Impact of Land Use / Cover Change on Streamflow:  
The Case of Hare River Watershed, Ethiopia

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Introduction

This study investigates land use/cover dynamics and its consequent impacts on streamflow at Hare River watershed, Southern Rift Valley Lakes Basin, Ethiopia. It further addresses the seasonal streamflow variability due to land use/cover dynamics and understand the upstream-downstream linkages with respect to irrigation water use. Hare River watershed is situated between 37° 27’ and 37°37’ Eastern longitude and 6° 03’ and 6° 18’ northern latitude and drains a land area of 167.3 km² into Lake Abaya. It is mainly covered by steep mountains characterized through abrupt faults and rises from 1180m a.s.l. to 3,480m a.s.l. The climate of the area ranges from tropical to alpine due to its great difference in altitude and topographical elevation. The average annual temperature are 23°C & 14°C, and mean annual rainfall are 890mm & 1430mm at the lowland and highland respectively. Though Hare River is small, it is extensively used by downstream farmers to irrigate a command area of 2224 hectares. Smallholder agriculture is the dominant form of resources use in upper watershed where the population density is high (323 persons per km²).

The knowledge how land use/cover change influence watershed hydrology will enable local governments and policy makers to formulate and implement effective and appropriate response strategies to minimize the undesirable effects of future land use/cover change or modifications. Given that impacts of land use/cover change on water resources are the result of complex interactions between diverse site-specific factors and offsite conditions, standardized types of responses will rarely be adequate. General statements about land–water interactions need to be continuously questioned to determine whether they represent the best available information and whose interests they support in decision-making processes (FAO, 2002).

Hydrologic response is an integrated indicator of watershed condition, and changes in land use/cover may affect the overall health and function of a watershed. Such changes vary spatially and occur at different rates through time. Direct and powerful linkages exist among spatially distributed watershed properties and watershed processes (Miller et al, 2002). To envisage the future effects of land use change on river flow, it is important to have an understanding of the effects of historic land use/cover changes have had on watershed hydrological system. Moreover, detecting and simulating the effects of land use/cover change and management on hydrological processes requires a new and improved procedure to instrument watersheds based on the hydrological sensitivity due to land use/cover changes at sub-watershed levels.

The method to evaluate the hydrological impacts due to land use/cover changes and land use modifications can be achieved through integrating Remote Sensing, Geographical Information System (GIS) and Soil and Water Assessment Tool (SWAT) model. SWAT model (Arnold et al.,
1998) is developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in watersheds with varying soils, land use and management conditions over long periods of time. It is semi-distributed physically based model that operates on a daily time step. SWAT is capable of simulating a high level of spatial detail by allowing the division of a watershed into a large number of sub-watersheds. It has been used to predict streamflow which were compared favourably with measured data for variety of watershed scales. Recently, some researchers applied SWAT to a meso-scale watershed to assess the impact of land use changes on the annual water balance and temporal runoff dynamics (Santhi et al., 2001, Van Liew, M.W., and J. Garbrecht. 2003)

Methodology

This study was carried out in four steps. First, a database was established and land use/cover maps 1967, 1975 and 2004 were produced to analyse the land use/cover dynamics. Second, SWAT simulation run was carried out using set of input variables and sensitivity analysis was performed to identify parameters that most influenced predicted streamflow. Third, the efficiency of the model was assessed by comparing simulated and observed annual and monthly streamflow. Fourth, in order to test the assumption that land use/cover change has affected watershed streamflow, further simulations were performed using both maps for the same period.

The basic data set that are required to develop an input database for the model are: topography, soil, land use and climatic data. A digital contour was processed and interpolated to derive a Digital Elevation Model (DEM) of the study area. The DEM was used to delineate the topographic characterisation of the watershed and determine the hydrological parameters of the watershed such as slope, flow accumulation, flow direction, and stream network. AVSWAT, an ArcView interface, was used to delineate the watershed. To capture heterogeneity in physical properties, the watershed was divided into fifteen sub-watersheds and each one of the sub-watersheds was partitioned into Hydrologic Response Units (HRUs) that consist of homogeneous land use, management, and soil characteristics. A total of ninety two HRUs were created at which the model computes the effect of management practices.

Simultaneously, spatial databases were developed using black and white aerial photographs of 1967, 1975 and satellite image of 2004 were obtained from Ethiopian Mapping Agency (EMA) and was verified by intensive on field land use mapping in 2005. Three land use/cover maps of 1967, 1975 and 2004 were produced through visual interpretation of the aerial photographs and supervised classification based on maximum likelihood of the satellite image. The generic approach of land use/cover change analysis is based on post-classification comparison method, which is commonly employed in land cover change detection studies (Liu and Zhou 2004). Spatial analyses were carried out at watershed and sub-watershed levels to describe land use/cover changes over time, measure the rate of change and relate overall land use/cover changes to streamflow variability and physical features of the landscape. For this study only the 1975 and 2004 land use/cover maps were utilized due to the limited availability of streamflow data.

