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Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda

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Abstract. The changing availability of freshwater resources is likely to be one of the most important consequences of projected 21st century climate change for both human and natural systems. However, substantial uncertainty remains regarding the precise impacts of climate change on water resources, due in part due to uncertainty in GCM projections of climate change. Here we explore the potential impacts of climate change on freshwater resources in a humid, tropical catchment (the River Mitano) in the Upper Nile Basin of Uganda. Uncertainty associated with GCM structure and climate sensitivity is explored, as well as parameter specification within hydrological models. These aims are achieved by running pattern-scaled output from seven GCMs through a semi-distributed hydrological model of the catchment (developed using SWAT). Importantly, use of pattern-scaled GCM output allows investigation of specific thresholds of global climate change including the purported 2 °C threshold of "dangerous" climate change. In-depth analysis of results based on the HadCM3 GCM climate scenarios shows that annual river discharge first increases, then declines with rising global mean air temperature. A coincidental shift from a bimodal to unimodal discharge regime also results from a projected reduction in baseflow (groundwater discharge). Both of these changes occur after a 4 °C rise in global mean air temperature. These results are, however, highly GCM dependent, in both the magnitude and direction of change. This dependence stems primarily from projected differences in GCM scenario precipitation rather than temperature. GCM-related uncertainty is far greater than that associated with climate sensitivity or hydrological model parameterisation.

1 Introduction

Historical (20th century) periods of wetter and drier conditions in the Upper Nile region have demonstrated the vulnerability of human and natural systems to changes in the availability of freshwater resources (Tate et al., 2004; Conway, 2005). This is of concern because projections of 21st century climate suggest an overall intensification of the global hydrological cycle, with substantial changes expected to result in the hydrology of the Upper Nile region (Sene et al., 2001; Arnell, 2003; Tate et al., 2004).

Throughout the Upper Nile Basin, river discharge sustains surface water levels upon which there is substantial dependence for fisheries (e.g. Nile Perch and Tilapia) and hydroelectric power generation (Bugenyi, 2001; Mwanja, 2004). Domestic water supplies depend primarily upon dispersed groundwater abstraction and spring discharges. Piped water supplies drawing from Lake Victoria, the world's second largest lake in area, are restricted to cities such as Kampala, Kisumu and Jinja. Similar to most of sub-Saharan Africa, almost all arable land is presently rainfall-fed (Giordano, 2006; Fischer et al., 2007); irrigation is restricted to commercial agriculture (e.g. fresh-cut flowers) primarily for export. Substantial increases in demand for freshwater are projected as a result of population growth not only for domestic purposes

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but also to increase food production through expansion of irrigation (Taylor et al., 2004, 2009; Carter and Parker, 2009).

Given the magnitude of projected climate changes and the role of water in the socio-economic development of the Upper Nile Basin, there is a clear need for improved understanding of the potential impacts of these changes on the availability of freshwater resources. However, many existing assessments of water resources (past and projected) do not directly consider soil water (i.e. water transpired by plants) or groundwater, focusing instead on mean monthly or annual river flow (e.g. Kamga, 2001; Legesse et al., 2003; Messager et al., 2006; Wit and Stankiewicz, 2006; Elshamy et al., 2009; Beyene et al., 2010). This focus remains despite the fact that soil water sustains almost all agricultural production in equatorial Africa, and groundwater comprises 75% of all safe sources of drinking water in sub-Saharan Africa (Taylor et al., 2009). Furthermore, freshwater resources defined in terms of mean annual river discharge fail to indicate the proportion of freshwater available ephemerally in channels as stormflow (i.e. runoff) and that which is more evenly distributed in time and space as groundwater. As such, a quantitative understanding of the impacts of climate change on both catchment stores (i.e. soil water, groundwater) and flows (i.e. river discharge) is of critical importance to the development of effective strategies for management and adaptation to climate change (Mileham et al., 2009; Nyenje and Batelaan, 2009; Taylor, 2009).

This paper addresses an urgent need for improved understanding of projected climate change impacts on water resources in the Upper Nile Basin, and the uncertainty associated with such projections of hydrological change. This analysis is achieved through hydrological modelling of the River Mitano, a catchment in southwestern Uganda that drains into Lake Edward. The catchment features one of the longest continuous records of river discharge in Uganda (from 1958 onwards). We resolve both surface and sub-surface contributions to river discharge. Following calibration the hydrological model is forced with a range of climate change scenarios, designed to allow investigation of uncertainty between different GCMs and climate sensitivities. This represents an advancement of previous research into climate change impacts on surface and sub-surface hydrology in the Mitano River Basin (Mileham et al., 2009), which did not directly consider uncertainty between different GCMs or climate sensitivities. Furthermore, the scenarios explored herein permit direct investigation of the impacts of specific (and policy relevant) thresholds of climate change on water resources including the hypothesised 2 °C threshold for so-called "dangerous" climate change.

