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Impacts of environmental change on water resources in the Mt. Kenya region

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Summary Water resources are becoming increasingly scarce in the Mt. Kenya region. Land use and climate change may pose additional challenges to water management in the future. In order to assess the impacts of environmental change, the NRM3 Streamflow Model, a simple, semi-distributed, grid-based water balance model, is evaluated as a tool for discharge prediction in six meso-scale catchments on the western slopes of Mt. Kenya, and used to analyse the impact of land use and climate change scenarios on water resources.

The calibration and validation results show an acceptable performance of the NRM3 Streamflow Model in simulating discharge. Input data represent the main limitation. Rainfall patterns in the mountainous catchments are very heterogeneous and difficult to capture with the monitoring network. River water abstractions make up 80–100% of naturalized dry season discharge, but amounts can only be approximately estimated.

Under the scenarios of land use and climate change examined, the total amount as well as the variability of discharge will increase: Conversion of the forest area to crop- or grassland will increase annual runoff by 11% or 59%, respectively, by mainly increasing flood flows and, under cropland, slightly reducing low flows. Climate change as projected by the IPCC Task Group on Scenarios for Impact Assessment [IPCC-TCGIA, 1999. Guidelines in the use of data for climate impact and adaptation assessment. Version 1. Prepared by Carter, T.R., Hulme, M.., Lal, M., Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment.] will result in an increase of annual runoff by 26%, with a severe increase in flood flows, and a reduction of the lowest flows to about a tenth of the current value.

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Introduction

Mt. Kenya is the water tower of the Ewaso Ng'iro Basin: Its slopes, which receive high rainfall, are the source of perennial rivers which, in the dry season, are the only source of surface freshwater in the semi-arid Laikipia plateau to the North-West of the mountain, and the arid lowlands of the lower Ewaso Ng'iro Basin. Population growth (a ten-fold increase from 1960 to 2000) and the intensification of irrigated agriculture in the footzone and along the rivers in the plateau have dramatically raised water demand in the past decades (Liniger et al., 2005; Wiesmann, 1998). As a result, the Ewaso Ng'iro and its tributaries fall dry with increasing frequency. This leads to conflicts between upstream and downstream water users (Liniger et al., 1998a; Gichuki et al., 1998). The situation in the Mt. Kenya region is symptomatic of semi-arid areas in developing countries, where rapid demographic and economic change leads to increasing water demand (UNESCO-WWAP, 2003).

There are several reasons for the reduced water availability in dry seasons. The most evident is the growing number of water abstractions for irrigation, livestock and domestic purposes (Aeschbacher et al., 2005). Rainfall exhibits no decreasing trend in the past two decades and can therefore not serve as an explanation for decreasing river flows (Liniger et al., 2005). However, hydrological monitoring at several scales and sites has revealed that land cover has a key impact on water resources. Thus there is a need to know the consequences of ongoing land use changes (McMillan and Liniger, 2005). Furthermore, projected global climate change, according to model predictions, will significantly affect the African continent, in particular arid and semi-arid areas (Hulme et al., 2001). This will have a considerable additional impact on water resources, which should be taken into account by water management plans.

Hydrological models provide a framework to investigate the relationships between climate, human activities and water resources, and have been applied in many studies in order to assess the effects of land use and climate change on runoff (examples: Bhaduri et al., 2000; Chiew and McMahon, 2002; Legesse et al., 2003; Nandakumar and Mein, 1997; Sharma et al., 2000). Moreover, models assemble knowledge on processes in a package and show if the theory is in conflict with observations, thus giving a feedback of how well processes are understood (Beven, 2000). However, studies in Tropical Africa often face the problem that many hydrological models have quite extensive input data requirements, while available data are scarce (Legesse et al., 2003). This increases insecurities in the results. Therefore, there is a need for assessments using models whose input data requirements match the availability of data.

This paper presents the evaluation and use of a hydrological model that has been designed to work with data available in the study area and comparable settings in Tropical Africa, in order to assess the impacts of environmental change. The NRM3 Streamflow Model (McMillan and Liniger, 2005; Thomas, 1993) is a simple, semi-distributed, grid-based water balance model working on a daily time-step. It requires only rainfall and pan evaporation time series inputs, along with GIS land cover and soil information; four recession parameters need to be adjusted in calibration. The NRM3 Streamflow Model was developed within the framework of NRM3 (Natural Resources Monitoring, Modelling and Management), a collaborative programme between the Universities of Berne and Nairobi. An initial calibration and evaluation of the model was carried out in relatively homogeneous small catchments of ephemeral streams in the Mt. Kenya area (McMillan and Liniger, 2005).

The objectives of this study are (1) to assess the performance of the NRM3 Streamflow Model as a tool for discharge prediction in meso-scale perennial river catchments of the Mt. Kenya area and (2) to assess and quantify the likely impacts of land use and climate change scenarios on water resources.

The study area

The study area is located within the Upper Ewaso Ng'iro basin, which drains the semi-arid Laikipia Plateau as well as the more humid slopes of Mt. Kenya and the Nyandarua Range. The study catchments of the perennial streams Naro Moru (four nested catchments, with river gauging stations A3–A6, and respective catchment areas of 24–173 km^2), Burguret (river gauging station A8, catchment area 99 km^2), and Nanyuki (river gauging station A9, catchment area 69 km^2), are located on the equator on the western slopes of Mt. Kenya, crossing five ecological zones from the peak to the plateau (Fig. 1): The afro-alpine zone (above 4000 m a.s.l.), the moorland zone (3200–4000 m), the forest zone (2300–3200 m), the footzone (2000–2300 m) and the savannah zone (below 2000 m) (Gichuki et al., 1998). The forest zone consists of dense, natural tropical montane forest with patches of bamboo, while in the savannah zone the dominant land cover is grass, in some places with 20–50% tree canopy. The footzone is naturally the transition zone between the Mt. Kenya forest and the savannah. Today it is mostly under cultivation; in the upper footzone some areas have been afforested with plantation forest (Liniger et al., 1998a).

The area experiences two rainy seasons a year when the Intertropical Convergence Zone crosses the equator: The Long Rains last from around March to June, and the Short Rains from September to December. However, the rainy seasons vary from year to year in their duration and rainfall totals. Average annual precipitation increases from 600 to 700 mm in the savannah to 1600 mm in the upper forest and lower moorland zone and drops to 800 mm in the summit region (Sturm, 2002; Gichuki et al., 1998). Potential evapotranspiration drops from around 1700 mm in the savannah zone to less than 500 mm in the summit region, making all areas below the forest zone experience a rainfall-evaporation deficit. As a consequence, the forest and moorland zones provide most of the discharge of the rivers in the dry periods (Liniger et al., 1998; Decurtins, 1992).

