Climate Change Impacts on Hydrology in Africa: Case Studies of River Basin Water Resources

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Abstract There is a growing consensus that anthropogenic climate change is a real phenomenon. There is strong evidence that changes to the hydrological cycle have occurred and will continue to do so in the future. Given our dependence on water resources and ecosystem services associated with the river system, this means it is important that appropriate adaptation strategies are developed. Such policies require information on future behaviour of the climate system and impacts on surface hydrology at the river basin scale. This chapter presents two contrasting case studies from river systems in Africa, in which climate change impacts on hydrology are examined. The methodology of climate change impact assessment is described and critically examined with particular respect to quantification of uncertainties. Finally, the implications for water resource management policy are considered.

Keywords Southern Africa · Hydrology · River systems · Water resources · Ecosystem services · Impacts · Water resource management policy

1 Introduction

There is a growing consensus that human activities, most notably emissions of greenhouse gases (GHG), have resulted in a discernable influence on global climate, and that this has been the primary driver of global warming in recent decades (Solomon et al. 2007). Anthropogenic climate change represents a considerable challenge at many levels of society. Recently there have been efforts to determine the level of GHG emission necessary to avoid dangerous climate change in the future. Nevertheless, on the basis of past GHG emissions and inertia in socioeconomic systems we must anticipate that future climate change is unavoidable and that adaptation is necessary. Decision-making bodies, including governments, need to incorporate climate-related risks into decision-making processes. Given that

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adaptation policy tends to be made at national, regional and local levels there is a need for climate change impact assessment at these scales. This chapter exemplifies this process for climate change impacts on river basin-scale hydrology over selected basins in Africa and the implications for policy.

Freshwater is vital to our life-support systems. Water is a pre-requisite for all forms of life on Earth and is required for almost all human activities. However, for much of the world the availability of adequate water poses a significant challenge to development and environmental sustainability. In recognition of these challenges there have been numerous international initiatives to address the issues associated with freshwater resources. These include the UN's Agenda 21, Millennium Development Goals, Millennium Ecosystem Assessment, World Water Development Report and the World Water Fora.

Climate change is likely to be an important constraint on water availability in the future. There is considerable evidence that the global hydrological cycle has already responded to the observed warming over recent decades (Solomon et al. 2007), through increased atmospheric water vapour content, changing patterns of precipitation including extremes, reduced snow and ice cover and changes to soil moisture and runoff. Climate models suggest further substantial changes to the hydrological cycle in the future under scenarios of GHG emission. Although there is considerable uncertainty in projected patterns of precipitation at the regional scale, the Intergovernmental Panel on Climate Change (IPCC) fourth report (AR4) suggests that precipitation and average annual river runoff are likely to increase in the midlatitudes and some areas of the humid tropics but likely to decline in many semi-arid regions, notably in the tropics (Solomon et al. 2007). The relationship between climate and water resources, however, does not exist in isolation but is strongly influenced by socio-economic and other environmental conditions. Various human activities influence available water resources, most notably agriculture, land use, construction, water pollution, water management and river regulation. At the same time water demand is highly variable, largely determined by population and levels of development.

In this context, African water resources may be particularly vulnerable to future climate change. Africa already suffers disproportionately from water related hazards of flood and drought (World Water Assessment Program 2003). Whilst there is uncertainty about the magnitude of current water issues in Africa, the analysis of Vörösmarty et al. (2005) suggests that about 25% of the African population experiences water stress and 69% live under conditions of water abundance. However, this analysis does not take into account actual water availability and the relative abundance reflects low water consumption resulting from limited water supply infrastructure. Moreover, much of the African continent experiences drought and about one third of the population live in such areas (World Water Forum 2000). Climate extremes are compounded by the relatively low level of economic development in much of Africa. Sub-Saharan Africa is the only region of the world that has become poorer in the last generation (Ravallion and Chen 2004). The continent makes up just 13% of the world's population (Population Reference Bureau 2005) but constitutes 28% of the world's poverty (World Bank 2005) and is home to 32 of the 38 heavily indebted poor countries (World Bank 2005). Its share of world trade more than halved between 1980 and 2002 (UNCTAD 2004). Africa is not currently on target to meet any of the Millennium Development Goals (Commission for Africa 2005). This challenge is made all the more difficult by rapidly growing population. Numerous factors have worked in concert to create this situation of poverty and underdevelopment, and among those is the difficulty of coping with climate variability and change in a continent subject to frequent droughts, floods, high temperatures, land degradation and being substantially dependent upon rain-fed agriculture.

There is a pressing need, therefore, for improved understanding of climate changes related to the hydrological cycle over Africa at scales relevant to decision making. In this chapter we explore this challenge. We begin with a summary of the projected water-related climate changes over Africa, drawing heavily on the findings of the IPCC AR4 (Solomon et al. 2007). This is followed by a more detailed examination of climate change impacts on basin hydrology for two basins located in southern and eastern Africa. These contrasting studies exemplify many of the issues associated with both the science of climate change impacts and associated human dimensions.

2 Summary of Changes to the Hydrological Cycle in Africa

2.1 Historical Observations

For many important hydrological variables, including precipitation, our observational record is relatively sparse. This, combined with high space/time variability in these parameters, means that identification of trends likely to be related to the observed warming in recent decades is problematic. More than any other continent (except Antarctica), Africa suffers from a paucity of observations (Washington et al. 2006), such that the challenge of detecting climate change is more acute. Nevertheless, it is clear that those regions with sufficient data indicate that Africa has warmed significantly over the twentieth century (Trenberth et al. 2007). For annual temperature averaged over all grid cells in Africa (from the CRUTEM3 data of Brohan et al. 2006) the trend is 0.07°C decade^{-1} over the period 1900–2007 and 0.3°C decade^{-1} since 1970, which are slightly lower and higher, respectively, than for global land regions. Associated with this, there have been trends of increasing extreme hot days/nights and decreasing extreme cold days/nights over much of subtropical Africa (Alexander et al. 2006). Regarding precipitation, observations show that the Sahelian sector of Africa has witnessed one of the largest hydrological climate changes observed anywhere, with above-average precipitation during the 1950–1960s and persistently low precipitation during the 1970–1990s (Dai et al. 2004a), resulting in devastating droughts. This multi-decadal climate signal is associated with changes in the large-scale circulation and ocean temperatures in the Pacific, Atlantic and Indian oceans (e.g. Giannini et al. 2003). Trends in precipitation elsewhere in Africa are not statistically significant over the twentieth century. However, Alexander et al. (2006) note an increasing contribution of heavy precipitation events to total precipitation over Southern Africa. There is evidence of increasing frequency of drought over both Northern and Southern Africa (Dai et al. 2004b) based on analysis of the Palmer Drought Severity Index (PDSI) which combines both precipitation and temperature data; separating natural and anthropogenic influences is, nevertheless, problematic. Jury (2003) notes some evidence of declining river discharge from a composite of major African rivers.

2.2 Future Projections

Projections of future climate for the twenty-first century from Global Climate Models (GCMs) have been coordinated by the IPCC for the AR4 through the 'multi-model ensemble of opportunity'. This allows an analysis of both the multi-model mean climate response and the associated uncertainty, most commonly through analysis of the degree of agreement between model ensemble members. According to the IPCC AR4 report, warming in Africa is very likely to be larger than the global annual mean warming with drier subtropical regions warming more than the moister tropics (Fig. 1, Christensen et al. 2007). The most consistent climate change

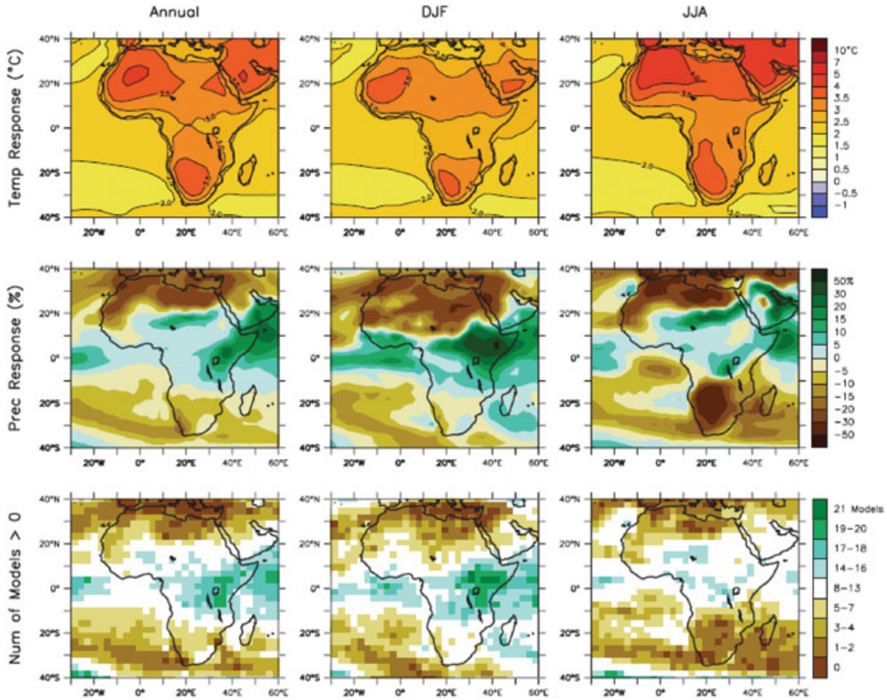

Fig. 1 Temperature and precipitation changes over Africa from the IPCC Multi Model Dataset under the A1B GHG emission scenario simulations. *Top row*: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. *Middle row*: same as *top*, but for fractional change in precipitation. *Bottom row*: number of models out of 21 that project increases in precipitation (From Christensen et al. 2007)

signals for precipitation across the AR4 GCMs include a likely decrease over much of Mediterranean Africa and northern Sahara, a decrease in winter precipitation over western southern Africa and a likely increase in annual mean precipitation in East Africa. There is less consistency between GCMs in projections of how precipitation over the Sahel, the Guinean Coast and the southern Sahara will evolve. The surface hydrological response in terms of river runoff is a complex function of both precipitation and evapotranspiration changes. Projections of river runoff from multiple GCMs indicate the largest and most consistent signals of reduced annual runoff is over North Africa and much of southern Africa, with increased runoff in East Africa (Milly et al. 2005, Fig. 2). This continental-scale pattern is consistent with the global pattern of GCM response to GHG forcing in which atmospheric moisture convergence increases in the equatorial zone (Kutzbach et al. 2005). Studies using off-line global hydrological models have produced similar results (e.g. Arnell 2004). Moreover, projected increases in population are predicted to result in increased water stress in north, eastern and southern Africa (Arnell 2004). Combined with the projected climate changes it is clear that water stress issues will increase for much of Africa.

