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Modeling impacts of climate and land use changes on catchment hydrology: Meki River, Ethiopia

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Abstract

Impacts of climate variability and land use change on catchment runoff of the Meki River basin were assessed using hydrological modeling. The Modular Modeling System (MMS) was used to build a suitable Precipitation Runoff Modeling System (PRMS) for the study area, perform sensitivity analysis, model calibration and validation, and scenario analysis. The model calibration and validation periods in this study were divided into three. The calibration period was a five years period (1981–1986). The validation period was divided into two: validation 1 (1986–1991) and validation 2 (1996–2002). Model performance was evaluated by using joint plots of daily and monthly observed and simulated runoff hydrographs and the Nash-Sutcliffe coefficient of efficiency to statistically analyze model performance in simulating daily and monthly runoff. Daily observed and simulated hydrographs showed a reasonable agreement for both calibration and validation periods. The model coefficients of efficiency were 0.71 for the calibration period and 0.69 and 0.66 for validation period 1 and 2, respectively. Simulated runoff was generally greater than the observed runoff values for the calibration and validation periods. The model was also limited in its capability of simulating complex hydrograph shapes and peak discharge values. However, the model performed well in simulating dry season flows for both validation and calibration periods. A 20% of change in rainfall and 1.5 °C increase in temperature was considered for climatic scenarios and one land use change scenario were used to assess the likely impacts of these changes on the runoff of the Meki River. The results of the scenario analysis showed that the basin is more sensitive to increase in rainfall (+80% for +20%) than to a decrease (−62% for −20%). Increase in temperature has also a significant impact both on the potential evapotranspiration and stream flow of the basin. Increase by 1.5 °C in temperature resulted in increase in potential evapotranspiration (6.02%) and decrease in stream flow (13%). The proposed land use scenario of converting areas between 2000 to 3000 m a.s.l. to woodland also resulted in a significant decrease in stream flow (11.8%) and increase in evapotranspiration (2.2%) of the study area.

1 Introduction

The hydrological cycle, a continuous process that describes the circulation and storage of water in the Earth, is being influenced by humans from the local to the planetary scales. Globally, temperature is increasing and the amount and distribution of rainfall is being altered (Cubasch et al., 2001). According to the International Panel on Climate Change (IPCC) Scientific Assessment Report, global average temperature would rise between 1.4 and 5.8 °C by 2100 with the doubling of the CO_2 concentration in the atmosphere (IPCC, 2001). Sea level rise, change in precipitation pattern (up to ±20%), and change in other local climate conditions are expected to occur as a consequence of rising global temperature (Cubasch et al., 2001). This is expected to have a potential impact on different socio-economic sectors (IPCC, 2001).

Climate change can cause significant impacts on water resources by resulting changes in the hydrological cycle. The change in temperature and precipitation components of the cycle can have a direct consequence on the quantity of evapotranspiration component, and on the quantity of the runoff components. Consequently, the spatial and temporal water resource availability, or in general the water balance, can be significantly affected, which clearly amplifies its impact on sectors like agriculture, industry and urban development (Hailemariam, 1999).

Land cover change, associated with the intensification of agriculture, cattle raising and urbanization, could have a profound influence on the hydrological processes in small watersheds and at the regional level (Mendoza et al., 2002). Streamflow plays an important role in establishing some of the critical interactions that occur between physical or ecological processes and social or economic processes (Choia and Dealb, 2008).

The purpose of water resources management is often to mitigate or prevent the adverse impacts of excessive runoff or shortage of water. Hydrological models have served as a valuable tool in water resources management for many years and are usually used to predict the impacts of proposed landuse and climate change scenarios and to evaluate management strategies. During the last several decades, the application of computers for the planning and operation of water resource systems has rapidly become an important field of research (Xu et al., 2001).

Generally, hydrological models provide a framework in which to conceptualize and investigate the relationships between climate and water resources (Leavesley, 1994; Lazzaratto et al., 2006; Kunstmann and Stadler, 2005; Choi and Deal, 2008). Global climate models that predict long-term trends in climate (rainfall, temperature, humidity) are often unsuitable for regional scale studies because of the course grid-size resolution. Consequently, there is a strong need for hydrological modeling tools that can be used to assess the likely effects of land use changes as well as climate variability on the hydrological cycle at a catchment scale (Legesse et al., 2003).

The Ethiopian Rift system hosts a series of lakes that are mainly fed by water flowing from the surrounding highlands and escarpments. Over the past few decades there has been a lot of activities that have modified the land use/land cover. Moreover, the hydrological dynamics has been strongly modified by intensive agricultural activities. This has a direct impact on the lakes downstream. Therefore, it is very important to understand the functioning of these lake catchments and their hydrological response under different land use and climate change scenario conditions and the water resources development of the basin requires a judicious planning for the protection of the fragile ecosystem.

This study will focus on a catchment scale hydrological modeling of the Meki River basin, which is part of the Central Main Ethiopian Rift lakes system.

The main objectives of this study are:

1. Test and validate a modified Precipitation Runoff Modeling System (PRMS) and assess the model performance in the basin.
2. Assessing the impact of land use change and climate variability on the catchment's runoff under different land use/land cover and climate change scenarios.

For this study a physically based distributed parameter catchment scale hydrological model called PRMS was selected. The model was then modified to accommodate the prevailing conditions of the catchment as described below.

2 Description of the PRMS

PRMS is a modular-design, physically based deterministic, distributed-parameter modeling system developed by the US Geological Survey to evaluate the impacts of various combinations of precipitation, climate, and land use on stream flow, sediment yields, and general basin hydrology (Leavesley et al., 1983). Basin response to normal and extreme rainfall events can be simulated to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields, and ground-water recharge (Leavesley et al., 1983). PRMS is physically based in that each component of the hydrological system is simulated with known physical laws or empirical relations formulated on the basis of measurable watershed characteristics. The modular design of PRMS provides a flexible modeling capability while allowing changes and adaptations to certain specific catchments. Detailed description of the model as well as the model itself can be obtained from Leavesley et al. (1983) and the USGS website.