Cultivation has traditionally been most intensive in the footzone, but the cultivated area has increased in the past decades. Its expansion upwards into the forest zone has been slowed down by a national policy of settling landless squatters outside the gazetted forest areas, and by more

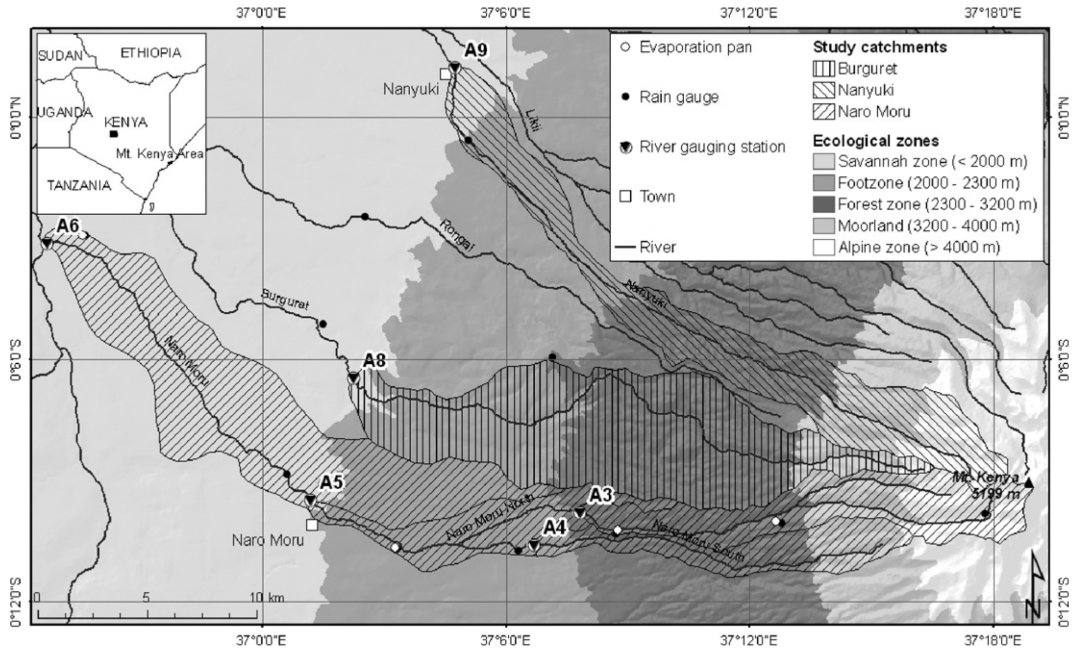

Figure 1 The study area on the Western slopes of Mt. Kenya (Source: NRM3 database).

effective measures of control. However, agriculture continues to expand upstream into the forest, as well as downstream along the rivers into increasingly dry areas, where rain-fed cultivation is not possible. As a result, forest and savannah vegetation is increasingly being replaced by cultivated areas (Niederer, 2000). At the same time, due to the drier climate in the lower footzone and savannah zone, the growing areas under agriculture require increasing amounts of water for irrigation, contributing to water scarcity and associated conflicts.

Methods

Field assessment of river water abstractions and groundwater influences

As a prerequisite to the hydrological modelling, the following tasks were carried out in the field in July—September 2002 in order to minimize sources of insecurities in model calibration:

- In order to be able to compare modelled to observed discharge in model calibration and validation, a ''naturalized'' flow series had to be obtained by adding the abstracted water amounts back to the measured actual discharge values. The term ''naturalized'' flow is used in different ways in hydrological literature: Some authors define ''naturalized'' flow as accounting for the effect of human-induced changes on the water course itself, like water offtakes, return flows, and impoundments (Jones et al., 2006; Wurbs, 2006). Others include accounting for the effects of human-induced land use change in the catchment in the definition (e.g. Smakthin, 1999). In this paper, the former definition is used, with ''naturalized flow'' referring to river flow without direct influence on the water course. River water abstractions in the Naro Moru catchment were assessed based on a campaign during which all abstraction points existing in 2002 were visited. The campaign resulted in a series of spot gaugings and volumetric measurements, data on the morphology of the furrows, and information obtained in interviews. Similar campaigns had been carried out in 1992 and 1997. Former campaigns included time series flume measurements of the larger furrow abstractions, which allowed a temporal pattern for these abstraction points to be approximated (Gathenya, 1992). Merging the results of all campaigns produced a naturalized flow series (Aeschbacher et al., 2005) that could be used in model calibration and validation.
- In order to verify the assumption that there is no significant groundwater discharge to streamflow from deep aquifers, but only from shallow, local aquifers, measurements of discharge, electric conductivity and temperature were carried out in regular intervals along the perennial rivers and on springs within the study catchments. For comparison, electric conductivity and temperature measurements were also taken at boreholes tapping the deep aquifers in the Laikipia Plateau. The stream water originating from Mt. Kenya has a very low electric conductivity (below 50 μS/cm) and quite low temperatures (below 15 °C) when it reaches the lower end of the forest zone. Water from Laikipia boreholes, by contrast, displays electric conductivity values of over 300 μS/cm and temperatures well above 20 °C. The results were plotted along the length of the streams (Fig. 3). Since the measurements were taken at a period of extremely low flow, significant inflows of deep aquifer groundwater to the streams would result in a sharp increase in the values of the measured parameters, distinguishable from the slight and steady increases that are expected without water inflow from deep aquifers.

Application of the NRM3 Streamflow Model

The NRM3 Streamflow Model (McMillan and Liniger, 2005, first version developed by Thomas, 1993) is a conceptual, semi-distributed, three-layer water balance model that runs on a daily time-step. It is based on the concept of the Hydrological Response Units (HRUs), for each of which the water balance is calculated (Fig. 2). The concept of the HRU is capable of preserving the spatial heterogeneity of the drainage area; the crucial assumption is that the variation of hydrologic process dynamics within one HRU must be small compared with the variation between different HRUs (Flügel, 1995). In grid-based models, the HRUs are basically equivalent to the grid cells; in order to minimize the computational effort, cells with the same characteristics are usually processed as one HRU.

Input data requirements of the NRM3 Streamflow Model are minimal and correspond to the data availability in the study area. Precipitation and pan evaporation are required as time-series input data. Additionally, for each HRU, land cover parameters (daily interception rate, Soil Conservation Service (SCS) curve number, critical soil depth, root depth, crop coefficient) and soil parameters (depth, available water capacity and drainage class) are required. These parameters are obtainable from catchment measurements (McMillan and Liniger, 2005). The only free parameters that are optimized in calibration (once curve numbers for each land cover type have been determined) are four groundwater parameters for the simple linear groundwater recession function.