Global analyses are useful but suffer from their coarse resolution and the fact that the hydrological models are not well calibrated by local observations. Adaptation to climate change and accelerated development will normally be conducted at the river basin scale. As such these global analyses may be inappropriate to inform decision-making, especially for smaller basins. Hydrological models at the basin scale allow for more explicit representations of available freshwater resources (e.g.

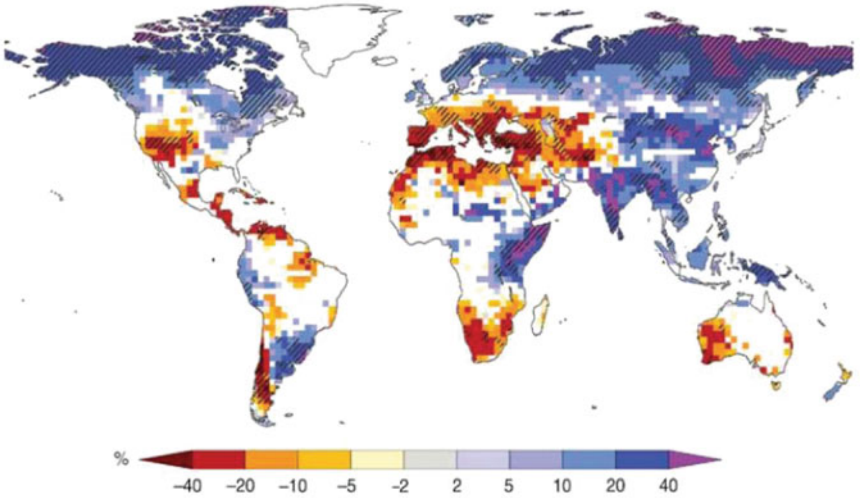

Fig. 2 Large-scale relative changes in annual runoff for the period 2090–2099, relative to 1980–1999, simulated by selected IPCC AR4 GCMs. *White* areas are where less than 66% of the ensemble of 12 models agree on the sign of change, and hatched areas are where more than 90% of models agree on the sign of change (adapted from Milly et al. 2005 by Bates et al. 2008)

groundwater, the primary source of freshwater for drinking) and water demand, than is permitted by global macro-scale models, and can provide more detailed evaluation of freshwater availability. Basin-scale studies also provide an excellent forum to assess indicator metrics of adaptation, risk and vulnerability defined at the global scale. To date, there are relatively few studies of climate change impacts on basin scale hydrology in Africa (Bates et al. 2008).

In the following sections we present results of river basin-scale climate change impacts studies for two river systems. These two examples were selected to provide contrasting conditions in terms of: (i) the sign of the projected precipitation change from the AR4; (ii) the climatic and physiographical context; (iii) basin size; (iv) population density; and (v) associated water resource issues. In the first example we consider the Okavango river system, a large trans-boundary river system in subtropical southern Africa, where population density and development are relatively low. The emphasis is on river flow and the extent and magnitude of flooding of the Okavango delta wetland in Botswana. As such we consider climate change impacts on environmental flows, the amount of water needed in a watercourse to maintain healthy, natural ecosystems. The second example considers the Mitano river basin in Uganda, equatorial east Africa. This is a relatively small river basin with a high population density and where groundwater resources, rather than surface water, are of primary importance. These studies utilize a common methodology in which a basin hydrological model driven by scenarios of future climate based on output from the IPCC GCMs.

2.3 Uncertainty in Projected Climate Change Impacts

The process of quantifying climate change impacts has been referred to as a ‘cascade of uncertainty’. Such uncertainty stems from a number of sources (Stainforth et al. 2007a): (i) forcing uncertainty associated with future GHG emission and other anthropogenic effects like atmospheric aerosol emission and land use change; (ii) initial condition uncertainty is associated with initializing GCMs; (iii) GCM imperfection which includes differences between models, choice of parameterizations and parameter values; and (iv) inadequacies in the impact models such as hydrological models. Considerable effort is being directed at exploring this uncertainty through the use of ensemble experiments which might include multiple GHG emission scenarios (e.g. IPCC SRES scenarios), multiple GCMs (e.g. the IPCC ‘ensemble of opportunity’), multiple initial conditions and perturbed physics ensembles (e.g. QUMP). Grand ensemble experiments involve ensembles of ensembles in which one or more ensemble is nested in another, e.g. multiple initial conditions for each perturbed physics ensemble member (e.g. the www.climateprediction.net project). Such experiments are relatively new but have raised important implications for the interpretation of uncertainty.

Clearly, ensembles increase our understanding of the range of possible model behaviour in response to future GHG emission. The size of the experiments involving many hundreds or thousands of model runs has raised the possibility of developing probabilistic climate change assessments (e.g. New et al. (2007) and references therein). This would allow us to move to a risk-based impact and adaptation decision-making framework. However, Stainforth et al. (2007a) argue that it is not possible to produce 'meaningful probability density functions for future climate. . .based on. . .such ensembles'. Rather, results from ensemble experiments can provide rather more qualitative information on climate change such as an estimate of the lower bound of maximum range of uncertainty. Stainforth et al. (2007b) outline an analysis pathway by which such information may be useful to present day decision making. We will return to this issue in Section 5 in relation to our case studies here.

3 Case Study I: The Okavango River System

3.1 Hydro-Climate and Development Context

For the people living in the semi-arid climate of southwest Africa water scarcity provides a major stumbling block to increasing societal and individual well-being. One of the major water resources in this region is the Okavango river system, perhaps best known for the Okavango delta in Botswana, an alluvial fan formed where the river terminates. The Okavango river is one of the largest river systems in Africa (the basin area upstream of the delta is ~165,000 km^2) and spans three riparian states of Angola, Namibia and Botswana (Fig. 3). Streamflow is mainly generated in the upland regions of central-southern Angola (82% of the basin area lies in Angola) where the Cuito and Cubango tributaries rise. The Okavango delta is maintained by annual flooding of the Okavango River creating the world's second largest inland wetland region; a unique, dynamic mosaic of habitats with exceptionally high beta diversity. The inundated area varies in area from about 5,000 to 6,000–12,000 km^2, depending on the size of the annual flood. It is one of the WWF's top 200 ecoregions of global significance and the world's largest Ramsar site. As a whole, the Okavango is perhaps the last near pristine river system in Africa.

The basin lies within a sharp northeast-southwest precipitation gradient across southern Africa. The climate of the basin region is characterized by a pronounced annual cycle with a single wet season of October to March (precipitation ~6 mm day^{-1}). The flood in the delta lags the precipitation maximum by about 6 months due to the very low topographic gradients within the delta and highly permeable soils, such that flooding of the delta occurs during the local dry season, a feature that contributes to the importance of the delta as a wildlife resource. The unique ecological status of the Okavango Delta is a function of the regional hydro-climatology and, as such, may be particularly sensitive to future changes in climate (Murray-Hudson et al. 2006). Over the observational period the Okavango system has exhibited pronounced variability in river discharge and flood extent. Most notably, there is a strong multi-annual signal with relatively wet and dry periods during 1974–1985 and 1990–2000, respectively (Wolski et al. 2006).

