academicJournals

Vol. 6(2), pp. 73-87, February, 2014
DOI: 10.5897/IJWREE2013.0449
ISSN 2141-6613

http://www.academicjournals.org/IJWREE

International Journal of Water Resources and Environmental Engineering

Full Length Research Paper

Catchment dynamics and its impact on runoff generation: Coupling watershed modelling and statistical analysis to detect catchment responses

Negash Wagesho

Department of Water Resources and Irrigation Engineering, Arba Minch University, Arba Minch, Ethiopia.

Received 30 September, 2013; Accepted 29 January, 2014

Catchment response as consequence of changes in vegetation cover and land use management could not be well explained by statistical methods alone. At the same time, long range periodic and trend components of time series are not adequately predicted by watershed modeling. Therefore, joint application of statistical time series analysis and watershed modeling better help to understand the underlying climate variability and catchment dynamics. In this paper, an attempt has been made to examine the effects of climate variability and catchment dynamics at two agricultural watersheds situated in Rift Valley lakes basin of Ethiopia. Distributed hydrologic modeling is used to characterize catchment dynamics whereas statistical methods (time-trend, double mass curve, flow duration curve analysis) are applied to explain the accompanying climate variability. The simulated surface runoff component increased progressively since 1970s. Percentage annual surface runoff varies from 10 to 23% at Bilate, and 16% to over twofold at Hare watersheds. Statistical time-trend analysis reveals that annual streamflow do not show significant monotonic trend, whereas, extreme daily streamflow at Alaba Kulito of Bilate catchment is characterized by increasing trend during the analysis period. Recurrent yet statistically weaker change point years are found and are independent of each other in two watersheds and hence they are governed by land use attributes unique to respective watersheds that influence overland flow. A rising slope of rainfall-runoff double mass curve during post-1992 and 1994 period at Bilate and Hare watersheds respectively supports increasing trend of streamflow that is not fully explained by time-trend analysis. Time-segmented FDCs of monthly streamflow at Bilate shows increased quantile estimates of high flows for similar level of exceedance probability for recent years. The resulting runoff variability over the analysis period is attributed to climate variability and altered land use/cover conditions, the latter being dominant in the watersheds.

Key words: Land use dynamics, runoff, watershed modeling, trend analysis, climate change.

INTRODUCTION

The response of a catchment, that is, the runoff process is time and space variant and influenced by anthropogenic and climatic factors. For example, a drop of water falling in the form of precipitation usually traverses long path until it reaches the main stream. This long journey is accelerated or decelerated by land cover, soil, rainfall intensity and catchment geomorphologic parameters (Tiwari et al., 2006). The ever-increasing

Email: nwagesho@gmail.com

need for food, fiber and shelter coupled with growing national economic interests has aggravated the land use/land cover condition far greater than that of the natural processes. It is estimated that anthropogenic induced land use/land cover changes have transformed one-third to one-fourth of ice-free surface of our planet into other forms (Vitousek, 1994; Vitousek et al., 1997).

In most parts of the globe, significant areas of pristine ecosystems with lush vegetation have been converted to other forms of land use practices. Conversion of forest cover and dense naturally vegetated area to arable land (Angelsen, 1999; Barbier, 2004) and cattle grazing field has modified bulk water yield from the watersheds. Land use change has been strongest in tropical regions and its contribution to global runoff outweighs that of climate change (Piao et al., 2007). The world's largest natural tropical rain forest of Amazon is currently experiencing a large-scale deforestation due to increasing number of cattle herds in the region that ultimately requires substantial pasturelands (Chaves et al., 2008).

The ever growing demand for food crops, eventually emerging market for commercial crops, timbering and local energy consumption largely transformed the natural forest cover over Ethiopia. The 1985 official document of Ethiopian Relief and Rehabilitation Commission asserts that the country's forest cover was 44% in 1885, 16% in 1950 and 4% in 1985 (McCann, 1997).

The Rift valley lakes basin is one that had undergone similar level of forest decline over the last century. Dense forest and riparian woodlands of the Rift Valley lakes basin eventually converted to open woodland and rangelands. Major fraction of riparian forest that covers in the fertile delta region underwent clear cutting for cultivation.

The scientific understanding of the influence of forest cover and land use changes on water yield of the basin dates back to the early 20th century during which advanced computational power to handle spatial data was almost none-existent. In 1911, the Wagon Wheel Gap experimental watershed in central Colorado and the Priest River experimental forest in northern Idaho of USA were established to study forest associated influences on streamflow and erosion. Similar attempts were further extended to Europe (Hegg et al., 2006), Southern and Eastern parts of Africa (Wight, 1940; 1943; Dagg and Blackie, 1965) during later years. Field experiments and catchment studies conducted in multiple watersheds across the globe showed that forest reduction increases water yield (Hibbert, 1967; Edwards and Blackie, 1981; Bosch and Hewlett, 1982; Fohrer et al., 2001; Hundecha and Bardossy, 2004; Yu et al., 2008) and sediment load (Alansi et al., 2009) from the catchment.

Effect of land use/land cover on runoff and sediment yield from the catchment is investigated following different approaches worldwide. The classical hydrologic models of a pair catchment consideration such as control and treatments (Bates, 1921; Bates and Henry, 1928; Nemec et al., 1967) are in vogue to simulate the effect of land cover on watersheds. However, the areal extent of a control watershed is usually very small (Troendle and King, 1987; Hessling, 1999; Iroume et al., 2005; Hegg et al., 2006) and hence the physical relationship developed between paired catchments is usually influenced by the watershed geo-morphological parameters.

Mati et al. (2008) investigated the response of land cover changes at Mara Basin of Eastern Africa and observed significant increase in runoff over less than a couple of decades. Forest cover was reduced by approximately 70% over the years 1971 to 2000 in the Upper Gilgel Abbay catchment of the Blue Nile basin of Ethiopia (Rientjes et al., 2011). Reduced forest cover induced contrastingly variable streamflow trend in two neighbouring catchments of Blue Nile basin. Increased deforestation and intensified cultivation due to burgeoning population accelerated soil degradation rate and increased surface runoff at Ethiopian highlands (Hurni et al., 2005).

Study of catchment response with respect to vegetation cover and land use management are documented in many studies (Dunford and Fletcher, 1947; Bari and Smettem, 2004; Shi et al., 2007; Syvitski et al., 2007; Yang and Tian, 2009; Li et al., 2010; Seibert and McDonnell, 2010; Greenwood et al., 2011). Streamflow variability analyses in literature rely on independent treatment of statistical time series analysis and watershed modelling. However, urban and rural watersheds are under temporally varying vegetation cover condition and hence time series models alone cannot capture runoff variability as a consequence of diminishing or expanding plantation.

Refsgaard et al. (1989) provides a comprehensive guide to distinguish between man-induced influences and natural climate variability on hydrological regimes of catchments. It is suggested that joint application of statistical tests and watershed modelling approach would help to detect the prevailing variability in the catchment. Even though the scientific merits of the methods suggested by Refsgaard et al. (1989) are appealing, studies reported based on similar notions are scanty (Lorup et al., 1998; Li et al., 2012). Couples of studies attempted to explore the impacts of altered land use/land cover condition on hydrological regimes of Ethiopian watersheds using hydrological models (Zeleke and Hurni, 2001; Legesse et al., 2003; Gebresamuel et al., 2010).

Computational advancements coupled with availability of satellite data to extract valuable spatial information provide an aura of confidence to analyze watershed hydrologic processes better; however, limited spatial and temporal datasets available to characterize the watershed processes besetting the endeavor of scientific communities in the developing countries. The Rift Valley lakes basin of Ethiopia is one among which access to real-time hydro-meteorological data and spatial information is scarce. It is a basin characterized by very limited historical hydro-climatic records and remains under significant water and land resources exploitation for the benefit of the rural population.

The present study concentrates on examining the response of a catchment to runoff for temporally varied land use/land cover conditions using physically based distributed hydrologic modelling. The catchment response is investigated by simulating runoff for temporally varied land use/land cover conditions over the last quarter of twentieth century. Finally, statistical analysis (trends, double mass curve and flow duration curves) of observed streamflow and rainfall is carried out to investigate the behavior of associated time-trend with respect to the prevailing land use/land cover conditions.

Description of the study area

The impact of land use dynamics was investigated in two rural watersheds (Bilate and Hare) in the Rift Valley lakes basin of Ethiopia. The watersheds are selected on the basis of multiple considerations. Prevailing land use dynamics over the last couple of decades and sedimentation of conveyance channels resulted in major anthropogenic disturbances in the watersheds. The highland portions of the watersheds are characterized by humid climatic condition whereas the lower flood plains are known for their semi-arid nature. Increased surface water resource competition for agricultural purpose is eminent in semi-arid parts of the watersheds.