Climatic input data were obtained from Ethiopian National Meteorological service Agency (NMSA) for the nearby weather stations. Daily precipitation, maximum and minimum temperature, wind speed, humidity and sunshine hour data of Arba Minch, Chencha and Mirab
Abaya stations were utilized for this study as per the availability. To account for the orographic effect of precipitation, a polynomial regression equation was fitted to rainfall-elevation relation and elevation bands were used to generate rainfall inputs for the sub-watersheds. On the other hand, soil database was established through an intensive data collection from forty two representative sites throughout the watershed. The physical characteristics including soil texture, bulk density, and hydraulic conductivity were identified from the samples collected at different layers. Similarly, the management operations required for the HRUs were determined through a socioeconomic assessment conducted during the field research work and secondary information obtained from the district Agricultural office.

The time series of discharge at the outlet of a watershed is the most important data to calibrate and validate a hydrological model. A daily streamflow data of 1980-2005 was obtained from Ethiopian Ministry of Water Resources (MoWR) that has been gauged at the outlet of the watershed. The data was divided into two sets of the periods 1980-1991 and 1992-2005 corresponding to the 1975 and 2004 land use/cover maps respectively. Both periods were again divided into two for calibration and validation processes. The streamflow data was also used to evaluate streamflow components with an automated digital base flow separation technique and compare the result provided by the SWAT2005 model.

In order to assess the variability of streamflow due to the land use/cover dynamics from 1975 to 2004, the SWAT model was run using the two land use/cover maps while setting all the other set of input variables similar for both simulations. Prior to the calibration and validation process, a sensitivity analysis, based on the integration of Latin Hypercube and One-Factor at a Time sampling techniques, was performed to reduce uncertainty and provide parameter estimation guidance. Both manual calibration and autocalibration tool of SWAT2005 based on Shuffled Complex Evolution (SCE_UA) algorithm, which is a global search algorithm for minimization of a single function, were utilized in the calibration process. Moreover, Parameter Solutions (ParaSol), which is an optimization and statistical uncertainty analysis method, and Sources of Uncertainty Global Assessment using Split Samples (SUNGLASSES) are being used to estimate the uncertainty originating from parameter uncertainty and evaluate the correctness of the model prediction to be used for decision making. In this study, the model performance was assessed using Coefficient of determination, Root Mean Square Error, and the Nash-Sutcliffe model efficiency. After calibrating and validating the model using the two land use/cover maps for their respective periods, the model was also run using both the 1975 and 2004 land use/cover maps for the period of 1992-2005 to quantify the impacts introduced on the streamflow due to the land use/cover change.

Results

The results of the land use/cover change analysis indicated that farmlands and settlements class has expanded which is mostly associated with the decrease in forest class. As indicated in fig1., the farmland and settlement land use class grows from 28.3% cover in 1975 to 52.0% cover in 2004 with a rate of change of +136.9 ha/year. On the other hand forest cover reduced from 28.4% in 1975 to 16.2% in 2004 with a rate of change of -70 ha/year. The upper watershed and the border zone in between the uplands and lowland were the most affected parts of the watershed.
The sensitivity analysis pointed out that eight parameters namely; Curve number (CN), Soil Available Water Capacity (SOL_AWC), Soil depth (SOL_Z), Soil Evaporation Compensation factor (ESCO), Saturated hydraulic conductivity (SOL_K), Slope (SLOPE), Groundwater “revap” coefficient (GW_REVAP) and Groundwater recession factor (ALPHA_BF) were found to be most crucial parameters for the studied watershed. These parameters generally govern the surface and subsurface hydrological processes and stream routing.

The measured and predicted streamflow was calibrated and validated on monthly and annual time steps. The results of these tests illustrated that the monthly coefficient of determination values range from 0.72 to 0.92, with the highest value (0.92) during the calibration of the model for the 2004 land use/cover condition. Likewise, the Nash-Sutcliffe coefficient varies from 0.41-0.92 for annual and 0.43-0.82 for monthly calibrations and validations that verified the model had predicted quite satisfactory annual and monthly flows.

Moreover, it was identified that mean monthly discharge for wet months had increased by 12.5% while in the dry season decreased by up to 30.5% during the 1992-2004 period due to the land use/cover change. As a result, at present Hare River only satisfies 15.75% of downstream irrigation demand even with 100% diversion during the dry season.

Use of GIS and remote sensing were found to be helpful tools to detect and analyse spatio-temporal land use/cover dynamics. SWAT2005 was useful in analyzing the impacts of land use/cover changes on streamflow and it provides an acceptable hydrological performance. Accordingly, this study reveals the successful application of the SWAT model in areas with limited readily available data and hence can be utilized in similar watershed elsewhere.
From the results of this study, it can be concluded that Hare watershed had experienced a significant change in land use/cover over the past four decades. It can be presumed that deforestation and increase in farmland that was manifested by the rapid increase in human population has altered the whole Hare watershed in general and some sub-watershed in particular. Modifications of land uses (rain-fed to small scale irrigations) are expected in the near future, since farmers in the upper watershed have already started using ground water and surface water to cultivate market oriented cash crops like apple. This study also highlighted that detail understanding of historical land use/cover changes and consequent impacts on streamflow will enhance our capability to predict future land use modifications. Therefore, further scenario simulations and optimization strategies that take in to account upstream-downstream water users can provide valuable information to devise more effective watershed management strategies to sustain the livelihoods of the local community.

References
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