2 Study catchment

The River Mitano catchment is located just south of the equator in southwestern Uganda (Fig. 1), and is the primary contributor to the larger Ntungwe Basin, which drains directly into Lake Edward. The main river channel is well incised along the catchment's western border and flows from an area of relatively high elevation (2500 m above mean sea level) in the south to the depression containing Lake Edward (975 m above mean sea level) in the northwest. The Mitano gauging station, 20 km upstream of Lake Edward (and run by the Ugandan Directorate of Water Resources Management), represents a catchment area of 2098 km^2. The water balance of Lake Edward is uncertain, but the Ntungwe is thought to account for approximately 10% of river flow input to the lake using values from Hurst (1927), Viner and Smith (1973) and Lehman (2002), as cited in Russell and Johnson (2006). Westward flowing tributaries in eastern and northeastern parts of the catchment drain areas of considerably lower relief that represent the eastern boundary of drainage induced by the downfaulting of the western arm of the East African Rift System during the Mid-Pleistocene (Taylor and Howard, 1998). Incised valleys characterise a runoff dominated regime whereas areas of low relief promote infiltration and give rise to substantial baseflow (Taylor and Howard, 1999). Mean annual precipitation for the period 1965–1979 ranges from 963 mm at Rwaishmaire (30.13° E, 0.83° S) in the east of the Mitano Basin to 1699 mm at Sabiano (29.63° E, 1.38° S) in the south. Similar to the rest of the Upper Nile Basin, monthly precipitation follows a bimodal regime with dominant modes occurring from March to May and September to November; these are known as "short rains" and "long rains", respectively (Basalirwa, 1995).

Land use in the River Mitano catchment is primarily agrarian (79%). Agriculture takes place principally on small land holdings, with the most common crops comprising banana (matoke), tea, millet, cassava, sugarcane, and groundnuts. As rain falls during every month of the year (in common with much of the inner tropics), crops are entirely rainfall-fed. Grasslands dominate the remainder of the catchment (17%), with small areas of forest plantations and wetlands also present. Domestic water supplies in rural areas derive invariably from groundwater via handpumped wells and protected springs. Discrete aquifers occur within deeply weathered Precambrian crystalline rocks including gneiss, schist and phyllites of the Bugando-Toro Formation. The town of Rukungiri (population approximately 14 000) is the only urbanised area in the catchment and obtains its water supplies from a series of deep boreholes drawing from aquifers within coarse-grained, weathered clasts at the base of the saprolite (unconsolidated regolith) and fissures in the underlying crystalline bedrock (saprock).

3 Data and methods

Baseline meteorological data for calibration of the hydrological model of the Mitano River Basin comprise monthly minimum and maximum temperature, precipitation totals and

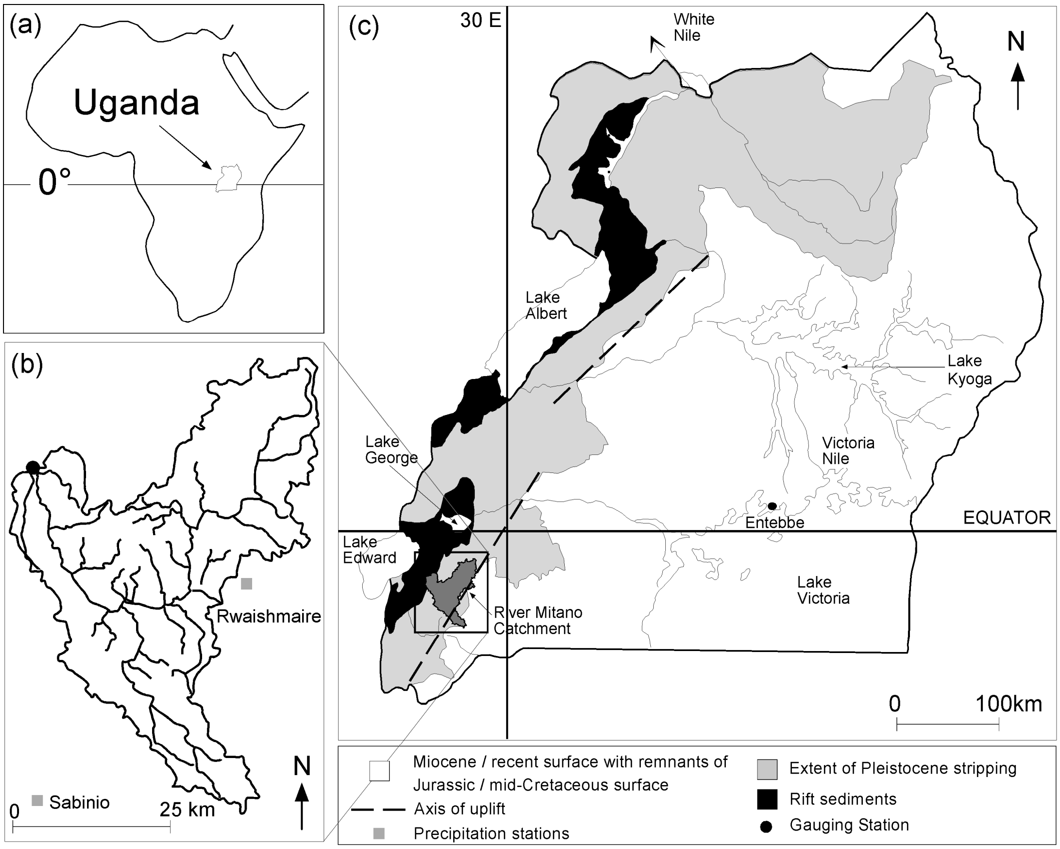

Fig. 1. **(a)** Location of the River Mitano Basin; **(b)** detailed map of the catchment drainage system; and **(c)** the location of the basin relative to the weathered land surfaces of Uganda (adapted from Taylor and Howard, 1999).

wet days for the period 1961–1990, obtained from the CRU TS 3.0 data set (Mitchell and Jones, 2005). With a gauged catchment area of 2098 km^2, the Mitano occupies part of four 0.5° grid cells from this global climate data set. Monthly data for these grid cells were disaggregated to daily resolution using a stochastic weather generator, following procedures outlined in Arnell (2003) and Todd et al. (2010). Whilst it would have been preferable to use daily data from locations within the Mitano basin for calibration of the hydrological model, such data are only available for 1965–1980 for precipitation, a period that is too short for adequate model calibration. Neither temperature nor evaporation data are available for the Mitano basin; the closest available observations are for the town of Mbarara, approximately 50 km to the east. Use of the gridded CRU TS 3.0 data permitted a calibration period of 1961–1990, to maintain consistency with the wider investigation of climate change impacts on freshwater (and other) resources that this study is part of (Todd et al., 2010; http://www.met.reading.ac.uk/research/quest-gsi/, accessed June 2010).

