Impact of climate change and development scenarios on flow patterns in the Okavango River

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Abstract

This paper lays the foundation for the use of scenario modelling as a tool for integrated water resource management in the Okavango River basin. The Pitman hydrological model is used to assess the impact of various development and climate change scenarios on downstream river flow. The simulated impact on modelled river discharge of increased water use for domestic use, livestock, and informal irrigation (proportional to expected population increase) is very limited. Implementation of all likely potential formal irrigation schemes mentioned in available reports is expected to decrease the annual flow by 2% and the minimum monthly flow by 5%. The maximum possible impact of irrigation on annual average flow is estimated as 8%, with a reduction of minimum monthly flow by 17%. Deforestation of all areas within a 1 km buffer around the rivers is estimated to increase the flow by 6%. However, construction of all potential hydropower reservoirs in the basin may change the monthly mean flow distribution dramatically, although under the assumed operational rules, the impact of the dams is only substantial during wet years. The simulated impacts of climate change are considerable larger that those of the development scenarios (with exception of the high development scenario of hydropower schemes) although the results are sensitive to the choice of GCM and the IPCC SRES greenhouse gas (GHG) emission scenarios. The annual mean water flow predictions for the period 2020–2050 averaged over scenarios from all the four GCMs used in this study are close to the present situation for both the A2 and B2 GHG scenarios. For the 2050–2080 and 2070–2099 periods the all-GCM mean shows a flow decrease of 20% (14%) and 26% (17%), respectively, for the A2 (B2) GHG scenarios. However, the uncertainty in the magnitude of simulated future changes remains high. The simulated effect of climate change on minimum monthly flow is proportionally higher than the impact on the annual mean flow.

Introduction

The Okavango River Basin, shared by Angola, Namibia and Botswana, is one of the least developed river basins in Africa (Kgathi et al, Kniveton and Todd, both this issue). However, socio-economic needs of a growing population may change this situation and the basin has been identified by the World Water Assessment as having the potential for water-related disputes within 5–10 years (Wolf et al., 2003). Most of the streamflow in the basin is generated within Angola, which has been called "*the sleeping giant*" in the sense that water resources in Angola are relatively unexploited. Future developments, however, could have serious consequences to the water availability of the downstream countries (Pinheiro et al., 2003). After 27 years of civil war, that has forced more than 4 million people away from their homes; the 2002 cease-fire raised the possibility of large numbers of returning refugees to the Angolan parts of the basin. Developments to fulfil the needs of the basin's inhabitants, including urbanisation, industrialisation and hydropower schemes, have the potential to change the face of the basin (Ellery and McCarthy, 1994). Although the provision of needs to basin inhabitants is undisputed, there are concerns that the resettlement of displaced communities might negatively affect "*one of the last pristine river systems in Africa*" (Green Cross International, 2000), and that the unplanned nature of the re-settlement will lead to environmental damage (Mbaiwa, 2004). Another potential threat to downstream ecosystems is that increasing agriculture in the Angolan highlands might lead to increased eutrophication (Ellery and McCarthy, 1994).

Although upstream water resources are abundant, the mid and downstream sections of the basin are very dry. Water is thus an extremely valuable good whether it is for human needs, or to sustain valuable ecosystems. The demand for basin water is further exacerbated by increasing demands from outside the basin. Though Windhoek constantly strives to develop other possibilities to provide its inhabitants with water, a 1993 study about supplying the central Namibian region with water (CSE/LCE/WCE Joint Venture Consultants, 1993) confirms an earlier Master Plan from 1972 (Water Resources Investigation and Planning for Part of the Central Area of South West Africa, 1972) which states that a pipeline would eventually be built from the Okavango River to Grootfontein, linking the river system with Windhoek (the 'Eastern National Carrier', Pinheiro et al., 2003). Stakeholders in the dry downstream state of Botswana are concerned about how such a potential pipeline and other upstream developments will affect the Okavango Delta, an area of extremely high biodiversity in both flora and fauna which supports an economically vital tourist industry. In many instances competition for resources has the potential to cause conflict. But the level of conflict between the riparian countries of the Okavango River Basin has to date been limited to verbal disputes particularly between Botswana and Namibia (Mbaiwa, 2004). Nevertheless, the Okavango River Basin will soon undergo much larger changes than it has seen in the past, and what remains to be determined is how these changes will affect downstream water supplies.

There is now considerable evidence of a discernible anthropogenic influence on global climate (IPCC, 2001) associated with greenhouse gas (GHG) emissions. Furthermore, it is highly likely that GHG emissions will increase over the coming decades, and that the human impact on climate is likely to continue. Nevertheless, any climate change signal will be imposed upon 'natural' patterns of climate variability and may well be expressed through these. The significance of climate variability and change for African hydrology has, e.g. been shown for Lake Victoria (Tate et al., 2004) and more widely in the Nile basin by Conway (2005). Sutcliffe and Knott, 1987 and Sutcliffe and Parks, 1988 reviewed the significance of variations in river flows and wetlands in Africa, including the Okavango.

Consequently, it is likely that any future developments will occur against the background of climate change. It is important, therefore, that we develop strategies to mitigate the effects of future climate change/variability on the terrestrial life support systems. This is important in regions where populations are particularly vulnerable, notably in the developing world, and where ecosystems are particularly sensitive to climate change. The development of such strategies first requires integrated assessments of climate change and variability on terrestrial systems.

In order to facilitate the regional development process and to pave the way for an Integrated Basin Development Plan, there is an urgent requirement for information about the riverine water resource situation and how it will be affected by human activities. It needs to be recognised that all policies have unintended, negative consequences. The use of models has been proven to be successful in identifying these consequences and allowing the development of mitigation measures, facilitating trade-offs between stakeholders (Dahinden et al., 2000). A model-based dialogue may create a common view of the problems at stake, as well as a platform to test the possible environmental impact of various suggested remedies (Schulze et al., 2004). It may lead to an increased understanding of why and how different groups act or think as they do and increases the possibility for public participation in the decision process as it serves as a pedagogical tool (Ravetz, 2003 and Andersson, 2004).

The contending sphere of influence in which demands for water management interventions takes place, as a response to drivers of change and development needs, represent specific stakeholder groups with potentially divergent needs and interests (Fig. 1). Local level subsistence-farming communities may find themselves in competing for a slice of the same water resource as big business interests (whether commercial agriculture or industries). A government may decide to initiate an interbasin transfer scheme to the benefit of overall economic development of the country, but with implications for local communities in the donor basin. The use of models to generate scenarios on the various possible water allocation and management options could serve to mitigate these inequalities in power between the various

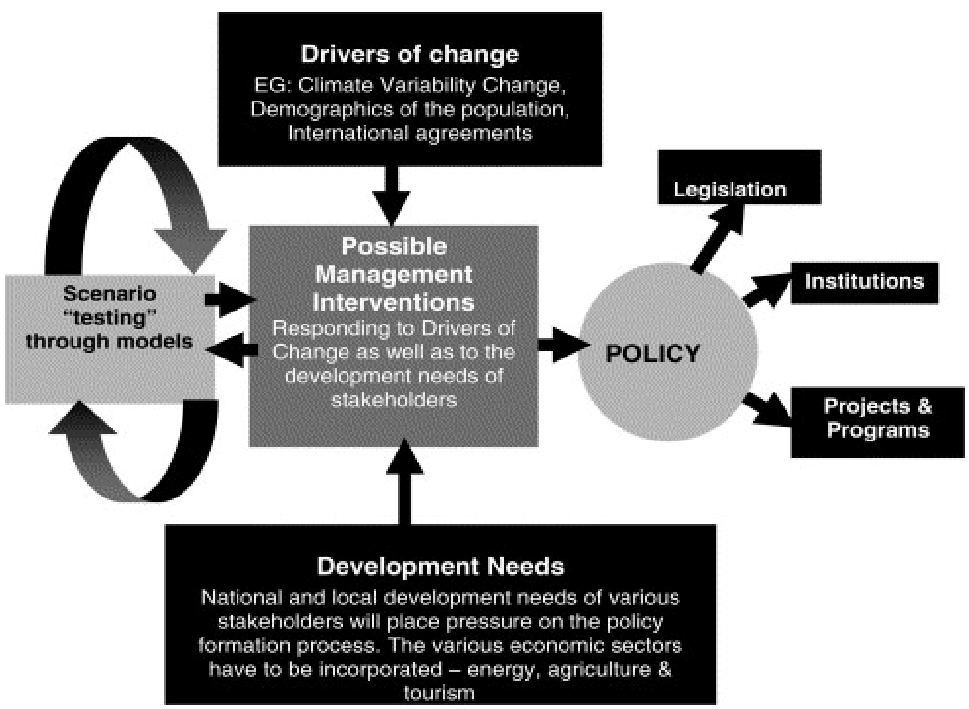

Figure 1. The policy development process, where scenarios of possible impacts of management interventions as a response to drivers of change as well as of the development needs of stakeholders can be tested through models.

stakeholders, assuming that all involved in the process in a way that ensures trust between those involved (Alkan Olsson and Andersson, in press). This may increase the possibility to create a common regional, national or local development vision, mirrored by common policies with regard to legislation, institutions and creation of projects and programmes (Fig. 1).