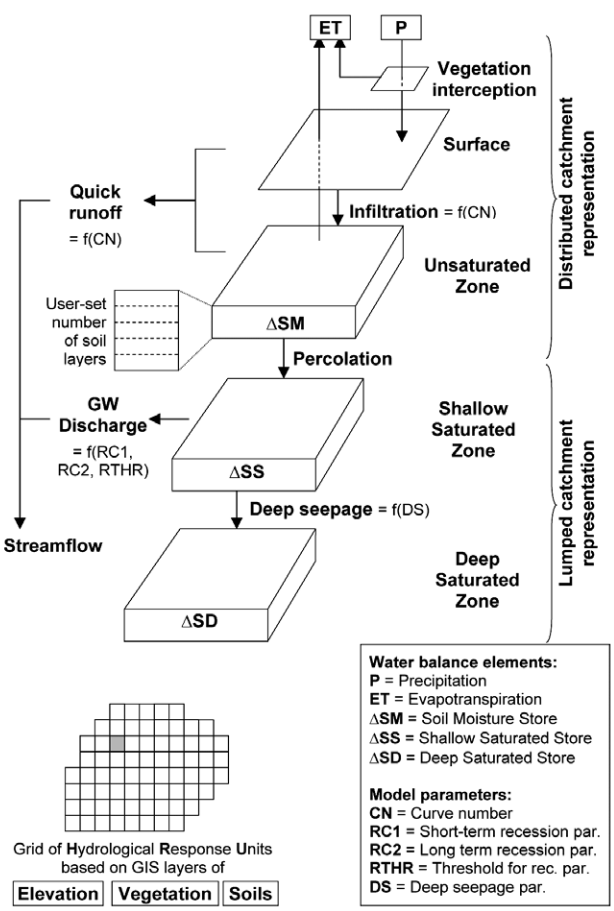

Figure 2 The NRM3 Streamflow Model structure.

In the present model version, the Hydrological Response Units are equivalent to the grid cells of the input GIS layers, for which the user can choose the spatial resolution. This makes the model easy to use in combination with a GIS.

For the estimation of areal precipitation, measured rainfall values from rain gauges are interpolated to each grid cell using Inverse Distance Weighting. Areal evapotranspiration is determined based on Reference Evapotranspiration (ET_0). ET_0 is defined as the evapotranspiration rate from a hypothetical extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water supply (Allen et al., 1998). In the NRM3 Streamflow Model, ET_0 is estimated from measured pan evaporation adjusted by a pan coefficient. Pan evaporation may not be the most reliable indicator, but can give a reasonable reflection of potential evapotranspiration (Allen et al., 1998; Morton, 1983). In the Mt. Kenya area, it has the advantage that it is available from many locations, whereas other available climatic data are spatially too scarce to represent the heterogeneous conditions. Pan coefficients for the NRM3 pans were determined based on the slope of regressions between pan evaporation and ET_0 calculated with the Penman—Monteith equation according to Allen et al. (1998), at locations where climatic parameters were available, and on considerations of the pans' location and surroundings. For each grid cell in a catchment, the NRM3 Streamflow Model selects the nearest evaporation pan to estimate ET_0. Actual evapotranspiration for each cell (ET_k) is determined based on ET_0, the crop coefficient for the respective land cover type of the cell (K_C), and the soil moisture at the critical soil depth on any given day (SMF):

$$ET_k = ET_0 * K_C * SMF \quad (1)$$

The separation of incoming precipitation into quickflow (fast runoff) and infiltration is based on the US Soil Conservation Service curve number method (USDA SCS, 1985). The origins of this method can be traced to empirical rainfall-runoff-analysis in the 1940s in many small US-Midwestern catchments from which the hydrologic soil group, land use class and surface condition were known. There are various interpretations of this method in relation to runoff generation processes, but its origins indicate that it ''incorporates some empirical knowledge of fast runoff generation, by whatever process, at the small catchment scale'' (Beven, 2000). Its application in a number of hydrological models (examples: AGNPS, Young et al., 1995; SWAT, Arnold et al., 1998; SWRRB, Williams, 1995) is based on its simplicity and the fact that it repeatedly fits the selected data well.

In the NRM3 Streamflow Model, base curve numbers for each HRU are determined based on land cover and soil properties. The model is thus land use sensitive, which is a key prerequisite to modelling the impacts of land use changes. Initial values for the curve numbers were taken from the USDA-SCS standard tables (USDA SCS, 1985). An additional source of information were tables of curve numbers as transferred to the South African land use classification for use with the ACRU model (Schmidt and Schulze, 1987). For few land cover types, these initial curve numbers were altered in the course of the initial calibration of the model in small, relatively homogeneous catchments in the Mt. Kenya area, as well as based on results from long-term runoff plots within the region. Base curve numbers for composite land cover types were determined using an averaging procedure taking into account the relative influence of cover components. For example, where a tree canopy covers more than 50% of the area, it was considered to have a greater impact on runoff generation than the underlying cover and thus the average curve number has a bias towards the canopy, with a weight of 70% assigned to the canopy and 30% to the underlying cover. Where the canopy is reduced to 20–50% of the area, then the underlying cover was considered to have the greater influence on runoff generation and thus the curve number was derived by assuming a 30% influence from the canopy and a 70% influence from the underlying cover. With a reduction in tree canopy to 2–20%, its influence on the curve number was reduced to 10% with the remaining 90% attributable to the underlying cover (Thomas, 1993; McMillan and Liniger, 2005).

Since infiltration properties of soils vary under different moisture conditions, the base curve numbers are adjusted within the model to short-term antecedent soil moisture conditions. The lowest (CNK1) and the highest possible curve number (CNK3) are calculated from the base curve number (CNK2) according to Ponce and Hawkins (1996):

$$\mathrm{CNK1} = \mathrm{CNK2}/(2.281 - (0.01821 - \mathrm{CNK2})) \tag{2}$$

$$\mathrm{CNK3} = \mathrm{CNK2}(0.427 + (0.00573 - \mathrm{CNK2})) \tag{3}$$

A linear relation between CNK1 and CNK3 is then assumed based on the actual soil moisture (TOTWAT) and maximum soil moisture (MAXWAT):

$$\mathrm{CNK} = (\mathrm{CNK3} - \mathrm{CNK1}) * (\mathrm{TOTWAT}/\mathrm{MAXWAT}) + \mathrm{CNK1} \tag{4}$$

So the final curve number is lowest when the actual soil moisture corresponds to the maximum possible. Most water thus infiltrates into the soil when it is most dried out.

The soil water balance is calculated for each HRU separately down to the level of the unsaturated zone. The soil has a user-set number of soil layers, each of which fills to field capacity before water continues to the next layer; in this study, five layers were used. The shallow saturated zone and the deep saturated store are represented in a lumped manner, i.e. averaged over the whole catchment. Channel routing is not performed within the NRM3 Streamflow Model, as for small catchments all runoff is assumed to reach the catchment outlet within a day.