On the MMS platform, parameter-optimization and sensitivity analysis capabilities are also provided to fit selected model parameters and evaluate their individual and joint effects on model output. PRMS can be run in daily and storm mode time scales. The daily mode simulates daily average runoff and the storm mode simulates runoff at time intervals that may be shorter than a day.

PRMS components are designed around the concept of partitioning a watershed into units on the basis of characteristics such as slope, aspect, vegetation type, and soil type and precipitation distribution. Each unit is considered homogeneous with respect to its hydrological response and is called a hydrological response unit (HRU) (Leavesley et al., 1983).

A water balance and an energy balance are computed daily for each HRU. The sum of the responses of all HRU's, weighted on a unit area basis, produces the daily system response and stream flow from the watershed. Partitioning provides the ability to impose land use or climate change on parts or all of a watershed, and to evaluate the resulting hydrological impacts on each HRU and on the total watershed. In PRMS a watershed is conceptualized as a series of reservoirs whose outputs combine to produce the total watershed response: the impervious-zone reservoir, the soil-zone reservoir, the unsaturated subsurface reservoir and the groundwater reservoir (Leavesley et al., 1983). Daily total stream flow from the watershed's outlet is the sum of surface runoff, subsurface interflow and baseflow.

One of the compelling reasons for the choice of this model is that it has already been tested in the same region with an apparent success (Legesse et al., 2003). However, the original PRMS was modifies to take into account the relatively big wetland that the river traverses. Moreover, the same model has already been used to estimate impacts of different changes on groundwater recharge (Abiye et al., 2009).

3 Description of the Meki Basin

The Meki River basin, which is part of the Ziway-Shalla basin, is located in the northern part of the Main Ethiopian Rift (Fig. 1). The area extends from the Guraghe Mountains, where the Meki River originates to the Ziway Lake where the river drains. The total gauged basin area of Meki is about 2154 km^2. Topography of the area is primarily determined by the rift system of faulting. The study area lies within altitudes ranging from 3600 m a.s.l. in the west to 1600 m a.s.l. to Lake Ziway with a mean elevation of 2056 m a.s.l. The upper riches of the basin are steep and mountainous while the lower basin is flat with a broad valley (Fig. 2).

The western plateau of the Gurage highlands with elevation ranging from 3500 to 3600 m a.s.l. are the perennial sources of the Meki River while the tributaries in the escarpment and rift floor are almost intermittent sources. The Meki River drains the western mountains and escarpments including a vast swampy area and travels for about 100 km before draining to the Ziway Lake.

The highland is characterized by higher drainage density than the escarpment and flat areas of lacustrine deposits in the southern part of the study area, which lack drainage due to differences in rock permeability, climate and slope (Tesfaye Chernet, 1982). Rift faults have affected the drainage of the area both by determining the river courses and by impounding river water and causing some marshy areas, in the southern part of the study area (Tesfaye Chernet, 1982).

The land cover of the study area can be categorized mainly as agricultural, with open woodlands, forest, and water bodies. According to the information collected during the field visit in the study area, irrigation is practiced along the courses of the Meki River. Teff (*Eragostis tef*) is a leading cereal crop on the hilly areas covered by deep soils and higher rainfall while maize and wheat are more prevalent on the valley floor with lower rainfall. Haricot beans (*Phaseolus vulgaris*), horse beans (*Vicia fabal L*), peas (*Pisum sativum L*), chickpeas (*Cicer arietinum L*) and Lentil (*Lens culinaris Medik*) are major pulse crops cultivated in the area. Onion, tomato, cabbage, chili pepper, carrot, and fruits are also widely cultivated.

The study area has soils closely related to the parent material and the degree of weathering (Makin et al., 1976). Basalt, ignimbrite, acidic lava, volcanic ash and pumice, and riverine and lacustrine alluvium are the main parent materials (Di Paola, 1972). Generally, soil types in the area could be grouped into three (Makin et al., 1976). The first group is a well-drained deep redish brown to red friable clays to clay loams with strong structure. The second group of soil is a well-drained, moderately deep-to-deep dark gray or brown, friable silty loam to sandy loam soils with moderate structure and good moisture storing properties. The third group of soil are dark grayish, free draining friable silty loam to sandy loam with moderate structure and good moisture storing properties (Fig. 2). The soil map for this study was extracted from the Soil and Terrain Database for northeastern Africa CD-ROM (FAO, 1998).

Climate of the study area consists of three ecological zones: humid to dry humid, dry sub-humid or semi arid and semiarid or arid lands (Makin et al., 1976). Temperature and rainfall in the area show strong altitudinal variations. Mean annual temperature ranges from about 15 °C in the highlands to around 20 °C in the rift (Fig. 3). The average annual rainfall also varies spatially and ranges from around 650 mm in the rift floor to more than 1200 mm in the highlands.

The Indian and Atlantic Oceans are the sources of moisture for almost all rains in Ethiopia (Degefu 1987; cited OEPO, 2005). Three main seasons characterize the study area: The first one is the long rainy season in summer, which lasts from June to September and locally known as "*kiremt*". The "*kiremt*" season is primarily controlled by the seasonal migration of the Inter Tropical Convergence Zone (ITCZ), which lies to the north of Ethiopia at that time. According to Degefu (1987), the "*kiremt*" rain represents 50–70% of the average yearly total. The second is the dry period, which extends between October and February and locally known as "*bega*". In "*bega*" the ITCZ lies to the south of Ethiopia when the northeasterly trade winds traversing Arabia dominates the region. Degefu (1987) indicated that occasional rains during this period bring 10–20% of the yearly average. The "*bega*" season is known as the main harvest season in the area. The third season, which is locally known as "*belg*" is of a "*small rain*" season accounting for 20–30% of the annual amount, and stays from March to May.

4 Model application to Meki River Basin

4.1 Model data preparation

In this study PRMS was calibrated and verified using daily-mode flow simulation. Measured daily runoff data from the Meki town gauging station was obtained from the Ministry of Water Resources and used in this study directly with no adjustments. Missing values were replaced by −9.99 in the model and these periods were avoided from model calibration and validation.