One of the main conclusions of the USAID funded project "*Sharing Water: Towards a Transboundary Consensus on the Management of the Okavango River Basin*" is that the water management process need to be inclusive and built on trust between those who have access to data (government or private), the modellers (consultants or academics) and other stakeholders involved in managing the resources in the basin. Model selection, development and use should proceed with the understanding and cooperation of as many experts and stakeholders as possible (Sharing Water Final Report, 2005). The success of scenario modelling as a tool for water resource management is identified to rest on three critical factors:

• creation of an open forum for discussions of how to equitably share costs and benefits;

• articulation of creative and innovative management strategies; and

• availability of transparent, easily manipulated analytic tools for comparative evaluation of these alternatives (Sharing Water Final Report, 2005).

The aim of the work presented in this paper, conducted under the EU-funded WERRD project (Water and Ecosystem Resources in Regional Development – Balancing Societal Needs and Wants and Natural Systems Sustainability in International River Basin Systems), is to lay the ground for the use of scenario modelling as a tool for integrated water resource management in the Okavango basin. The paper presents a setup of the Pitman monthly rainfall-runoff model in order to assess the impact of various development and climate change scenarios on the flow in the Okavango River system. The relative importance of various potential developments and of climate change on the river flow are assessed, uncertainties in the assumptions used for scenario developments are discussed, as well as the requirements for successful implementation and operational use of scenario modelling as a tool for integrated water resource management. The results from this study have also been used in a study of the potential impacts of upstream changes on Delta flooding (see Murray-Hudson et al., this issue).

Data and methods

Hydrological modelling strategy

The model of the river basin is applied to both 'present day' historical conditions and also various development and climate change scenarios to assess the impact of these on river flows. Hydrological scenario modelling is carried out using a modified version of the monthly Pitman model, set-up for the Okavango basin upstream of the delta panhandle (Hughes et al., this issue). As described by Hughes et al. (this issue), the majority of the runoff is generated in the wetter headwater tributaries, while the lower sub-basins are dominated by channel loss processes with very little incremental flow contributions, even during wet years. The channel transmission losses were represented by dummy-reservoirs based on a quantification of channel lengths and widths of floodplains and swamps (Hughes et al., this issue). Soils information was obtained from FAO, while the geological information and topography map are from the USGS, and land cover was derived by GLC2000. The application of these databases is further described in Hughes et al. (this issue).

The basin is sub-divided into 24 sub-basins, of which 18 have gauging stations at their outlet. The baseline simulations are forced by gauged rainfall from 1960 to 1972 and satellite based rainfall estimates for the 1991–2002 period. The satellite based rainfall was corrected; using an equation developed by comparing gauged and satellite rainfall (Wilk et al., this issue). The 1960–1972 period, dominated by moderate to wet years, was used for model calibration, while the 1991–1997 period includes several dry years. This period was used for model validation to ensure that the calibrated parameter values were appropriate to describe a drier flow period and to ensure that the model setup performs satisfactory when forced by the satellite derived rainfall data, which probably will be the only available source of rainfall information in the foreseeable future. The baseline conditions are, therefore, representative of observed interannual and decadal variability in river flow.

Hughes et al. (this issue) concluded that the Pitman model used in this study more than adequately represented the hydrological response of the Okavango basin over a range of historical climatological conditions (Fig. 2). As such, the

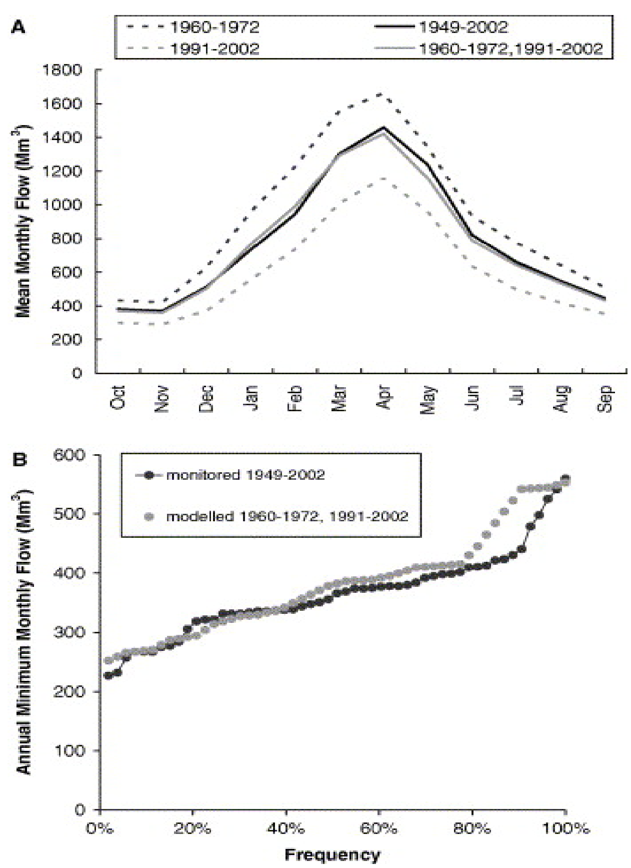

Figure 2. Comparison of gauged flow for the time periods used for the baseline simulations (1960–1972, 1991–2002) and the full record of streamflow from the gauging station in Mukwe (1949–2002). A: Mean monthly flow; B: Annual minimum monthly flow.

model is a suitable tool for simulating hydrological impact of development and climate change scenarios. The impacts on river flow of the various development and climate change scenarios are evaluated through comparison of simulated mean monthly and minimum monthly river flow frequencies under the various scenarios with the simulated ‘present day’ baseline conditions.

Modelling the impact of development scenarios

Estimation of baseline water abstraction rates

In order to quantify water use under future development scenarios baseline conditions related to water use in the basin need to be determined. Population estimates for Angola are derived from Mendelsohn and el Obeid (2004), who used urban population estimates supplied by the OCHA (Office for Co-ordination of Humanitarian Affairs), combined with estimates of village sizes from aerial and ground surveys and density estimates from the UNEP database. The population estimate of the Angolan portion of the basin is 370,000 people, of which approximately 16% are heads of a farming family. The estimate for the Namibian portion is 163,000 (Mendelsohn and el Obeid, 2004). Water use in the Angolan part of the basin is estimated to be 17 l day^{-1} per capita for rural domestic use, based on estimates by Gleick, 1996 and HR Wallingford, 2003 and 68 l day^{-1} per capita for urban consumption. The respective figures for the Namibian part of the basin are 34 and 100 l day^{-1} (pers. comm., de Wit, October, 2004). Water use by tourists in the Rundu area is estimated to be 200 l day^{-1} per capita, with 45,500 tourist beds yr^{-1} (pers. comm., Schachtschneider, 2004). The monthly average is increased by 50% during the high season and decreased by 70% for the low season months. Estimates of the numbers of livestock are based on sub-basin adjusted cattle and goat densities obtained from Mendelsohn and el Obeid (2004). Cows and goats are assumed to consume 45 and 7.5 l day^{-1}, respectively. The water used for irrigation is a combination of small-scale informal irrigation by small farmers that apply water to their crops manually and through ditching and that from larger existing irrigation schemes. Figures related to existing irrigation schemes are provided from Mendelsohn and el Obeid (2003). Estimates of small-scale irrigation for the Angolan part of the basin, are based on 10,000 farmers irrigating on average 0.25 ha per capita, whereas for the Namibian part of the basin, it is estimated that 500 farmers, irrigate 0.2 ha per capita (Mendelsohn and el Obeid, 2004). Calculations of water requirements for irrigation are further described in “Modelling the impact on river flow of the development of scenarios”, where the hydrological model is presented.

