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Hydrological effects of land use /land cover changes on stream flow at Gilgel Abay River Basin, Upper Blue Nile, Ethiopia

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Abstract: Water is the most important resource for the survival of living things and it is the most essential resource associated with land use/ land cover (LU/LC) changes. Therefore, it is very important to make evaluations of the expected impact on the hydrology and water resources due to expected changes. The main objective of this study is to assess the hydrological effect of land use/ land cover changes on stream flow at GilgelAbay river basin using Precipitation Runoff Modeling System (PRMS) model. System inputs are daily time-series values of precipitation, minimum and maximum air temperature, and parameter files which are generated from GIS Weasel. To identify effect of changes in LU/LC, vegetation type and vegetation density on stream flow, LU/LC, vegetation type and vegetation density data from 1990-2000 and 2001-2010 years were considered. This different period LU/LC, vegetation type and vegetation density with soil data and DEM were given to GIS Weasel to generate different parameters for PRMS model. These generated parameters together with time series data (daily minimum and maximum air temperature, daily precipitation and daily stream flow) feed to PRMS model to simulate stream flow for the years 1993-2000 and 2001-2008. From the time series data, climate changes (daily maximum and minimum temperature and daily precipitations) were kept the same as baseline period (1993-2000). The stream flow of 2001-2008 compared with baseline period (1993-2000) and the effect of LU/LC, vegetation type and vegetation density was identified using calibrated and simulated PRMS model. Hence, as LU/LC, vegetation type and vegetation density changed from 1993-2000 period to 2001-2010 period, stream flow increased from 7.8% (128.4 Mm^3) to 25.3% (432 Mm^3) and ET decreased from 4.2% (75 Mm^3) to 20% (524 Mm^3) from baseline period. For the whole simulation periods (2001-2008) stream flow increased by 10.9% (784 Mm^3), but ET decreased 6.7% (43 Mm^3) related to baseline periods.

Keywords: *Stream flow, Precipitation Runoff Modeling System, GIS Weasel, Vegetation type, Vegetation density*

1. Introduction

Water is the most important resource in the world for the survival of living things and it is the most essential resource associated with changes in land use/ land cover (LU/LC). Therefore, it is very important to make evaluations of the expected impact on the hydrology and water resources due to expected changes (Ringius et al. 1996) [1]. Land use change is the conversion of land for a particular production or purposes, which was not used before for crop production. Land is used to meet a variety of human needs and serving for different purposes. When the users of land decide to employ its resources towards different purposes, land use change occurs producing both desirable and undesirable impacts. Land use/land cover change influences the hydrological cycle and water resources availability by changing canopy interception, surface roughness, soil properties, albedo and evapotranspiration (Wang et al., 2013) [2]. Changes in land cover has an effect on overall health and function of a watershed, hence investigations on the impacts were reported as land cover change and rainfall spatial variability affect the rainfall runoff relationship to watershed (Hernandez et al., 2000) [3]. The analysis of land use change is essentially the analysis of the relationship between people and land. Assessment of the impacts of land-use change on stream flow is important for basin environment protection and water resources sustainable development, because it has a significant effect on the hydrological processes at the watershed level (Li et al., 2013) [4].

Hydrological assessments on stream flow in many catchments in Ethiopia are limited though emphasis must be given to support water resource management. The Ethiopian high land is a major source of water for Blue Nile River basin, hence reliable runoff information from the region is very important for the sustainable management of water resources. Gilgel Abay catchment is one of the largest catchments in the Blue Nile basin that drains to Lake Tana and is the origin of Blue Nile River. Human activities and natural phenomena have an impact on the hydrological water balance of this catchment. Kebede (2009) [5] reported that an increase in population caused changes in land use/ land cover and various hydrological processes of upper Blue Nile river basin. Therefore, it is important to address the effect of land use/land cover changes on hydrological processes. The objective of this study is to assess the hydrological effect of land use/ land cover changes on stream flow at Gilgel Abay river basin using PRMS model. PRMS is a modular-design, deterministic, physically based and distributed-parameter modelling system that has been developed by the US Geological Survey (USGS) 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) [6].