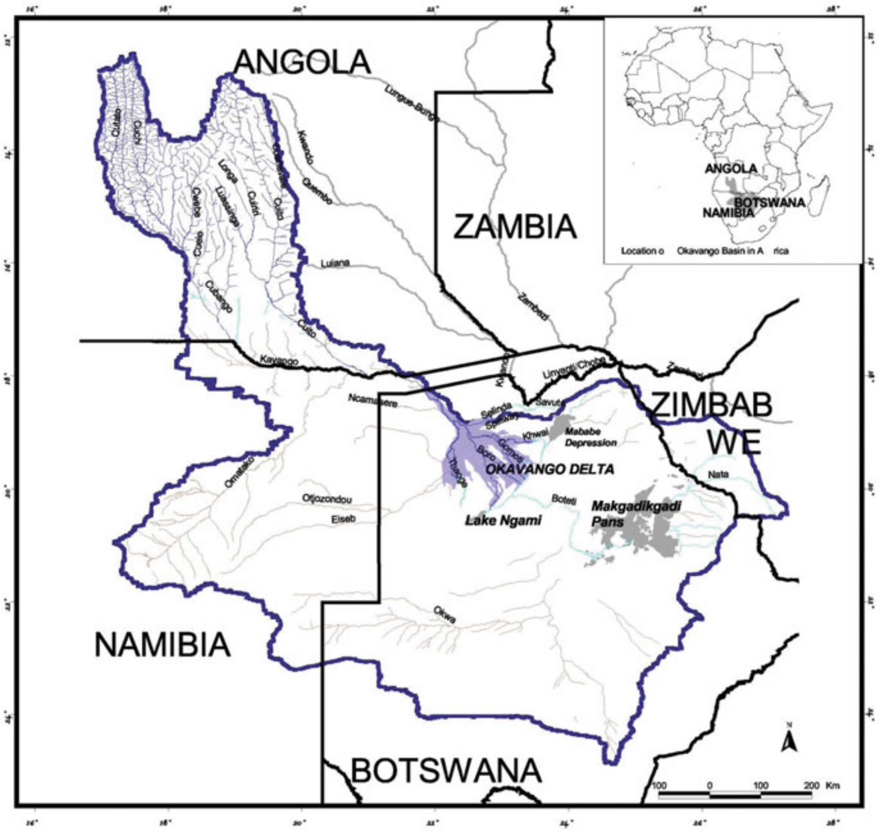

Fig. 3 The Okavango River basin region

The Okavango River Basin is one of the least developed river basins in Africa. However, socio-economic needs of a growing population threaten to change this situation and the basin has been identified by the World Water Assessment as having the potential for water-related disputes (Wolf et al. 2003). Water resources in Angola are particularly unexploited. This situation is likely to change however following the end of the 27-year civil war in Angola in 2002. Future developments in Angola to fulfill the necessary needs of the basin's inhabitants, including urbanisation, industrialisation and hydropower schemes, have potential consequences for water availability in downstream countries (Pinheiro et al. 2003, Ellery and McCarthy 1994) and negative environmental consequences (Green Cross International 2000, Mbaiwa 2004). Likewise, future development in the semi-arid downstream sections of the basin must be considered. The demand for basin water is further exacerbated by increasing demands from outside the basin includingplans for a pipeline from the Okavango River to Grootfontein, linking the river system with Windhoek (Pinheiro et al. 2003). Any future developments in the basin will occur within the context of climate variability and change. It is important, therefore, that appropriate adaptation strategies are developed.

The development of adaptation strategies first requires integrated assessments of the potential impact of climate change and variability and human interventions on the river system. Possible management interventions must respond to drivers of change as well as to the development needs of stakeholders. The EU-funded project WERRD (Water and Ecosystem Resources in Regional Development – Balancing Societal Needs and Wants and Natural Systems Sustainability in International River Basin Systems) has involved multi-disciplinary research to address these issues (Kgathi et al. 2006). The 3-year multi-disciplinary project ended in 2004 but project partners have continued the work since then. The project had a number of inter-related aims: (i) to develop baseline data on the physical and socio-economic processes in the river basin; (ii) to develop a suite of hydrological models; (iii) to utilise the hydrological models to simulate the response of the hydrological system to these future development and climate change scenarios. The results are available to inform dialogue on future management of the river system at the national and international level.

3.2 Hydrological Modeling Tools

To enable simulation of the hydrological response to climate change and variability (as well as potential development policies) and taking account of the contrasting hydrological characteristics of the basin region and the delta region, two hydrological models were developed. First, for the Okavango river basin upstream of the delta panhandle, a modified version of the Pitman (1973) monthly precipitation-runoff model was developed (see Hughes et al. 2006 for full description). Hereafter this is referred to as the '*basin model'*. This is a conceptual model consisting of storages linked by functions designed to represent the main hydrological processes prevailing at the basin scale. A semi-distributed implementation of the model was undertaken for the Okavango basin above the delta with 24 sub-basins (Fig. 3). The basin model requires estimates of monthly precipitation (P) and potential evaporation (E_p) for each sub-basin in the Okavango River Basin. The model was calibrated satisfactorily against river discharge data from the period 1960–1972 and (using satellite precipitation data) for the period 1990–2000. Therefore, the basin model adequately represents the hydrological response of the basin across a range of historical climatic conditions (wet and dry periods), such that it can be used to assess the impact of future development and climate scenarios.

Second, the hydrological model of the Okavango delta (Wolski et al. 2006) integrates 'reservoir' modeling of water volume and GIS-modeling of flood spatial distribution. Hereafter, this is referred to as the '*delta model*'. The Okavango delta is represented as a set of inter-linked linear 'reservoirs' representing major distributaries in the delta (Fig. 4). For each 'reservoir', the volume of surface water (and therefore the total flooded area) is calculated on a monthly basis from the sum of

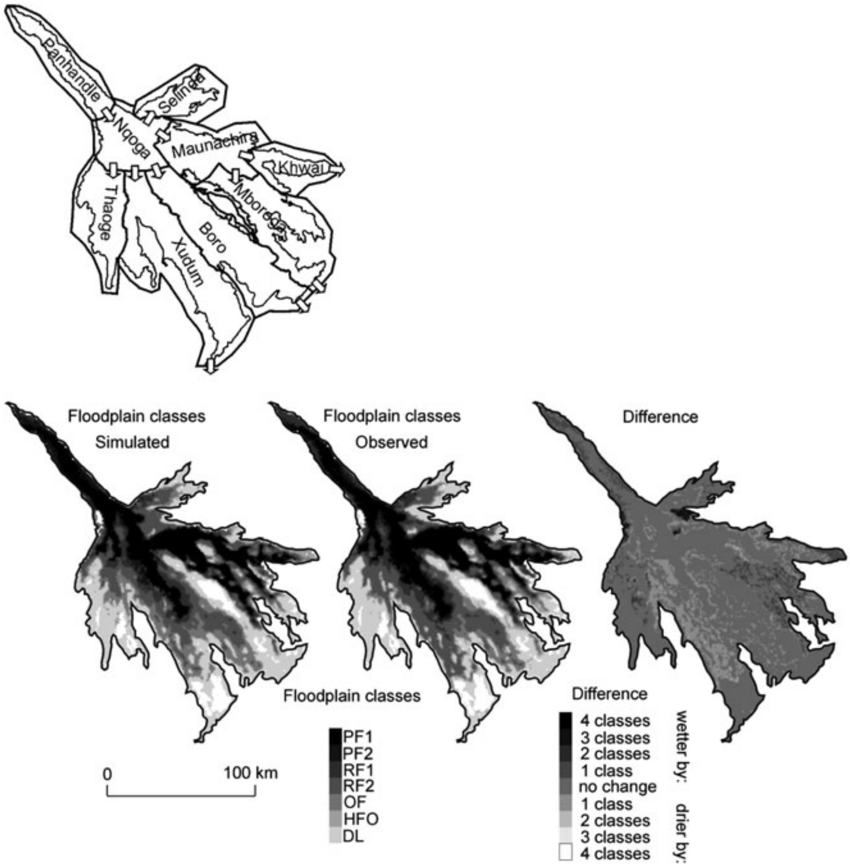

Fig. 4 **a** surface water reservoir units used in the Okavango Delta hydrological model **b** Okavango delta flood frequency map for the 1990–2000 period (observed, simulated and difference). Floodplain classes are explained in Table 1

upstream inflow, local precipitation and evapotranspiration, groundwater flux and outflow. The delta model requires monthly inflow from the basin model and local P and E_p over the delta region. The lumped value of flood area in each reservoir unit is then used as an input to a GIS model, in which the spatial distribution of that flood is determined based on a 15-year time series of flood maps obtained from classification of NOAA-AVHRR satellite images (McCarthy et al. 2004). Although the spatial resolution of the hydrological model is very coarse (units vary in size from 500–2 000 km^2, Fig. 4a), the GIS model provides the distribution of flood at a much finer spatial resolution of 1 km (Fig. 4b). The delta model simulations of flood volume and its spatial distribution were validated against historical data with satisfactory results. Flood frequency in each 1 km grid cell was then translated into the distribution of functional floodplain classes and the associated ecological status using the relationships given in Table 1 (Fig. 4).

Table 1 Okavango delta hydrological characteristics of functional floodplain classes

Floodplain class	Sub-class	Class code	Flood frequency	Flood duration (months/year)
Permanent floodplain	Proper	PF1	1	12
	Fringe	PF2	1	8–12
Regularly flooded seasonal floodplain		RF1	1	4–8
		RF2	0.5–1	
Occasionally flooded seasonal		OF	0.1–0.5	1–4
High floods only		HFO	<0.1	<2
Dryland		DL	0	0

3.3 Methodology for Climate Impacts Simulation

The impacts on Okavango river flow and delta flooding of climate change is evaluated through comparison of simulated mean monthly river flow frequencies and delta flood frequencies under various future climate scenarios with the ‘present day’ baseline conditions. The various sources of uncertainty in the climate change impact assessment process are described in Section 2.3, and in this case, some of these were quantified by using numerous simulations of the basin and delta hydrological models, driven by multiple estimates of future climate. To quantify uncertainty associated with GCM inadequacy we: (i) use monthly data from single ensemble runs of four GCMs from the IPCC Third Assessment Report (TAR); and (ii) evaluate the climate change signal of all GCMs included in the IPCC AR4. To account for uncertainty in future 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. (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 gases.

Simulations of the impact of the climate change scenarios on the river flow are made by driving the basin model with perturbed time series of spatially distributed P and E_p. The delta model is then forced with the simulated future output from the basin model and perturbed time series of spatially distributed P and E_p over the delta, and the simulated change in future flood extent calculated. This flood extent was then was translated into the change in size and distribution of functional floodplain classes (Table 1) for assessment of the changes in ecological terms.