In this study, the NRM3 Streamflow Model was calibrated and validated in six perennial, meso-scale study catchments with areas of 20–175 km^2 (Fig. 1). The years 1987–1991 were selected for model calibration and the years 1992–1996 for validation. Additionally, calibration and validation period were switched and the model was also calibrated using the 1992–1996 period data and validated using the 1987–1991 period data, in order to assess the robustness of results. The data used in calibration and validation are described in the section ''Data used in the study''.

Model performance was evaluated using different techniques: (1) visual inspection of daily, decadal and monthly simulated and observed hydrographs, (2) quantification of overall model performance by common performance measures, i.e. r^2 = coefficient of determination, E_2 = Nash and Sutcliffe Efficiency Score (Nash and Sutcliffe, 1970) at different time scales, (3) evaluation of differences between observed and simulated flows, and (4) evaluation of low flow measures like the LMQ30 (mean of the 30 consecutive days with the lowest flows in a year). The strategy for adjusting the values of the four free model parameters during calibration involved first adjusting the deep seepage parameter if total discharge was overestimated, and then adjusting the recession parameters by trial and error until the highest possible E_2 score was reached. Special attention was paid to the simulation of the recession curve after floods, as well as low flow periods. In cases where equal or similar E_2 values were reached using different combinations of parameter values, the combination producing the best visual agreement between observed and simulated recession curves and the lowest difference between observed and simulated LMQ30 values was chosen as the final parameter set. The model's sensitivity to differences in parameter values and to the temporal and spatial resolution of inputs was also explored.

Assessment of land use and climate change impacts

Four land use and two climate change scenarios were analysed for the Naro Moru catchment. The 15-year period 19870–2001 was used as the baseline period, from which meteorological data were used to simulate the ''base case'', a run under current conditions that the scenarios could be compared to.

The four land use change scenarios include three scenarios representing possible outcomes of land use change trends:

(1) Conversion of savannah and forest to small-scale cropland (less than 2% tree cover).
(2) Conversion of savannah and forest to small-scale cropland with 2–20% tree cover.
(3) Conversion of savannah and forest to bare grassland (grassland with less than 2% tree cover and 20–50% bare ground).

The mentioned land use changes take effect only up to 3200 m a.s.l., since the boundary of Mt. Kenya National Park roughly follows this contour, and it is therefore assumed that land cover above this altitude will remain natural. It is recognized that these land use scenarios represent the upper end of the envelope of change.

The fourth land use change scenario represents approximate ''natural'' conditions:

(4) Grassland with 2–20% trees below 2000 m a.s.l., dense natural forest and bamboo from 2000 to 3200 m a.s.l., current land use above 3200 m a.s.l.

This implies that approximately 9% of Naro Moru A5 catchment currently under agricultural use is reconverted to natural land cover types – mostly forest, since most of the A5 catchment is located above 2000 m.

The land cover distribution in the Naro Moru A5 catchment under base case and scenario conditions is shown in Table 1.

For the climate change scenarios, the guidelines of the IPCC Task Group on Scenarios for Impact Assessment

Table 1 Distribution of land cover classes expressed in % of the Naro Moru A5 catchment area (87 km^2) under base case and scenario conditions

Land cover class	Base case				
	Scenarios 5 & 6	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Natural forest	41.1	11.7	11.7	11.7	59.4
Plantation forest	3.2	0.0	0.0	0.0	0.0
Bamboo forest	8.0	0.4	0.4	0.4	8.4
Grassland (2—50% tree cover)	27.1	18.4	18.4	18.4	22.3
Grassland (<2% tree cover)	5.4	2.6	2.6	2.6	4.2
Bare Grassland (<50% bare ground)	0.0	0.0	0.0	61.1	0.0
Cropland (up to 2% tree cover)	0.8	61.1	0.0	0.0	0.0
Cropland (2—20% tree cover)	8.6	0.0	61.1	0.0	0.0
Rock (<50% vegetation)	5.0	5.0	5.0	5.0	5.0
Ice	0.7	0.7	0.7	0.7	0.7
Urban	0.1	0.1	0.1	0.1	0.0

Scenarios 1—4 for land use change and scenarios 5—6 for climate change.

(IPCC-TCGIA, 1999) were followed. In order to produce meteorological time series for the scenarios, projections of the General Circulation Model (GCM) ECHAM4 for the years 2040—2069 were used to modify the daily meteorological data from the study area. This was achieved by multiplying the daily data values from the baseline period 1987—2001 with the average monthly change values between the baseline period and the projections for the years 2040—2069. Using GCM outputs for climate change impact assessments helps produce more realistic scenarios than assuming fixed increases or decreases in the values of climatic parameters as done in previous studies (Legesse et al., 2003). While the annual average value of parameters like rainfall or evaporation may change by a certain percentage under a given scenario, the change of the same parameters in some months may amount to a multiple of the average annual change, thereby also affecting water resources to a different extent. Therefore, using monthly GCM predictions will lead to results which indicate the range of possible changes more realistically than if annual average changes are used.

In order to downscale the GCM outputs to the study area, the outputs from the four nearest grid boxes were interpolated to the study area using Inverse Distance Interpolation. This was the most accurate possible method of downscaling in the absence of long-term observational data or high-resolution weather models in the region. A comparison of the monthly ECHAM4 outputs for the baseline period, interpolated to the study area, with measured precipitation data from the study area, reveals a high correlation with an r^2 value of 0.98 (Notter, 2003).

The scenarios examined here are based on the SRES emissions scenarios A2 and B2 (IPCC, 2000):

(5) The A2 scenario assumes high global population growth with moderate economic growth and little technological innovation as basis on which greenhouse gas emissions are modelled.
(6) The B2 scenario assumes a world that puts emphasis on local solutions to sustainability; accordingly, greenhouse gas emissions are on average lower than in the A2 scenario.

Data used in the study

Fig. 1 shows the study catchments as well as the positions of the river gauging stations, the rainfall gauges and evaporation pans. Precipitation and evaporation data from manual rain gauges and evaporation pans operated by NRM3 as well as by local farmers and the Kenyan government were used as meteorological time-series inputs. All data series were quality-controlled and checked for plausibility at the NRM3 office. However, missing periods occur in the rainfall data from some of the gauges not operated by NRM3, due to breakdown of equipment and financial constraints in its replacement.

In Naro Moru catchment, the instrument coverage is relatively dense, with 5—7 rain gauges (depending on the time period) at elevations between 1840 and 4200 m a.s.l., four of which are operated by NRM3. Four evaporation pans were used at elevations of 1840 m, 2070 m, 2420 m, and 3050 m a.s.l., in locations where microclimatic conditions can be assumed to be representative of the surrounding area. The altitudinal variance in meteorological conditions can thus be assumed to be satisfactorily represented. In the other catchments, instrument coverage is poorer — one rain gauge exists in Burguret and none in Nanyuki catchment; however, several rain gauges and evaporation pans are located close to their catchment boundaries.