Selection of development scenarios

In August 2003, a workshop was arranged by the WERRD project, with participation of stakeholders including members of the Okavango River Basin Commission (OKACOM) and Steering Committee, representatives of relevant NGOs and related projects, Dept of Water Affairs, Namibia, UNDP, FAO, Kavango Regional Council (Namibia), Kavango Basin Wide Forum (Namibia), NNF, International Water Unit, MMEWR, Botswana and researchers within the WERRD project. Three future sets of development scenarios were defined: low impact, “business-as-usual” (medium) and high impact development. The “business-as-usual” was that deemed by stakeholders to contain the most plausible development elements. Many of the components of the high impact development were considered highly unlikely to happen, e.g. the construction of hydropower dams in Angola in all potential areas, at least in the foreseeable future. The "low impact development" scenario is assumed to be linked to the establishment of ecotourism in transfrontier parks and of a Ramsar site in the Angolan part of the basin. The selection and quantification of scenarios, presented in this paper, is based on conclusions from the workshop, followed up by a literature review and advice from local experts.

Development scenarios

Development scenarios are based on predictions of levels of population growth and demand for water and the possibilities for development including irrigated agriculture, industry and hydropower, which are used as input to the Pitman model in order to estimate how these might affect downstream water resources. With the exception of the use of population increase projections for the years of 2015 and 2025 in the estimates of water abstractions from households, livestock and informal irrigation, no assessments are made of when (or if) various developments are expected to occur, nor of which combinations of various developments that are plausible.

Low impact development

The low impact development scenarios are based on a change in water demand due to increased consumptive use from population, livestock and informal irrigation, based on population projections for 2015 and 2025 from the US Census Bureau (2000); rural population increases of 2.2% and 1.6% per annum for Angola and Namibia, respectively. For urban areas, an increase of 6% is assumed, which corresponds to the medium forecast for the Rundu area, Namibia, according to CSE/LCE/WCE Joint Venture Consultants (1993). Although the low impact development scenario could be assumed to include increased (eco) tourism, the impact on river flow is assumed to be negligible and is therefore ignored. Increase in livestock is assumed to be proportional to population increase. North of Rundu it is assumed that 20% of the farmers own five cattle and five goats, while south of Rundu 40% own 10 cattle and 10 goats, i.e. similar proportions to the baseline conditions (Mendelsohn and el Obeid, 2004). Informal irrigation is based on the same assumptions as for the baseline water abstractions and changes in water consumption related to population increases.

Business as usual

The "business as usual" scenarios include formal irrigation schemes, deforestation and construction of one hydropower dam, in addition to population increase. All potential irrigation schemes in the lower Angolan portion of the basin as described by Crerar (1997) and all planned schemes in the Namibian part of the basin, including those proposed under the Green Scheme (Mendelsohn and el Obeid, 2003) are included. With regard to deforestation, an area corresponding to a 1 km buffer around major water courses is assumed to be clear-cut. This was performed by determining the amount of forest cover within this zone for each sub-catchment (from the GLC2000 land use cover map) with the help of GIS tools and decreasing this amount accordingly in the modelling set up. It is assumed that one dam at Malobas (Table 1, Fig. 3) will be constructed in Angola (Crerar, 1997).

Table 1. Potential hydropower reservoirs in the Angolan part of the basin included in the scenarios

Reservoir name	**Sub-catchment**	**Full supply capacity (Mm^3)**	**Generating releases ($m^3\ s^{-1}$)**	**Annual release volume ($Mm^3\ yr^{-1}$)**	**Mean annual power output ($GWh\ yr^{-1}$)**
Cuvango	Chinhama	393	54.7	841	29.8
Chazenga	Artur de Paiva	440	110.3	1783	67.4
Mumba	Caiundu	656	190.5	3154	183.5
Mucundu	Mucundu	2541	422.0	6765	330.8
Calemba	Cutato	385	58.2	941	23.8
Malobas	Cuchi	1634	206.9	1903	215.5

Geographical positions of the reservoirs are shown in **Fig. 3**.

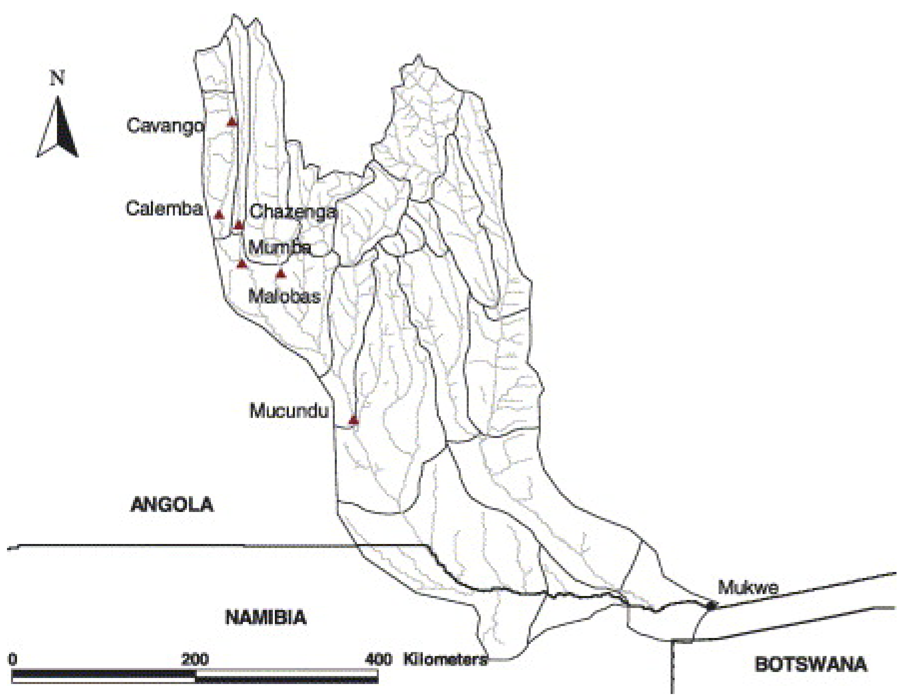

Figure 3. The Okavango River basin with sub-basins and with potential sites for construction of dams, according to **Crerar (1997)**.

High impact development

In addition to the developments under the previous two groups of scenarios, the “high impact development” scenario includes irrigation of all areas estimated as suitable for irrigation by Diniz and Aguiar (1973), which corresponds to 1040 km^2 (0.2% of the total upstream basin area). It is also assumed that 5% of the cultivated area (Perfil Provincial do Kwando Kubango, 2003) around the two urban areas of Menongue and Cuito-Cuanavale will be irrigated. A buffer of 2 km around major watercourses is assumed to be clear-cut, and all potential dams (Table 1) (Crerar, 1997) are considered operational. Finally, this scenario includes the operational use of the Eastern National Carrier; a pipeline planned to transfer water from the Okavango to the central area of Namibia near Windhoek. The operation would be based on management decisions taken by NamWater at the end of each rainy season, taking into account the level of storage by dams in the central area of Namibia and the level of aquifers in the central area and Grootfontein. A reasonable estimate of a “worst case scenario” is that about 100 Mm^3 needs to be abstracted at a rate of 3–4 $m^3 s^{-1}$ on a continuous basis (Heynes, pers comm., 2004). As no details were available regarding monthly distributions, 3 $m^3 s^{-1}$ is assumed to be pumped throughout the year, giving an annual total of 94.6 Mm^3.

Modelling the impact on river flow of the development scenarios

Water abstractions for domestic use and livestock are combined into one value for each sub-basin and abstracted from the river discharge at each sub-basin outlet. Return flows of 85% for the domestic water supply, and 30% for the livestock water supply (Hoekstra et al., 2001) are assumed. For each sub-basin, the crop water demand is calculated by the model as a function of the irrigated area and a crop demand factor, derived from prevailing crop distributions. Type of crops and their monthly distribution factors are based on Mendelsohn and el Obeid, 2003 and Perfil Provincial do Kwando Kubango, 2003. The monthly water used for irrigation is calculated as the difference between the effective rainfall and the crop demand, with return flows set to 20%. Streamflow generation impacts of the deforestation scenarios are simulated by altering parameters that control interception, infiltration and actual evaporation (Hughes et al., this issue).