It is not appropriate to use the GCM data directly due to bias in the GCM estimation of the climate basic state. Instead mean monthly GCM ‘change’ factors are defined (ΔP, ΔT, ΔT_{max} and ΔT_{min} where T is near surface temperature) for each GCM and each GHC scenario, for future 30-year epochs, representing the middle (2020–2050), late (2050–2080) and end (2070–2099) of the twenty-first century.

These ‘change’ 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. For the basin model, the Hargreaves equation is used to calculate ΔE_p from ΔT, ΔT_{max} and ΔT_{min} (Hargreaves and Allen 2003). Perturbed P and E_p records to drive the basin and delta hydrological models are obtained by multiplying the available baseline records (1960–1972, 1991–2002) of sub-basin monthly time series of P and E_p with average monthly ΔP and ΔEp values, respectively. This “GCM change” approach is the most common method of transfering the signal of climate change from climate models to hydrological or other impact models.

3.4 Simulated Future Climate Change

The simulated impact of future climate change on Okavango River discharge is highly time and model dependent (Fig. 5, Table 2, see et al. 2006 for full details). 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 simulations predicting dramatically increased flow (e.g. those driven by the CCC model) 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,

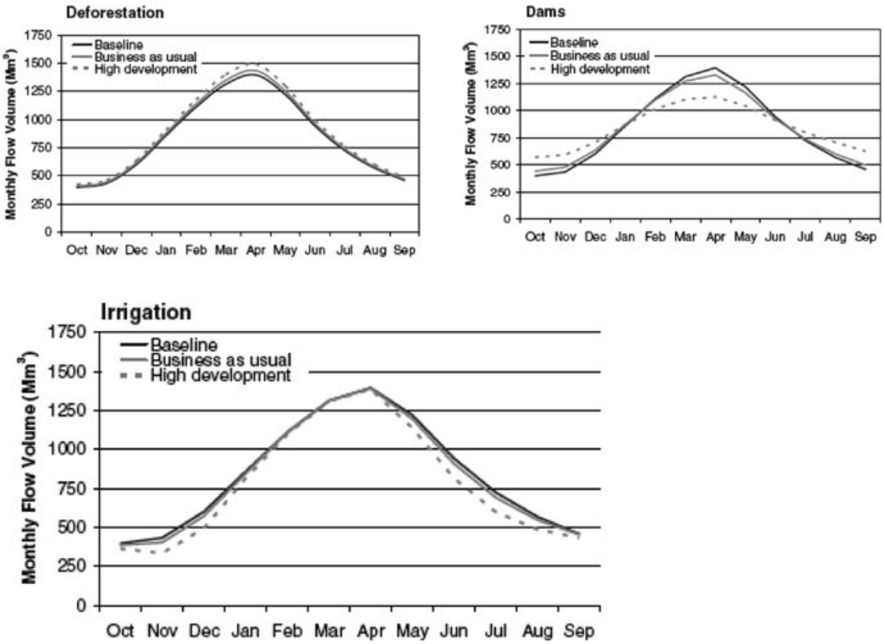

Fig. 5 (continued)

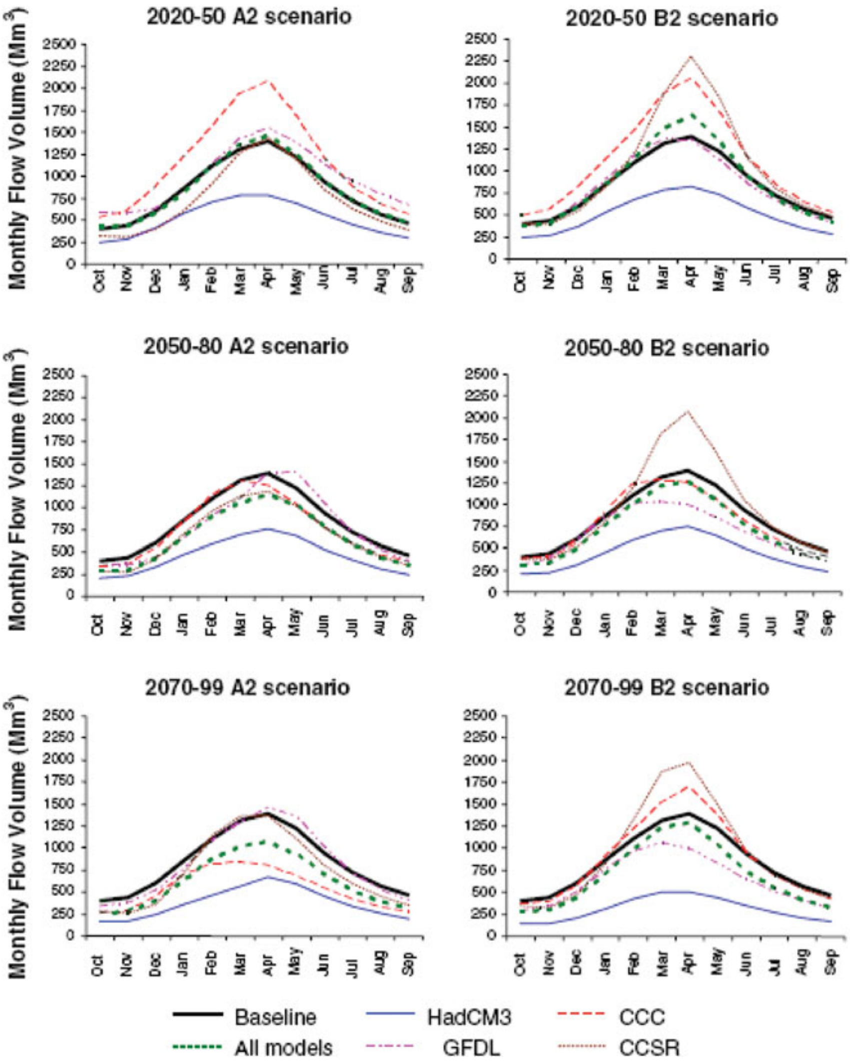

Fig. 5 Simulated effect of climate change and development on the Okavango river basin discharge upstream of the delta region. Plots mean monthly flow (Mm^3) of Okavango river at Mukwe, Namibia (see Fig. 3) simulated by basin hydrological model driven by (a)–(g) changes in precipitation and evaporation derived from various GCMs under the A2 and B2 *greenhouse* gas emission scenarios and (g)–(i) various development scenarios (see text for explanation). Each plot also shows observed historical 'baseline' conditions

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

Table 2 Impact of climatic change on annual mean and minimum monthly flow for the Okavango river at Mukwe, Namibia, upstream of Okavango delta (see Fig. 3)

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 (%)	Minimum monthly flow vs. baseline conditions (%)	Annual mean flow vs. baseline conditions (%)	Minimum monthly flow vs. baseline conditions (%)
	All-GCM mean/highest GCM/lowest GCM output	All-GCM mean/highest GCM/lowest GCM output	All-GCM mean/ highest GCM/ lowest GCM output	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

likely that this consistency in response reflects the increasing influence of rising temperatures predicted 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. The results suggest that future climate change is likely to have a proportionally larger impact on minimum monthly flow compared to mean flow. This may be indicative of a more extreme hydroclimatic regime and will have implications for the maintenance of environmental flows.

It is instructive to view the projected changes in mean flow in the context of historically observed variability (Table 2). Projected changes in the 30-year median annual flow and minimum monthly flow for the selected time slices in the second half of the twenty-first century are similar in 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 (Andersson et al. 2006).

The impact on the Okavango delta flood extent (see Murray-Hudson et al. 2006 for full details) is shown in Fig. 6, first as proportions of the floodable area made up

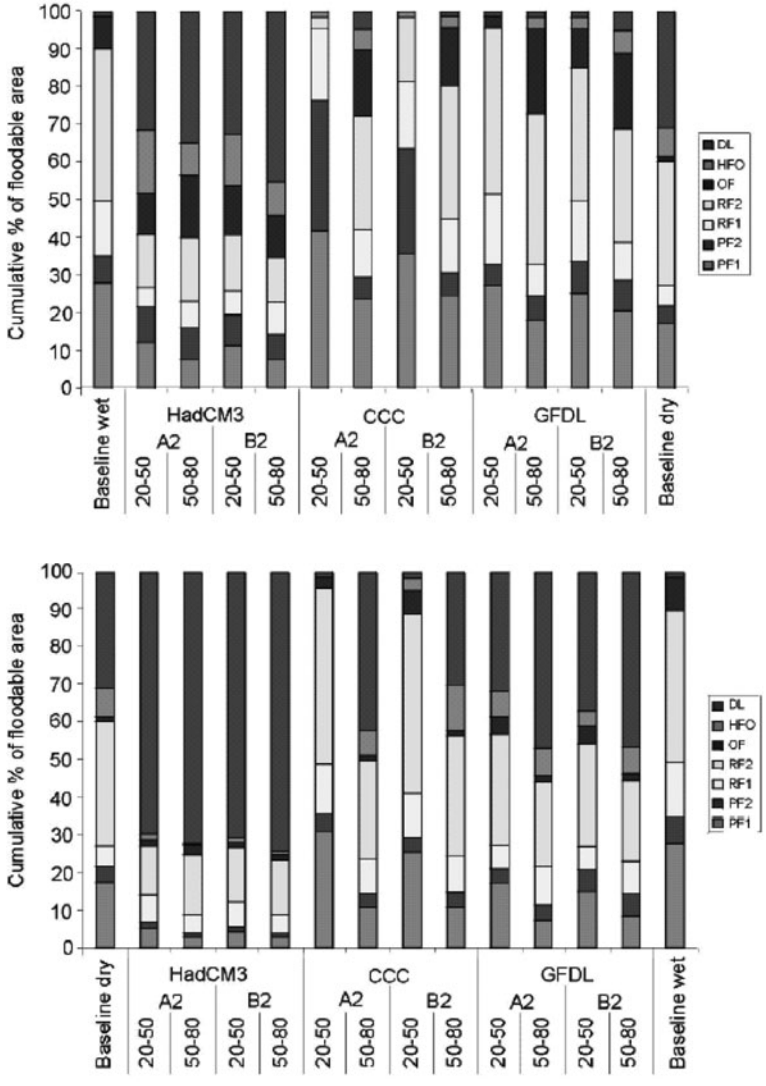

Fig. 6 Simulated effect of climate change on the Okavango Delta flooding. Plots show proportional floodplain class composition of Okavango Delta floodplains simulated for hydrological conditions obtained from selected climate models (HadCM3, CCC, GFDL) under *greenhouse* scenarios A2 and B2 with respect to **a** historical wet conditions **b** historical dry conditions. Floodplain classes as in Table 1