Measured climate data including daily rainfall and maximum and minimum air temperatures were obtained from the National Meteorological Services Agency (NMSA) and daily solar radiation data measured at Addis Ababa (about 160 km from the study area and found at mean elevation of about 2500 m) was obtained from the Addis Ababa University Geophysical Observatory since solar radiation data was not available for any of the stations in the study area. Linear regression method was used to fill in missing climatic data values. All the available climatic and hydrological data cover a period of 25 yr from January 1980 to December 2005.

4.2 Delineating hydrological response units (HRUs)

The distributed parameter capabilities of PRMS are enabled by partitioning a watershed into sub-areas that are assumed to be homogeneous in their hydrologic response, termed hydrological response units (HRUs). There is no hard and fast rule on how to delineate hydrological response units (Leavesley et al., 1983). The crucial assumption for each HRU is that the variation of the hydrological process dynamics within the HRU must be small compared with the dynamics in a different HRU. Heterogeneity within an individual HRU is accounted for by computing spatially weighted averages for each characteristic (Flügel, 1995).

In this study partitioning was made based on basin characteristics such as soil, vegetation, elevation, slope, aspect and mean annual rainfall distribution using ESRI's ArcGIS®.

Topographic maps at a scale of 1:50 000 were digitized to generate Digital Elevation Model, slope, and aspect maps needed to delineate the HRUs. Existing digital soil map (FAO, 1998) and satellite image derived land use/land cover map were integrated in a GIS.

Daily precipitation data recorded at five meteorological stations (four in the catchment and one nearby station were interpolated using kriging technique to obtain mean monthly and annual spatial distribution maps of the precipitation in the basin. These layers were brought together and spatial overlay analysis was used to delineate the HRUs. After simplification of the resulting polygons obtained from the overlay process, 28 HRUs were delineated for the basin (Fig. 4).

In this study, initial estimates of parameter and coefficient values for the basin were taken largely from a previous PRMS modeling study (Legesse et al., 2003) on Ketar River basin, an adjacent basin, with similar hydrological context, except for the physical parameters. Physical parameter values were computed for the watershed using GIS analysis.

Soil texture and available water holding capacity are the two soil characteristics that are used to define model parameters in the PRMS. Soil texture classes and depth were derived from the FAO Soil and Terrain database. The other important soil parameter is the available water holding capacity of the soil profile in the study area, which depends on both soil texture and the rooting depth of the predominant vegetation. Unfortunately, very little is known about the rooting depths of plants in the region. For this study, values estimated by Leopold et al. (1989) based on relationships linking vegetation class, soil texture, rooting depth and moisture capacity of soil were adopted.

The depth of the upper soil layer is user-defined and was assumed to consist of the top half of the maximum root zone since this is the area in which more than half the root density is found (Evans and Sneed, 1996). PRMS has predefined land cover types and hence original land use classes were assigned one of the four vegetation types defined in PRMS (bare soil, grass land, shrubs or trees). Vegetation cover density (percentage of green vegtation on a patch of land, HRU in this case) was estimated using normalized difference vegetation index (NDVI) from Landsat ETM+ satellite images.

Although the geology of the Meki River watershed is non-uniform, one subsurface reservoir and one ground-water reservoir were used to describe the unsaturated subsurface and the groundwater systems. In other words, excess soil-zone water from each of the 28 HRUs in the Meki River watershed is routed into the same subsurface and ground-water reservoirs. The physical characteristics values of the HRUs are summarized in Table 1.

4.3 Model building using the modular modeling system

The PRMS model was slightly modified for this study using both existing standard PRMS modules and additional new modules. The original PRMS doesn't take wetlands and lakes into account and hence couldn't be directly used for this study. A new soil moisture balance module modified by Mastin and Vaccaro (2002) was used instead of the original soil moisture balance module in the standard PRMS. Figure 5 depicts the general schematics of the various modules consituting PRMS.

In this new soil moisture balance module, a new soil type representing water-covered areas was added (Mastin and Vaccaro, 2002). For this soil type, the actual evapotranspiration is set equal to potential evapotranspiration. Moreover, its parameters are set such that the total available water capacity of the soil and recharge zones defined for PRMS are made equal and set to 1769 mm, and land-cover parameters are made to represent bare ground as suggested by (Mastin and Vaccaro, 2002). A value of 1769 mm approximates the annual evaporation from Lake Ziway (Vallet-Coulomb et al., 2001).

4.4 Model calibration, validation and results

The availability of concurrent runoff and climate data primarily dictated the selection of the time periods used for model calibration and validation. A period of one year (1980–1981) was used for model initialization. The purpose of model initialization is to estimate initial conditions in the basin at the beginning of a simulation period. The model calibration and validation periods in this study were divided in to three. The calibration period was a five years period (1981–1986). The validation period was divided in to two: validation 1 (1986–1991) and validation 2 (1996–2002). This was due to missing discharge records between the two validation periods.

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The model was first run in a daily runoff-prediction mode with parameter values that were estimated for the basin and were believed to be reasonable. After selection of initial parameter values, a daily sensitivity analysis was used to identify parameters that had the most effect on predicting daily runoff during the calibration period.

Results of the sensitivity analysis indicated that the basin response is more sensitive to the rainfall correction factor (RAIN_ADJ), a monthly temperature adjustment factor for calculation of PET (jh_coef), soil moisture related parameter SOIL_MOIST_MAX and subsurface flow related parameter SSRCOEF_LIN and surface runoff related parameter CAREA_MAX. The model results were also fairly sensitive to two other parameters related to surface runoff (SMIDX_EXP) and (SMIDX_COEF). These parameters were selected for the calibration process. After preliminary model results were examined, the purpose of model calibration was to estimate realistic model parameter and coefficient values for the study area so that the PRMS model closely simulates the hydrological processes of the watershed.