Bilate watershed (5330 km^2 at the gauging outlet) is characterized by humid and semi-arid climatic conditions with bimodal rainfall pattern with major rainfall during the summer monsoon season. The average annual rainfall variability is linearly correlated to the altitude in the watershed. Deforestation due to expansion of agricultural lands, cattle grazing and timbering substantially reduced the vegetation cover in the watershed. Deep gullies and massive bare soil pillars at upstream part of the watershed testifies its vulnerability to erosion hazard. The entire watershed practices a mixed cropping pattern where the lower foot of the watershed utilizes irrigation (approximately 1260 ha of government owned farm) to grow commercial crops such as tobacco and maize. Currently the demand for irrigation water is increasing and small scale communal and medium scale private investors are under urgent course of water demand.

Hare watershed (166.5 km^2 at the gauging outlet) is characterized by steep valleys at upstream mountainous highland and progressively stretches to flat fluvial plain until it joins the terminal lake Abaya. The lower plain area of the watershed is known for its intense competition for irrigation water among the local farmers, state and private owned irrigation firms. The upstream highland region of the watershed experiences a humid climate with an average annual rainfall magnitude of 1250 mm in contrast to 870 mm of rainfall at Arba Minch region of the downstream sub-watershed area.

The upstream community of Hare basin is fully engaged on rain-fed cultivation and associated agricultural activities. The lower fluvial plains utilize communal based traditional and modern irrigation schemes to supplement rain-fed cultivation on nearly 2200 ha of land. Maize, sweet potato, banana, mango and cotton are among the major crops growing in the semi-arid irrigated watershed territory. Land resource competition as a result of growing number of population aggravated conversion of forest cover into agricultural plots and residential area. Household energy consumption is almost entirely based on wood biomass in the watershed and becomes another culprit to forest reduction. Figure 1 presents the major river basins in Ethiopia and location of study watersheds (Bilate and Hare).

MATERIALS AND METHODS

Data sources

The datasets utilized to investigate the impact of land use/land cover changes on runoff generation at agricultural watersheds include time variant landsat imageries, DEMs, soil and hydro-meteorological dataset. Table 1 provides details of orthorectified four band Multi-Spectral Scanner (MSS) LandSat-4, Thematic Mapper (TM) and seven band Enhanced Thematic Mapper Plus (ETM+) land cover imageries acquired from Global Land Cover Facility archives (http://glcf.umiacs.umd.edu/data/landsat) for the present study.

An enhanced 90 m x 90 m longitudinal resolution processed Shuttle Radar Topographic Mission DEM data version 4.1 (Jarvis et al., 2008) is accessed from International Centre for Tropical Agriculture (CIAT) online source (http://srtm.csi.cgiar.org) and processed using ERDAS Imagine 9.3 following unsupervised image classification. Soil feature classes and respective physical properties for the study watersheds are customized from World Food and Agricultural Organization (FAO) soil map. Required weather data to run hydrologic model has been gathered from regional and national meteorological offices. Daily rainfall, maximum and minimum temperature, wind speed, sun shine hours and relative humidity for five nearby stations for a record length between 1980 and 2009 are collected for subsequent analysis. Table 2 describes details of weather input data available for analysis. Daily streamflow records are collected from Ministry of Water Resources (MoWR) hydrological data archives of Ethiopia. Standard preliminary data analysis for consistency is conducted.

Land use/Land cover data

Temporal landsat images (1973/76, 1984/86 and 2000) acquired from Global Land Cover Facility archives have been processed to extract required land use information. The selected temporal landsat images are sufficiently long enough to each other to observe the expected land use changes and consequent catchment responses. Geometrically corrected landsat images are processed using ERDAS Imagine image analysis facilities. Supervised and unsupervised image classification is applied and further assimilated based on land use class similarity. Classified land use map units are also verified against coarser resolution land use maps developed by the Ministry of Water Resources (MoWR) of Ethiopia. The present classification is based on small spatial scale and hence identified more land use classes than the existing broad classification by MoWR. The land use management classes for the

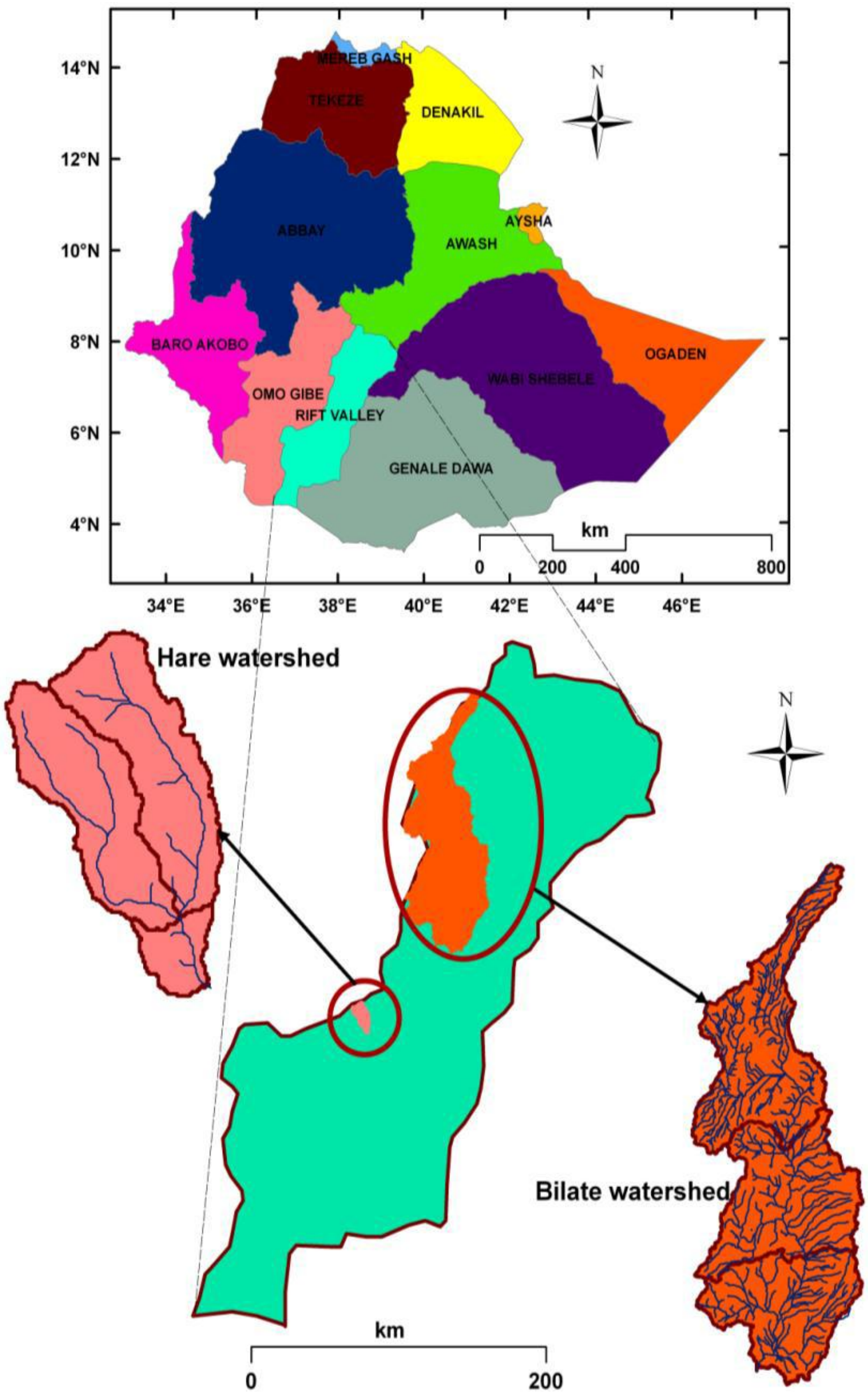

Figure 1. Description of the study area: The figure shows major river basins in Ethiopia (top) and the two study watersheds in the Main Rift Valley lakes basin of Ethiopia (bottom).

Table 1. Orthorectified landsat images used for land use/land cover classification.

Landsat image ID	Sensor type	Date acquired	Path/Row	Producer	Watershed associated
029-736	MSS	Jan. 31, 1973	181/055	Earthsat	Bilate
044-075	MSS	Jan. 25, 1976	181/056	Earthsat	Hare
012-383	TM	Nov. 22, 1984	169/055	Earthsat	Bilate
012-382	TM	Nov. 22, 1984	169/054	Earthsat	Bilate
012-371	TM	Jan. 21, 1986	168/055	Earthsat	Bilate
012-384	TM	Jan. 28, 1986	169/056	Earthsat	Hare
037-658	ETM+	Nov. 26, 2000	169/055	Earthsat	Bilate
037-883	ETM+	Feb. 05, 2000	168/055	Earthsat	Bilate
037-659	ETM+	Jan. 27, 2000	169/056	Earthsat	Hare

Table 2. Details of hydro-meteorological dataset used for analysis.

Hydro-meteorological data/stations	Alaba Kulito	Hawassa	Bilate Farm	Arba Minch Farm	Chencha
Daily weather data					
Rainfall	√	√	√	√	√
Max. and Min. Temperature	√	√	√	√	√
Wind Speed	√	√		√	
Sunshine Hours	√	√		√	
Relative humidity	√	√		√	
Record Length	1980-2009	1980-2009	1980-2009	1980-2009	1970-2006
Daily streamflow					
Bilate at Alaba Kulito (1971-2006)	√			√	
Hare near Arba Minch (1980-2006)					

study area are defined following Anderson et al. (2001) land use/land cover classifications described herein under.