by the various floodplain classes (Table 1) compared to wet (1974–1985) and dry (1990–2000) baseline conditions. When driven by the HadCM3 model under both the A2 and B2 GHG scenario, the hydrological models suggest substantial drying of the Okavango delta relative to wet and dry baseline conditions. There are large increases in dryland (more than double), and occasionally flooded regions, with similarly large decreases in permanent flood regions. The magnitude of this drying increases over time. In contrast, the results under the CCC GCM suggest an initial expansion of the Okavango delta area for the period 2020–2050 but a reversal to conditions slightly drier than the current baseline conditions by 2050–2080. When driven by the conditions perturbed by the GFDL GCM, hydrological models suggest that the only small changes for 2020–2050 but substantial drying during 2050–2080 with a large increase in seasonally flooded classes and dryland. However this change over time is no greater than the difference between wet baseline and dry baseline conditions. Overall, differences in flooding associated with the two GHG scenarios are not as great as those associated with the different GCMs or the difference between the two future epochs.

These changes are shown spatially in Fig. 7 for GHG scenario A2 and the period 2020–2050 with differences related to the dry baseline. The drier conditions simulated with HadCM3 scenarios are clearly manifest throughout the delta, including the panhandle, with changes of up four classes affecting large areas of the more seasonal (central and western) distributaries in particular. Wetter conditions produced by CCC and to a lesser extent by GFDL outputs are shown affecting peripheral occasionally flooded and dry land areas, with extensive areas showing an increase in flooding of between two and three classes.

The above analysis was based output from the IPCC TAR GCM experiments. The IPCC AR4 includes a more extensive ‘ensemble of opportunity’ comprising 21 GCMs many of which feature multi-member ensemble runs. These new data provide the potential for a more comprehensive uncertainty analysis. The results described above indicate that the climate change signal in the first half of the twenty-first century is dominated by uncertainty in GCM precipitation. From Fig. 8 it is clear that uncertainty in the precipitation signal is considerable across the range of AR4 models with 13 of the 23 models suggesting an increase in wet season precipitation and 10 showing a (larger magnitude) decrease. As such, the large uncertainties in the simulation of the hydrological impacts of climate change in the WERRD project are relatively robust and not simply a function of the relatively small sample of GCMs used in the analysis above. The wide range of precipitation signals from the IPCC models may result partly from the Okavango basin straddling the boundary between the equatorial zone of increased precipitation and subtropical and decreased precipitation projected by the multi-model mean (Fig. 1, Christensen et al. 2007). It has been well documented that to date most GCMs operate at coarse spatial resolution relative to the scales of basin hydrological processes. Dynamical downscaling of GCM output using regional climate models (RCMs) indicates that the climate change signal varies between the driving GCM and the nested RCM

→

Fig. 7 Simulated effect of climate change and development on the spatial structure Okavango Delta flooding. Maps show (a)–(c) simulated floodplain classes for models driven by climate models (HadCM3, CCC and GFDL) under A2 *greenhouse* gases scenario. (d)–(f) change in floodplain classes with respect to baseline dry conditions. (g)–(i) change in floodplain classes for development scenarios (see text for details) with respect to baseline dry conditions. Colour coding as in Fig. 4

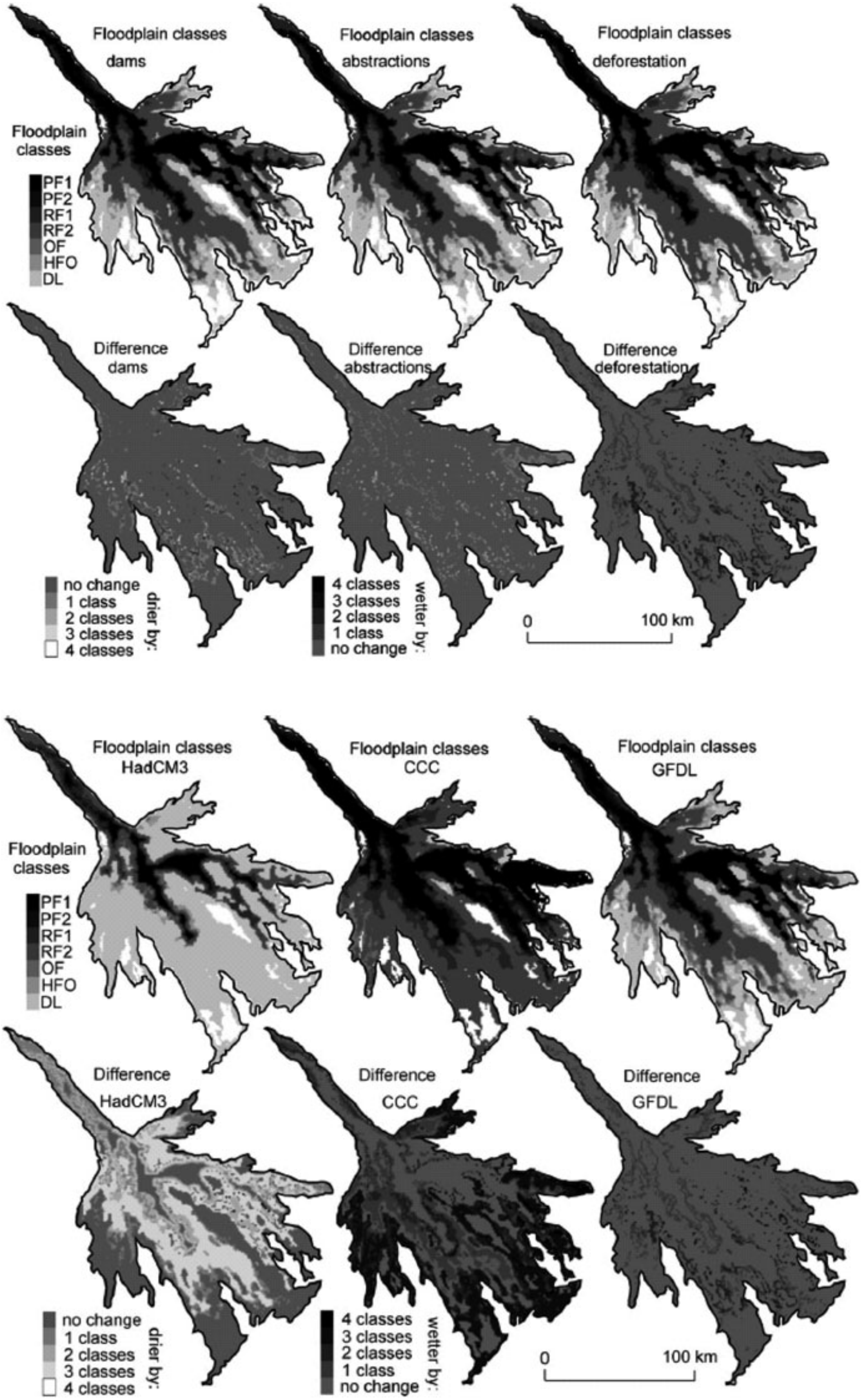

Fig. 7 (continued)

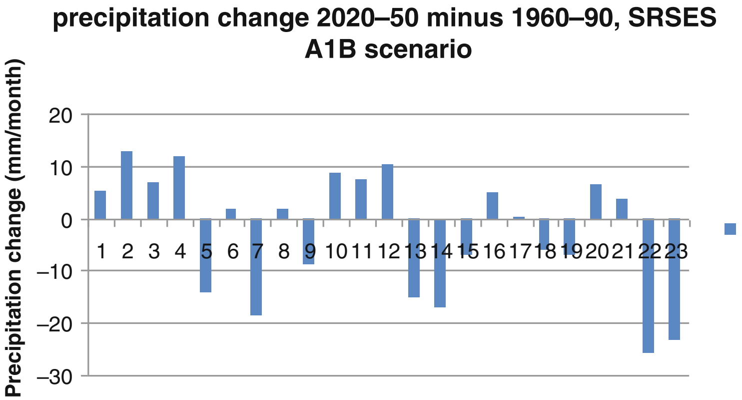

Fig. 8 Projected change in precipitation (%) over the Okavango River basin region (17º–12ºS, 15º–19ºE) from IPCC Multi Model Dataset under the A1B GHG emission scenario simulations for 2020–2050

