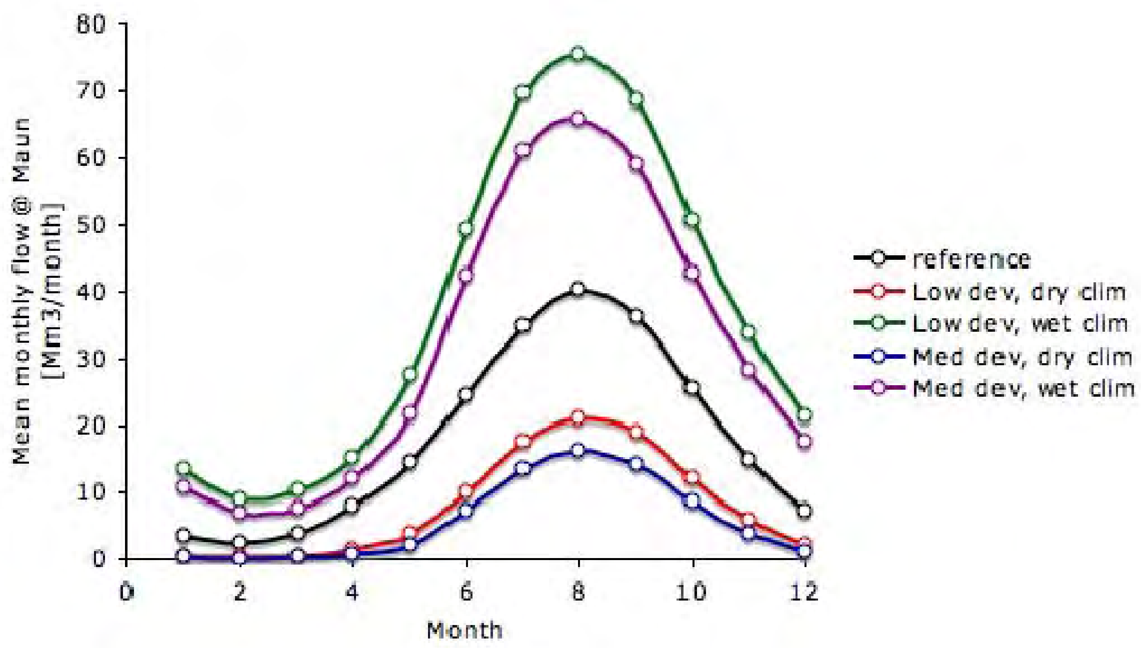


Fig. 40 Mean monthly flows of Thamalakane River under reference conditions and four combined climate change and development scenarios

8 Summary and discussion

Analyses carried out in this project, based on data available for the Okavango system, reveal the following:

Past climate variability and change in the Okavango

- Past rainfall time series (1920-to date) from the Okavango region bears no clear signatures of changes in total annual rainfall and interannual variability exceeding ranges of natural variability expected within a 30-year period. For the Okavango Delta, this statement can be extended to several other rainfall indices such as mean and maximum daily rainfall and number of rain days, and onset of rainy season. These statements do not exclude the possibilty of anthropogenic, GHG-driven change, but recognize that such changes were not stronger than, and thus not distinguishable from the natural rainfall variabiltiy.

- Temperature records exhibit long-term variability that exceeds ranges of natural variabiilty expected within a 30-year period. It is beyond the scope of this report to attempt attrubution of this long-term variaibility.

Projected climate change signal

- Projections of future climate accepted in this report give a general increase in future temperatures and increase in rainfall. Temperatures are projected to increase by 2.3-3 deg C, with stronger increase in the south, weaker in the north. Rainfall is projected to increase by 0-20%. Relative change in rainfall (expressed in %) is projected to be weaker in the north, and stronger in the south. However, due to north-south rainfall gradient, these translate to absolute change (in mm) being stronger in the in the north and weaker in the south.

- Projections accepted here give significant changes only in the total rainfall and in the number of raindays. No significant shift in timing of rains, rainfall intensity and interannual variability is projected.

- There are marked differences in magnitude of change between seasons. Strongest temperature change is projected to occur in Sep-Nov, the weakest in Mar-May. For rainfall, the strongest increase is projected for Mar-May, the weakest for Sep-Nov.

Projected hydrological change (present levels of water use)

- In the Okavango catchment, the projected increase in rainfall overcompensates for the projected increase in evaporation caused by higher temperatures. As as result, an increase in runoff (total and monthly) is projected. The increase in peak flows is projected to be proportionately stronger than that in low flows.