River discharge data were obtained using automatic water-level recorders installed by NRM3 and operated jointly by NRM3 and the Kenyan Ministry of Water Development (MoWD). The rating equations for the calibration and validation periods at most river gauging stations are based on gaugings carried out in the late 1980s and early 1990s. Only at A5 and A9, the rating equations were updated after 1993. This implies that the reliability of the river flow records from the other gauges decreases towards the end of the study period. Further, the scarcity of gaugings during extreme flood flow events reduces the reliability of the rating equations in the highest value ranges. For a few short periods at some stations, data series are interrupted due to weir leakage or improper functioning of the water level recorders.

Land cover information was obtained from a 1988 Landsat TM image classified according to a locally developed, composite classification system, which takes into account the hydrological influence of vegetation and the occurrence of multi-layer and multi-type vegetation at the scale of mapping units (Niederer, 2000; Liniger et al., 1998a). The soil type information used in the study is based on maps by Speck (1983) and Klingl (1996).

Results

River water abstractions and groundwater influences in the study catchments

Water abstractions for irrigation draw a large percentage of the natural discharge, especially low flow discharge, from the rivers. At Naro Moru river gauging station A5, 40 l/s were measured at the time of field work; about 160 l/s were abstracted upstream. At river gauging station A6, the river was running dry due to water abstractions in the section between A5 and A6. Abstracted amounts have been steadily rising since the early 1980s. In 2002, the amount of water withdrawn from Naro Moru between the source and A6 varied from approximately 200 l/s (dry season) to 900 l/s (wet season). Wet season abstractions are higher due to the large water volumes diverted from the river through furrows (Aeschbacher et al., 2005). However, considerable insecurities remain with regard to these figures, since the abstracted water amounts at many sites can only be approximately estimated, and apart from the furrow abstractions, the temporal pattern of water use is not always reliably known. The value of 200 l/s for the dry season on Naro Moru represents the ''best estimate'' of withdrawn water amounts, using gauged values and volumetric measurements where available, and pumping rates for pumps where direct measurements were not possible. Using the lowest possible estimates at each abstraction point results in a total value of 180 l/s, while using the highest estimates adds up to over 500 l/s; however, the highest estimates are based on the estimated water demand at each abstraction point (using per capita demands for humans and livestock, and irrigation water demands for different crop types). Due to the water scarcity during dry seasons on one hand, and financial constraints in buying petrol to operate pumps on the other hand, it is likely that the full demand is by far not satisfied. In addition, since water demand was calculated based on information obtained from the water users in interviews, the demand-based estimates are likely to be less reliable than the estimates based on measurements.

The analysis of discharge and electric conductivity measurements shows that in the lower forest zone and the footzone, groundwater from shallow aquifers is discharged to the streams during dry periods, indicated by increasing naturalized flow in downstream direction and slightly increasing electric conductivity. The savannah zone appears to be characterized by transmission losses: Naturalized flow slightly decreases — probably due to bank and sediment storage and evaporation — while electric conductivity continues to increase at low rates (Fig. 3). However, the decreasing naturalized flow could also be an artefact caused by water abstractions not accounted for. Temperature values exhibit a steady increase in the downstream direction, caused by higher air temperatures at lower altitudes. However, temperature is found to be a poor indicator of groundwater influences, since during low flow periods, its variations might be more strongly affected by different degrees of shading of the river water by the riparian vegetation than by water from deep aquifers.

Evidence of water emerging from deep aquifers could only be found in Burguret catchment, where some small tributaries of the main river emerge from a series of small springs at an altitude of about 2000 m a.s.l. The water of these springs has an electric conductivity of more than 300 μS/cm, which is comparable to the water from boreholes on the plateau, where similar values were measured in aquifers more than 50 m below the surface. However, the spring water in Burguret catchment only amounted to 3% of the naturalized catchment discharge at the time of the measurements, which was a period of extremely low flows.

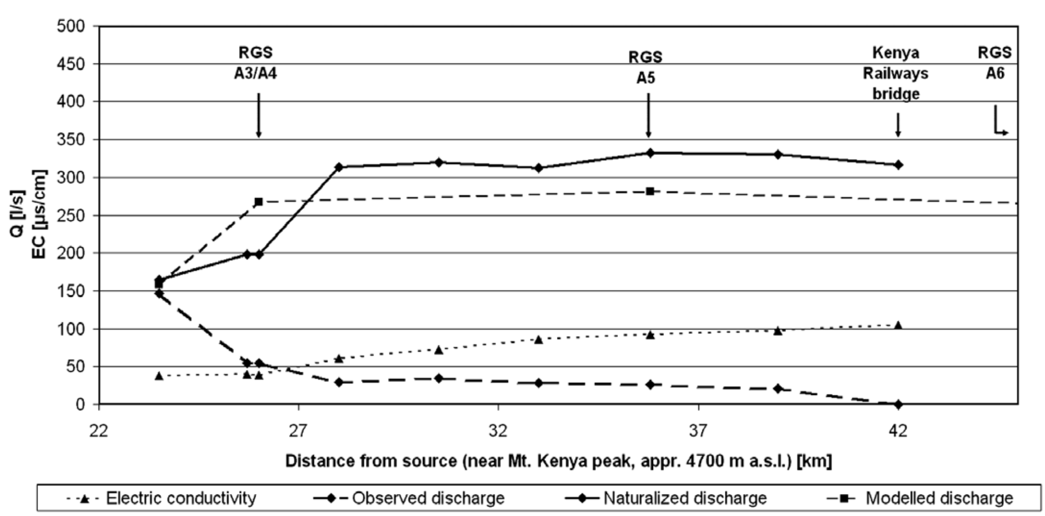

Figure 3 Observed and naturalized discharge, electric conductivity, and modelled discharge along the profile of Naro Moru River in the footzone and savannah zone. The graphs of the observed parameters are discontinued at the crossing of the Kenya Railways Bridge since the river was running dry downstream from this point at the time of the measurements.

Application of the NRM3 Streamflow Model

The calibration and validation results for the Naro Moru A5 catchment (Table 2) show that the NRM3 Streamflow Model is able to produce an acceptable simulation of discharge at the daily time-step, with E_2 scores of 0.66 for the calibration (1987–1991) and 0.56 for the validation period (1992–1996). A value of 0.5 is a minimum target indicating an effective simulation (Zappa, 2002). At the decadal and monthly time-steps, modelled and naturalized observed flows show a better agreement, with E_2 values of 0.76 and 0.80, respectively for the calibration period, and 0.66 and 0.69, respectively for the validation period. Switching the calibration and validation periods produced almost identical results (with almost identical parameter sets), with a maximum E_2 score of 0.57 at the daily time-step reached in the 1992–1996 period when calibrating the model using the data from this period, and a corresponding E_2 score of 0.65 in the 1987–1991 period. This indicates that the modelling results are robust with regard to subjective changes in the choice of the calibration/validation periods.