2. Methodology

2.1. Description of the Study Area

GilgelAbay river basin has an area of 5000 km^2. It is the largest of the main four sub-catchments of Lake Tanaand contributes about 60% of the lake inflow. It has a geographical coordinates of 10^{0}56` to 11$^0$51`N latitude and 36^{0}44` to 37$^0$ 23` E longitude with an elevation range of 1787m to 3524m above M.S.L. The southern part of the catchment is mountainous and it has undulating topography while the remaining part is low laying plateau with gentle slope. The geology of the area is mostly composed of quaternary basalts and alluviums. Most dominant soil types are clay and clayey loam soils.

Moist air coming from the Atlantic and Indian oceans following the north-south movement of the Inter Tropical Convergence Zone is source of rainfall (Mohammed et al. 2005) [7]. June to September is the main rainy season having about 70 to 90% of the annual rainfall in the study area (Kebede et al., 2006 [8]; Tarekegn and Tadege, 2005) [9]. The rainfall data from meteorological stations indicates significant spatial variability of rainfall following the topography, with a decreasing trend from south to north. The temperature variations are small throughout the year (BCEOM, 1999) [10].

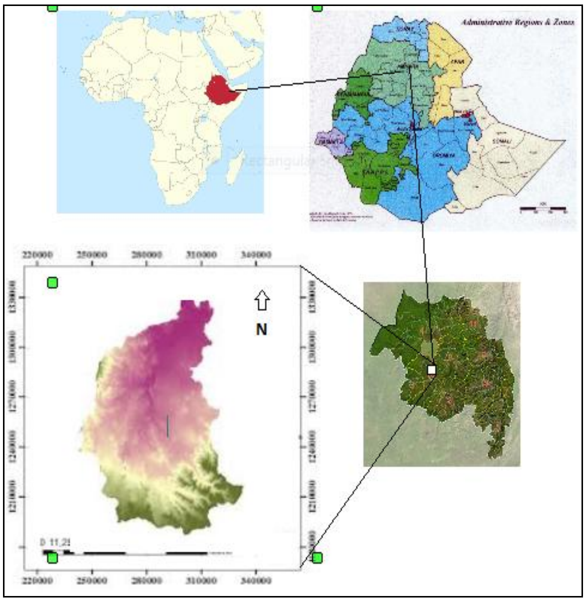

Fig.2.1 *Location map of GilgelAbay River Basin, Upper Blue Nile, Ethiopia*

2.2. Data Products Used

Daily precipitation data, daily minimum and maximum air temperature from 1993-2012 were acquired from Ethiopian meteorological Agency. Total daily mean stream flow data from 1993-2012 and River basin topography Digital Elevation Model (DEM) acquired from Ethiopian minister of water resources. Vegetation type and density data acquired from global 1km gridded database (geodata.grid.unep.ch), and Land cover data prepared from satellite image. Soil data acquired from Harmonised world Food and Agricultural Organization (FAO) soil map.

2.3. Description of PRMS

PRMS is a modular-design, deterministic, physically based and distributed-parameter modelling system that has been developed by the US Geological Survey (USGS) 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) [6]. The response of Basin to normal and extreme rainfall and snowmelt is simulated to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields, and ground-water recharge. Parameter-optimization and sensitivity analysis capabilities are provided to fit selected model parameters and evaluate their individual and joint effects on model output (Leavesley et al., 1983). The modular design provides a flexible framework for continued model-system enhancement and hydrologic-modelling research and development.

PRMS is used to evaluate the effect of land use/ land cover changes on stream flow in data scarce Tropical African catchments and it divides a watershed into smaller modelling subunits based on its physical characteristics of slope, aspect, elevation, vegetation type, soil type, land use, and precipitation distribution(Leggess et al., 2003) [12]. HRU are considered as the equivalent of one flow plane, orare delineated into a number of flow planes. In this study, the model is calibrated for daily and monthly mode for simulating daily and monthly stream flows of the River Basin.

System inputs are daily time-series values of precipitation, minimum and maximum air temperature, short-wave solar radiation and parameters which are generated from GIS Weasel. Daily short-wave solar radiation can be estimated internally by the model if it is not provided by the user. Precipitation in the form of rain, snow, or a mixture of both is reduced by vegetative canopy interception; precipitation not intercepted by the canopy becomes the net precipitation through fall that is delivered to the watershed surface. Energy inputs of air temperature and solar radiation drive the processes of evaporation, transpiration, sublimation, and snowmelt (Markstrom et al., 2015) [13] (Figure 2.2)