Agricultural lands: These include diverse class of cultivated land, plots covered by food and commercial crops (croplands) and land units covered by residuals after immediate harvest.

Forest lands: Forest lands have usually tree-crown areal density capable of modulating the micro climate and water holding capacity of watershed. They range from densely populated tall trees of tropical rain forest used for timbering to moderately grown green forest. Forest lands could be evergreen, deciduous or mixed forest land.

Woodlands: Woodland is a low-density forest forming open habitats for wildlife with limited sun shade. Under drier weather condition and early stage of forest succession, woodlands may convert into Shrublands.

Shrublands: Shrublands are a plant community characterized by vegetation dominated by shrubs, often also including grasses, herbs, and geophytes.

Range lands: These land cover units are typical to arid and semi-arid lands characterized by xerophytic vegetation and transition zones from forest land to sparse woodlands.

Grass lands: These are land units where the potential natural vegetation is predominantly grasses and grass-like plants. It is dominated by naturally occurring grasses as well as those areas of actual rangeland that have been modified to include grasses.

Water and marshy land: Area that remains water logged and swampy throughout the year, and rivers.

Pasture land: Pastureland is an area covered with grass or other plants suitable for the grazing of livestock.

Barren land: Land of limited ability to support life and in which less than one-third of the area has vegetation or other cover. It is an area of thin soil, sand or rocks and the areal coverage of available vegetation is much less than that of range land.

The major land use/land cover units identified for the study watersheds are forest land, woodland, shrub land, pasture, green vegetation, agricultural land, settlements and water body.

Watershed modelling under changing land use/land cover conditions

Physically based distributed hydrologic models such as Syst`eme Hydrologique Europ´een (SHE) (Abbott et al., 1986), Institute of Hydrology Distributed Model (IHDM) (Beven et al., 1987) and SWAT model (Arnold et al., 1993; 1998) have the ability to synthesize various spatial information and weather data to predict catchment responses. SWAT model (Arnold et al., 1993; 1998) has got growing demand among watershed modelers due to its capability to model the watershed responses at very small spatial scale characterized by unique land use, soil and slope attributes called hydrologic response units (HRUs). It is a process oriented hydrologic model developed to predict the impact of land use management practices on water, sediment, agricultural chemical yields from large and complex watersheds with varying degree of spatial information over long period of time.

In the present study, SWAT model is used to analyze the impact of change in land use/land cover on runoff generation in study basins. The ArcHydro module of the ArcSWAT model delineates the watershed boundary and generates prevailing stream network from available digital elevation model with assigned draining area threshold magnitude. The smaller the draining area threshold the denser the stream network. This helps capture the spatial variability of a channel network at very small areal extent. Runoff is generated from individual HRUs and routed to form the main channel flow. The overland flow velocity is affected by the prevailing land cover and soil properties. As a consequence of which both overland and channel flow travel time is affected and subsequent runoff accentuation or attenuation occurs.

Land use/land cover information separated by moderately sufficient time periods (1976/1986/2000) are used as input dataset to the watershed modeling. Other spatial input parameters such as soil, slope and weather information are organized to suit SWAT modeling. Runoff simulation in the watersheds is carried out on daily basis. The model is calibrated using the year 2000 land use/land cover information for both watersheds. The model parameters are further utilized to simulate runoff at desired temporal and spatial scale for the years 1976 and 1986. In SWAT model, the bulk simulated water yield is comprised of surface runoff (SUR Q), lateral flow (LAT Q) and groundwater flow (GW Q). The model has the capability to separate each component independently so that the relative response of catchment to individual components can easily be evaluated. Catchment morphometric parameters and spatial variables such as soil and land covers affect the partition of liquid mass flow into the corresponding components. The study attempts to examine how the land use/land cover has either enhanced or retarded the quick surface flow component being all other factors held constant. Runoff has been simulated for three different land use/Land cover conditions in the watersheds outlet and subsequently analyzed.

Land use/Land cover change and streamflow trend

To reinforce the justification from watershed modeling, the behavior of observed streamflow and rainfall in the study watersheds is examined. Detection of monotonic trends and abrupt changes are assessed using statistical trend analysis and rainfall-runoff double mass curve analysis. The behaviour of historical streamflow is further examined from flow duration curve analysis for time-segmented series.

Monotonic and step changes in annual and daily extreme streamflow magnitude are examined applying the commonly used Mann-Kenadill (MK) (Mann, 1945; Kendall, 1955) and Mann-Whiteny-Pettitt's (MWP) (Pettitt, 1979; Zhang and Lu, 2006) change detection approaches. The MK test statistic is broadly explained in many literatures and hence a concise statistical background of MWP is presented here.

The MWP change detection method is a non-parametric test that can be used to analyze data from two independent groups when measurement is ordinal. It analyzes the degree of separation or overlap between the two groups. For a sequence of random variables X_1, X_2, …, X_T which have a change point at τ (X_t) for t = 1,2,…, τ have a common distribution function F1(x) and X_t for t= τ +1, … T have a common distribution function F2(x) where F1(x) ≠ F2(x) (Pettitt, 1979). The null hypothesis (Ho) assumes that the two set of scores are samples from the same population (no change) and the alternative hypothesis (H1) is that the two sets of scores differ systematically (there is change).

The test statistic is:

$$K_T = \max_{1\le t\le T} \left|U_{t,T}\right| = \max\left(K_T^{+}, K_T^{-}\right) \quad (1)$$

where $$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} \operatorname{sgn}\left(X_i - X_j\right) \quad (2)$$

and $$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 0 \\ 0 & \text{if} \quad \theta = 0 \\ -1 & \text{if} \quad \theta < 0 \end{cases} \quad (3)$$

For changes in one direction, that is, for downward (K_T^+) or upward shift (K_T^-), K_T is given as:

$$K_T^{+} = \max_{1\le t\le T} U_{t,T} \quad \text{and} \quad K_T^{-} = -\min_{1\le t\le T} U_{t,T} \quad (4)$$

The significance level associated to K_T is estimated by:

$$\rho = \exp\left(\frac{-6K_T^{2}}{T^3 + T^2}\right) \quad (5)$$

If the magnitude of ρ is smaller than the specific significance level (for example α =0.05) the null hypothesis is rejected. The time t when K_T occurs is the change point time.

RESULTS AND DISCUSSION

Land use/Land cover dynamics in the study watersheds during 1973 to 2000

Temporal land use/land cover map developed from satellite imageries for three different time spans (1973/76, 1986 and 2000) shows major transformation of land cover and land use management over the last quarter of twentieth century.

A phenomenal increase in cultivated land and settlement area over the analysis period is observed at both watersheds. Forest cover decreased by 34.5 and 50.7% during 1976/86 and 1986/2000 time period respectively at Bilate watershed (Figure 2). The total area covered by cultivated land, settlement area and barren land increased by 30.9 and 23.4% for 1976/86 and 1986/2000 land use condition respectively. However, on aggregate the rangelands increased by 26.7% whereas the pasture land units decreased by 43.8%. The decrease in pasture land might be the result of growing demand of arable land for crop cultivation in most parts of the watershed. Land units that lost its fertile top soil formation due to excessive erosion and weathering activities are commonly located as small patches in the middle and lower Bilate basin.

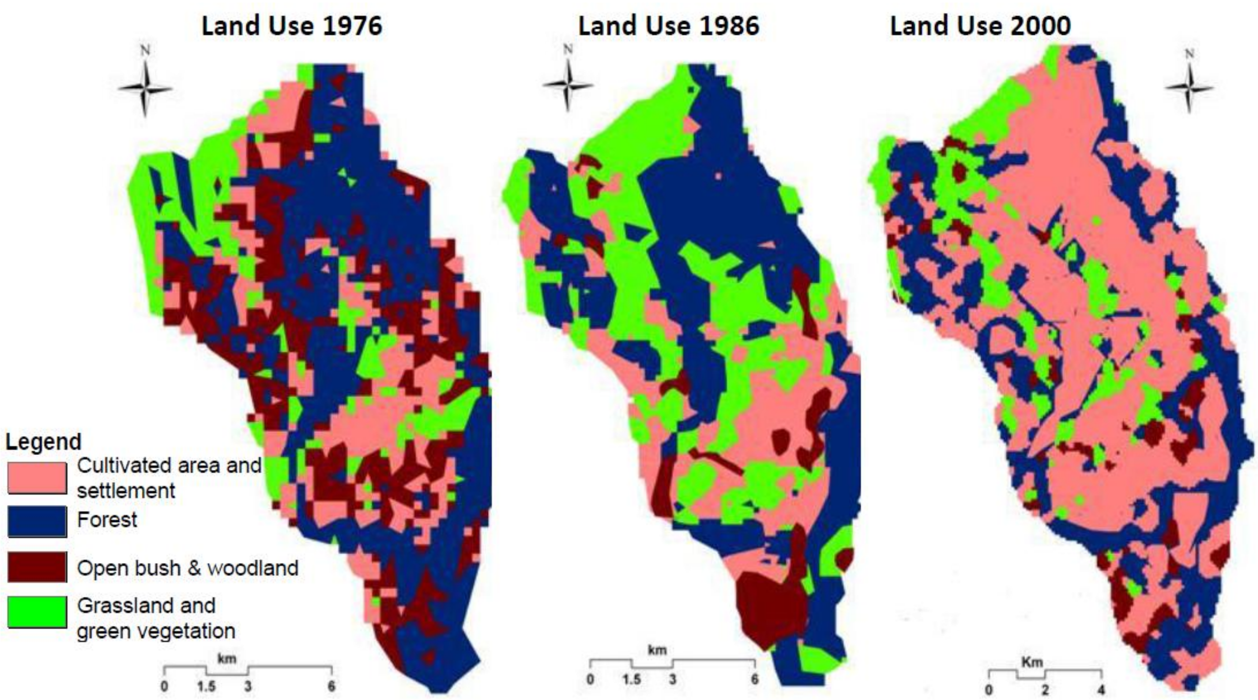

Figure 2. Reclassified land use/land cover classes for use in hydrologic modeling at Hare watershed.