High flows are both over- and underestimated by the model. The poor simulation of high values is the main reason for the lower performance at the daily resolution (Fig. 4a and b). The deviations are mainly caused by the high spatial variation of rainfall, which is not sufficiently captured by the measuring network. Further reasons for poor high flow replication might include varying rainfall intensity or multiple storms in a day, which are not modelled at the daily scale, or the poorer reliability of the observed discharge data in the highest value ranges.

Low flows tend to be underestimated with respect to naturalized discharge. However, they are generally higher than the observed (not naturalized) low flow discharges, suggesting that insecurities in the determination of abstracted water amounts could also be a reason for underestimation. The interannual pattern of the naturalized LMQ30 is followed well by the simulation, indicating that the model is able to cope with different low flow conditions in different years.

Total runoff is underestimated by 11.5% in the calibration period and overestimated by 3% in the validation period. This may be due to the fact that the ''Moorland'' rain gauging station, which lies in the zone receiving most rainfall on average, began operation at the end of 1989, halfway through the calibration period.

Table 2 Performance measures of the NRM3 Streamflow Model in Naro Moru A5 catchment

Performance measure	Calibration (1987–1991)	Validation (1992–1996)
Daily r^2	0.655	0.564
Decadal r^2	0.820	0.721
Daily E_2	0.693	0.513
Decadal E_2	0.760	0.659
Annual runoff deviation (S − O) [%]	−11.5	3.0
r^2 of (annual) NMQ30	0.618	0.906

Abbreviations: r^2 = coefficient of determination; E_2 = Nash–Sutcliffe Efficiency score; (S − O) = total simulated minus total observed runoff; LMQ30 = mean of the 30 consecutive days with the lowest flows in a year.

In the Naro Moru A6, Burguret (A8) and Nanyuki (A9) catchments, the model performs less well, which is mainly due to insufficient rainfall inputs: only one rain gauge exists within Burguret catchment and none in Nanyuki catchment, which means that the simulation had to rely largely on rainfall measurements outside these catchments. In the case of Naro Moru A6 catchment, the large size of the catchment causes time lags between simulated and observed discharge, since channel routing is not included in the model.

The most crucial model inputs are the rainfall data. A run in the A5 catchment, using the data from only three of the seven gauges located within the catchment, resulted in a daily E_2 score of only 0.18 for the calibration period. The reason is that the spatial distribution of rainfall is very heterogeneous, which is common in the tropics due to a mainly convective atmospheric circulation pattern – a small area can experience heavy rain while at a distance of only one kilometer no rainfall occurs at all. The situation is further complicated by altitude-dependent and other topography-induced modifications of rainfall, which are not simulated in the model rainfall interpolation module used in this study. By contrast, the simulation is not nearly as sensitive with regard to evaporation data – using monthly mean pan evaporation instead of daily measurements did not significantly reduce E_2 and r^2 values.

Of the parameters adjusted in calibration, the deep seepage parameter has the most significant influence on overall model performance. It removes groundwater from the shallow saturated store to the deep saturated store, and is therefore used if runoff is consistently overestimated; this was not the case in any of the study catchments, so the parameter was set to zero. The values of the three parameters defining the rate at which groundwater discharges to the stream (a short-term and a long-term recession parameter, and a threshold parameter separating long- and short-term recession) have little influence on the r^2 and E_2 scores of the simulation; however, they influence the visual appearance of the simulated hydrograph and low flow measures like the LMQ30. A large amount of subjectivity is involved in their determination. In most cases, no clear ''best set'' of parameter values emerged. In this study, the parameter set producing the best agreement of modelled and observed LMQ30 values was chosen as the final set if several sets displayed the same overall performance.

The resolution of GIS inputs did not affect the modelling results up to a grid cell size of 500 m; at resolutions of 1 km and more, the results were poorer due to the loss of high runoff-generating HRUs.

Environmental change scenarios

The examined *land use change* scenarios show that in the Naro Moru A5 catchment, conversion of the remaining forest and savannah vegetation below 3200 m a.s.l. to cropland (scenario 1) would result in an increase of average annual runoff by 11%, with a marked increase in flood flow and a very slight decrease in low flows (compare the hydrographs