A trial and error adjustment of the selected parameters was performed in an attempt to adjust volume and timing and the flow components of the simulated runoff hydrograph. Selected parameter values were adjusted upward and downward manually between each model run for the calibration period (1981–1986). Finally an in-built automatic calibration technique, the Rosenbrock optimization technique (Leavesley et al., 1996), was performed to see if calibration results could be further modified. The same parameters were used to perform automatic calibration.

Simulation results from the modified PRMS model were examined both graphically and statistically. Daily observed and simulated hydrographs showed a reasonable agreement for both calibration and validation periods. The volume of the simulated runoff was greater than the observed runoff values in general for the calibration period and both validation periods. The model was also limited in its capability of simulating complex hydrograph shapes and peak discharge values. However, the model performed well in simulating dry season flows for both validation and calibration periods. The coefficients of efficiency were 0.71 for the calibration period and 0.69 and 0.66 for validation periods 1 and 2, respectively. Figure 6 shows the results obtained for the calibration and validation periods.

Overall, the PRMS model simulated the timing and volume of streamflow for the watershed reasonably well. Errors for the validation periods were expected to be larger than those for the calibration period. The PRMS model was calibrated to obtain the best fit to the calibration period data while the validation periods' results represent an independent assessment of model utility. Though small in value, the Nash-Suttcliffe simulation efficiency values fulfilled the requirements suggested by Santhi et al. (2001) for $E_{NS}>0.5$.

One of the main objectives of the calibration was to have a realistic flow component of the simulated flow hydrograph. The simulated hydrographs for the calibration period were composed of mostly subsurface flow (43.4%) followed by groundwater flow (32.1%) and finally surface runoff (24.5%; Fig. 7). Results of mean monthly runoff simulations seemed to correspond better with observed values with R^2 value of 0.81 for the calibration period. This shows the model was able to represent the dynamics of the hydrograph at the monthly scale better than at the daily scale. The coefficient of efficiency was calculated to be 0.74 and 0.72 for the first validation period (1986–1991) and the second validation period (1996–2002), respectively. Figure 8 shows the results obtained for monthly scale simulations.

4.5 Scenario simulation

Water resources are likely to be severely affected by the changing climate. This is mainly because of the fact that even a minor long-term change in temperature and precipitation may have significant impacts on the hydrologic cycle especially at the basin scale (Loe et al., 2001). Consequently, it is quite essential to identify the level of impact on such resources.

In this study simulations under different scenario conditions in order to analyze the impact on the catchment hydrology of possible changes in climate variables or in land use that may occur have been performed. This involves calibrating and validating the hydrological model using present conditions and running the model with parameters and input data corresponding to the proposed scenario conditions and comparing the two simulations.

4.5.1 Climatic scenarios

For this study, incremental climatic scenarios were used. Incremental scenarios or synthetic scenarios describe techniques where particular climatic elements are changed incrementally by plausible though arbitrary amounts (e.g., +1, 2, 3, 4 °C change from the baseline temperature and +5, 10, 15, 20% change from the baseline precipitation) (IPCC-TGCIA, 1999). Such scenarios do not necessarily present a realistic set of changes that are physically plausible. They are usually adopted for exploring system sensitivity prior to the application of more credible, model-based scenarios (Mearns et al., 2001). In this study a 20% change in precipitation and a 1.5 °C increase in temperature were assumed and nine climatic scenarios were then developed in order to assess the response of the river runoff to climate variability.

Results of the simulated scenarios revealed that the runoff volume is sensitive to both temperature and rainfall change.

The runoff was found to be more sensitive to increase in rainfall than to decrease. It also showed that increase in temperature also reduces the runoff significantly. Simulated runoff values for all scenarios were compared with simulated runoff values for the first validation period (1986–1991). An increase in temperature by 1.5 °C resulted in 13% decrease in simulated runoff and an increase of potential evapotranspiration by 6.02%. A year round increase in rainfall by 20% resulted in 80% increase in simulated runoff while a decrease in rainfall by the same magnitude 61.9% decrease in simulated runoff. For the summer season (June to September), an increase in rainfall by 20% brought 50% increase in simulated runoff and a decrease in rainfall by similar magnitude caused a decrease in simulated runoff by 38%. For the spring season (March to May), an increase in runoff by 27% resulted from an increase in rainfall by 20% and the simulated runoff decreased by 20.6% for a decrease in rainfall by the same amount.

The results of the scenario analysis are shown in Figs. 9 and 10.

4.5.2 Land use scenario

Land use/land cover changes occur in the country as a whole and in the Ziway–Shala basin in particular (Woldu and Tadesse, 1990) due to increasing population, which has almost doubled in the country over the past 40 yr (CSA, 1999). It is thus essential to analyze the possible impacts of these changes at different scales. In this study, one scenario of land use change was used in the region to assess the impact of this change on the runoff.

Parameters that were adjusted with respect to changes in the vegetation cover included maximum soil water holding capacity (SMAX), and maximum interception storage. The change in runoff resulting from the change in land use is determined by comparing the simulated flows using the calibrated parameters (calibration) with that obtained with parameters estimated for the assumed land use changes.

By assuming the scenario that the part of the catchment between 2000 and 3000 m a.s.l., was covered by dense woodland and introducing the corresponding parameters to this change, the model produced an increase in daily evapotranspiration of 2.2% and a decrease in the mean daily river flow of about 11.8% with respect to the actually simulated value for the calibration period indicating the role that this type of change may have in the hydrological response.

5 Discussions and conclusions

In this study, a modified precipitation modeling system (PRMS) was developed to assess the impacts of climate and land use changes on the runoff of Meki River basin using the Modular Modeling System (MMS). Initial parameter estimates were taken mainly from literature during preliminary model run, which were later modified through calibration. Both manual and automatic calibration techniques were used in this study on selected model parameters.

The model has performed reasonably well in simulating daily and monthly runoff volumes for both calibration and validation periods. It was generally capable of simulating observed daily runoff volume of the river and performed better in simulating monthly flow volumes. The model was also able to capture monthly and seasonal patterns (bi-modal) of runoff though it was limited in its capability in simulating complex hydrograph shapes and peak flows.