Station-based daily precipitation data that provided the basis for the coefficient of variation used to generate daily data were obtained from the five gauging stations within the River Mitano catchment (operated by the Ugandan Meteorology Department). Station-based daily temperature data for setting the standard deviation of the generated daily data were obtained from the Mbarara weather station. The Hargreaves method of estimating potential evapotranspiration (Allen et al., 1998) was applied instead of more data intensive methods such as Penman Monteith and Priestley-Taylor.

Future climate scenarios for temperature and precipitation were generated at a monthly resolution using the ClimGen pattern-scaling technique (Arnell and Osborn, 2006; Todd et al., 2010). These data were subsequently downscaled to the daily scale using the weather generator as described above. ClimGen is essentially a spatial scenario generator (e.g. Hulme et al., 2000), based on the assumption that the pattern of climate change, expressed as change per unit of global mean temperature change, is relatively constant for a given GCM (Arnell and Osborn, 2006). As such, this allows the pattern of climate change (for a given GCM) to be scaled upwards and downwards in magnitude, enabling specific thresholds of global climate change to be explored. This is an important and policy relevant aspect of this study, given the recent focus (and UNFCCC aim) of avoiding dangerous climate change (e.g. 2 °C rise in global mean air temperature). Here, scenarios were generated for a prescribed warming of global mean temperature of 0.5, 1, 1.5, 2, 2.5, 3, 4, 5 and 6 °C using the UKMO HadCM3 GCM, and for 2 °C warming with six additional GCMs: CCCMA CGCM31, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM30, and UKMO HadGEM1. This subset of CMIP-3 GCMs was selected in order to span a range of "plausible" different modelled global climate futures (e.g. Indian monsoon weakening/strengthening, magnitude of Amazon dieback).

The hydrological model used to investigate climate change impacts in the River Mitano catchment was developed using the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998). This is a physically based, semi-distributed hydrological model that operates on a daily time step. Different versions of SWAT have been widely used throughout the world for agricultural and water resources applications (Gassman et al., 2007), and have been demonstrated to be suitable for equatorial river basins in Africa (e.g. Ndomba et al., 2008, Schuol et al., 2008). Here, AVSWAT-X 2005 was used (Di Luzio et al., 2004), which is nested within the ArcView software package. The Mitano model was calibrated for the 1961–1990 baseline period (with a preceding 3-year model spin-up period) using daily river discharge data from the single gauging station within the catchment. The 15 period 1991–2005 (i.e. to the end of the CRU TS 3.0 data set) was then used to validate the model.

The Mitano river basin topography and boundary were calculated within SWAT, based on data from the Shuttle Radar Topography Mission (SRTM) 3 arc second dataset (Farr et al., 2007). Based on these analyses, the Mitano was divided into five sub-basins. Land-cover data were derived from the Africover dataset generated by the Food and Agriculture Organisation of the United Nations (FAO; available online at http://www.africover.org/index.htm, accessed June 2010). Land-use classifications from this dataset were matched with appropriate land cover groupings within the SWAT internal database. The FAO soil map of the world (FAO, 1990) was used as the basis for soil parameters within the hydrological model.

4 Hydrological model calibration and validation

The SWAT hydrological model was run at a daily time step, but model calibration and subsequent analyses were undertaken on a monthly basis as daily data derive from a stochastic weather generator (Arnell, 2003; Todd et al., 2010). Initial model runs, following basic adjustment of model parameters, resulted in reasonable agreement between 30-year means of monthly observed and simulated discharge. However, the resultant Nash-Sutcliffe efficiency was −0.09, indicating that the model was slightly less useful than the observed long-term monthly mean discharge as a basis for prediction. This reflects the occasionally very poor month-to-month performance of the model, with substantial monthly flow events either missing or erroneously introduced in the modelled time series. Even in the context of possible errors in the observed discharge data of ±15% (Mileham et al., 2008), errors are large and contrast strongly with the good agreement between observed and simulated monthly means and flow duration curves.

Autocalibration routines were employed with the aim of improving the agreement between the model and observations. AVSWAT-X 2005 includes the ParaSol autocalibration routine (van Griensven and Meixner, 2007) or, alternatively, can be coupled to the SWAT-CUP (Calibration, Uncertainty and Prediction) programme for autocalibration using either the SUFI-2, ParaSol or GLUE routines (Abbaspour et al., 2007). None of these routines resulted in satisfactory improvement of the hydrological model. It is thought that this is because there are some model-observation divergences within the 1961–1990 calibration period that are simply too large to be resolved by an autocalibration routine.

Following the unsuccessful application of autocalibration routines, a more extensive manual calibration was undertaken. This calibration was undertaken by manually varying the ten most sensitive parameters in the hydrological model (Table 1). These parameters were identified using the automated sensitivity analysis procedure within SWAT, which tests 27 parameters within SWAT based on a combination of a Latin Hypercube and one-factor-at-a-time sampling strategy (van Griensven et al., 2006). Following manual calibration of model parameters a more satisfactory fit between observed and simulated monthly river flow was obtained, particularly with respect to 30-year monthly means and flow duration curves (Fig. 2a and b). In agreement with the close match of flow duration curves, comparison of results from a simple baseflow separation procedure (Arnold et al., 1995) of modelled and observed discharge reveals a similar quickflow: baseflow ratio in both series (with a modelled baseflow fraction of 58% and observed of 65%). Importantly, whilst the absolute numbers are different, these derived model versus observed baseflow fractions are similar to previously defined graphical baseflow separation of observed and modelled Mitano discharge (modelled baseflow fraction: 43%, observed: 50%; Mileham et al., 2008).