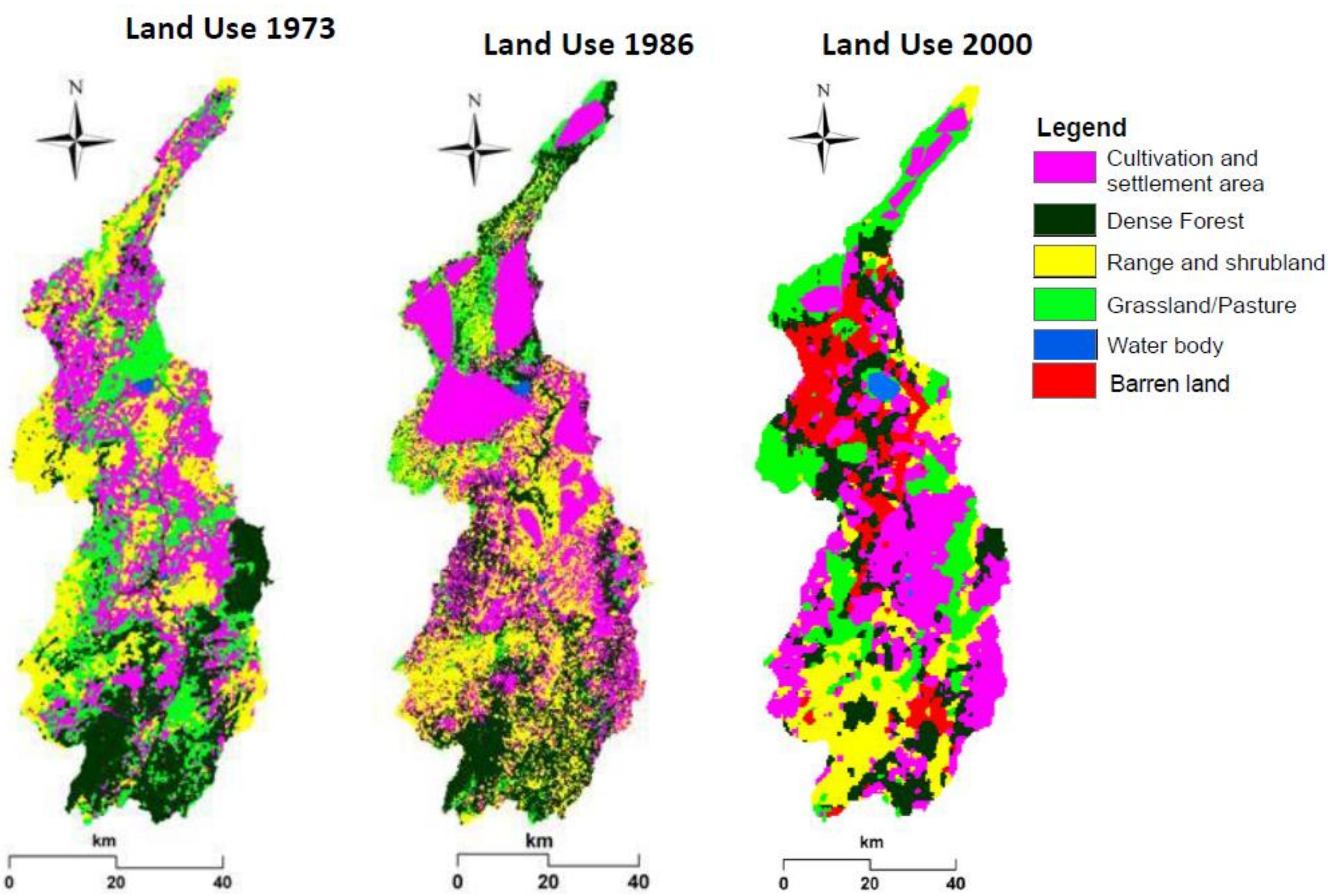

Figure 3. Reclassified land use/land cover classes for use in hydrologic modeling at Bilate watershed.

Table 3. Areal coverage of reclassified land use /land cover condition for study watersheds.

Land use/Land cover class	Percentage Land use/Land cover			Percentage change		
	1976	1986	2000	1976-1986	1986-2000	1976-2000
Bilate Watershed						
Cultivation and Settlement	36.1	47.2	58.3	30.9	23.4	61.6
Forest-mixed	26.5	17.4	8.6	-34.5	-50.7	-67.7
Range and shrubland	17.2	24.8	21.8	44.0	-12.0	26.7
Pasture	20.2	10.6	11.4	-47.4	6.7	-43.8
Hare watershed						
Cultivation and Settlement	29.6	36.4	47.4	22.7	30.3	59.9
Forest-mixed	30.2	25.3	18.2	-16.2	-28.1	-39.8
Rangeland	24.3	27.2	24.2	12.1	-11.0	-0.2
Pasture	15.9	11.1	10.2	-30.0	-8.1	-35.7

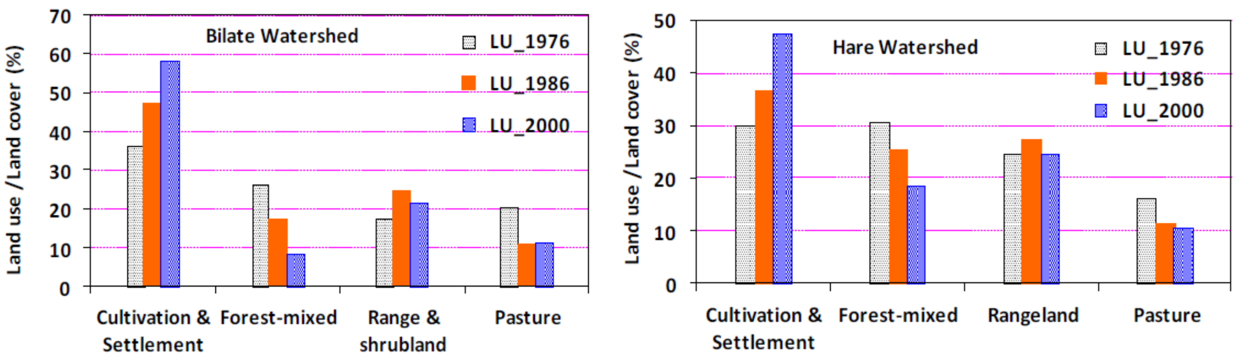

Figure 4. Temporal variations of dominant land use/land cover proportion in the study watersheds.

The land use/land cover condition at Hare basin follows similar temporal trend to that of Bilate basin. An aggregate increment of 60% in cultivated land and rural settlement whereas 40% decrement in forest cover is identified during 1976 to 2000 analysis period (Figure 3). Area under pasture and rangeland found to decrease during the same period. Table 3 provides major land use /land cover conditions and respective percentage changes over the time period 1976/1986/2000 at Bilate and Hare watersheds of the Rift Valley lakes basin of Ethiopia. The major fraction of land use/land cover is occupied by cultivation, settlement and forest cover during 1970s, however, the forest cover eventually reduced during the last two decades of twentieth century (Figure 4). The upstream riverine course of Hare watershed commonly grows an evergreen bamboo plantation. Its dense and fibrous roots have soil gripping capability hence minimizes erosion of top soil layers.

Land use/Land cover dynamics and hydrologic modeling

Land use/land cover affects runoff in the form of accelerated or retarded overland flow as a result of slow or fast infiltration rate and initial abstraction due to canopy cover (Jinno et al., 2009). The surface runoff component is separated from the total water yield of a catchment to assess its variability due to altered land use/land cover conditions. The impact of temporally varying land use/land cover condition on runoff generation in the watersheds is modeled using Soil and Water Assessment Tool.