The model was also found to simulate very well potential and actual evapotranspiration in the catchment both at daily and monthly scale. According to the analysis of the flow components of the simulated hydrograph, majority of the stream flow comes from subsurface flow, which was estimated to be 42% on average for the entire simulation period. The contribution of the groundwater flow to stream flow was also significant, 39% on average. The contribution of surface runoff to stream flow was found to be the least which was estimated to be about 19% on average for the entire simulation period.

A synthetic climate change scenarios were developed in this study. An arbitrary 20% change in rainfall and 1.5 °C increase in temperature was considered. Rainfall change scenarios were introduced both on year round basis and on seasonal basis. This was to assess the sensitivity of the catchment runoff to both seasonal and general rainfall changes.

Results of the scenario analyses showed that the Meki River runoff is sensitive to temperature and rainfall changes. The simulated runoff volume however was found to be more sensitive to increase in rainfall than to a decrease.

Scenario analyses were performed considering one variable at a time and keeping other values unchanged and hence the combined effects resulting from a proposed scenario are not addressed in this study.

It should be noted that the model simulation results of this study are subject to various sources of uncertainty. Some uncertainties are inherent in the model structure and some are due to errors in the calibration input data and parameter estimates. Examples of inherent uncertainties in the PRMS model include simulations that oversimplify

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complex hydrological processes and the failure of HRUs to adequately describe the heterogeneity of watershed characteristics.

Most physically based models cannot fully account for the complexity and heterogeneity of processes occurring in the watershed (Yeung, 2005). The accuracy of the model calibration is dependent on the accuracy of the input data. Errors associated with the assumed distribution of rainfall over the watershed affect model results. For example, overestimation of streamflow in the model in general may have resulted from overestimation of rainfall in the watershed. Rainfall distribution on the study area was calculated by using stations on highlands outside the catchment due to the insufficient distribution of rainfall stations in the basin. The available rainfall stations are not also well distributed but rather limited to lower altitude areas.

Meanwhile, this study should be extended by considering more scenarios of changes in landuse, soil conditions and other climate variables in addition to the changes in precipitation and temperature. Continuing studies; however, should consider the wide range of uncertainties associated with models and try to reduce these uncertainties by the use of different GCM outputs, and downscaling techniques. Application of a number of GCMs can help to generate a more "reliable" ensemble mean.

A more promising perspective would be the application of the current PRMS model in other watersheds of Ethiopia. The result of any model depends on the quality of the input data. Input data should, therefore, be checked for missing and unrealistic values in order to come up with good results. Lack of reliable climate and hydrological data were one of the challenges in this study.

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Table 1. Some physical characteristics of HRUs delineated for Meki Catchment.

HRU	Area (km^2)	Cover type[a]	Soil type[b]	Elevation (m)	Slope (%)	Aspect	SMAX (mm)[c]
1	87.05	3	3	2158.80	9.89	S	350
2	54.03	1	3	2401.81	17.98	E	75
3	122.49	3	3	2022.95	8.51	S	350
4	112.79	3	3	2922.84	33.65	E	350
5	46.92	3	3	2410.96	20.58	E	350
6	75.51	3	3	2456.17	21.31	SE	350
7	148.51	1	2	2173.22	7.64	E	200
8	39.35	1	3	2592.99	8.84	E	75
9	22.69	3	3	3140.54	21.60	SE	350
10	456.27	1	2	1907.02	3.34	E	200
11	61.45	1	3	2939.50	15.73	E	75
12	136.41	1	2	1906.49	4.49	E	200
13	23.03	1	3	2409.17	12.33	SE	75
14	108.21	0	4	1843.82	2.16	SE	1769[d]
15	22.90	3	3	2153.64	18.64	SE	350
16	2.83	0	4	1820.56	0.57	NE	1769[d]
17	116.12	1	2	1814.10	4.59	SE	200
18	69.83	1	3	2730.40	12.03	E	75
19	23.82	1	3	2895.68	10.66	E	75
20	90.55	1	3	1959.50	7.06	SE	150
21	20.20	1	3	1886.73	3.32	E	150
22	107.02	1	2	1719.62	1.39	E	200
23	39.95	1	2	1671.28	1.04	E	200
24	25.15	1	2	1856.00	6.36	E	200
25	29.89	1	3	1931.19	7.31	E	150
26	42.65	1	2	1886.41	4.71	S	200
27	27.62	1	3	2171.14	9.46	SE	150
28	41.10	3	3	2062.53	19.75	SE	350

[a] 0=Bare or Water Body, 1=Grass (includes cultivated lands), 2=Shrub, 3=Trees (includes mature forests and woodlands)

[b] 1=Sand, 2=Loam, 3=Clay, 4=Water

[c] Maximum available water holding capacity of the soil profile in mm

[d] Tenalem Ayenew (1998)

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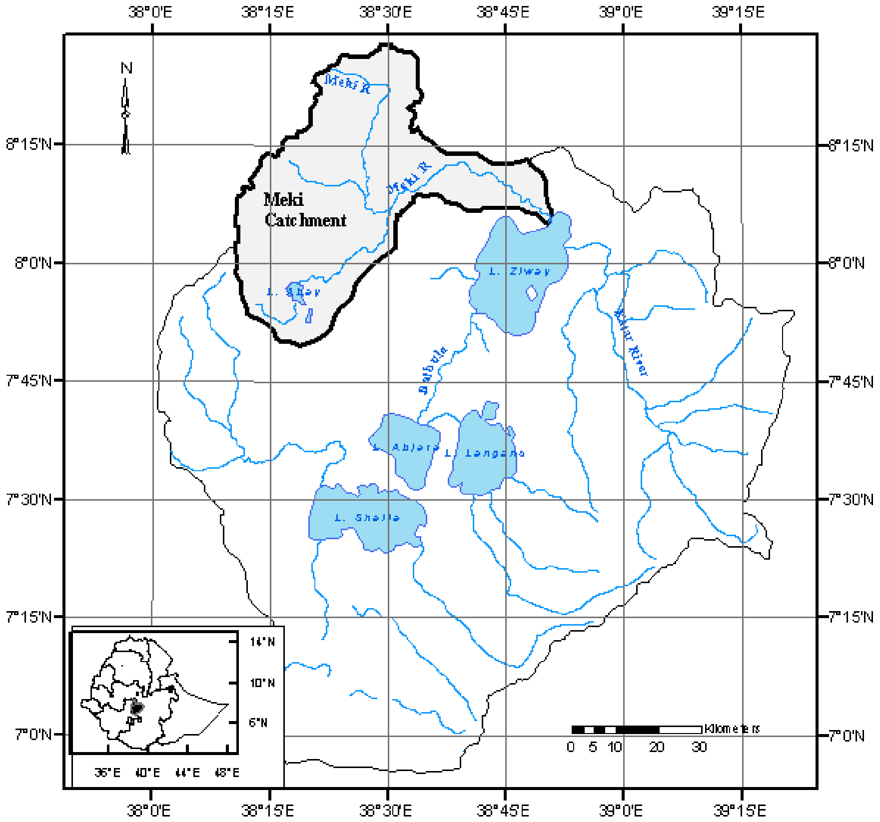