To calculate the impact of potential hydropower dams in the Angolan part of the river basin information from Crerar (1997) is used to estimate the following parameters:

$$Q = \frac{C * 10^6}{\rho g(\alpha H)}, \qquad (1)$$

where: Q is the discharge (in $m^3 s^{-1}$) required for the generating capacity C (in MW), ρ the density of water (1000 kg m^{-3}), g is the gravity constant (9.81 m s^{-1}), α is the efficiency, and H is the head difference (in m). The average number of hours per day of power generation δ is computed as:

$$\delta = \frac{P}{C * 365} \qquad (2)$$

where P is the annual power output (in MW h/year). The efficiency (α) is assumed to be 0.7 and the full supply capacities of the reservoirs are taken directly from Crerar (1997). Eq. 2 generally resulted in an average duration of power generation of 12 h per day and is applied to the release rate for the generating capacity to estimate the annual release volumes given in Table 1. The annual release volume from the dam (discharge) is, therefore, the generating release integrated over the year, based on the 12 h per day necessary to achieve the annual power output. Table 1 includes a column to indicate which sub-basin of the modelling distribution system each dam has been associated with. Mumba is in the middle of the Caiundo sub-basin, and receives inflows from Kubango and Cutato but not from Cuchi and Cuelei (Fig. 3). To be able to represent the effects of this dam correctly, it would be necessary to sub-divide the Caiundo sub-basin. However, its inclusion is not important; the reservoir at the outlet of Mucundi (downstream) is much larger than the upstream schemes.

Climate change scenarios

Quantifying uncertainty in future climate

Here, the sources of uncertainty associated with assessments of future impacts of climate change are examined by using numerous simulations of the Pitman hydrological model, driven by multiple estimates of future climate. We use a methodology simpler than, but similar to, that developed by New and Hulme (2000). Global Climate Models (GCMs) are the primary tool for estimating future climate. However, there is considerable uncertainty in GCM simulations of future climate associated with: (i) uncertainly in future GHG emission (ii) uncertainty in the global GHG cycles usually simulated 'off-line' (iii) uncertainty in the GCM response to a particular forcing, associated with model structure, parameterisation and spatial resolution. GCMs differ widely in their depiction of precipitation patterns due to differences in the parameterisation of cloud and rainfall. Differences between GCMs in terms of their climate sensitivity (usually expressed as the global mean surface temperature response to a doubling in atmospheric CO_2), are largely associated with the magnitude of positive internal feedback mechanisms, notably the water vapour feedback. To quantify these multiple sources of uncertainty monthly data from single ensemble runs of four GCMs (Table 2) archived at the IPCC Data Distribution Centre are used . GCMs typically have a grid cell size of 2–3°, which is roughly the dimension of the Okavango River basin. In this study, GCM data are averaged over all grid cells whose centres lie within the Okavango basin region (roughly 16–19°E, 12–15°S, and 17–22°E, 15–18°S). Clearly, the GCM cannot resolve the spatial structure of climate at the sub-basin scale used in the hydrological model. There are numerous methods for downscaling GCM estimates (Giorgi et al., 2001). In this study, however, we have adopted a simpler process in which we utilise estimates of climate at the coarse resolution of the GCMs directly, such that sources of uncertainty are quantified as far as possible.

The future climate at the local/regional scale of interest here as simulated by a GCM reflects not only the global climate sensitivity of that model but also the particular characteristics of the model climatology for that region. An evaluation of the present day climatology of the study region in each model was undertaken ("GCM evaluation") to inform the

Table 2.

Details of GCMs for which data is available at IPCC, DCC and used in this study

Model	Country of origin	Approximate resolution	Integration length
HadCM3	UK	3.75 * 2.5	1950–2100
CCSR/NIES	Japan	5.625 * 5.625	1890–2100
CCCma CGCM2	Canada	3.75 * 3.75	1900–2100
GFDL R30	USA	3.75 * 2.25	1961–2100

interpretation of the future simulations. It is assumed that models which simulate well the present day basic state are likely to do so during simulations of the future. To account for uncertainty in future greenhouse gas (GHG)/sulphate emissions data from GCMs forced with two contrasting future GHG emission scenarios are used, namely the IPCC preliminary SRES marker scenarios A2 and B2. The A2 scenario assumes an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development. The B2 scenario envisages less rapid, and more diverse technological change with emphasis on community initiative and social innovation to find local, rather than global solutions (Nakicenovic and Swart, 2000). As such the range of future GHC concentrations in the atmosphere between these two scenarios may encompass much of the uncertainty in the future global cycles of carbon and other GHGs.

Modelling the hydrological impact of future climate

The Pitman hydrological model requires estimates of monthly precipitation (P) and potential evaporation (E_p) for each sub-basin in the Okavango River Basin (Fig. 3), in contrast to the climate change scenarios, which are based on averaged GCM data over the basin. Historical time-series of sub-basin precipitation representing 'present day' conditions, are derived from a rain-gauges in the basin (1960–1972) and satellite derived records (1991–2002) (Wilk et al., this issue) and time-series of baseline sub-basin potential evaporation are based on spatial interpolation of available measurements of pan evaporation from a few locations in the basin. Simulations of the impact of the climate change scenarios on the river flow are made by forcing the Pitman model with perturbed time series of spatially distributed P and E_p. It is not appropriate to use the GCM data directly due to bias in the GCM estimation of the climate basic state ("GCM evaluation") and due to the different spatial resolutions of the GCM and the hydrological model. A common method to transfer the signal of climate change from climate models to hydrological models or other impact models is the "delta change" approach, where differences in climate variables are extracted from the GCM control and scenario simulations and projected onto an observed database (e.g., Bergström et al., 2001). In this study, mean monthly 'delta' factors are defined (ΔP, ΔT, $\Delta T_{\max}$ and $\Delta T_{\min}$) for each combination of GCM and GHC scenario, for future 30 year epoch, representing the middle (2020–2050), late (2050–2080) and end (2070–2099) of the 21st century. These 'delta' factors are the GCM simulated value for a particular quantity relative to the GCM value over the 'present day' period (1960–1990), and therefore represent the relative change in a quantity as simulated by the GCM.

The Hargreaves equation (Hargreaves and Allen, 2003, Eq. 3) has been recommended by Shuttleworth (1993) as one of the few valid temperature-based estimates of potential evaporation. This equation is used in calculations of the ratio between average E_p for the Okavango basin during 'baseline' period and during various scenarios.

$$E_p - 0.0023 * S_0(T + 17.8) * \sqrt{\delta_T}, \tag{3}$$

where E_p is the potential evaporation, S_0 is the water equivalent of extraterrestrial radiation (mm d^{-1}) for the given location, T is monthly mean temperature (°C), and δ_T is the difference between mean monthly maximum and mean monthly minimum temperature (°C).

Baseline (control period) basin-average monthly, minimum and maximum air temperatures for the basin were provided by the Tyndal Centre (Mitchell et al., 2004). Estimates of basin average air temperatures during various scenarios were obtained by multiplying the baseline temperature variables with 'delta' factors, derived from calculation of the relative change in these variables, as simulated by the GCM. Finally, perturbed sub-basin P and E_p monthly time series to drive the hydrological model are obtained by multiplying the available baseline records (1960–1972, 1991–2002) of sub-basin P and E_p with the calculated basin ΔP and ΔE_p values, respectively. This procedure created simulated series of P and E_p with the appropriate spatial resolution for the hydrological model, which retains the structure of spatial and temporal variability of the observed historical data overlain by relative changes simulated by the GCMs under the future GHG emission scenarios. It should be noted also that irrigation demands are affected by the climate change scenarios, since the water requirements is calculated as the difference between effective rainfall and crop demand.

GCM evaluation

It is likely that some GCMs simulate the basic state of the study region climate better than others. Knowledge of this can inform our interpretation of the resulting climate change delta factors. Thirty-year mean present day (1961–1990) regional precipitation fields simulated by the GCMs were compared to observed data, using the gridded raingauge dataset of Hulme (1992) and the merged gauge/satellite dataset from the Climate Diagnostics Centre Merged Analysis of Precipitation for 1979–2003 (Xie and Arkin, 1997). In terms of the annual rainfall cycle for the Okavango Basin region, the two observational datasets both indicate a peak rainfall of around 4–6 mm day^{-1} over the November–March wet season. Of the GCMs, HadCM3 provides the closest agreement with observations with a similar seasonal cycle and an over-estimation of monthly mean rainfall by about 0–30%. GFDL is similar but with over-estimations up to 60%. The CCC and CCSR/NIES models exhibit substantially weaker wet season rainfall and a rather late onset such that the early (peak) wet season rainfall during October–December (January–March) is less than 30% (50%) of the observed. In terms of the spatial structure of mean wet season rainfall across the sub-continent as a whole HadCM3 in particular replicates well the pronounced rainfall gradients in the wider study region. The spatial correlations of mean January–

March precipitation between the CMAP observations and the GCMs over the domain (0–35°S, 0–40°E) are 0.91, 0.78, 0.66 and 0.74 for the HadCM3, GFDL, CCSR/NIES and CCC GCMs, respectively.