Hydrologic modelling

The Soil and Water Assessment Tool is data intensive model that captures the underlying hydrologic processes at small spatial scale with unique soil, land use and slope attributes. DEM, soil, land use, weather and an optional stream outlets location data are required for initial model setup. The slope map of the watersheds is reclassified into three slope classes (0 to 5%, 5 to 10% and >10%) based on the topography of the watersheds. Feature class soil maps and corresponding soil physical properties are extracted from FAO soil map for dominant soil units. Local soil information organized from *in-situ* observations are further used to augment the soil classification. The soil units are categorized into 9 and 4 dominant soil classes at Bilate and Hare watersheds respectively. Land use/land cover information is extracted from Satellite imageries for three different time period are described in the findings of this research used for SWAT model run. Model sensitivity analysis is carried out for both with and without observed discharge cases to identify the most sensitive model parameters. SWAT model is calibrated for the year 2000 land use condition and subsequently used to predict runoff for 1976 and 1986 land use conditions. The Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm (Abbaspour, 2009) is applied for model calibration. Model calibration and validation is covered widely in previous works for the study watersheds. Other input variables such as weather, soil and catchment morphologic parameters remain constant for each simulation. This enables us to identify the catchment response uniquely to land use changes.

SWAT model disaggregates the output into surface runoff component, lateral flow and shallow aquifer flow. The response of a catchment as a result of land use change is evaluated in terms of simulated surface runoff component. It is observed that the surface runoff component increases progressively since mid 1970s at both watersheds. The rate of change of runoff with respect to the base period (1976) is more significant during wet years. This is due to high intensity and extended duration of rainfall events that are more likely to produce runoff immediately with minimal travel time. Moreover, availability of sufficient antecedent moisture condition in the soil retards infiltration rate and accelerates overland flow.

Catchment geomorphologic factors also attributed to varying rate of change of surface runoff magnitude. In steep and smaller size Hare watershed the rate of change is more profound. This is because, the diminishing rate of vegetation cover over the analysis period aggravated runoff generation in Hare watershed. The catchment response is more significant during wet years of the analysis period. The land use condition in the year 2000 increased annual surface runoff by 10 to 23% at Bilate watershed with respect to 1976 reference line. The rate of change is higher at smaller size Hare watershed. The increment extends from 16% to more than 100% during the very wet years. Figure 5 presents the relative proportion of simulated surface runoff component for three different land use conditions at two watersheds maintaining all other factors constant throughout the three simulations.

Average monthly predicted surface runoff is compared against respective rainfall in the watersheds during the analysis period. The surface runoff component shows better agreement to corresponding rainfall for all simulations. The coefficient of determination (R^2) ranges from 0.85 to 0.96. A better correlation (R^2 = 0.91-0.96) is observed at Hare watershed where the statistical relationship follows an exponential law (Figure 6). Intercomparison of simulated annual surface runoff to corresponding annual rainfall clearly shows increasing runoff magnitude since 1976 land use condition at both watersheds. Simulations for specific land use conditions are approximated by a lower order polynomial and exponential curves where simulated runoff values for recent land use conditions are modestly lying above the early ones (Figure 7). This indicates the recent land use condition is able to generate higher runoff magnitudes than the past years.

Summer monsoon season rainfall dominates at Bilate watershed and subsequently yielded substantial amount of total water yield during June-October months whereas, bimodal rainfall pattern at Hare watershed produced alternating raised hydrograph limbs during the rainy seasons. The major rainfall season at Hare extends from mid of March to the first decade of June and produced higher peaks during April-May heavy rainfall. The average monthly total runoff was found to increase since the 1976 land use condition. During the dry months the variability in simulated total runoff is insignificant (Figure 8).

Streamflow trend analysis

Statistical trend analysis to detect possible monotonic trends and step changes is conducted for annual and extreme daily streamflow events at Bilate (1971 to 2005) and Hare (1970 to 2007) watersheds. We further examined the historical variability of observed streamflow at Alaba Kulito using flow duration curve (FDC). Mann-Kendall (MK) trend analysis is conducted both for original and prewhitened series to account for the effect of significant serial correlation while detecting possible trends. MK-trend analysis for original and prewhitened series reveals that annual streamflow shows insignificant monotonic trend at both watersheds. However, daily extreme (daily maximum and minimum) streamflow events at Bilate basin are characterized by increasing trends at 5% significance level. No statistically significant streamflow trend is detected at Hare watershed for annual and extreme daily events. The prewhitened series of daily minimum streamflow of Hare is characterized by increasing trend at 10% significance level (Table 4).

Mann-Whitney-Pettitti's method employed for step change detection shows couple of statistically weaker change points at both watersheds. The years 1999 and 1992 are estimated to be with statistically significant yet weak change points at Bilate basin whereas the years 1990 and 1986 are detected as possible change points at Hare watershed. The change points detected at two neighbouring watersheds show that the magnitude and temporal location of change points vary slightly. The change points are noticeable in the mid of 1980s and 1990s. These change points are associated to low annual

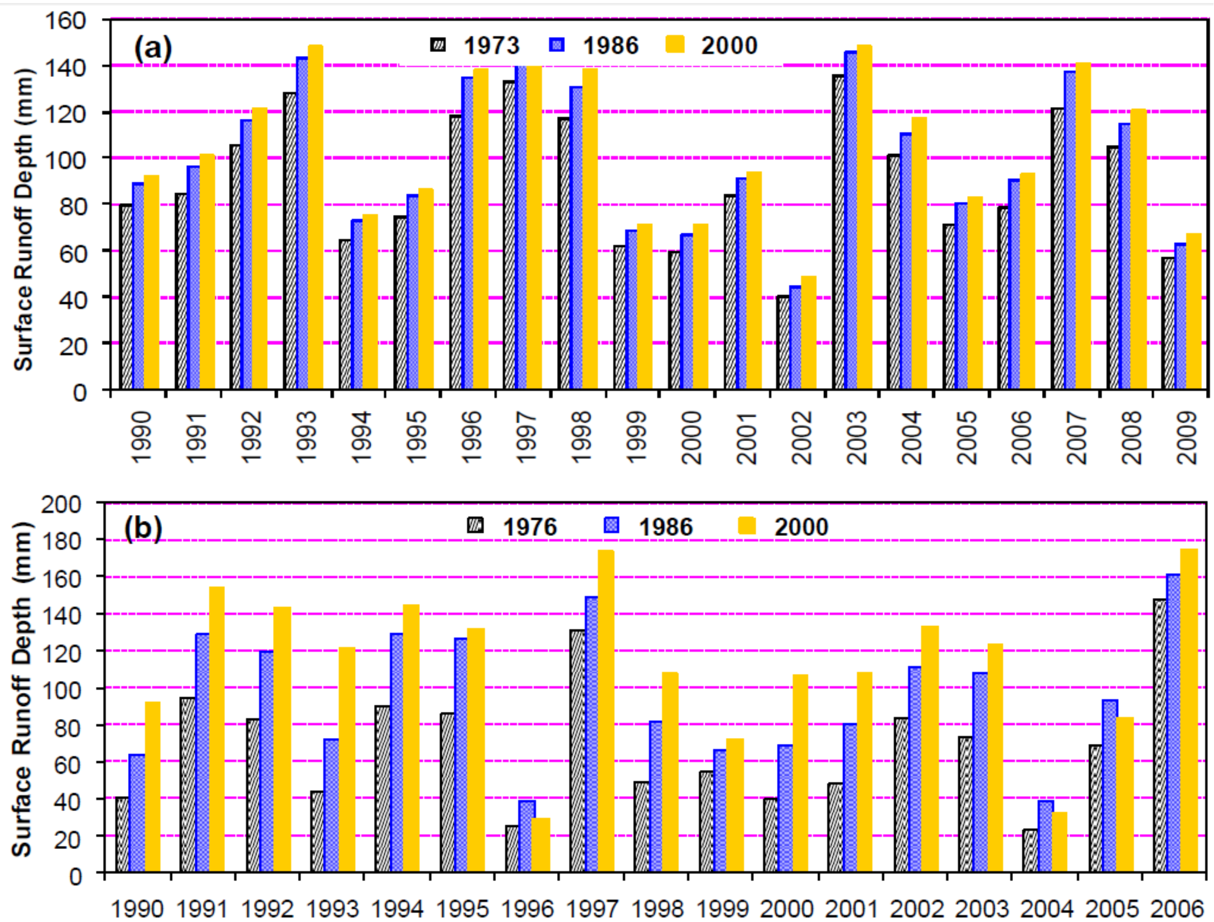

Figure 5. Simulated surface runoff component for different land use/land cover condition during the analysis period.

rainfall years. Minor seasonal water abstraction and other unspecified catchment condition that are not quantified in the present context might have attributed to this recurrent and statistically weak change points. The observed land use changes in the watersheds are not dramatic but they have been developed gradually over the years.

Cumulative mass analysis of rainfall and runoff provides statistical information regarding the underlying input-output relationship. When there is no significant alteration in rainfall and runoff pattern due to various circumstances, the data points in the double mass curve fit into a straight line with uniform slope. However, sudden break in slope line of the mass curve is eminent when either or both of the variables undergo localized or long term deviations from the preceding values.