Fig. 1. Location Map of the Meki Catchment within the Ziway-Shalla basin in the main Ethiopian Rift (MER).

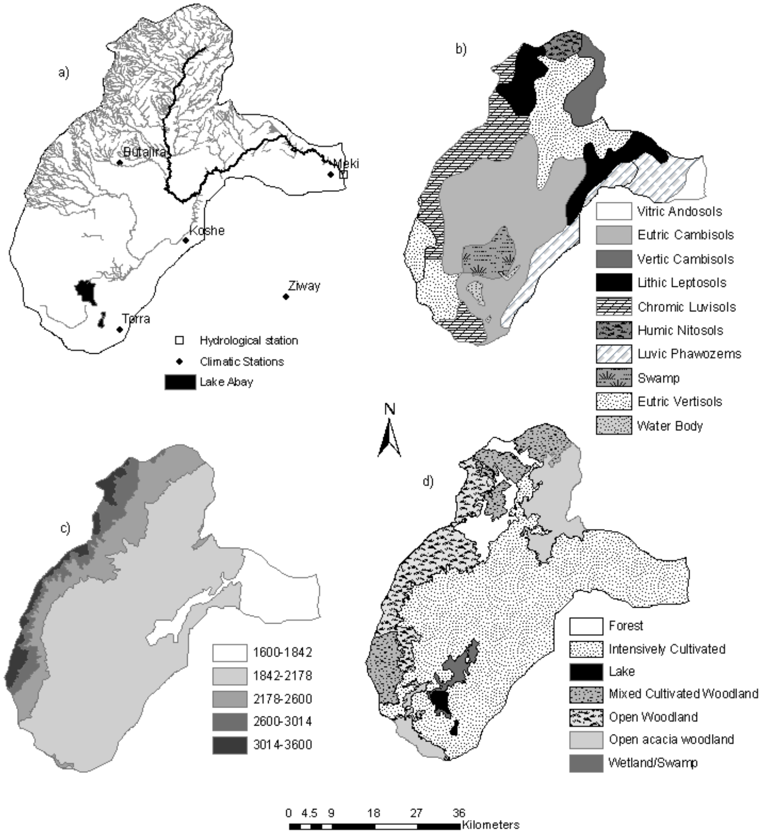

Fig. 2. **(a)** Drainage network, **(b)** Soil map, **(c)** Topographic elevation m a.s.l. and **(d)** Generalized land use map of Meki River Catchment.

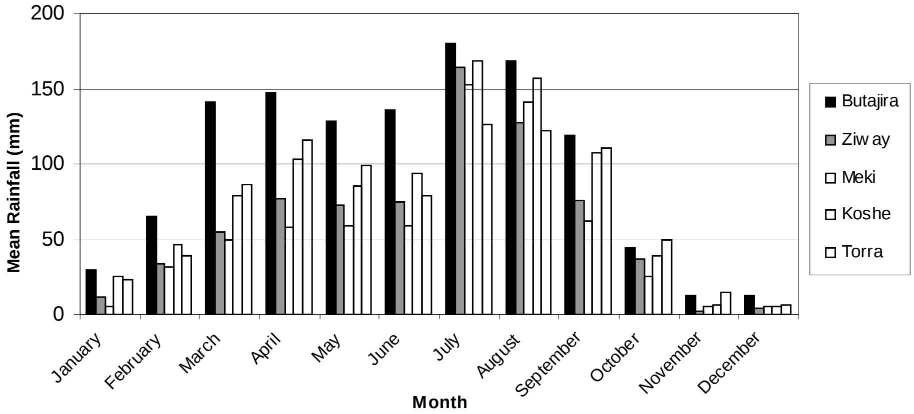

Fig. 3. Mean Monthly rainfall at some stations in the Meki Catchment.