Despite the improvements in model simulation, and close matching of the flow duration curves, occasional poor month-to-month sequencing remains (Fig. 2c). This is reflected in the low (albeit slightly higher) Nash-Sutcliffe coefficient of 0.06 for the period 1961–1990, and high RMSE value of 8.65 (in comparison to 1.62 for 30-year monthly means). For similar reasons to those discussed above, renewed application of autocalibration routines was again unsuccessful.

Given the discrepancy between the apparently well-matched flow duration curves and poor month-to-month sequencing, the model input data were investigated as a possible cause of poor model monthly sequencing. Observed

Table 1. The ten most sensitive parameters in the SWAT model of the Mitano River Basin.

Sensitivity rank	SWAT parameter name	Parameter description
1	CH_K2	Hydraulic conductivity of channel
2	CH_N2	Manning's n for main channel
3	SURLAG	Surface runoff lag coefficient
4	SOL_AWC	Soil water capacity
5	CANMX	Maximum canopy water storage
6	ESCO	Soil evaporation coefficient
7	CN_2	Curve number
8	SOL_Z	Soil depth
9	SOL_ALB	Moist soil albedo
10	GWQMN	Threshold level for baseflow in shallow aquifer

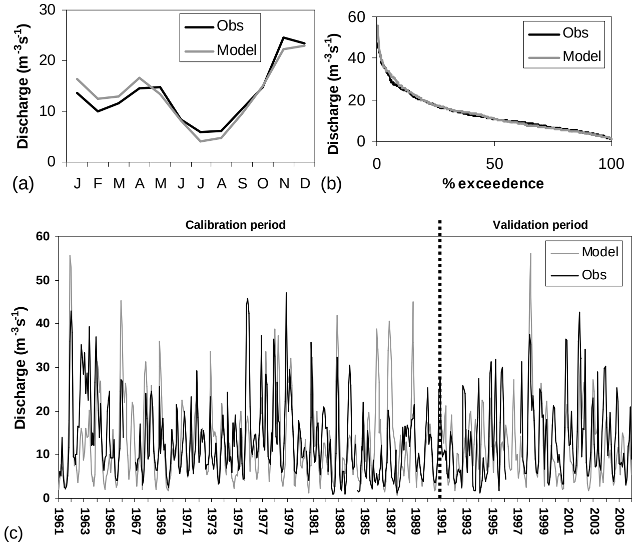

Fig. 2. Comparison of 1961–1990 modelled and observed **(a)** monthly mean flow; **(b)** flow duration curve); and **(c)** 1961–2005 month-to-month sequencing for the River Mitano.

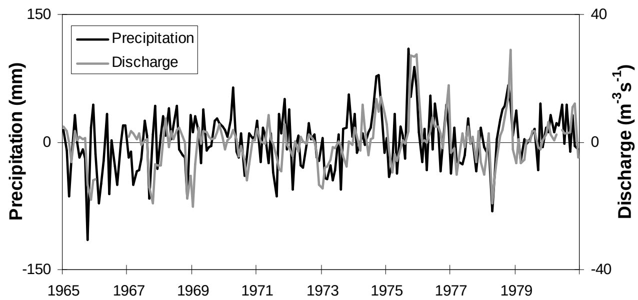

Fig. 3. Comparison of difference in monthly precipitation between CRU TS 3.0 and station-based records with modelled-observed differences in the discharge of the River Mitano for the period 1965–1980.

(station-based) precipitation data were available for five stations within the Mitano Basin for the 1965–1980 period. These five stations are not included in the CRU TS 3.0 data set; the CRU station nearest to the Mitano that is available during the calibration period is located approximately 35 km south of the basin. The mean rainfall across these five stations was compared to the CRU TS 3.0 data used to drive the hydrological model. Differences between the mean station-based rainfall and the mean CRU TS 3.0 rainfall across the four Mitano grid cells correspond well with the differences between observed and modelled river flow (correlation coefficient 0.47; Fig. 3), particularly given consideration of the approximate 2 week lag time between precipitation occurrence and river discharge (Mileham et al., 2008). Importantly, the largest model-observation discrepancies in discharge closely match the largest discrepancies between the CRU and station-based precipitation time series. This correspondence provides an explanation for the strong agreement between mean monthly observed and modelled river discharge but occasional poor month-to-month sequencing. This is because it could be expected that rainfall at a location 35 km away would have a similar long-term climatology to the Mitano River Basin, but that there would be some difference in month-to-month rainfall totals, due to the high spatio-temporal variation in the occurrence of precipitation events.

The role of the disaggregation of monthly data to a daily time-step was also investigated by running the disaggregation procedure multiple times to determine the sensitivity of the hydrological model to the random sequencing of rainfall events within each month. Results suggested that the model is not sensitive to this sequencing, with similar performance of model month-to-month and 30-year monthly mean river flow.