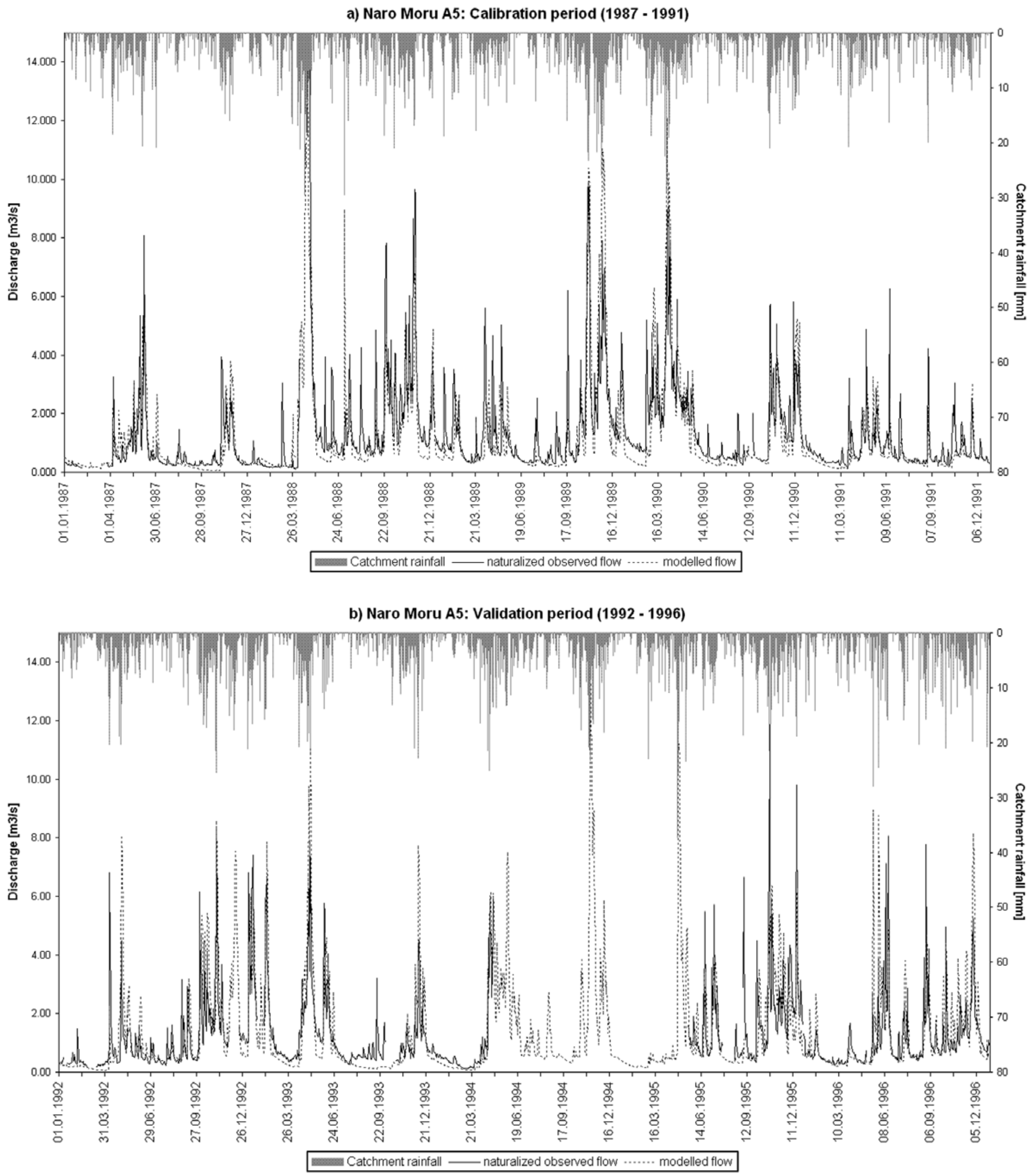

Figure 4 Simulated and naturalized observed discharge in the calibration period (a) and the validation period (b) at Naro Moru A5 (87 km^2). Catchment rainfall as interpolated by the NRM3 Streamflow Model is included for comparison. The missing data period in the observed discharge series in 1994/95 is due to weir leakage.

in Fig. 5). The spatially distributed grid outputs of the model suggest that the decrease in low flows is mainly due to deforestation at higher altitudes, where most of the dry season discharge originates from.

The presence of tree cover on 2—20% of the surface (scenario 2) slightly reduces the increase in flood flows compared to cropland without trees, but the decrease in low flows and the change in total flow are identical to scenario 1. It should be kept in mind that river water abstractions, which are not included in the figures presented here, would also increase under both scenarios.

Scenario 3 (bare grassland replacing the current land use) produces an increase in annual runoff of 59%, with a substantial increase in flood flows and reduction of low flows (LMQ30) to less than half of the current value. The latter effect is attributed on one hand to the fact that evaporation losses are smaller on bare grassland than on cropland, and on the other hand to the high proportion of quick runoff, since minor rains on the higher mountain slopes in the dry seasons produce small flow peaks under scenario conditions, which under current land cover conditions are intercepted by the vegetation. The impact of bare ground grass cover on surface runoff (and land degradation i.e. erosion, productivity loss) is confirmed by other studies carried out in the region (Liniger and Thomas, 1998).

Scenario 4, representing ''natural'' land cover conditions, displays little change to current conditions (reduction in annual runoff by 1.6%, with a very slight reduction of high flows and an even slighter increase of dry season flows). This indicates that human-induced land use changes on the slopes of Mt. Kenya in the past have not yet had a large impact on discharge by influencing the infiltration properties of the land cover. It confirms that the negative trends of low flow discharges from the 1960s to the 1990s are largely due to river water abstractions (Aeschbacher et al., 2005). However, it has to be kept in mind that up to the 1990s, only 9% of the A5 catchment area has been converted to cropland.

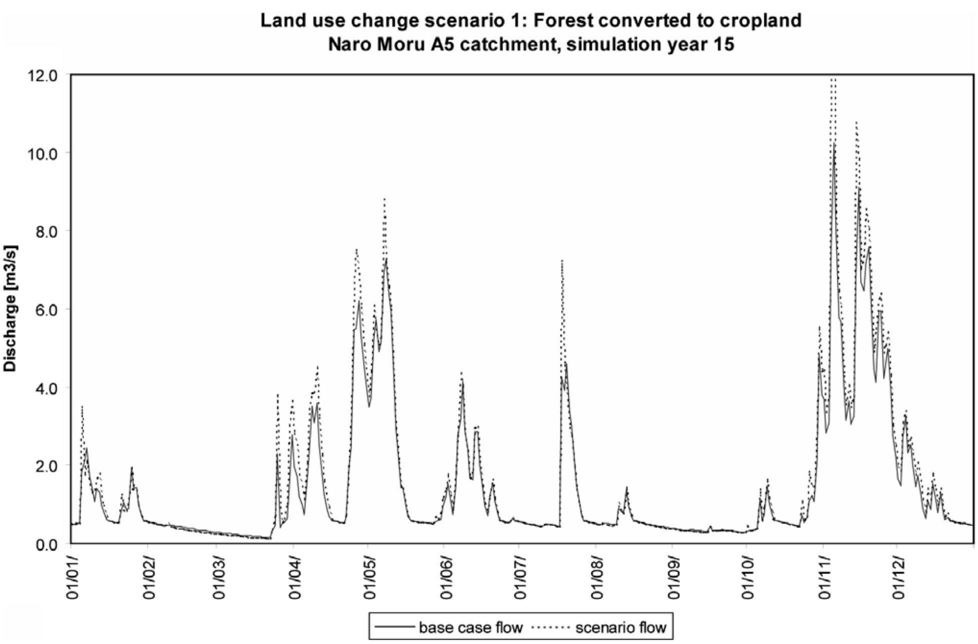

Figure 5 Base case and scenario hydrographs for the conversion of forest to cropland (scenario 1) in the Naro Moru A5 catchment.