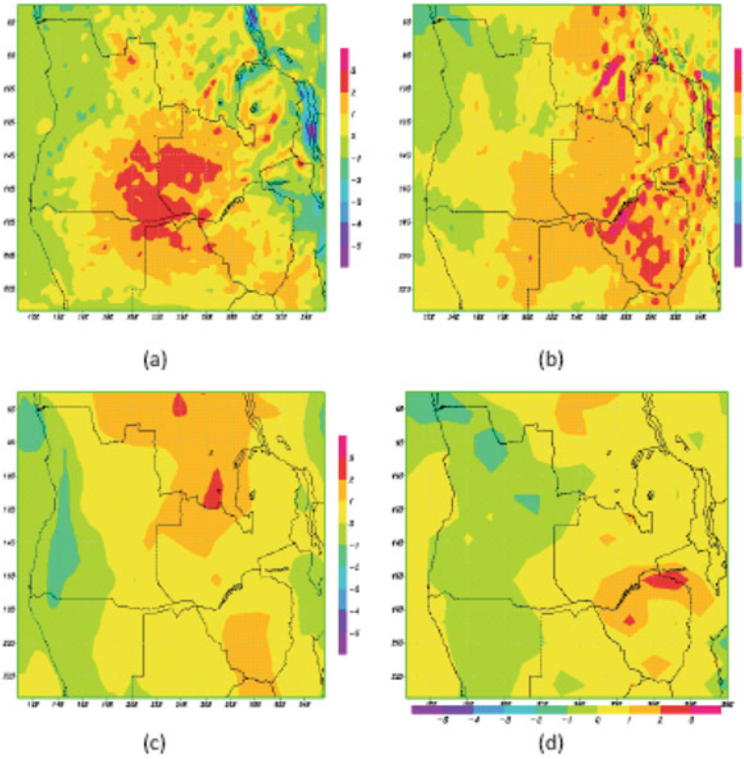

Fig. 9 Comparison of projected change in precipitation over southwestern Africa simulated by selected GCMs and nested RCMs. Figures show percentage change for 2070–2080 relative to 1990–2000

(Fig. 9) adding further uncertainty to estimates of future climate change. As such, further hydrological model simulations driven by climate changes from the full suite of IPCC AR4 GCMs and downscaled by RCMs are likely to expand the envelope of non-discountable climate change impacts beyond that presented above.

Given the context of water resource policy it is useful to consider the projected climate change impacts within the context of potential development scenarios. To this end the WERRD project developed a range of possible development scenarios through stakeholder dialogue and expert analysis. Three scenarios of development were defined in which varying degrees of water use, river abstractions and flow regulation through hydro-electric power generation were quantified (see Andersson et al. 2006) for full details. The low-impact development scenario considers only a change in water demand due to increased consumptive use from population, livestock and informal irrigation, based on standard population projections for 2015 and 2025. The ''business-as-usual'' scenario also includes formal irrigation schemes described by Crerar (1997) and Mendelsohn and el Obeid (2003), deforestation in a 1 km buffer around major water courses, and construction of one hydropower dam at Malobas in Angola (Crerar 1997). The high impact development scenario includes all the other developments plus irrigation of all areas estimated as suitable for irrigation by Diniz and Aguiar (1973) (1,040 km^2 or 0.2% of the total upstream basin area), irrigation around the two urban areas of Menongue and Cuito-Cuanavale, deforestation of a 2 km buffer around major watercourses, all six potential dams in headwater rivers in Angola (Crerar 1997), and the operational use of the Eastern National Carrier pipeline planned to transfer water from the Okavango to the central area of Namibia near Windhoek.

The effect of the development scenarios is included in Figs. 5 and 7 and indicates that only the high impact development scenario will have a substantial impact on river flow and delta flooding, largely associated with changes to the flow regime associated with dam operations in Angola. However, it is clear that the potential climate change impacts are far greater than even the most extreme development scenarios. This suggests that evaluation of hydrological impacts of the future development considered in these scenarios should be conducted within the context of projected climate changes and associated uncertainty. This has important implications for environmental impact assessment of proposed developments.

3.5 *Summary of Results from Okavango River Case Study*

This work has quantified climate change impacts on the Okavango river system in Southwestern Africa, and in particular on the extent and frequency of flooding in the Okavango delta, a unique wetland system of global importance whose ecological status is primarily driven by hydrology. The study is particularly challenging given the location of the basin in a region of pronounced gradients in mean climate and projected changes. The work shows that: (i) climate changes even by the middle of the twenty-first century are potentially very large and could exceed the very substantial natural variability experienced in recent decades; (ii) uncertainty in the sign and magnitude of the climate change signal is large; (iii) in the first half of twenty-first centrury this uncertainty in largely associated with uncertainty in the GCM precipitation signal; (iv) toward the latter decades of the twenty-first century there is greater convergence in the projected response towards a drying of the system, as the effects of increased temperature on evapotranspiration losses come to dominate; and (v) the climate change signal even in forthcoming decades, irrespective of the chosen GHG emission scenario, may be bigger than any development scenarios.

It is not unreasonable to infer that future development decisions in the basin (e.g. the development of headwater river dams and the proposed extension of the Eastern National Carrier pipeline to the Okavango) should incorporate projected climate changes and crucially the full range of non-discountable climate change into account. The tri-nation Permanent Okavango River Basin Water Commission (OKACOM) has been established to provide a coherent approach to managing the basin's resources, based upon equitable allocation, sound environmental management, and sustainable utilization. Recognition of potential climate change should be a central component of OKACOM's efforts to develop integrated basin water management. To better inform agencies such as OKACOM, further research should focus on a number of themes. Firstly, to extend the uncertainty analysis to include grand-ensembles of GCM experiments and hydrological model experiments, such that a more comprehensive estimate of non-discountable climate change impacts can be determined. This is being addressed partly through the UK NERC funded project QUEST-Global Scale Impacts (GSI) project. Secondly, to determine the effects of projected climate changes on river basin, delta ecology and biodiversity. The aim must be to determine appropriate 'environmental flows' to maintain aquatic and terrestrial biodiversity and ecological status of the Okavango system. This is being explored through the BIOKAVANGO (http://www.orc.ub.bw/biokavango/) and Aquatic biodiversity and Climate Change in the Okavango River Delta (ACCORD) projects, amongst others.

4 Case Study II: The Mitano River Basin, Uganda

4.1 The Hydro-Climate and Development Context

This study differs from the previous example in a number of ways, not least of which is the explicit emphasis on groundwater resources rather than river flow and wetland flooding. Groundwater is the primary source of freshwater for drinking and irrigation around the world. In sub-Saharan Africa, groundwater supplies 75% of all improved (safe) sources of drinking water (Foster et al. 2006). The impacts of climate change on groundwater resources remain, however, very poorly understood (Bates et al. 2008). At present, estimates of freshwater resources (e.g. Shiklomanov 2000) and predictions of freshwater resources as a result of climate change (e.g. Arnell 2004) are commonly defined in terms of mean annual river discharge (runoff). Such estimates and predictions disregard soil water (i.e., water transpired by plants), despite the fact that this sustains almost all agricultural production in equatorial Africa, and fail to represent the proportion of riverflow derived from groundwater despite its importance to water supply. A quantitative understanding of the impacts of climate variability and change on both basin stores (i.e. soil water, groundwater) and flows (i.e. river discharge) is of critical importance to the development of climate change adaptation strategies. These issues are particularly important in Uganda where there is substantial dependence on precipitation-fed agriculture and heavy reliance upon localised (untreated) groundwater as a source of potable water. Here, we present results of a study that focuses on groundwater recharge in the Mitano basin in Uganda. The East African sector, including Uganda, is one of the few regions of the world where a consistent projection of future precipitation change is suggested, with most models showing increased precipitation in the future (Christensen et al. 2007, Meehl et al. 2007). However, concern over future water resources in Uganda is heightened by projections of a near doubling by 2025 of the current (2005) population of 25.8 million (UNDESA 2006).

The River Mitano basin is a relatively small basin (2,098 km^2), in southwestern Uganda (Fig. 10). The River Mitano drains areas of relatively high elevation (2,500 m) to the south and flows in a north-westerly direction towards the depression containing Lake Edward (975 mamsl). The basin is underlain by Precambrian crystalline rock that have are deeply weathered. Groundwater from the weathered

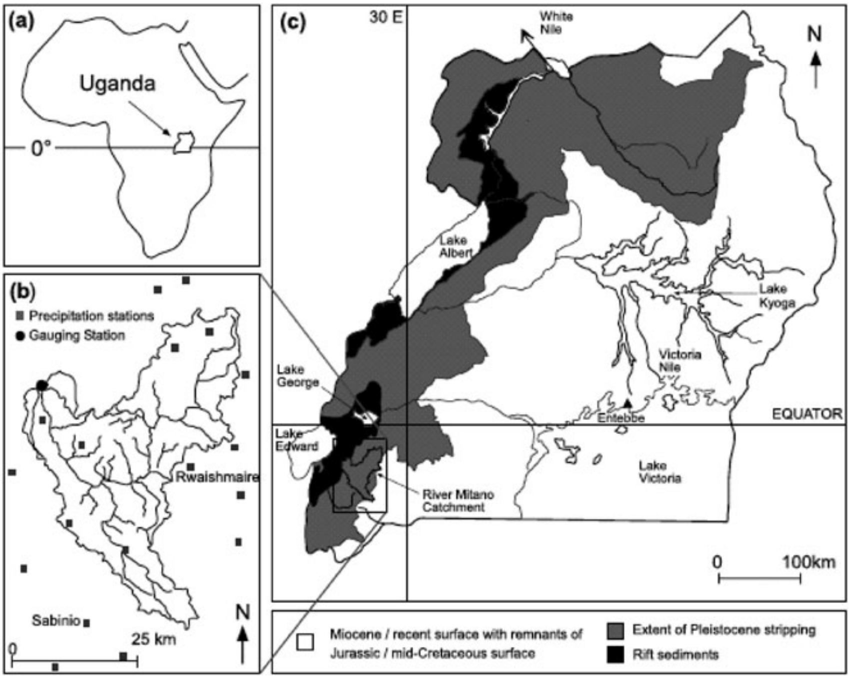

Fig. 10 The Mitano river study region in Uganda

overburden and fractured bedrock discharges into the River Mitano drainage network. Land use is primarily agrarian (79%). Mean annual basin precipitation for the period 1965–1979 is 1,190 mm and exhibits a bi-modal regime with dominant modes (wet seasons) in March–May (MAM) and September–November (SON). Mean annual pan evaporation for the period 1967–1977 is 1,535 mm measured at Mbarara (approximately 50 km to the east of the basin) and exceeds precipitation in all months except SON. Discharge records (1965–1979) for the River Mitano reflect the bi-modal precipitation but lag peak precipitation by approximately 2–6 weeks.