- In the Delta, for “dry” scenarios, the increase in evaporation and transpiration may exceed the increase in local rainfall and inflow from the catchment, with an overall decrease in system’s wetness. However, for “wetter” scenarios, overall increase in system’s wetness is projected. The “dry” conditions will manifest by decrease in frequency and duration of inundation throughout the Delta and in reduction of low flows in the rivers draining the system, as exemplified by the Thamalakane. The wetter conditions will show through the increase in duration and frequency of inundation throughout the Delta, and the increase of high and low flows in the rivers draining the system.

Projected hydrological change with increased water use

- In the Okavango catchment, the projected increase in rainfall overcompensates for the projected increase in evaporation caused by higher temperatures. Under the dry climate change scenario the loss of additional water use is reversed for the low and medium water use scenario. Under the wet scenario mean annual runoff is increased by up to 20% above present day levels even under the Medium water use scenario.

- In the Delta, for “dry” scenarios, the increase in evaporation and transpiration may exceed the increase in local rainfall and inflow from the catchment, with an overall decrease in system’s wetness. This is exacerbated by increased levels of water use but the impacts would be limited to some extent if future water use development is concentrated in the Cubango sub-basin. For “wetter” scenarios, the projected overall increase in system’s wetness compensates for increased water use to the extent that inundation patterns under a medium water use scenario closely resemble those associated with present day conditions. is projected. Under the wet climate change scenario, some of the impacts of development on Thamalakane flows are reversed. Under these climate conditions, flow conditions resemble the present day situation even with Low and Medium development included. Under the drier conditions, drying out of the Delta has a corresponding impact of outflows into the Boteti/Thamalakane system with the medium water use / dry climate scenario representing conditions half way between the medium and high water use scenarios with no climate change.

The above conclusions are based on datasets and procedures used in the analyses, and are subject to a range of uncertainties, most importantly:

- Uncertainty in future GHG emissions. The study is based exclusively on the SRES A2 GHG scenario that represents “business-as-usual” emissions. Other scenarios are viable, with higher and lower emission levels, however, differences in between them in the period of interest (near future – up to 2060) are rather low. Analyses carried for GCM data (not presented here) indicate that the use of a different GHG scenario would affect quantitative results, but will have little bearing on the overall direction and magnitude of climatic and hydrological change.

- Long term natural variability in climate. The Okavango system is experiencing rather strong variability on the decadal to multidecadal time scales. Analyses (not presented here) indicate that GCMs simulate ranges of long term variability comparable to observations, but fail to represent its temporal pattern. Thus, the effects of long-term variabilty can potentially be confused with effects of GHG-driven climate change. However, the effects of long-term variability affect results of a single GCM run, but will average out when multiple runs are used, and when an ensemble of GCMs is used. The long-term climate variability is not explicitely accounted for in the results presented above. However, because of the results being based on the ensemble of GCM/SD outputs, possible effects of long-term variability are expected to be low, and affect quantiative results with little influence on the overall magnitude and direction of projected climatic and hydrological change.

- Data limitations. In this project, no continuous series of daily rainfall and temperatures were available from Angola, and very limited data were available from Botswana. The use of substitute data undobtedly introduces uncertainty into final results.

    - Conclusions about past changes are based on the observed station data for Botswana, and reanalysis data for Angola. Results from Botswana are, therefore, realistic, while these for Angola can be questioned. Analyses of consistency between datasets used show that there are no major biases between observed and reanalysis datasets, and that temporal patterns are consistent. No conclusions are drawn here with respect of rainfall indices that could not be derived from reanalysis data for Angola.

  - In the downscaling procedure, FEWS satallite dataset was used instead of observations. Inacuracies of that datset caused that only relative change could be determined, as this was shown to be robust with respect to the quality of input dataset. Absolute values of future rainfall were likely to be erroneous. As shown in the analyses carried out, errors involved in the use of FEWS dataset in the downscaling were not systematic. The use of FEWS dataset introduces therefore a potential quantitative error into the final results, but is expected to have no influence on the overall magnitude and direction of projected climatic and hydrological change.