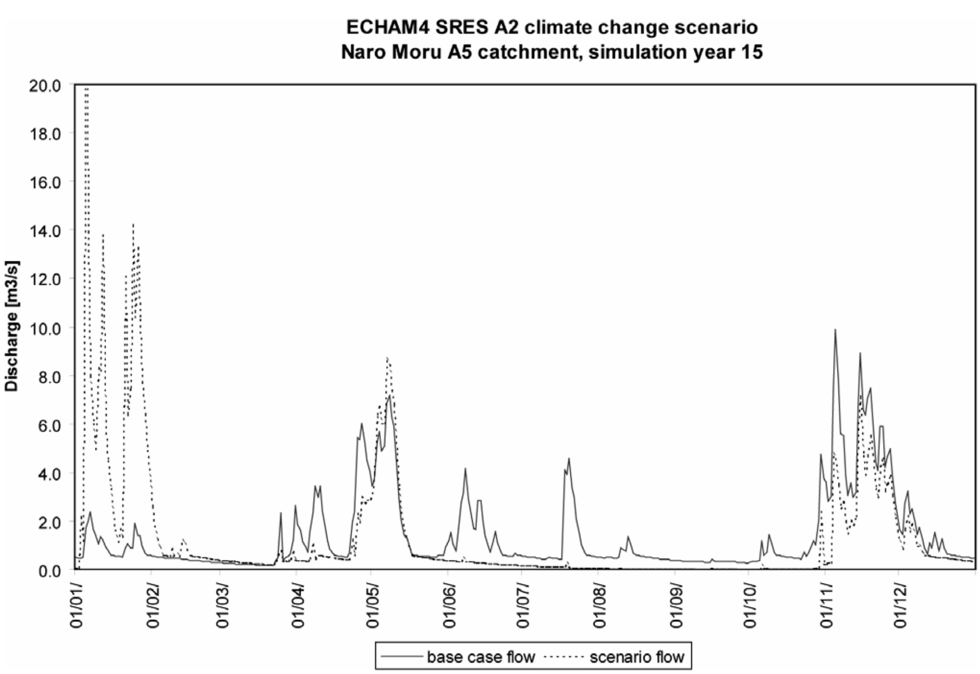

Figure 6 Base case and scenario hydrographs for the projections of the GCM ECHAM4 under the IPCC SRES A2 illustrative marker scenario, assuming current land use conditions (scenario 5). The climate simulation predicts a heavy increase of rainfall at the beginning of the year, resulting in extreme flood flows, while the second half of the year is predicted to be drier than under current conditions.

The impact of the *climate change* scenarios is more dramatic. A higher variability of rainfall and evaporation results in more extreme conditions than today. Under scenario 5 (the SRES A2 scenario, IPCC, 2000), annual average precipitation in the study area increases by 17.6% and potential evapotranspiration by 5.5%. This results in an increase of 26% in annual runoff with respect to current climatic conditions. The GCM simulations predict a heavy increase of rainfall in the months of January, February and May, and a decrease in all other months. Model results indicate that this could lead to extreme flood flows at the beginning of the year (reaching a multiple of current flood flow amounts), while reducing low flow discharge to about a tenth of the current value in the second half of the year (Fig. 6).

Under scenario 6 (the SRES B2 scenario), precipitation increases by 20.9% and potential evapotranspiration by 5.5% in the study area. This results in more total runoff (increase by 28%) than under scenario 5, but the differences between high and low flows are not as extreme, although considerably greater than under current conditions.

Discussion

The modelling results show an acceptable performance of the NRM3 Streamflow Model in simulating discharge in meso-scale catchments in the Upper Ewaso Ng'iro Basin. The study demonstrates that a simple hydrological model with minimal input data requirements is able to simulate discharge from perennial, meso-scale catchments in the Mt. Kenya area.

In spite of the adaptation of the NRM3 Streamflow Model to a data-scarce environment, and the presence of a relatively dense monitoring network density in the study region, the limitations of modelling remain attributable to a high degree to data limitations:

- With regard to discharge data: On one hand, the insecurity concerning the abstracted water amounts prevents a sound judgement on the accuracy of low flow simulation. On the other hand, for the highest measured flows, scarcity of gaugings in these ranges adds insecurity to the data values.
- With regard to meteorological inputs: Rainfall data are the most crucial inputs to river flow modelling. The highly heterogeneous rainfall pattern allows good modelling results only in catchments with a dense measuring network. Similar limitations have been experienced in other hydrological modelling studies in Tropical Africa (Legesse et al., 2003). This clearly shows the high importance of monitoring rainfall, if hydrological models are to be tested, further developed, and applied in watershed management. However, it also indicates that the spatialization of meteorological point measurements is a key issue which should be given priority in order to improve hydrological simulations in tropical regions with mountainous topography.
- With regard to land cover inputs, the question of land use changes during the study period (1987–1996) emerges. However, given that from the beginning of cultivation up to 1988, only 9% of the A5 catchment area have been converted to cropland, it can be assumed that land use changes not accounted for during the 10-year study period have a minimal effect on the calibration/validation results compared to the other mentioned data limitations.

Another source of insecurity related to land cover lies in the assignment of appropriate curve numbers for each land cover type. Especially the areal averaging procedure employed in the determination of curve numbers for composite land cover types is subjective and conceptual (based on judgement rather than any measured data). However, in the initial calibration of the NMR3 Streamflow Model in small catchments in the Mt. Kenya region, r^2 and E_2 scores of over 0.9 were reached (McMillan and Liniger, 2005), indicating an accurate estimation of base curve numbers.

The NRM3 Streamflow Model itself could mainly be improved by the introduction of channel routing, which would allow a more reliable simulation of flood flows, as well as the application of the model in larger catchments.

The results of the scenario analysis show that cultivation or degradation of natural land cover types in this area result in higher runoff, mainly in increased high flows. The reduction of low flows through reduced groundwater contributions under cropland is comparably small, but still worrying given the scarcity of water in dry periods already experienced under current conditions – and irrigation water demand would greatly increase if more land was turned to cropland. Modelling results also indicate that deforestation in the upper forest zone might have the greatest influence on low flows.

Climate change, according to the GCM predictions applied here, has a much larger impact on the water resources in the area than land use change. This corresponds to the results of other combined land use/climate change impact assessments in Tropical Africa (Legesse et al., 2003). The use of monthly GCM predictions as inputs reveals the magnitude of variability which is to be expected: Not only are dry periods more severe and last longer, reducing water availability almost to zero, also flood flows of a multiple amount of what is experienced nowadays could destroy crops, settlements and infrastructure along the rivers in the rainy seasons.

The figures presented here should not be interpreted as accurate predictions of discharge amounts, due to uncertainties in NRM3 Streamflow Model as well as GCM predictions. They only indicate an order of magnitude of the hydrological response to hypothetical changes in land cover and climate, without taking into account feedbacks between land-use, hydrology and climate – e.g. possible changes in rainfall patterns due to changed land use, changes in soil properties due to land cover change, or vegetation changes due to changed climate. Additionally, consequences of combining land use change with climate change scenarios could result in more dramatic changes in the river flows. These scenarios as well as the combination with increasing river water abstractions due to growing irrigation demand remain subject to further investigations.

However, the results clearly show that under current trends water resources, which are already very scarce nowadays, will be subject to greater variability in the future.

Socio-economic and demographic developments will further aggravate the situation. This underlines the importance of more efficient water management in the Mt. Kenya area and other semi-arid regions of Tropical Africa. Hydrological models can contribute to this goal as a part of decision support systems, by estimating the consequences of trends and scenarios on water resources, as demonstrated in this paper. The implementation of measures is in the hands of authorities and water users in the area: From governmental and non-governmental institutions, coordination and financing for the construction of water storage and supply infrastructure is required, so that excess water from the rainy seasons can be stored for dry periods. Flood protection measures will also be necessary if climate change predictions are to come true. Farmers need to invest in and promote water-saving irrigation technologies like drip irrigation. Finally, authorities and water users must work together to ensure a fair allocation of water between upstream and downstream users, without which future conflicts will be unavoidable.

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