The correspondence between observed and simulated discharge over the 1991–2005 validation period is similar to that of the 1961–1990 calibration period (Fig. 2c). The

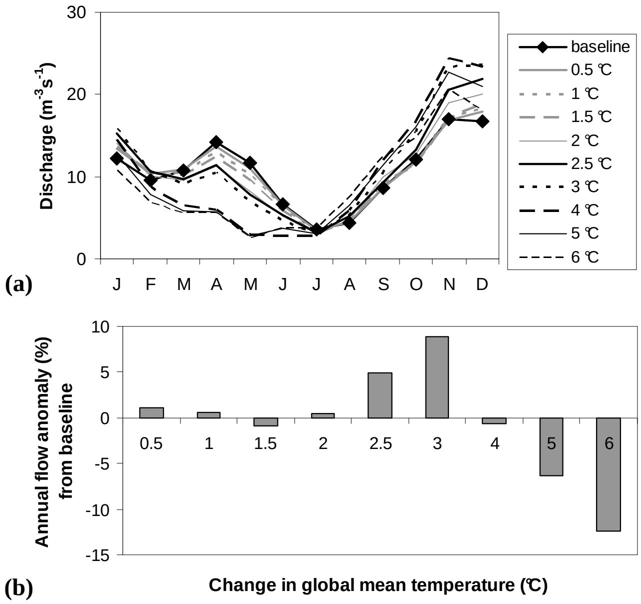

Fig. 4. Climate change signal in **(a)** monthly and **(b)** annual discharge for the River Mitano under HadCM3 prescribed warming scenarios.

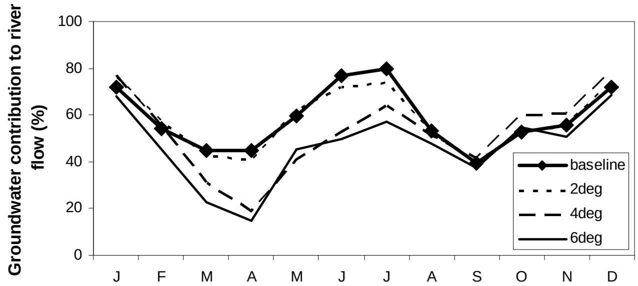

Fig. 5. Changes in the contribution of groundwater flow to the River Mitano under HadCM3 prescribed warming scenarios.

fifteen-year mean monthly modelled runoff agrees relatively well with observed values though performance is slightly poorer than that of the calibration period with an underestimation of river discharge during the September–November second rainy season. This may be due to the closest rainfall station to the Mitano River Basin in the CRU TS 3.0 data set becoming unavailable from 1996 onwards, with the new nearest available rainfall station approximately 115 km from the basin. Similar issues of poor month-to-month sequencing again occur in the validation period, although the Nash-Sutcliffe value of 0.13 is slightly higher than that of the calibration period.

It can be summarised that the model appears to capture successfully the underlying hydrology of the River Mitano, as evidenced by the model long-term monthly mean discharge, flow duration curve, and results from the baseflow separation analysis. However, the model is much less reliable in terms of month-to-month sequencing. The latter may be due to the model being run with gridded rainfall data of questionable accuracy over the Mitano Basin. The climate change scenario runs will be evaluated within this context.

5 Simulation of climate change scenarios

5.1 Prescribed warming on HadCM3

Prescribed change climate scenarios for the River Mitano catchment show that temperature increases at a near-linear rate between scenarios, with a 6 °C rise in global mean temperature resulting in increases of between 7.2 and 9.5 °C in monthly temperature over the catchment. The largest increases occur from May to July, whereas the smallest take place from September to December. Precipitation also changes at a near-linear rate, with an annual increase of 6.7% from the baseline for the 6 °C scenario. At a monthly resolution, however, both increasing and decreasing linear trends in precipitation occur, most of which are within ±9% of the baseline for the 6 °C scenario: exceptions are March (+13%), May (−46%), June (+19%), July (+54%) and August (+25%). Trends in monthly precipitation totals are mirrored by those in the number of wet days per month.

The impacts of prescribed increases in global mean temperature on the hydrological regime of the River Mitano comprise increases in mean annual river discharge up to the 3 °C scenario, followed by decreases (to a level lower than the baseline) for rises in global mean air temperature of 4 to 6 °C. Substantial changes in intra-annual river discharge are associated with the non-linear response in annual river discharge to increasing global mean air temperature (Fig. 4). For the 0.5–3 °C scenarios, small decreases in river discharge are projected during the first wet season (March–May) whereas large increases in discharge are projected during the second wet season (October–December). From 0.5–2 °C, these seasonal changes in discharge have a negligible influence on mean annual river discharge (<1% change from baseline) but for the 2.5 and 3 °C scenarios, increases in annual river discharge are >8% from baseline. For the 4–6 °C scenarios, projected decreases in March–May river discharge are more substantial, eliminating the March–May seasonal peak so that the River Mitano flow regime shifts from bimodal to unimodal. This shift is associated with projected decreases in annual river discharge of >12% from baseline for the 6 °C scenario.

The SWAT model divides contributions to river flow into three categories: surface (i.e. overland) flow, lateral flow (i.e. quickflow within the upper soil profile), and groundwater flow (i.e. return flow from shallow aquifers). For the Mitano, surface flow is relatively unimportant, contributing approximately 1% of total annual river flow for the baseline period,

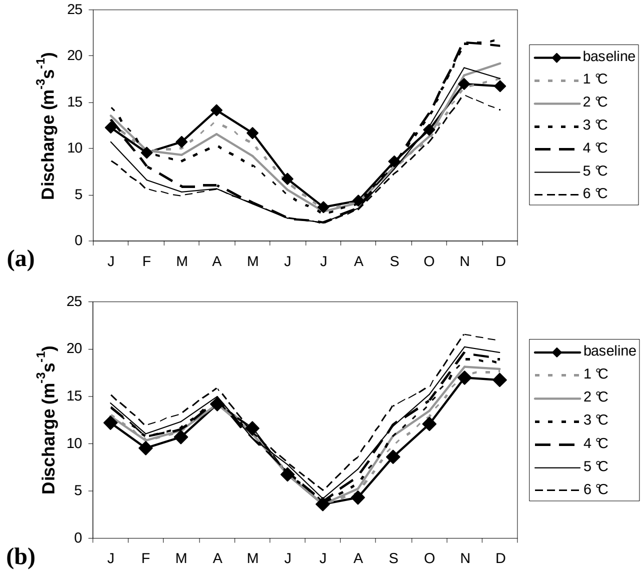

Fig. 6. **(a)** Temperature and **(b)** precipitation only climate change signals in River Mitano discharge under HadCM3 prescribed warming scenarios.