Double mass curve analysis of observed annual streamflow and rainfall conducted in the study watershed shows slight deviation in slope line of the double mass curve around the year 1992 and 1994 at Bilate and Hare watersheds respectively (Figure 9). This shows that changes occurred in land use/cover condition in the two watersheds are independent. Even though the change in slope after the break point is small (0.005 MCM/mm at Bilate and 0.012 MCM/mm at Hare watersheds), yet it is indicative of increased runoff after 1990s.

Contrary to insignificant trends of annual rainfall in the study watersheds, the maximum daily streamflow at Alaba Kulito of Bilate basin follows statistically increasing trend since 1980. However, average annual streamflow at both watersheds does not reveal statistically significant trends. Altered land use/cover condition enhanced quick storm responses with less attenuated hydrograph. The increasing trend of maximum daily streamflow at Bilate is a characteristic example of such less diffused streamflow in time and space.

The percentage of time a given flow magnitude equaled or exceeded an observation period, described as flow duration curve (FDC), explains the prevailing relationship between the magnitude and frequency of streamflow. The behavior of historical streamflow variability could be studied from the plot of discharge versus corresponding probability of exceedance. It should be noted that the underlying relationship is dependent up on the total record length (n-values) utilized for FDC construction. Average monthly streamflow records are divided into segments of preferably ten years and FDCs are

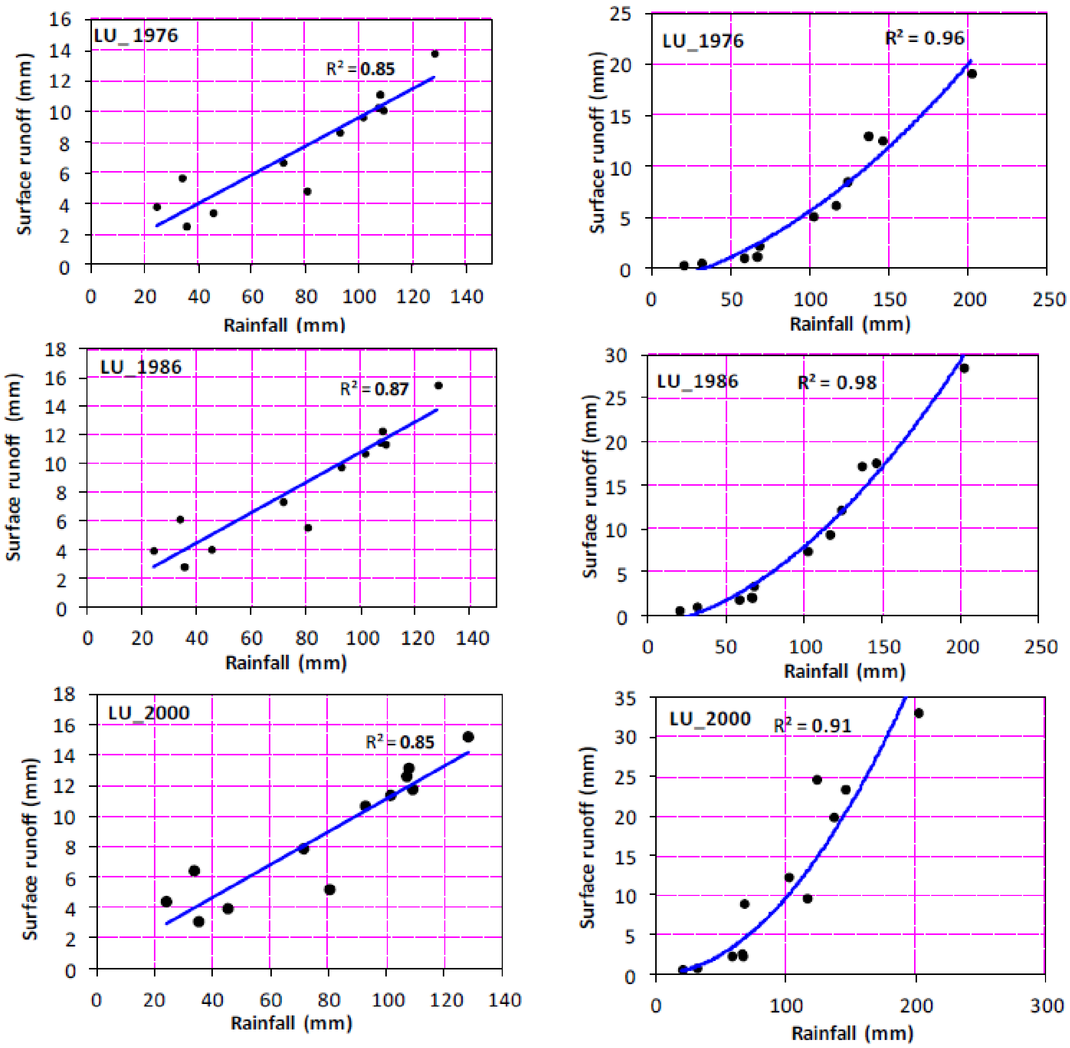

Figure 6. Average monthly simulated surface rainfall-runoff relationship for different land use condition at Hare (left column) and Bilate (right column) watersheds.

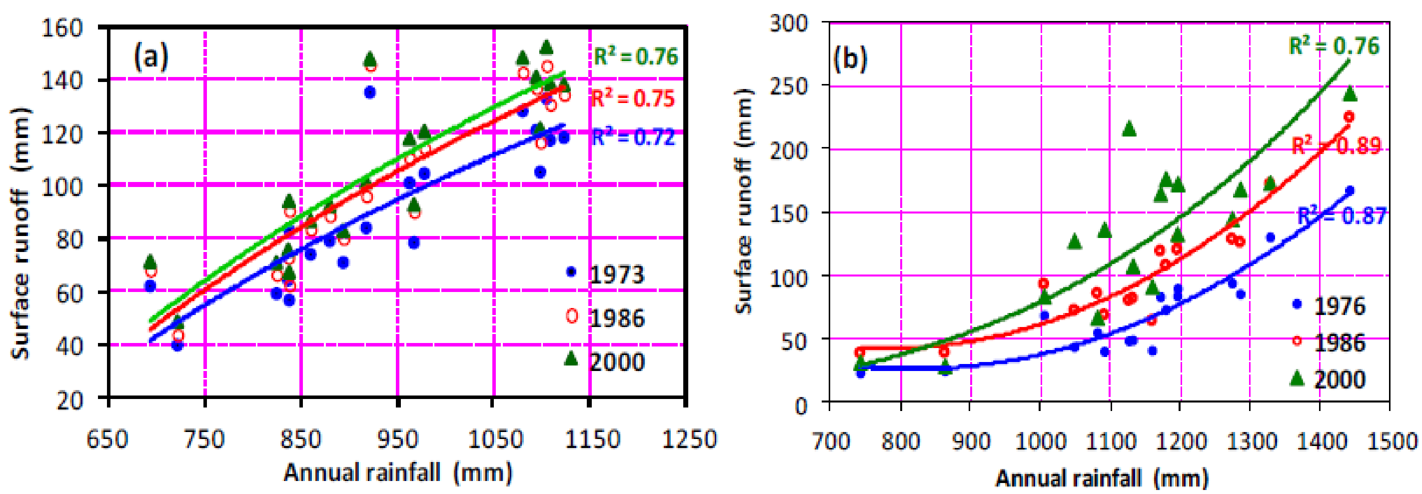

Figure 7. Average annual simulated surface runoff and rainfall relationship for three (1976, 1986 and 2000) land use/land cover conditions at Bilate (a) and Hare (b) watersheds. Smooth lines are polynomial (a) and exponential (b) curves fit to the data points. The best fit line lies atop the other for recent year's rainfall-runoff relationship.

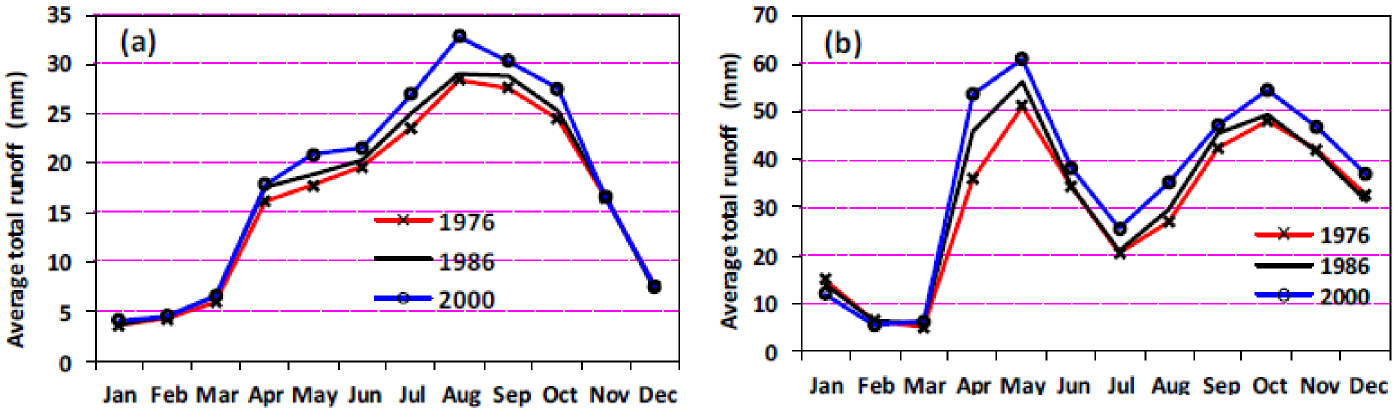

Figure 8. Simulated average monthly total water yield for three (1976, 1986, 2000) land use/land cover conditions at Bilate (a) and Hare (b) watersheds. The simulation is averaged for 1990-2009 at Bilate and 1990-2006 at Hare watersheds.