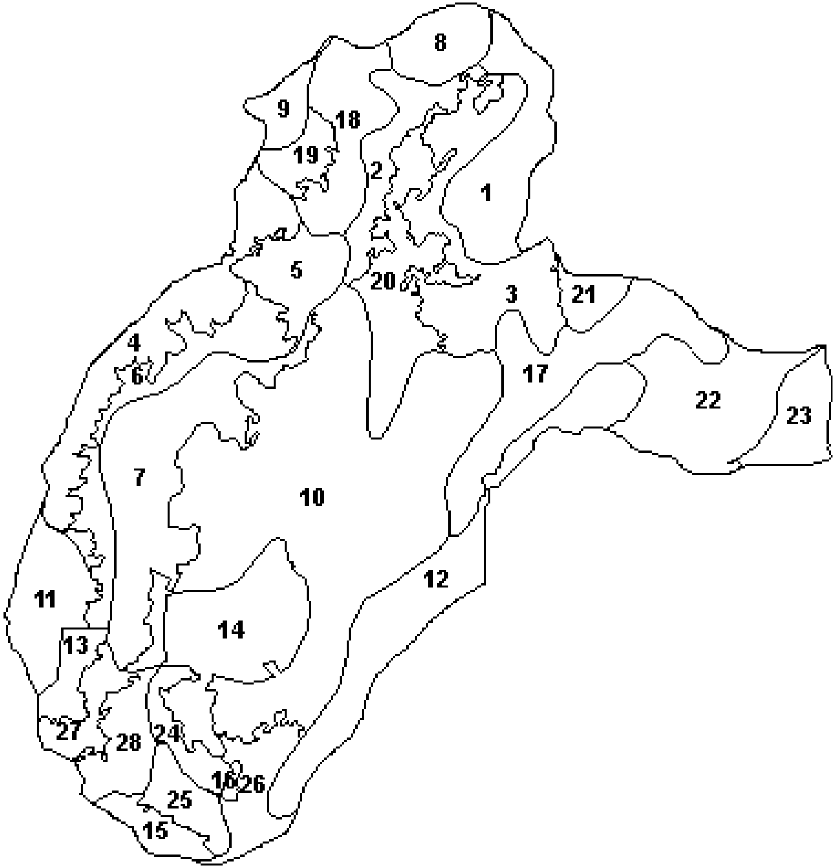

Fig. 4. Delineated HRUs of the Meki Catchment.

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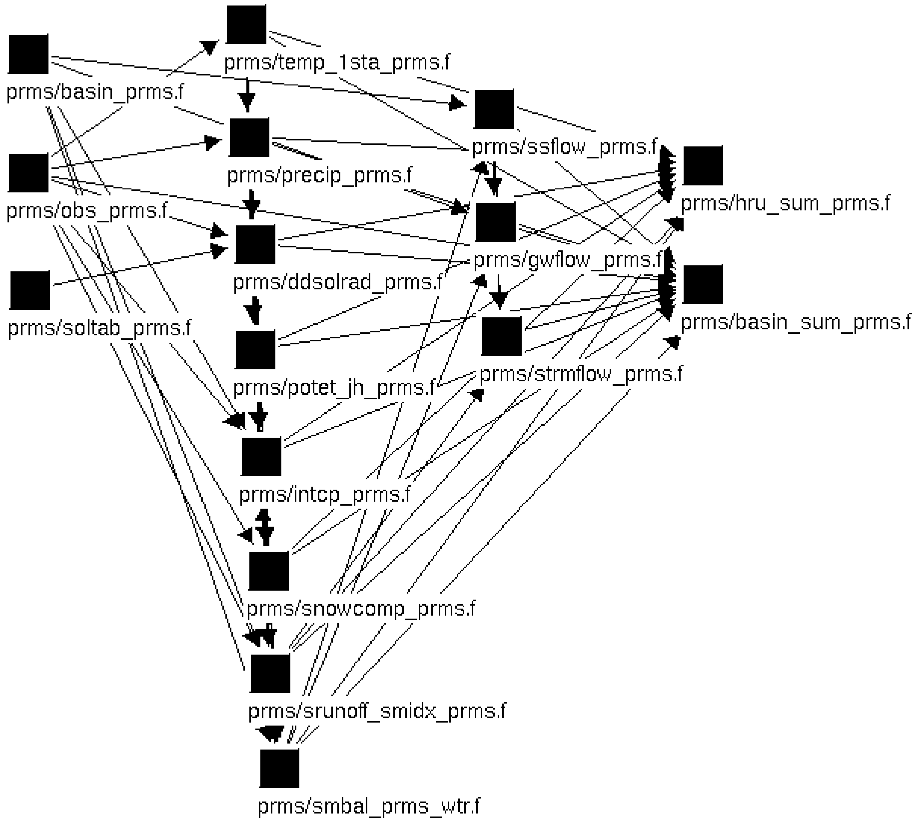

Fig. 5. Specific modules linked to build PRMS for Meki Catchment.

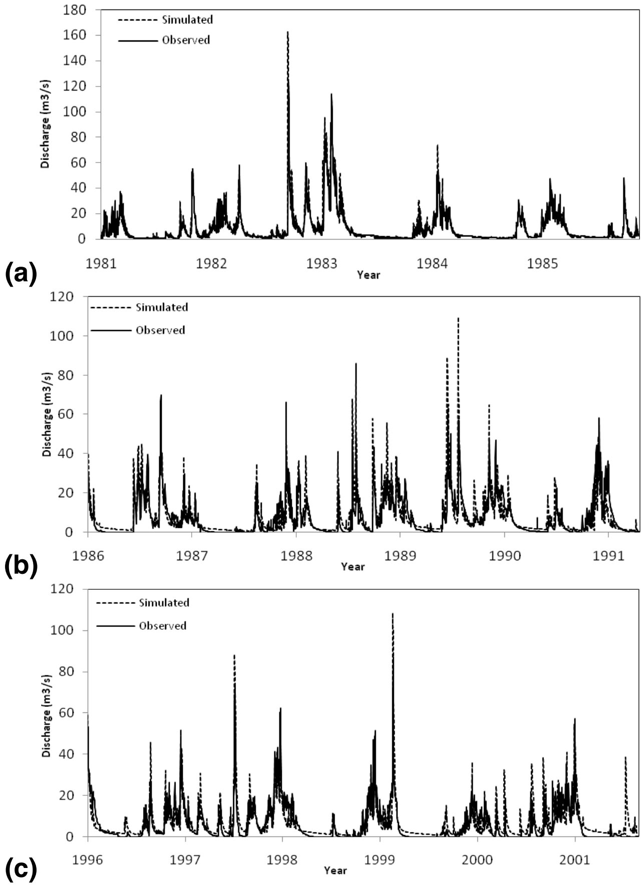

Fig. 6. Daily observed and simulated discharge of Meki river for the **(a)** Calibration period, **(b)** validation period 1 and **(c)** Validation Period 2.