Results

Hydrological impacts of development scenarios

Low impact development

The low impact development scenario is based on a change in water demand due to increased consumptive use from population, livestock and informal irrigation as a consequence of increased population. The abstractions have a minimal impact on mean annual downstream river discharge (0.08% for the 2015 and 0.1% for the 2025 population increase projection). The impact on minimum monthly flow is equally small (0.09% for the 2015 and 0.16% for the 2025 population increase projection), and even during the year with the lowest minimum monthly flow the simulated impact is much smaller than the likely errors involved in the modelling exercise (0.17% for the 2015 population increase projection and 0.30% for the 2025 population increase projection).

Business as usual

The “business as usual” scenarios included, in addition to population increase, formal irrigation schemes, deforestation and construction of a hydropower dam. The impact for the “business as usual” irrigation scenarios is evident during the dry season but negligible during the wet season. Consequently, mean annual flow is only reduced by 2% compared to the baseline, whereas the minimum monthly flow decreases by 5% (Fig. 4). The deforestation scenario increases mean annual flow by 2.5%, the impact being most pronounced during high flow periods (Fig. 5). For the “business as usual” scenario, only the Malobas dam is assumed to have been constructed (Fig. 3). The annual flow volume remains unchanged, but with a slight increase of dry season flow and a corresponding decrease of wet season flow. As shown by the minimum flow frequency distribution, minimum monthly flows are increased during wet years, but not during dry years (Fig. 6).

High impact development

In addition to the development under the previous scenarios, the “high impact development” scenario includes irrigation of all areas estimated as potentially suitable for irrigation, extended deforestation buffers around water courses, all potential dams being constructed and operational use of the Eastern National Carrier. According to the modelling results, irrigation of all potentially suitable land would decrease mean annual flow by 8%. However, most of this decrease takes place during the dry season, with a reduction of monthly minimum flow by 17% (Fig. 4). The “high impact development” deforestation scenario results in increased mean annual flow of 6%, with the highest impact during the wet season (Fig. 5).

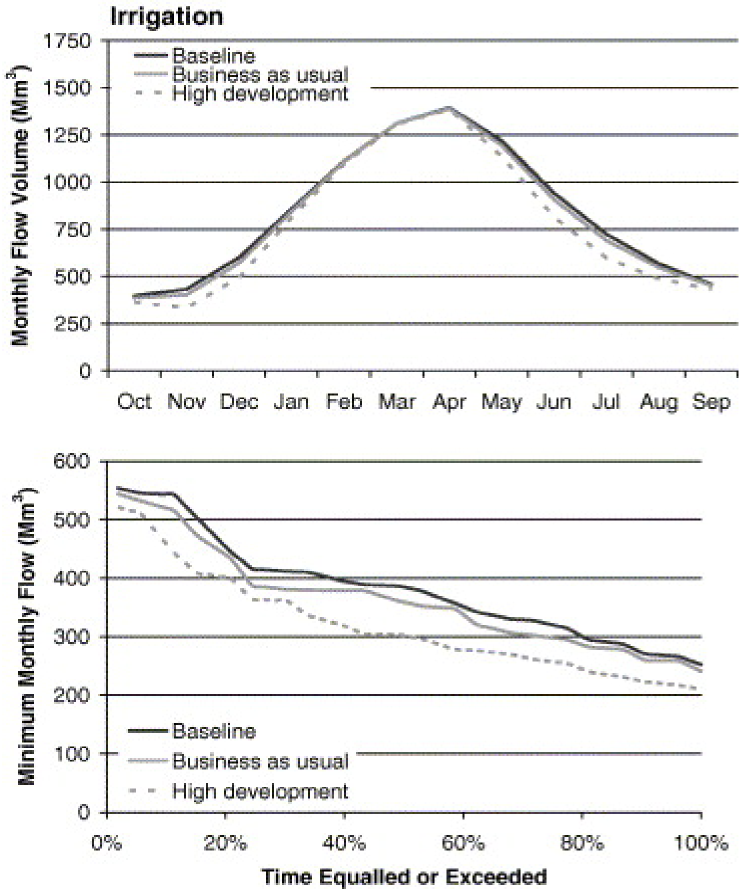

Figure 4. Comparison of mean monthly flow volumes and annual minimum monthly flow for the baseline conditions and with the "business as usual" and "high impact development" irrigation scenarios.

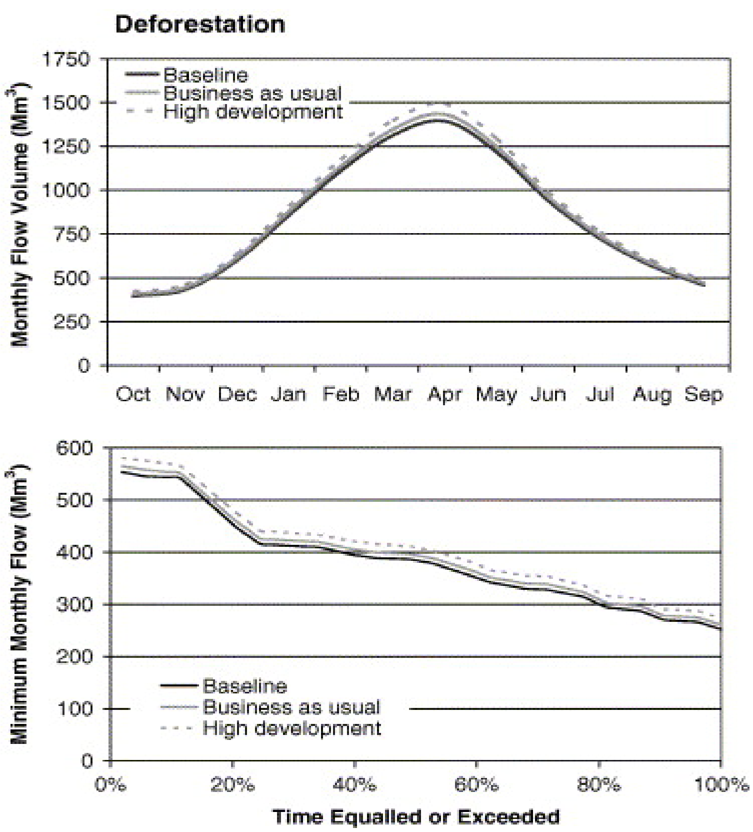

Figure 5. Comparison of mean monthly flow volumes and annual minimum monthly flow for the baseline conditions and with the "business as usual" and "high impact development" deforestation scenarios.

The effect of the operation of the hydropower reservoirs under the assumed rules is to substantially decrease the wet season flows and increase the dry season flows in most cases (Fig. 6). The largest impact of the reservoir scenario is at the outlet of Mucundi (Fig. 3), where the simulated mean monthly flow varies from 150 to 1072 Mm^3, compared with a monthly release volume of 563 Mm^3.However, there are several years where the peak wet season flow does not reach the monthly release volume, including a six year period in the 1990s, when the mean monthly wet season flow is not exceeded during four years, and only slightly exceeded during the remaining two. During this dry period the downstream simulated flows are very similar for the baseline and high impact development scenarios, since the inflow is less than or equal to the specified dam generating release and almost all of the inflow is released as it occurs. The impact of the dams is therefore only pronounced during wet years (Fig. 6) in which wet season flows are reduced and dry season flows enhanced. The "worst case" scenario of the operational use of the Eastern National Carrier results in a 1% reduction of the mean annual flow, and a 2.5% reduction of the monthly minimum flow.