Table 4. Trend analysis of annual and extreme daily streamflow series for the study watersheds.

Streamflow series	Trend test statistics					
	Mann-Kendall original series			Mann-Kendall prewhitened series		
	S	Z	Trend	S	Z	Trend
Bilate Streamflow						
Annual series	49	0.676	NS	47	0.648	NS
Daily maximum series	186	**2.612**	+	227	**3.291**	+
Daily minimum series	197	**2.807**	+	213	**3.090**	+
Hare streamflow						
Annual series	27	0.536	NS	35	0.701	NS
Daily maximum series	-41	0.826	NS	-57	1.175	NS
Daily minimum series	68	1.398	NS	94	**1.943**	+

S= Mann-Kendall trend test statistic; Z= Standard normal variate; NS= No statistically significant trend; += Increasing trend; Critical Z-value is 1.96 and 1.645 at 5 and 10% confidence levels.

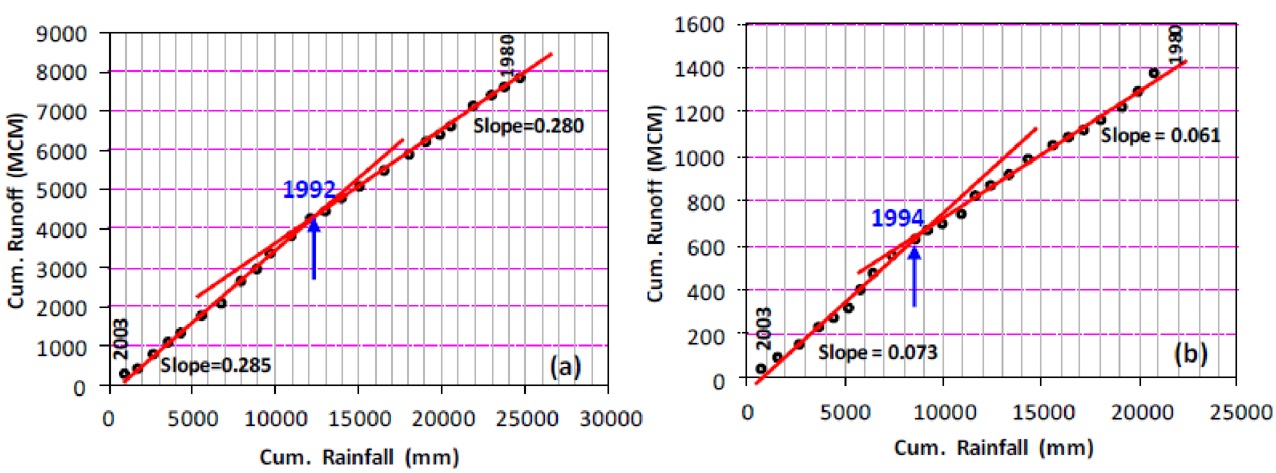

Figure 9. Double mass curve analysis of observed runoff and rainfall at Alba Kulito (a) and Hare-near Arba Minch (b). The slight break in slope of mass curve is observed around 1992 and 1994.

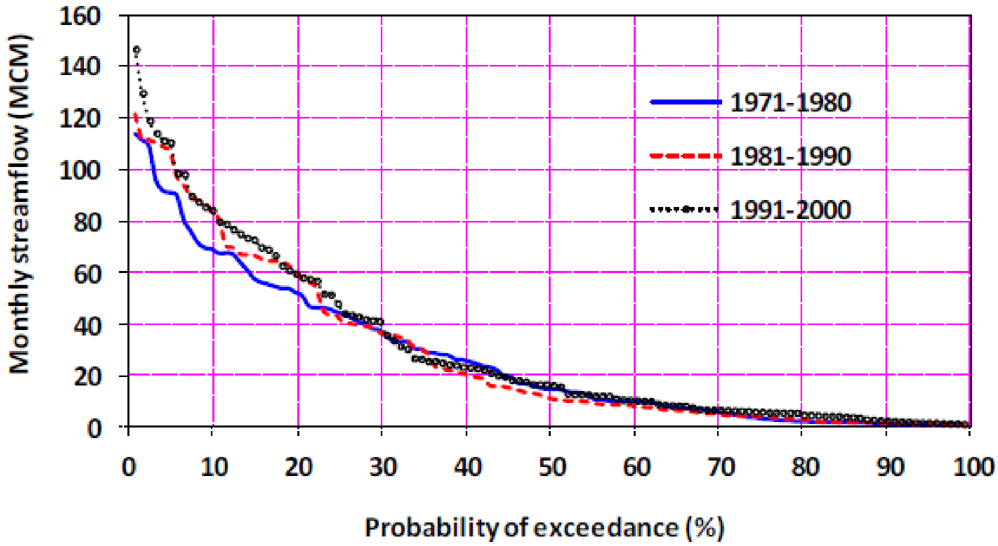

Figure 10. Flow Duration Curves (FDCs) for various segments of average monthly streamflow records of Bilate River at Alaba Kulito station. The FDC for recent decade is lying above the earlier one for the same probability of exceedance.

constructed for each segment. The intent of sub-segmented FDC is to study the relative variability in the behavior of streamflow over three decades; namely, 1970s, 1980s and 1990s. Our analysis of FDC is limited to Bilate streamflow with relatively long and uninterrupted flow records. The corresponding average monthly streamflow at Bilate in the 1990s are positioned at higher level than that of 1970s and 1980s for the same level of exceedance probability. The transition segment, that is, 1980s is characterized by slightly wiggling FDCs (higher quantile estimates during the high flow period and lower estimates during the low flow period) that lies between the 1970s and 1990s (Figure 10). The decadal variability in streamflow could be inferred from such short segmented FDCs which otherwise could not be captured from long term time-trend analysis.

Conclusions

The studied watersheds are under intensive catchment modification since the 1970s. Substantial fraction of riparian forest and pristine vegetation cover were converted to agricultural land and grazing field. Compared to its 1976 reference period, the percentage of forest cover declined by 68 and 40% at Bilate and Hare watersheds respectively. Meanwhile, the gross area of agricultural land, permanent settlements and barren land were collectively expanded by approximately 60% of its baseline proportion at both watersheds during the same period.

The response of a catchment as a result of changing land use/land cover condition is modeled using SWAT for three different (1976/1986/2000) temporal land use conditions. The SWAT model separates overland flow component from total catchment water yield. The simulated surface runoff component increases progressively since 1970s. Percentage annual surface runoff varies from 10 to 23% at Bilate, and 16% to over twofold at Hare watersheds. Statistical time-trend analysis reveals that annual streamflow do not show significant monotonic trend, however, extreme daily streamflow at Alaba Kulito of Bilate catchment is characterized by increasing trend during the analysis period. Recurrent yet statistically weaker step change points are observed in the years 1986, 1990, 1992 and 1999 in the watersheds. The change point years are independent of each other in two watersheds and hence they are governed by land use attributes unique to respective watersheds that influence overland flow. Slightly rising slope of rainfall-runoff double mass curve during post-1992 and 1994 period at Bilate and Hare watersheds respectively supports the subtle increasing trend of streamflow that is not fully explained by time-trend analysis. Time-segmented FDCs of monthly streamflow at Bilate shows increased quantile estimates of high flows for similar level of exceedance probability for recent years.

The attribution of land use/land cover to inter-annual streamflow variability is clearly demonstrated in the present analysis. The increasing trend of observed daily maximum flow at Alaba Kulito and slightly raised slope of rainfall-runoff double mass curve since 1992 supports the attribution of climate induced changes at Bilate catchment. There are an obfuscated time-trend responses for other variables such as average annual and daily minimum flow at both catchments, but not justified statistically. Annual rainfall time-trend analysis in the study watersheds is marked by statistically insignificant trends. This has been covered by previous studies of the authors. Therefore, joint application of statistical methods and watershed modeling has an advantage to distinguish the underlying variability between climate change and catchment dynamics. The effect of catchment dynamics is modeled by watershed model and accompanying long term climate variability, if any, is explained by statistical tests. This avoids the propensity to associate the resulting variability to either of the two (natural climate variability and land use changes).

Conflict of Interests

The author(s) have not declared any conflict of interests.