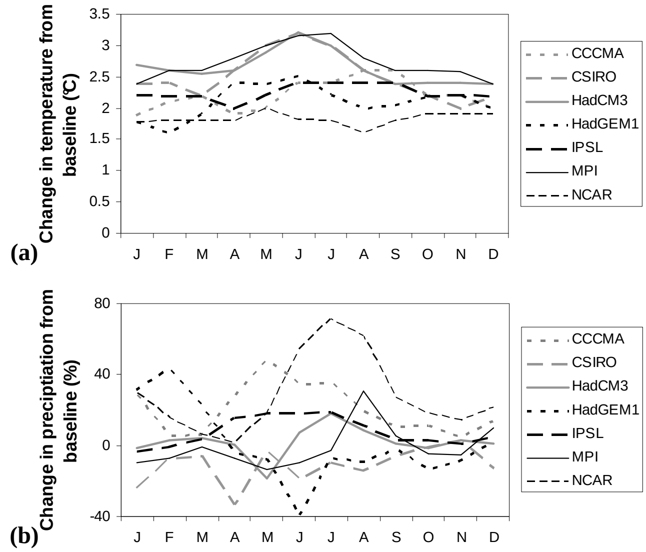

Fig. 7. Comparison of baseline and scenario **(a)** temperature and **(b)** precipitation for the 2 °C prescribed increases in global mean temperature across 7 GCMs.

compared to 38% and 61% for lateral and groundwater flows, respectively. Although surface flow remains unimportant on a monthly basis (i.e. <5% of the total), the relative importance of lateral and groundwater flow varies, with a 55:45 ratio during the first wet season, a 20:80 ratio during the June–July dry season, and a 45:55 ratio during the second wet season (Fig. 5). Whilst annual contributions vary by only small amounts with increasing global mean temperature (for the 6 °C scenario lateral flow increases to 41% whilst groundwater flow decreases to 54%), changes in monthly contributions are more marked (Fig. 5). Changes in monthly contributions occur primarily from February–July, with the groundwater component of river flow progressively decreasing with increasing global mean temperature. Although the absolute magnitude of lateral flows during this time of year remain similar, reductions in the groundwater component increase the importance of lateral flow to the extent that it comprises between 70–85% of total runoff in March–May under the 6 °C scenario. As such, these results suggest that decreasing groundwater flow is the primary cause of reduced early season river flow in the 4–6 °C scenarios.

Analysis of the relative importance of changing precipitation versus temperature (and hence evapotranspiration) for driving trends in Mitano river flow was performed by running the SWAT model with scenario temperature and holding precipitation constant, and vice versa (Fig. 6). Although precipitation decreases at the end of the first wet season (i.e. May) in the climate change scenarios, projected reductions in early season river flow are shown to result primarily from increasing temperature (and so evapotranspiration). This finding is in contrast to the increases in late-season river flow, which are primarily linked to rising precipitation. Combined with the changing lateral and groundwater contributions to river flow, these results suggest that increasing evapotranspiration (rather than reduced precipitation) limits the amount of water penetrating the soil profile and replenishing the shallow groundwater store during the first wet season. This change leads to the reduced contribution of groundwater to river flow and the overall decrease in discharge.

5.2 2 °C warming scenario across seven GCMs

The 2 °C prescribed warming scenarios from seven different GCMs result in contrasting changes in climate over the River Mitano catchment. Although all GCMs show a rise in temperature of close to 2 °C in all months, the rise in air temperature on an annual basis ranges from approximately 1.8 °C for the NCAR GCM to 2.7 °C for the MPI GCM (Fig. 7a). This apparent contradiction can be explained by the fact that each GCM has a different pattern of global temperature change, meaning that while the global average temperature change is the same between GCMs, regional patterns are not. Differences between GCMs are even more apparent for precipitation. Projected change in mean annual precipitation over the Mitano basin varies from a 23% increase (NCAR) to a 23% decrease (CSIRO). On a monthly basis, some GCMs project greater or lower precipitation in all months whereas others project a mixture of increasing and decreasing precipitation over the course of the year (Fig. 7b).

Simulated discharge under the 2 °C scenario shows substantial disparities between GCMs, with little consistency in

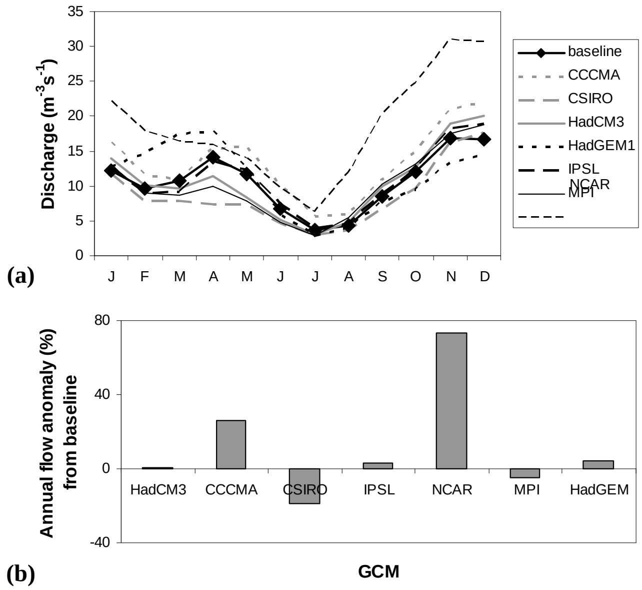

Fig. 8. Climate change signal in **(a)** monthly and **(b)** annual Mitano discharge under the 2 °C prescribed warming scenario across 7 GCMs.