4.2 Hydrological Modeling

A daily soil moisture balance model (SMBM) for the basin was developed (see Mileham et al. 2008 for full details) to simulate groundwater recharge (R) from the infiltration of precipitation (P) based on changes in soil-moisture. According to Equations (1) and (2), R occurs when effective precipitation, P minus runoff (RO) at the soil surface exceeds evapotranspiration (ET) and when soil-moisture content exceeds field capacity. The additional P inputs are considered to pass through the soil into underlying strata. When the water content of the soil is less than field capacity, a soil-moisture deficit (SMD) exists and direct recharge is prevented.

$$R = (P - RO) - ET, \text{when SMD}_t = 0 \tag{1}$$

,

$$R = 0, \text{when SMD} > 0 \tag{2}$$

A daily precipitation threshold (10 mm) is applied, above which it is assumed interception and evaporation are overcome and runoff occurs. Runoff is calculated as a percentage of daily precipitation above this threshold (i.e. runoff co-efficient). According to the SMBM, ET equals potential evapotranspiration (E_p) until the SMD reaches the root constant (the maximum rooting depth) that is a function of rooting depth and soil porosity. Beyond this, ET continues at a reduced rate (10% of PET). A SMD of a further 51 mm can develop before the wilting point (maximum SMD) is reached, beyond which transpiration ceases. E_p is estimated using a modified Thornthwaite temperature-based equation, weighted (2:1) toward maximum air temperature, which produces estimates of PET that replicate (<5% bias) estimates of pan-derived evaporation observed at Mbarara (0°36’S, 30°39’E).

Daily precipitation data for twenty precipitation stations (1965–1980, within and surrounding the River Mitano basin) were obtained and gridded to the 0.25° resolution SMBM grid. Recharge and runoff estimated by the SMBM were calibrated over the period 1965–1979 using estimates of basin baseflow and stormflow derived from a hydrographic separation of river discharge.

4.3 Methodology for Climate Impacts Simulation

Given the small basin size and relatively high resolution of the SMBM, estimates of future climate were derived from downscaled GCM output using the PRECIS regional climate model (Jones et al. 2004) at 0.25° spatial resolution. PRECIS was nested in output from the HadCM3 GCM for historical baseline period 1960–1990 and for the future 2070–2099 period under forcing from the IPCC SRES A2 scenario. PRECIS precipitation and temperature-derived E_p (using the modified Thornthwaite method) were used to derive the changes in future climatic conditions. Two methods were used to derive future estimates of P and E_p as outlined below. (i) Monthly mean change factors derived from the future and historical PRECIS data were applied to the historical daily precipitation and E_p data (as in the Okavango river study in Section 3) for each of the six grid cells. These Mean monthly change factors are a favoured approach for impact studies as a convenient way to circumvent the problem of GCM bias. (ii) A daily precipitation frequency distribution transformation was also developed in which the lognormal frequency distribution of historical daily precipitation is transformed to match the change in the mean and variance of the PRECIS daily precipitation frequency distribution. This will account for changes to the precipitation distribution not just the precipitation mean as in method (i). Given the non linear relationship between daily precipitation and groundwater recharge rate changes to the frequency distribution of precipitation is likely to be important.

4.4 Simulated Future Climate Change

Under the IPCC SRES A2 scenario the PRECIS model suggests an increase in annual precipitation of 17% with increases in all months except January (Fig. 11) and a 4.2°C increase in mean annual temperature, which gives rise to a 53% increase in annual E_p. These values are broadly similar to that of the driving GCM HadCM3. The projected increase in precipitation is in line with many other IPCC AR4 models (Meehl et al. 2007). Using the standard change factor approach (method (i) in Section 4.3) the SMBM indicates this will lead to a 49% reduction in recharge and a 72% increase in runoff (Table 3). In terms if the seasonal cycle (Fig. 12), under future climatic conditions little recharge occurs between January and July representing the first rains and most of the first dry season. Increases in precipitation in this period are more than offset by increases in E_p. During the second wet season recharge is reduced but not as dramatically as during the rest of the year.

However, PRECIS simulations also suggest important changes to the daily precipitation frequency distribution with reduction in the occurrence of small precipitation events (<10 mm) and an increase in the occurrence of large precipitation events (>10 mm) (Fig. 13). Applying a transformation in this daily precipitation frequency distribution (method (ii) in Section 4.3), the SMBM suggests an increase in both recharge and runoff under future climatic conditions relative to that observed by 62 and 137%, respectively (Table 3). The increase in intensity of precipitation

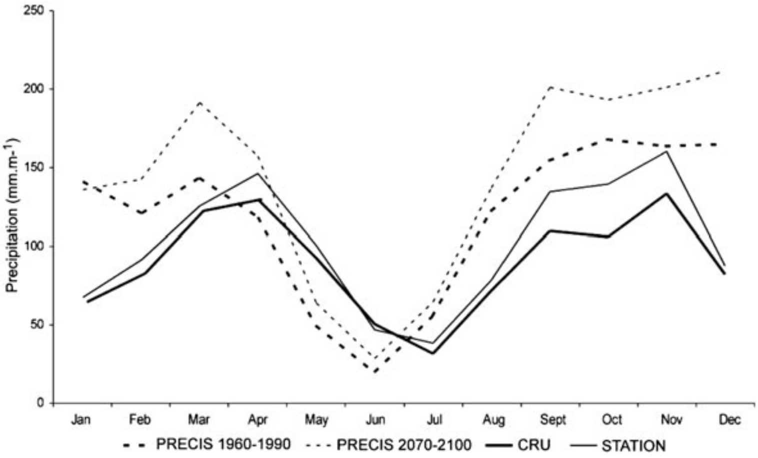

Fig. 11 Simulated change in monthly mean precipitation over the Mitano river basin from PRECIS RCM under IPCC A2 GHG scenario. Plot also shows historical observations from interpolated gauge data and CRUTEM3 gridded dataset

events under future climate substantially increases recharge (and runoff) by overcoming the increase in E_p on individual days so that infiltration and recharge occur more frequently. In terms of the seasonal cycle increases in recharge are most pronounced to the second rainy season (Fig. 14), most notably the early wet season (September) driven by the earlier precipitation onset and lower SMD.

The daily precipitation transformation approach results in substantially different climate change projections for groundwater recharge compared to the projections using monthly 'change' factors, namely a projected increase rather than decrease. This difference results solely from a more comprehensive representation of precipitation intensity under future climates, to which recharge and runoff are sensitive. The results indicate that the sign of the climate change signal for groundwater

Table 3 Simulated groundwater recharge and runoff for the river Mitano basin in Uganda

	For 1965–1980	For 2070–2099 using mean 'change' factors (method (i) Section 4.3)	2070–2099 using transformed daily precipitation frequency distribution (method (ii) Section 4.3)
Mean annual groundwater recharge (mm)	104	53	169
Mean annual river runoff (mm)	144	247	341

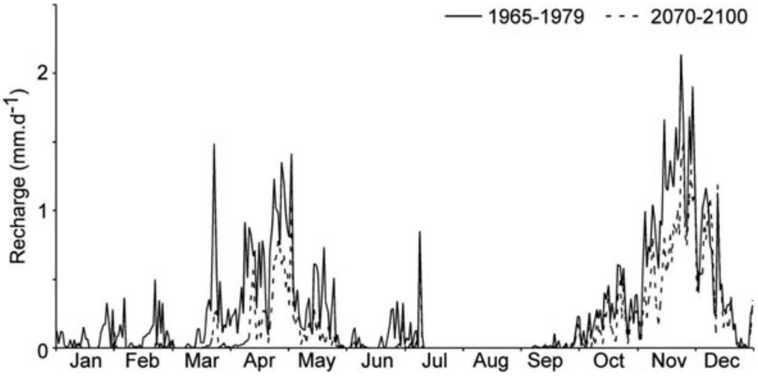

Fig. 12 Simulated effect of climate change on groundwater recharge in the Mitano river basin for hydrological models driven by historical and future climate (PRECIS RCM under A2 GHG scenario). Climate change signal is simulated by perturbation of historical daily rainfall using monthly mean 'change' factors (method (i) in Section 4.3)

recharge is highly sensitive to the method by which the projected change in precipitation is applied. Simply scaling the daily historical precipitation data using the monthly change factor results in a projected decrease in groundwater recharge as the large projected increase in E_p dominates the groundwater budget. However, when we account for projected changes in the daily precipitation frequency distribution in which there is a shift toward a greater contribution from intense precipitation events, a substantial increase in recharge is suggested. In this case we might assume that the latter, more sophisticated approach is preferable. However, the results highlight how a comprehensive end-to-end quantification of uncertainty in climate change impacts