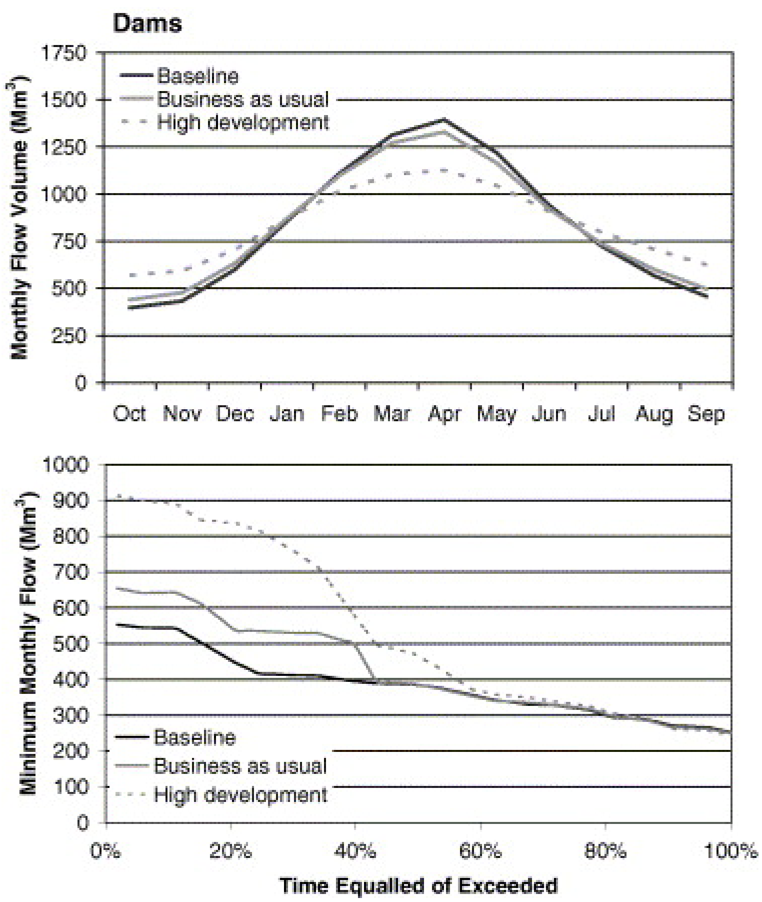

Figure 6. Comparison of mean monthly flow volumes and annual minimum monthly flow for the baseline conditions and with the "business as usual" and "high impact development" dam scenarios.

Hydrological impacts of climatic change scenarios

The simulated impact of future climate change on Okavango River discharge is highly variable, both in terms of mean monthly flow (Fig. 7, Table 3) and minimum monthly flow (Fig. 8, Table 3). Under most scenarios the annual cycle of

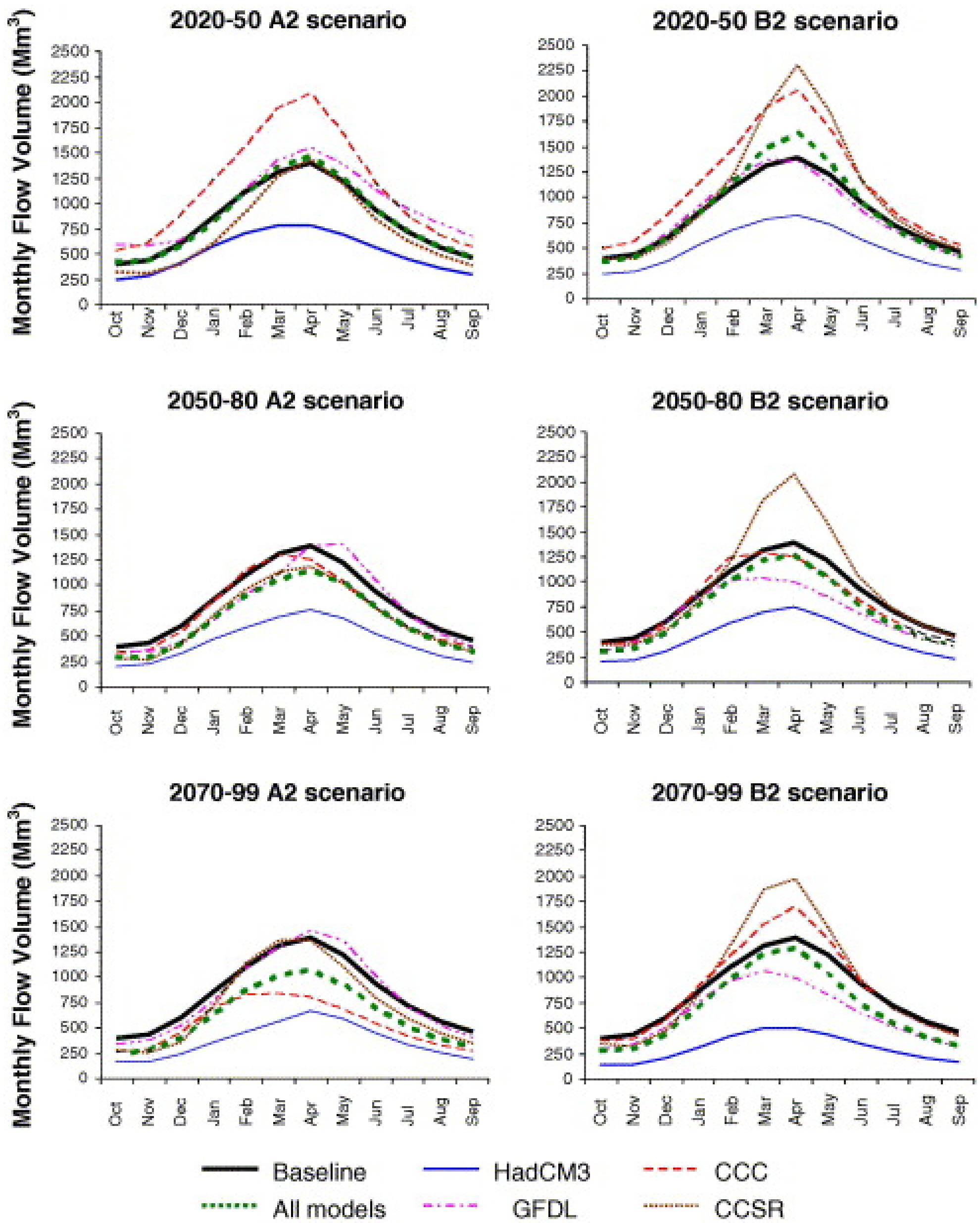

Figure 7. Mean monthly flow at Mukwe with baseline simulations, and with assessment of changes of precipitation and evaporation derived from various GCMs, driven by the A2 and B2 greenhouse gas emission scenarios. The legends show the highest to the lowest simulation.

Table 3 Impact of climatic change on annual mean and minimum monthly flow at Mukwe

	Annual mean flow (minimum monthly flow)			
	Highest year vs. median (%)		Lowest year vs. median (%)	
Monitored flow 1949–2002	+70 (+53)		−38 (−38)	
	A2 GHG emission scenario		B2 GHG emission scenario	
	Annual mean flow vs. baseline conditions (%) All-GCM mean/highest GCM/lowest GCM output	Minimum monthly flow vs. baseline conditions (%) All-GCM mean/highest GCM/lowest GCM output	Annual mean flow vs. baseline conditions (%) All-GCM mean/highest GCM/lowest GCM output	Minimum monthly flow vs. baseline conditions (%) All-GCM mean/highest GCM/lowest GCM output
Modelled flow 2020–2050	+1/+38/−39	−2/+29/−40	+4/+32/−39	−6/+18/−39
Modelled flow 2050–2080	−20/−8/−45	−27/−16/−48	−14/+16/−47	−20/−5/−49
Modelled flow 2070–2099	−26/−2/−55	−36/−14/−59	−17/+13/−67	−29/−8/−64