REFERENCES

Abbaspour KC (2009). SAWT-CUP2 calibration and uncertainty program user manual version 2. Eawag: Swiss Federal Institute of Aquatic Science and Technology.

Abbott MB, Bathurst JC, Cunge JA, O'Connell PE, Rasmussen J (1986). An introduction to the European Hydrological System – Syst`eme Hydrologique Europ´een, "SHE", 2: History and philosophy of a physically-based, distributed modelling system, J. Hydrol. 87:45-59.

Alansi AW, Amin MSM, Halim GA, Shafri HZM, Thamer AM, Waleed ARM, Aimrun W, Ezrin MH (2009). The effect of development and land use change on rainfall-runoff and runoff-sediment relationships under humid tropical condition: Case study of Bernam watershed Malaysia. Eur. J. Sci. Res. 31(1):88-105.

Anderson JR, Hardy EE, Roach JT, Witmer RE (2001). A land use and land cover classification system for use with remote sensor data. Geological Survey Professional Paper, 964, first printing, 1976.

Angelsen A (1999). Agricultural expansion and deforestation: Modelling the impact of population, market forces and property rights. J. Dev. Econ. 58:185-218.

Arnold JG, Allen PM, Bernhardt G (1993). A comprehensive surface-groundwater flow model. J. Hydrol. 142:47-69

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998). Large area hydrologic modeling and assessment. Part 1: Model development. J. Amer. Water Res. Assoc. 34(1):73-89.

Barbier EB (2004). Explaining agricultural land expansion and deforestation in developing countries. Amer. J. of Agr. Econ. 86(5):1347-1353.

Bari M, Smettem KRJ (2004). Modeling monthly runoff generation processes following land use changes: Groundwater-surface water interactions. Hydrol. Earth Syst. Sci. 8(5):903-922.

Bates CG (1921). First results in the streamflow experiment, Wagon Wheel Gap, Colorado. J. Forest. 19(4):402-408.

Bates CG, Henry AJ (1928). Forest and streamflow experiments at Wagon Wheel Gap, Colorado. U.S. Weather Bureau Monthly weather review, Suppl. No. 30. pp. 79.

Beven K, Calver A, Morris EM (1987). The Institute of Hydrology distributed model. Institute of Hydrology Report 98. Wallingford, UK.

Bosch JM, Hewlett JD (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55:3-23.

Chaves J, Neill C, Germer S, Neto SG, Krusche A, Elsenbeer H (2008). Land management impacts on runoff sources in small Amazon watersheds. Hydrol. Proc. 22:1766-1775.

Dagg M, Blackie JR (1965). Studies of the effects of changes in land use on the hydrological cycle in East Africa by means of experimental catchment areas. Int. Assoc. Sci. Hydrol. Bull 10(4):63-75.

Dunford EG, Fletcher PW (1947). Effect of removal of stream-bank vegetation upon water yield. Trans. Amer. Geophys. Union 28(1):105-110.

Edwards KA, Blackie JR (1981). Results of the East African catchment experiments 1958-1974. Trop. Agric. Hydrol. Edited by Lal, R. and Russel, E.W., John Wiley and Sons Ltd.

Fohrer N, Haverkamp S, Eckhardt K, Frede HG (2001). Hydrologic response to land use changes on the catchment scale. Phys. Chem. Earth (B) 26(7-8):577-582.

Gebresamuel G, Singh BR, Dick O (2010). Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia, Acta Agricult. Scandinavica, Section B - Soil Plant Sci. 60 (3):211-226.

Greenwood AJB, Benyon RG, Lane PNJ (2011). A method for assessing the hydrological impact of afforestation using regional mean annual data and empirical rainfall-runoff curves. J. Hydrol. 411:49-65.

Hegg C, McArdell BW, Badoux A (2006). One hundred years of mountain hydrology in Switzerland by the WSL. Hydrol. Proc. 20:371-376.

Hessling M (1999). Hydrological modelling and a pair basin study of Mediterranean. Phys. Chem. Earth (B) 24(l-2):59-63.

Hibbert AR (1967). Forest treatment effects on water yield. In "Forest Hydrology", Sopper WE, Lull HW (eds.), Pergamon, Oxford, 813 pp.

Hundecha Y, Bardossy A (2004). Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model. J. Hydrol. 292:281-295.

Hurni H, Tato K, Zeleke G (2005). The implications of changes in population, land use and land management for surface runoff in the Upper Nile basin area of Ethiopia. Mount. Res. Dev. 25(2):147-154.

Iroume A, Huber A, Schulz K (2005). Summer flows in experimental catchments with different forest covers, Chile. J. Hydrol. 300:300-313.

Jinno K, Tsutsumi A, Alkaeed O, Saita S, Berndtsson R (2009). Effects of land-use change on groundwater recharge model Parameters. Hydrol. Sci. J. 54(2):301-315.

Kendall MG (1955). Rank correlation Methods, Charles Griffin, London.

Li Q, Cai T, Yu M, Lu G, Xie W, Bai X (2010). Investigation into the impacts of land-use change on runoff generation characteristics in the upper Huaihe River basin, China. J. Hydrol. Eng. DOI:10.1061/(ASCE) HE.1943-5584.0000489.

Li H, Zhang Y, Vaze J, Wang B (2012). Separating effects of vegetation change and climate variability using hydrological modelling and sensitivity-based approaches. J. Hydrol. (420-421):403-418.

Lorup JK, Refsgaard JC, Mazvimavi D (1998). Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe. J. Hydrol. 205:147-163.

Mann HB (1945). Nonparametric tests against trend. Econometrica, 13:245-259.

Mati BM, Mutie S, Gadain H, Hame P, Mtalo F (2008). Impacts of land-use/cover changes on the hydrology of the transboundary Mara River, Kenya/Tanzania, Lakes Reservoirs. Resour. Manag. 13(1):169-177.

McCann JC (1997). The Pillow and the forest: Narratives of deforestation in Ethiopia, 1840-1992. Environ. Hist. 2(2):138-159.

Nemec J, Pasak, V, Zeleny V (1967). Forest hydrology research in Czechoslovakia. In Sopper, WE and Lull, HW (Eds): Int. Symposium on Forest Hydrology, Pergamon Press, New York, pp. 31-33.

Piao S, Friedlingstein P, Ciais P, de Noblet-Ducoudre N, Labat D, Zaehle S (2007). Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. Proc. Nat. Acad. Sci. 104(39):15242-15247.

Refsgaard JC, Alley WM, Vuglinsky VS (1989). Methods for distinguishing between man's influence and climatic effects on the Hydrological cycle. IHP-III Project 6.3, UNESCO, Paris.

Rientjes THM, Haile AT, Mannaerts CMM, Kebede E, Habib E, Steenhuis TS (2011). Changes in land cover and stream flows in Gilgel Abbay catchment, Upper Blue Nile basin – Ethiopia. Hydrol. Earth Syst. Sci. 15:1979-1989.

Shi PJ, Yuan Y, Zheng Z, Wang JA, Ge Y and Qiu GY (2007). The

effect of land use/cover change on surface runoff in Shenzhen region, China. Catena 69:31-35.
Seibert J, McDonnel JJ (2010). Land-cover impacts on streamflow: A change-detection modelling approach that incorporates parameter uncertainty. Hydrol. Sci. J. 55(3):316-332.
Syvitski JPM, Milliman, JD (2007). Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. J. Geol., 115:1-19.
Troendle CA, King RM (1987). The effect of partial and clearcutting on streamflow at deadhorse creek, Colorado. J. Hydrol. 90:145-157.
Tiwari SP, Kurothe RS (2006). Effect of vegetative barriers on soil and nutrients losses at 2% slope on agricultural lands of reclaimed Mahi ravines. Indian J. Soil Conserv. 34(1):37-41.
Vitousek PM (1994). Beyond global warming: Ecology and global Change. Ecology 75(7):1861-1876.
Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997). Human domination of Earth's ecosystems. Science 277.
Wight CL (1940). A preliminary account of rainfall in Jonkershoek. Trans. Royal Soc. South Afr. 28 (2):161-73.
Wight CL (1943). Determination of the effects of watershed management on mountain streams. Amer. Geophys. Union Trans. 2:594-608.
Yang Y, Tian F (2009). Abrupt change of runoff and its major driving factors in Haihe River Catchment, China. J. Hydrol. 374:373-383.
Yu DS, Shi XZ, Wang HJ, Zhang XY, Weindorf DC (2008). Functions of soils in regulating rainwater in Southern China: Impacts of land uses and soils. Pedosphere 18(6):717-730.
Zeleke G, Hurni H (2001). Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian highlands. Mount. Res. Dev. 21(2):184-191.
Zhang S, Lu XX (2006). Long-term water and sediment change detection in a small mountainous tributary of the lower pearl river, china. Adv. Geosci., Hydrological Science (eds.) Namsik Park et al., World Scientific Publishing Company, 6:97-108,
Zhao RJ, Zhang YL, Fang LR, Liu XR, Zhang QS (1980). The Xinanjiang model. In: Hydrological Forecasting Proceedings Oxford Symposium. IASH, pp. 351-356.