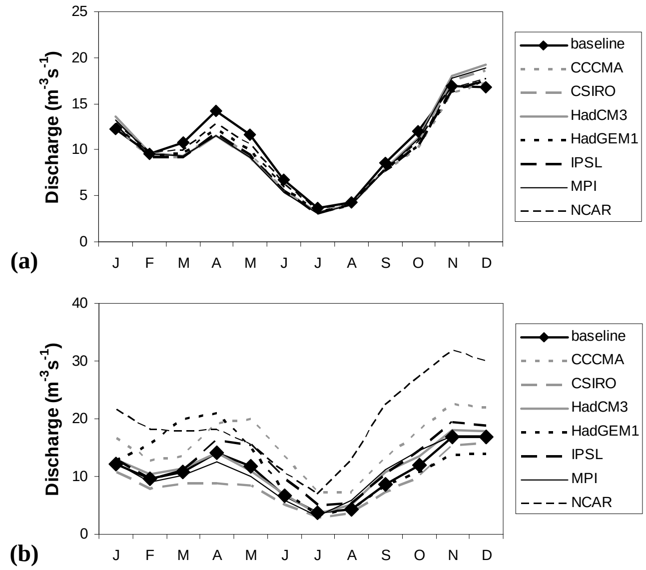

Fig. 9. **(a)** Temperature and **(b)** precipitation only climate change signals in River Mitano discharge for 2 °C prescribed warming scenarios across 7 GCMs.

either magnitude or direction of change on either a seasonal or annual basis (Fig. 8). For example, the CSIRO GCM projections result in reductions in river discharge at 2 °C that are greater than those from the HadCM3 GCM at 6 °C. In contrast, the NCAR GCM projections result in increased river discharge in all months that in some situations is double that of the baseline. There is, however, no particular clustering of GCMs. The results show that the NCAR and CSIRO projections lead to the greatest increase and decrease, respectively, in river discharge (although it is not technically correct to label these two GCMs as outliers, because the seven GCMs used here are drawn from a larger population of 23 CMIP-3 GCMs).

Resolution of the climate change signal for each of the GCMs derived from changing temperature and precipitation independently reveals consistency in the 2 °C temperature signal between GCMs (Fig. 9a). This signal results in a slight decrease in March–May river discharge. It is clear from the precipitation-only climate change signal that changes in precipitation are the dominant driver of changing river flow for the 2 °C scenario (Fig. 9b). It is also clear that differences in the precipitation climate change signal between GCMs are far greater than those in the temperature climate change signal, with different GCMs giving rise to both positive and negative changes in discharge in all months.

5.3 Parameterisation uncertainty

In the absence of quantitative estimates of uncertainty in model parameterisation from an autocalibration routine, a manual assessment was undertaken to provide an indication of model parameterisation uncertainty. This analysis was undertaken by manually varying the ten most sensitive parameters in the hydrological model (Table 1). Each parameter was varied by ±10% and the model re-run with baseline climate data. The model was then run using the same perturbed parameter set with scenario climate data: HadCM3 2 °C prescribed warming was used as an exemplar scenario. The difference between the reference and perturbed runs was then compared for baseline and scenario situations. If the difference between the reference and perturbed runs was greater for the scenario than the baseline, the model parameterisation was considered as a possible cause for additional uncertainty in climate change projections (and vice versa).

Results of the uncertainty analysis (Fig. 10) indicate that model parameterisation generally imparts little uncertainty to the climate change projections compared to that associated with GCM structure. Differences in the reference-perturbed percent anomaly between baseline and scenario runs are below 5%, with the most sensitive parameters relating to evapotranspiration and soil water capacity. These results only pertain to HadCM3, however, with the possibility existing that greater parameter uncertainty might be present for more extreme climate scenarios (e.g. NCAR or CSIRO 2 °C projections).

6 Discussion

In this paper we assess the projected impacts of climate change on river discharge and contributions to flow (runoff,

Table 2. Percent change in monthly PET from baseline to HadCM3 2 °C scenario.

	Hargreaves	Penman-Monteith	Priestley-Taylor
Mean monthly change	6.7	6.4	9.6
Max monthly change	9.3	14.9	17.0
Min monthly change	4.7	1.5	6.0

baseflow) in a humid tropical catchment in the Upper Nile Basin. Importantly, this assessment includes evaluation of the range of uncertainty in this assessment due to climate sensitivity, choice of GCM, and hydrological model parameterisation. The primary outcome of these results is the overwhelming dependence upon the GCM used for climate change projections, in agreement with the findings of previous studies (e.g. Chiew et al., 2009; Prudhomme and Davies, 2009). Furthermore, we show that single-GCM evaluations of climate change impacts are likely to be wholly inadequate and potentially misleading as a basis for the analysis of climate change impacts on freshwater resources.