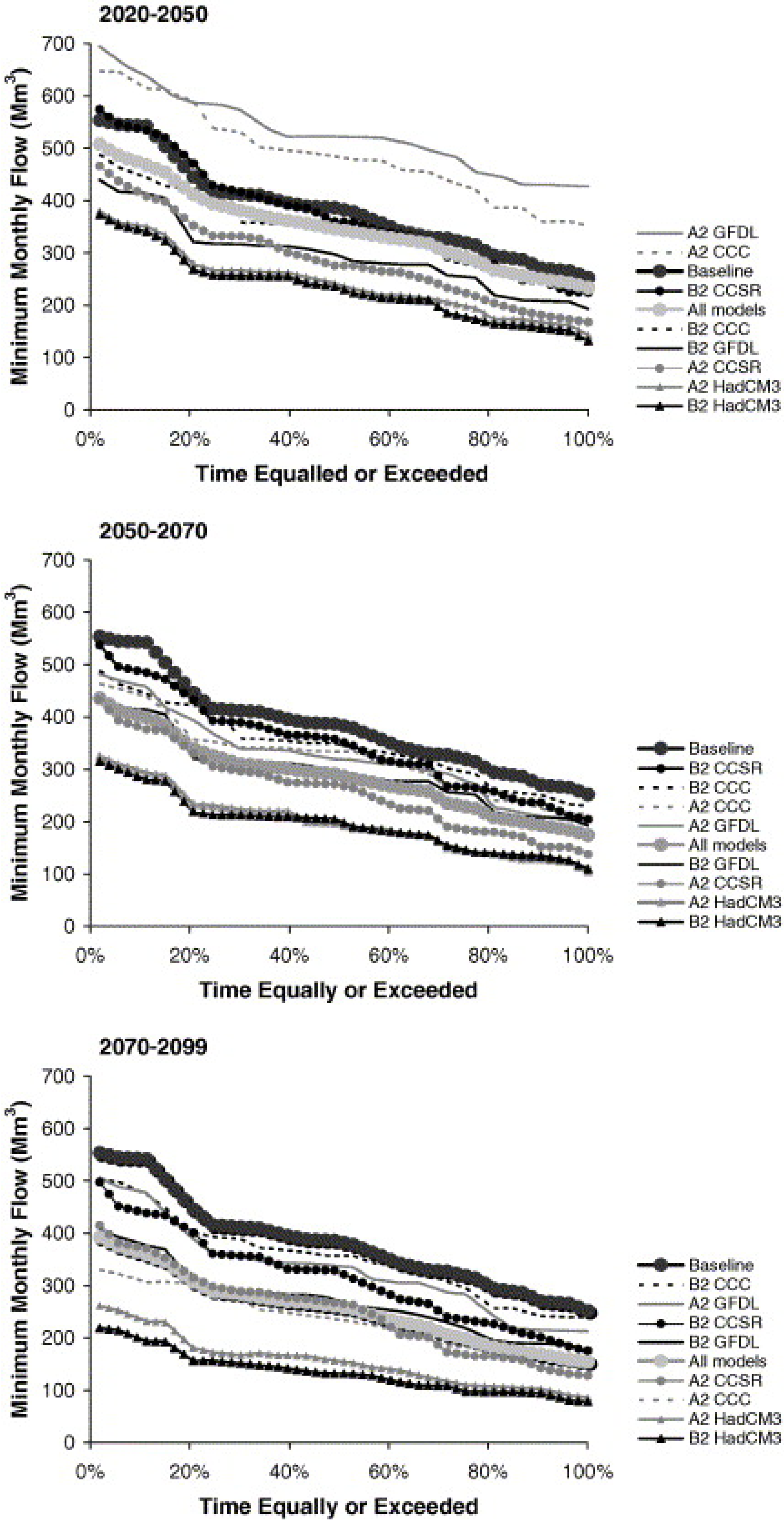

Figure 8. Minimum monthly flow at Mukwe with baseline simulations, and with assessment of changes of precipitation and evaporation with various GCMs, driven by the A2 and B2 greenhouse gas emission scenarios.

discharge is maintained with maximum flow in April and minimum in October. Under certain CCC and GFDL GCM scenarios, however, peak discharge is predicted to occur one month early in the 2050–2080 and 2070–2099 periods. In terms of predicted flow magnitudes there is a clear time dependency to the results. For the period 2020–2050 the 'all-GCM mean' flow is very close to the baseline conditions for both A2 and B2 GHG scenarios. The results for this period are essentially sensitive to the choice of GCM with certain models predicting dramatically increased flow (e.g. CCC) and some dramatically reduced flow (e.g. HadCM3). There is therefore very little certainty in the sign or magnitude of future river flow for this period. Differences in future precipitation estimates between models are largely responsible for this. For the period 2050–2080, however, there is a clear tendency for the models to simulate reduced flows, with a greater magnitude of change for the A2 than the B2 GHG scenarios. By 2050–2080 the all-GCM mean shows a reduction of 20% (14%) in mean annual flow for the A2 (B2) scenarios. The respective figures for the period 2070–2099 are 26% (17%) when all but one of the GCMs suggest reduced flows under the A2 scenario. It is likely that this reflects the increasing influence of a consistent prediction of increased temperatures by all the GCMs. Nevertheless, there remains considerable variability in the magnitude of the simulated response associated with both the different GCMs and GHG emission scenarios, such that uncertainty in our predictions of future mean river discharge is high. Our results indicate that future climate change is likely to have a proportionally larger impact on minimum monthly flow compared to mean flow, with reductions in minimum flow of 27% (20%) and 36% (29%) for the 2050–2079 and 2070–2099 periods, respectively, under the A2 (B2) GHG scenario. This may be indicative of a more extreme hydroclimatic regime.

Given the importance of precipitation to the hydrological response it is important to bear in mind that the GCMs tend to have larger errors in their representation of precipitation compared to temperature and therefore the differences between the basic state of the models should be considered. It is, therefore, notable, that the GCM with the most accurate representation of the present day climate over the study region (HadCM3) indicates consistently and substantially reduced flow in all time slices and for both GHG scenarios. This is associated with consistent HadCM3 predictions of reduced precipitation and increasing temperatures leading to increased E_p. A sensitivity study indicates that the simulated river discharge is rather more sensitive to changes in precipitation as predicted by HadCM3 (Fig. 9). For the period 2070–2099, under the HadCM3 scenarios, precipitation changes are responsible for most of the simulated decrease in mean annual flow under the A2 and B2 GHG scenarios.

It is instructive to view the projected changes in mean flow in the context of historically observed variability (Table 3). Projected changes in the 30 year median annual flow and minimum monthly flow for the selected time slices in the 21st century are of similar magnitude to the absolute observed range during the observed historical period (i.e. the extremes of interannual variability). This implies that under certain scenarios the mean future regime may be similar to the most extreme conditions observed to date. Overall, the results indicate the potential for dramatic changes to Okavango River discharge under future climate conditions, but with considerable uncertainty in the magnitude of any future changes. This uncertainty is largely associated with inter-model differences in projected precipitation changes.

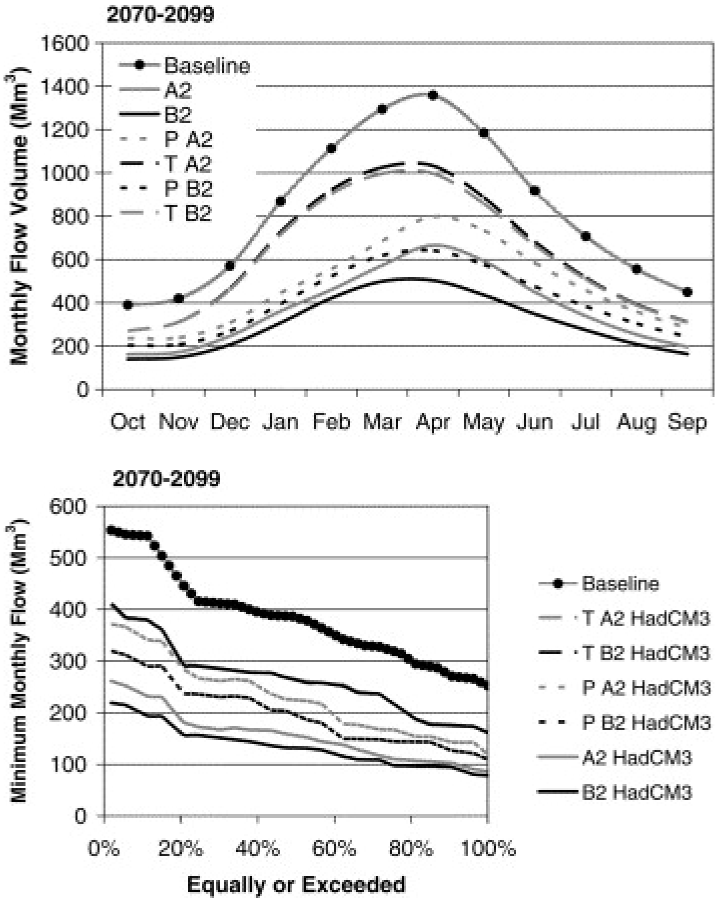

Figure 9. Mean monthly flow and minimum monthly flow at Mukwe with HadCM3 GCM driven by the A2 and B2 greenhouse gas emission scenarios. Both the combined impact of predicted precipitation and temperature changes and the impact of only precipitation or only temperature changes are shown. The legend show the highest to the lowest simulation.