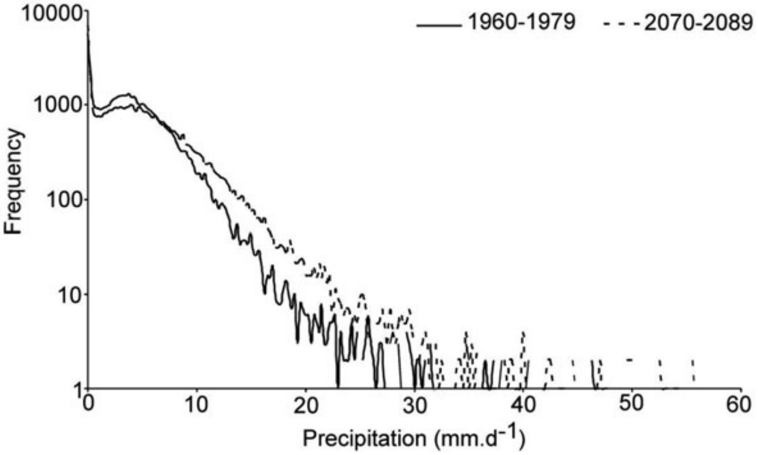

Fig. 13 Simulated change in frequency distribution of daily precipitation over the Mitano river basin from PRECIS RCM under IPCC A2 GHG scenario

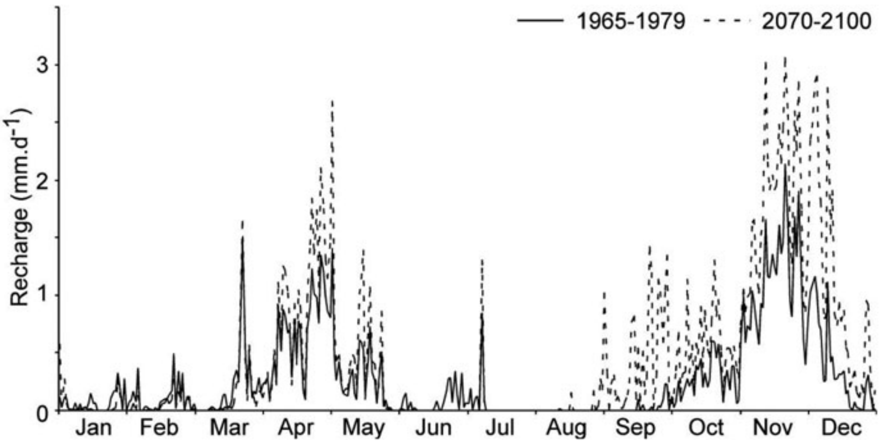

Fig. 14 As Fig. 12, except climate change signal is simulated by perturbation of historical daily rainfall using transformation of the daily precipitation frequency distribution (method (ii) in Section 4.3)

studies should systematically address the propagation of uncertainty in complex, non-linear systems like surface hydrology (New et al. 2007).

4.5 Summary of Results from Mitano River Case Study and Implications for Water

This study illustrates the potential for determining the response of groundwater resources to changing climate in a small basin in equatorial east Africa. High-resolution estimates of climate change are generated using a RCM. The hydrological response simulated by the SMBM is sensitive to the method by which the future climate change signal is determined. When the change in the frequency distribution of daily precipitation is considered rather than just the change in daily mean precipitation, groundwater recharge is projected to increase, rather than decrease. However, unlike the Okavango study only a single combination of GCM/RCM and emission scenario was examined. Although, the IPCC AR4 models indicate a relatively consistent mean precipitation change signal over East Africa (Christensen et al. 2007) the degree of consistency in projected changes to frequency and intensity of daily precipitation is as yet unclear. Therefore, further model simulations are required including grand-ensembles of GCM experiments and hydrological model experiments to determine the fuller extent of non-discountable climate change impacts. In addition, given the highly non-linear relationship between precipitation and recharge further work is required to improve our understanding of groundwater recharge processes.

Projected increases in recharge under future climatic conditions provide a promising outlook for future populations, yet increases in demand due to very rapid population increase in coming decades are likely to exert considerable pressure on finite water resources. Initial studies indicate that increased demand is already driving increases in motorised groundwater development, which has expanded dramatically since 2003 (MWLE 2006). Furthermore, the water supply system in Rukungiri town, the main urban area in the River Mitano basin has already been singled out as being inadequate for meeting current town water demand, making future expansions of intensive groundwater abstraction inevitable. Increases in intensive groundwater development are further expected as the Ugandan government intensifies its efforts to provide safe drinking water to urban populations (MWLE 2006). For example, 782 small towns were identified for the provision of piped water by June 2006 (Tindimugaya, C., pers. com.). Around 70% of water supplied to these towns is provided by groundwater, mainly through deep boreholes. Uncertainties in the future development of intensive irrigation under a changing climatic regime with increased dry-day frequency also pose a problem for future water resources demand. Socio-economic change rather than direct climate change impacts may therefore have a substantial influence on basin water resources. Nevertheless, plans for future development initiatives to develop groundwater resources, notably intensive groundwater abstraction for town water supplies or irrigation, need to account for the full range of possible hydrological responses to future climate.

5 Discussion and Conclusions

There is a clear consensus that anthropogenic climate change is real and that it presents a major challenge to many levels of society. Given that we are committed to increasing GHG levels for the foreseeable future, adaptation to climate change will be necessary. Therefore, various agencies need to incorporate climate related risk into their decision making. Vulnerability to climate change is likely to be most acute in the less developed parts of the world, including much of Africa. Within much of the tropics, the water resources sector will be particularly susceptible to climate change (Bates et al. 2008). Changes to the terrestrial hydrological cycle will further impact on the quality and availability of the ecosystem services on which many livelihoods depend. The development of strategies for climate risk management requires information on how climate may change in coming decades and the impact on water resources and ecosystem services. Such frameworks are the subject of ongoing research.

This chapter has provided a summary of two contrasting case studies of climate change impacts on basin scale hydrology in Africa. The large-scale Okavango river study addresses model uncertainty in a region where uncertainty in GCM projections of precipitation is high. Results show wide range of projected hydrological impacts with associated likely ecological impacts. At least in the first half of twentieth century uncertainty is dominated by GCM uncertainty rather than GHG emissions. The Mitano river study does not address GCM uncertainty explicitly but highlights how the projected impact on groundwater resources is critically sensitive to the method by which the projected precipitation change signal is transferred to the hydrological impact model. The project illustrates how hydrological processes are sensitive to projected changes in the frequency distribution of daily rainfall, at least in relatively small river basins.

These studies raise the issue of how such climate change impact projections might be incorporated into long-term decision making. Given the magnitude of projected climate change impacts in these cases there is a clear need to 'mainstream' climate information in development policies. To date, there are very few examples of this in practice (Washington et al. 2006). Stainforth et al. (2007b) have suggested an 'analysis pathway' which can guide the use of climate information and associated uncertainty in decision making. We draw on this to explore the policy implications of the two case studies presented in this chapter. Stainforth et al. (2007b) suggest that climate change adaptation is most relevant for decisions which exist irrespective of climate change but which have decadal time scale implications. There is often pressure to stabilise river flow regimes (through dams and interbasin transfers) in regions, such as the Okavango basin, where variability in flow is high and where the river corridor flow resource is especially valuable in a relatively dry environment. In the case of the Okavango, therefore, we might consider how decisions regarding large scale water abstractions (e.g. extending the Namibian Eastern National Water Carrier pipeline to the Okavango river) or construction and operation of dams for hydro-power generation in headwater streams (see Sections 3.3 and 3.4) might be influenced by projected climate change. The envelope of projected climate change impacts described in Section 3.4 can prove useful here, and there can be little doubt that the non-discountable climate change is highly relevant, even on the basis of this relatively limited exploration of uncertainty. In both these examples of infrastructural investment, determining the economic viability and environmental impact of the projects should be undertaken with respect to the full range of future hydro-climatic condition simulated in the model experiments, not solely on the basis of historical conditions. Still, there is a clear need for further uncertainty analysis using perturbed physics GCM experiments and assessment of uncertainty in hydrological models. For the Mitano River in Uganda, there can be little doubt that developing policy for investment to provide sustainable groundwater abstraction in the context of increasing demand will benefit from the kind of hydro-climate projection described here. A much more comprehensive uncertainty analysis is required, however, to determine the envelope of non-discountable climate change impacts. The study highlights how it is not just the changes in mean precipitation that are important to water resources but also the higher moments of the daily precipitation frequency distribution. It will be interesting to determine how the range of IPCC AR4 GCMs represent these features, and whether this leads to significantly less consistent hydrological response than that suggested by the relatively consistent response in the GCM mean precipitation climate change signal.

The development of climate change adaptation policy is in its infancy. Success in this requires a two-way communication between climate scientists and users of climate info. Further work should explore the link between climate change and real-world decision-making. Overall, in the context of large uncertainty in climate change impact projections, adaptation strategies should stress flexibility and resilience to future changes, including the adoption of water-efficient technologies and practices. This is particularly relevant in Africa where population growth is high and existing infrastructural capacity to cope with future climate change and variability is relatively low. There is no doubt that the process of ‘mainstreaming’ climate into development policy in Africa will be challenging. Nevertheless the existence already in Africa of regional centres disseminating climate information and the Regional Climate Outlook Fora (RCOF), which provide a unique dialogue between climate scientists and the wider user community, albeit for shorter seasonal timescales, provides a valuable platform for the development of adaptive strategies with relevance to climate change timescales.

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