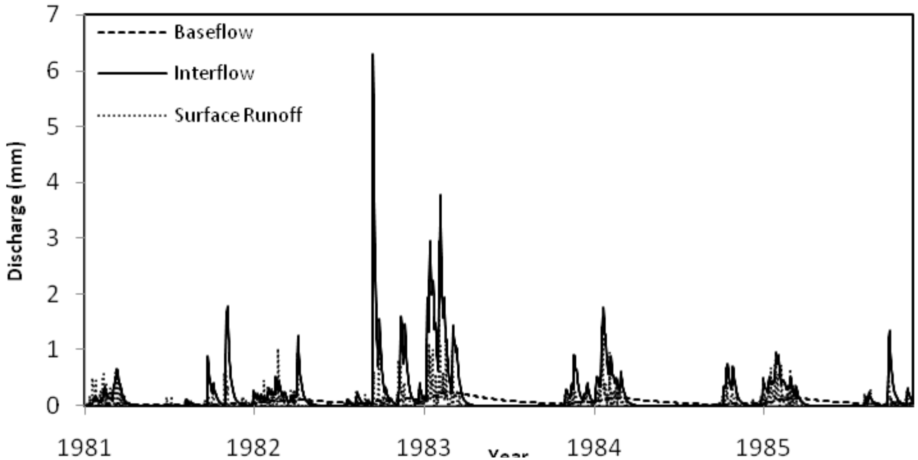

Fig. 7. The three flow components of the daily simulated discharge at the outlet of the Meki River.

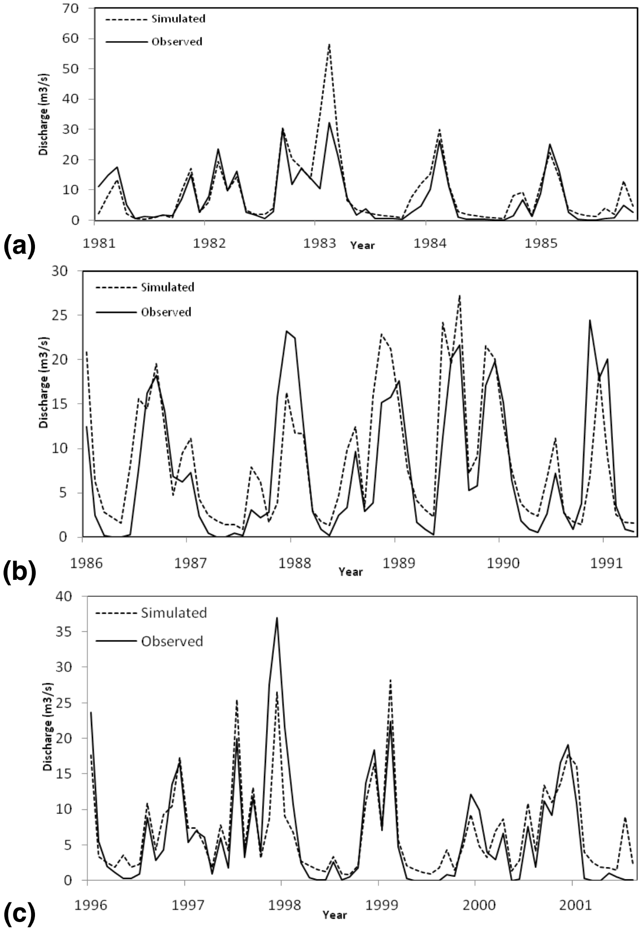

Fig. 8. Mean monthly simulated and observed discharge at the outlet of Meki River for **(a)** the calibration period, **(b)** Validation period 1 and **(c)** Validation period 2.

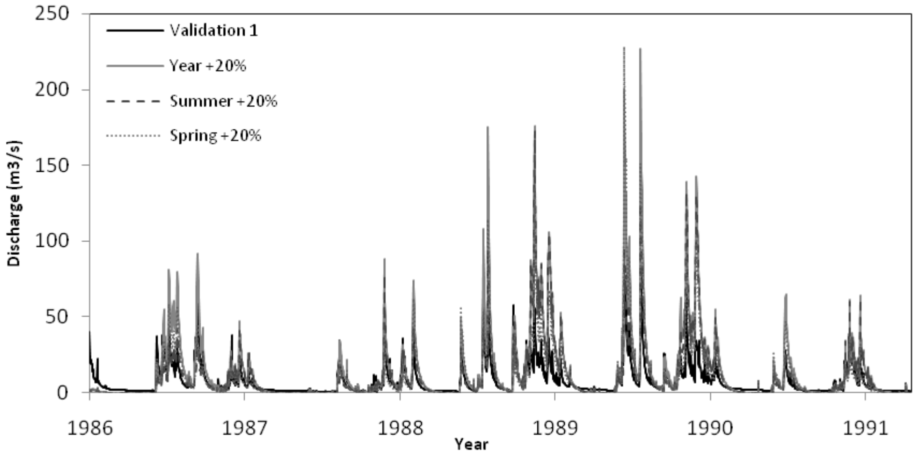

Fig. 9. Simulated discharge for validation period 1 and selected rainfall scenarios.

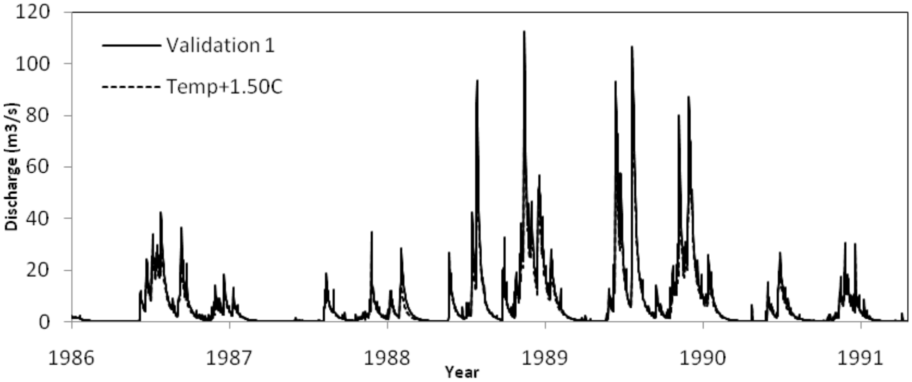

Fig. 10. Simulated discharge for validation period 1 and temperature scenario.