- Accuracy and adequacy of GCMs and modelling error. This report is based on the unquestioned assumption that GCMs are suitable tools for modelling future climate. It also recognizes that there is an error involved in each model's results. In line with current methodologies of climate change assessment, it utilizes an ensemble of GCMs/SD results. Such an ensemble defines a range of possible future climates that encompass modelling errors. Techniques exist to stratify members of the ensemble according to their reliability, thus narrowing the range of possible climate scenarios. However, this was not done due to the few models available, and other errors involved, which the relatively large range of scenarios adopted here is believed to encompass.
- Accurracy and adequacy of dowscaling procedure.
  - The most problematic issue revealed in this study is the disparity between direction of rainfall change projected by raw GCM data and that projected by SD. Earlier work with this method revealed similar differences in change between SD and GCMs to these revealed here, with preservation of spatial pattern of change. The disparity is not, therefore, unique to the Okavango, and cannot be an effect of input data artefacts or procedural errors. Nonetheless, the results of SD method in that matter should be verified, preferably against independent downscaling method. At the time of writing this report, CSAG SD method used in this study was the only operational method available for Africa, and such a verification was beyond the scope of this project.
  - Statistical downscaling procedures have their inherent uncertainties related to their empirical nature – they tend to underestimate change in extremes and interannual variability. Thus, conclusions related to these indices are to be treated with reservations.

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The Okavango River Basin Transboundary Diagnostic Analysis Technical Reports

In 1994, the three riparian countries of the Okavango River Basin – Angola, Botswana and Namibia – agreed to plan for collaborative management of the natural resources of the Okavango, forming the Permanent Okavango River Basin Water Commission (OKACOM). In 2003, with funding from the Global Environment Facility, OKACOM launched the Environmental Protection and Sustainable Management of the Okavango River Basin (EPSMO) Project to coordinate development and to anticipate and address threats to the river and the associated communities and environment. Implemented by the United Nations Development Program and executed by the United Nations Food and Agriculture Organization, the project produced the Transboundary Diagnostic Analysis to establish a base of available scientific evidence to guide future decision making. The study, created from inputs from multi-disciplinary teams in each country, with specialists in hydrology, hydraulics, channel form, water quality, vegetation, aquatic invertebrates, fish, birds, river-dependent terrestrial wildlife, resource economics and socio-cultural issues, was coordinated and managed by a group of specialists from the southern African region in 2008 and 2009.

The following specialist technical reports were produced as part of this process and form substantive background content for the Okavango River Basin Transboundary Diagnostic Analysis.

Final Study Reports	***Reports integrating findings from all country and background reports, and covering the entire basin.***		
		Aylward, B.	*Economic Valuation of Basin Resources: Final Report to EPSMO Project of the UN Food & Agriculture Organization as an Input to the Okavango River Basin Transboundary Diagnostic Analysis*
		Barnes, J. et al.	*Okavango River Basin Transboundary Diagnostic Analysis: Socio-Economic Assessment Final Report*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Project Initiation Report (Report No: 01/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment EFA Process Report (Report No: 02/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Guidelines for Data Collection, Analysis and Scenario Creation (Report No: 03/2009)*
		Bethune, S. Mazvimavi, D. and Quintino, M.	*Okavango River Basin Environmental Flow Assessment Delineation Report (Report No: 04/2009)*
		Beuster, H.	*Okavango River Basin Environmental Flow Assessment Hydrology Report: Data And Models(Report No: 05/2009)*
		Beuster, H.	*Okavango River Basin Environmental Flow Assessment Scenario Report : Hydrology (Report No: 06/2009)*
		Jones, M.J.	*The Groundwater Hydrology of The Okavango Basin (FAO Internal Report, April 2010)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Ecological and Social Predictions (Volume 1 of 4)(Report No. 07/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Ecological and Social Predictions (Volume 2 of 4: Indicator results) (Report No. 07/2009)*
		King, J.M. and Brown, C.A.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Ecological and Social Predictions: Climate Change Scenarios (Volume 3 of 4) (Report No. 07/2009)*
		King, J., Brown, C.A., Joubert, A.R. and Barnes, J.	*Okavango River Basin Environmental Flow Assessment Scenario Report: Biophysical Predictions (Volume 4 of 4: Climate Change Indicator Results) (Report No: 07/2009)*
		King, J., Brown, C.A. and Barnes, J.	*Okavango River Basin Environmental Flow Assessment Project Final Report (Report No: 08/2009)*
		Malzbender, D.	*Environmental Protection And Sustainable Management Of The Okavango River Basin (EPSMO): Governance Review*
		Vanderpost, C. and Dhliwayo, M.	*Database and GIS design for an expanded Okavango Basin Information System (OBIS)*
		Veríssimo, Luis	*GIS Database for the Environment Protection and Sustainable Management of the Okavango River Basin Project*
		Wolski, P.	*Assessment of hydrological effects of climate change in the Okavango Basin*
Country Reports Biophysical Series	***Angola***	*Andrade e Sousa, Helder André de*	*Análise Diagnóstica Transfronteiriça da Bacia do Rio Okavango: Módulo do Caudal Ambiental: Relatório do Especialista: País: Angola: Disciplina: Sedimentologia & Geomorfologia*

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Environmental protection and sustainable management of the Okavango River Basin

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