Discussion

This project has provided a modelling framework for the operational implementation of integrated assessments of water resources in the Okavango River basin. The linkage of the hydrological model system and climatological, physiographic, and anthropogenic databases enables descriptions of present day conditions and the impacts on river flow of various possible development and climate change scenarios. However, although definitions of development scenarios are based partly on conclusions from a stakeholder workshop, the project has been mainly research driven. Consequently, the outcome from this project is only a first step toward the incorporation of models into integrated water resource management of the Okavango River Basin. Although the results demonstrate that the model system is able to simulate well the historical monitored hydrological conditions, uncertainties both in model input data and the assumptions used in defining scenarios are relatively high. Operational use of the model system, both for short and long-term planning, requires a sustainable regional personnel and instrument resource base, including increased accessibility to and quality assessment of databases, where reconstruction of rainfall and river discharge gauging networks in Angola is a vital component. In addition, there is a need for extended regional hands-on experience of the opportunities and limitations presented by modelling tools. An important point raised at the WERRD technical workshop held in Johannesburg in October 2004 is the need to include the socio-economic aspects of the region under development in any future operational model applications.

Stakeholders and decision-makers in the river basin might view other scenarios than those presented as more relevant. The main outcome of the study is to indicate the relative impact of a range of possible development and climate change scenarios, and view these in relation to the natural variability of the flow regime. Various degrees of uncertainty are linked to the assumptions used in the definition of the scenarios and their relative importance is discussed below.

The impact on river flow from increased household water consumption due to population increase, including informal irrigation has been simulated as negligible. The assumption used in the study does not consider that a population increase might be linked to increased urbanisation. However, since no values that support such a change in the region were available, the proportions are kept static.

The potential for irrigation in the basin is rather limited (pers. comm., Diniz, 2004). Increased irrigation is only found to appreciably affect water flow in the downstream parts of the basin if expanded to the maximum potential areas in both Angola and Namibia. The amount of water used for informal irrigation, carried out individually by small-scale farmers, is predicted to be negligible compared to that from formal, large-scale irrigation schemes. Irrigation demand is estimated as the difference between monthly rainfall and crop demand. The assumptions used are based on irrigated crops never suffering from water deficiency. The estimated impact of irrigation should be viewed as the highest possible potential water abstraction, rather than as an accurate prediction of a possible future.

The development costs of the hydropower reservoirs included in the "high impact development" scenario will be extremely high, and it is probably unrealistic to assume that all of the potential locations for reservoirs will be developed in the foreseeable future. In addition, the operation rules of the reservoirs have been represented in the model in a very simplistic way (minimum power generation for 12 hours a day while the water is available). In this paper, only the riverine impact at Mukwe, located in the downstream part of the basin (Fig. 3), is discussed. In the case of the "business as usual" scenario, while the impact is limited at Mukwe, it is substantial in sub-basins immediately downstream of the suggested reservoir site. It should also be noted that the results from these simulated scenarios only pertain to water flow, without consideration of the impacts on sediment transport, which if reduced could have consequences for the ecological functioning of the Delta (Ashton and Neal, 2003).

Factors considered by the model in the deforestation scenarios include changed interception, infiltration and evaporation. The model results correspond to experiences from small-scale basins rather than from larger ones, where the links between deforestation and water yield are more complex (Wilk and Andersson, 2001). Deforestation is usually a gradual process, and consequently, there will be regrowth in parts of the basin at the same time as trees are felled in other parts of the basin. Consequently, the predictions of the hydrological impacts of the deforestation scenarios indicate a maximum possible impact rather than a prediction of a likely future.

The scenario of the construction of the water carrier from the Okavango River indicates that the impact on water flow is small compared to the climatic variability. However, as noted by Ashton (2000), it is possible that, without further evidence to the contrary, future water shortages will be blamed on upstream abstractions, even if they are caused by climatological factors. As with most of the tested development scenarios, the water carrier scenario can be seen as a "worst case", i.e., the maximal possible impact, with the estimated annual withdrawals spread equally over the year. To refine the scenario to make it more responsive to the rainfall regime and storage capacities in central Namibia, it would be necessary to extend the modelling approach to include a system analysis, based on operational policies. It should also be noted that although the hydrological impact of development scenarios such as irrigation are predicted to be rather small; the impact on water quality may be more substantial (Ellery and McCarthy, 1994) and increased urban and rural water withdrawals for consumptive use may also impact on water quality variables through their associated return flows.

With regard to the impact of the climatic change scenarios, there is considerable uncertainty surrounding the magnitude and direction of any future discharge response, associated with both the GCM and the IPCC emission scenarios. Whilst over southern Africa as a whole the projected climate change and river runoff response has been shown to be quite consistent in previous studies (e.g. Arnell, 2003), the focus on a single basin highlights the importance of sub-regional detail in climate change impact studies. Nevertheless, on average, the experiments indicate a reduction in future flow after about 2050 for both the A2 and B2 GHG scenarios that increases over time, which is consistent with results from previous work (e.g. Hulme et al., 2001 and Arnell, 2003). It should be noticed that the magnitude of predicted changes under climate scenarios is far in excess of that associated with the development scenarios. It is likely that the variability of river discharge will also increase (Arnell, 2003). These findings highlight the need to develop appropriate mitigation strategies for water resource use in the region. To reduce the uncertainty in future climate predictions there is a need for more detailed research into this topic. In particular, given that the GCMs tend to produce quite similar estimates of future temperature the critical issue is likely to be GCM simulation of precipitation. Changes in future precipitation may be more adequately specified on the sub-basin scale if the rather coarse GCM data is downscaled using regional climate models, allowing for more detailed assessments of spatially heterogeneities in climate change impacts on water resources.

Conclusions

This study has laid the foundations for the use of scenario modelling as a tool for integrated water resource management in the Okavango River Basin. However, uncertainties are high both due to the presently limited availability of physiographic data, and due to the limited knowledge about economic and social factors that will be important for developments in the headwaters of the basin. The scenarios presented should therefore be seen as indications of the relative importance of various factors, rather than as predictions of the "real" future conditions. In order to introduce river basin modelling tools for operational planning purposes in the Okavango basin, extended regional experience of the use of models must be combined with the reconstruction of rainfall and river discharge gauging networks in Angola. In addition, socio-economic aspects need to be covered, either as part of the modelling system, or parallel to it.

The impact on downstream streamflow from the “low impact development” scenario, which only included increased domestic water use, livestock and informal irrigation, proportional to the expected population increase is very limited. Over a 20 year perspective, the mean annual river flow is only reduced by 0.1% and the monthly minimum flow by 0.16%. Impacts from the “business as usual” scenarios are rather limited. Implementation of all potential formal irrigation schemes mentioned in the available reports would only decrease annual flow by 2% and minimum monthly flow by 5%, whereas deforestation of 1 km buffer zones adjacent to the river would increase the flow by 2.5%. Downstream hydrological impacts of construction of one upstream hydropower dam is small with regard to annual flow, with only a slight increase of the low season flow, corresponding to a similar decrease of the wet season flow. Whilst our simulations consider each development factor separately, it is likely that in reality future development will involve numerous factors simultaneously. Finally, the “high impact development” scenarios should be seen as estimates of the highest possible impact of various developments, not as a realistic future prediction. The maximum impact of irrigation on annual average flow is estimated to be 8%, with a reduction of minimum monthly flow by 17%. Deforestation is estimated to increase the flow by 6%. Construction of all potential hydropower reservoirs in the basin would change the flow regime considerably. However, under the assumed operational rules, the impact of hydropower reservoirs is only substantial during wet years.

The potential impact of climate change on long term mean flow, as simulated by a selection of GCMs, is far in excess of that associated with the development scenarios. However, the uncertainty in these predictions is high. Nevertheless, there is a clear indication of reduced flow from 2050 onwards, with implications that the mean future river regime may be similar to the most extreme conditions observed from historical records. Given that future development initiatives are likely to be imposed on a background of changing climate there is a clear need for further work to reduce the uncertainty associated with our predictions of future climate conditions. Work should focus particularly on improving the ability of models to resolve precipitation regionally over the region.

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