Despite the substantial uncertainty associated with choice of GCM, a number of additional important issues are highlighted by our results from the River Mitano catchment. For example, river discharge, at least on an annual basis, may not respond linearly to increases in global mean air temperature (i.e. a combination of linear changes in monthly river flow can give rise to a non-linear annual response). This finding emphasises three key issues: firstly, the potential for thresholds of climate change associated with impacts on water resources (i.e. 3 °C here), secondly the important and original findings that can be obtained from the pattern-scaling approach employed herein, and thirdly, the importance of investigating changing water resources on an intra-annual basis.

A further important finding is that whilst there is great uncertainty in the precipitation climate change signal between GCMs, the temperature signal is very consistent (as documented extensively elsewhere; e.g. Meehl et al., 2007). This is despite East Africa being identified as a region where there is relatively good agreement between precipitation projections (Christiansen et al., 2007). Given the consistent temperature climate change signal, relatively high confidence can be placed in the projections of increased evapotranspiration in the River Mitano catchment during the first wet season as this result is consistent across all GCMs and scenarios examined (but with the caveat that the influence of windspeed, humidity and net radiation on evapotranspiration were not explicitly modelled). This is of interest because the results from simulations of different HadCM3 warming scenarios demonstrate that increased evapotranspiration will lead to reductions and changes in the seasonality of groundwater contribution to river discharge. Some confidence can therefore be placed in the assertion that irrespective of the magnitude or direction of future changes in precipitation, the proportion of precipitation that contributes to Mitano river discharge via groundwater flow will decrease as a result of increasing temperature. Furthermore, such a change would likely result in an altered seasonal distribution of river flow, affecting local and regional groundwater resources, and consequently agricultural and domestic water availability. However, the occurrence of such impacts will depend on the scale of the temperature increase (which is relatively high for HadCM3) and the direction and magnitude of precipitation changes.

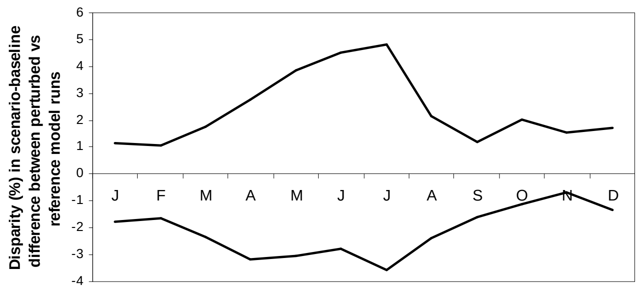

Fig. 10. Model parameter uncertainty in River Mitano discharge under the HadCM3 2 °C scenario: maximum extent of the disparity between the scenario-baseline difference in the perturbed parameter versus reference model runs.

The projected changes in groundwater contributions to river flow and subsequent shift in annual regime (under HadCM3 scenarios) demonstrate the importance of understanding the interaction between changing temperature (and thus evapotranspiration) and precipitation for river flow in areas where there is a seasonal switch between P-PET deficit and surplus. Our ability to understand this balance is, however, constrained by the substantial uncertainty regarding estimation of both baseline and scenario PET. Although the relative advantages and disadvantages of many different methods of estimating historical PET from meteorological data have been widely considered (e.g. Vorosmarty et al., 1998; Lu et al., 2005), relatively little attention has been given to how representative different PET methods remain when transferred from baseline to scenario climatology. Indeed, recent work (Kingston et al., 2009) shows that different methods of estimating PET can produce markedly different climate change signals. This tendency can be demonstrated for the Mitano Basin by a brief comparison of baseline: scenario PET ratios for the commonly used Hargreaves, Penman-Monteith and Priestley-Taylor methods of calculating PET (Table 2). Penman-Monteith PET was calculated following the guidelines in Allen et al. (1998), and Priestley-Taylor according to Lu et al. (2005). Substantial differences are found in the PET climate change signal between the three methods, with this difference (for the HadCM3 2 °C scenario) most apparent during May, where the increase in PET ranges from 9–17% between methods.

Whilst further uncertainty in the climate change signal for the Mitano Basin is likely to arise from the parameterisation and structure of the hydrological model used, the findings presented here indicate that such uncertainty is much smaller than that associated with choice of GCM, climate sensitivity, and PET algorithm. Despite this, it should be noted that only a limited and subjective assessment of model parameter uncertainty has been conducted, so these findings should be taken as indicative rather than definitive. Future work will aim to treat model uncertainty in a more objective and probabilistic manner by using, for example, autocalibration routines.

7 Conclusions

Investigation of uncertainty in future river discharge of the River Mitano Basin based on results from different GCMs, climate sensitivities and hydrological model parameter specification reveals the overwhelming dependency of hydrological projections on the GCM used. This dependence stems primarily from projected differences in GCM scenario precipitation rather than temperature. Within this overriding constraint, however, a number of interesting results have emerged. These include: (1) non-linear responses in annual discharge to increasing global temperature; (2) the importance of the precipitation–evaporation balance for determining the direction of changes in river discharge, and (3) intra-annual change in river flow and groundwater discharges (baseflow) in response to climate forcing.

The above findings represent an important basis for interpretation of previous climate change-hydrology studies and for designing future studies of possible climate change impacts on river flow. However, the utility of the results with respect to future changes in Mitano river discharge remain limited by the large uncertainty between GCMs. This is a key research gap, given the likely changes to the groundwater regime of the Mitano (and wider region), and the importance of groundwater as a water resource. As such, there is an urgent requirement for research to develop from the current approach of equal probability ratings assigned within an ensemble of opportunity of GCMs. Alternative approaches include development of reliability ratings for GCMs, and more widespread generation of probabilistic climate change scenarios and GCM output–impact model couplings (e.g. Manning et al., 2009). However, the challenge of objectively undertaking such tasks remains difficult.

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