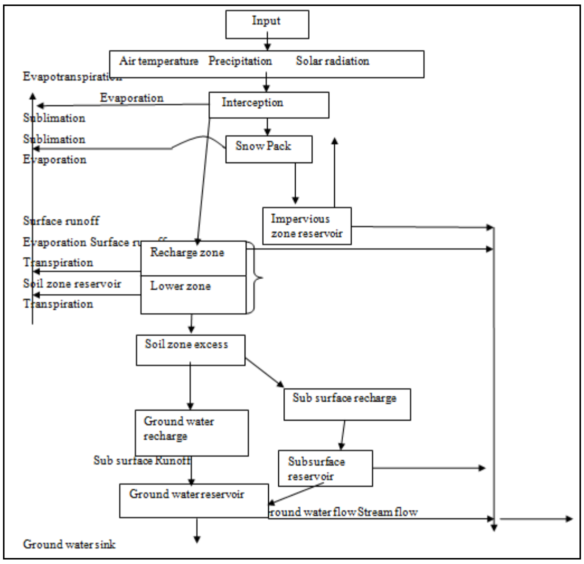

Fig.2.2. *Schematicre presentations for different components of PRMS model (Source: Leavesley etal., 1983) [6].*

The Modular Modelling System (MMS) used to build a suitable Precipitation Runoff Modelling System (PRMS) for the study area. Distributed parameter capabilities of PRMS enabled by portioning catchment into subareas that are assumed to be homogeneous in their hydrologic response by using GIS Weasel. FAO digital soil map and satellite image derived land use/land cover, vegetation type and vegetation density data-bin fed to GIS Weasel to generate parameters for PRMS model.

2.4. Delineation of HRU and Generation of Model Parameters

GIS Weasel is used to delineate HRU and generate input parameters for PRMS model and it provides a Geographical Information System (GIS) tools to create maps of geographic features relevant to user`s model and to generate parameters from those maps(Viger et al., 2007) [14]. It has three phases: set up, delineation and parameterization. In the setup phase GIS Weasel derives a variety of topographic surfaces from DEM. The most important of these products is a version of the DEM useful for routing hydrologic flow, surface flow direction values, surface flow accumulation values, and map depicting the area of interest (AOI). In this phase the most important GIS data sets for delineating geographic features relevant to PRMS model are generated using GIS Weasel. In delineation Phase, the tool panel from GIS Weasel delineates maps of different kinds of geographic features within the Area of Interest. In Parameterization Phase, after the user has created maps of the different kinds of geographic features, the GIS weasel generates input parameters for PRMS model from those maps(Markstrom et al., 2015) [13].The soil-zone reservoir represents the part of the soil mantle that can lose water through the processes of evaporation and transpiration. The depth of root zone is the average rooting depth of the predominant vegetation covering the soil surface. The average root zone depth in this research is about 30-36 meter. Infiltration of rainfall and snowmelt increased water storage in the soil zone. Maximum retention storage occurs at field capacity; minimum storage (assumed to be zero) occurs at wilting point. The soil zone is classified as two layered zones: the upper and the lower zones. The upper layer is the recharge zone and losses are assumed to occur from evaporation and transpiration; whereas losses from the lower zone occur only through transpiration (Viger et al., 2007) [14].

The computation of infiltration into the soil zone is dependent on whether the input source is rain or snowmelt. All snowmelt is assumed to infiltrate until field capacity is reached. At field capacity, any additional snowmelt is partitioned between infiltration and surface runoff. At field capacity, the soil zone is assumed to have a maximum daily snowmelt infiltration capacity. All snowmelt in excess of this capacity contributes to surface runoff. Infiltration in excess of field capacity first is used to satisfy recharge to the groundwater reservoir, having a maximum daily limit. Excess infiltration, above this limit, becomes recharge to the subsurface reservoir. Water available for infiltration as the result of a rain-on-snow event is treated as snowmelt if the snowpack is not depleted and as rainfall if the snowpack is depleted (Figure 2.2).

2.5. Model Calibration and Validation

Model calibration, which is parameter estimation, involves adjustment of parameters to minimize the difference between measured and simulated values. Model validation involves the ability of model to the hydrologic response unit for conditions different from that used during calibration period. Luca software used to calibrate PRMS model. It is a multiple-objective, stepwise, automated procedure used for calibration of hydrologic model (Hay et al. 2006) [15]. Luca used Shuffled Complex Evolution global search maximization algorithm to calibrate PRMS model (Duan et al. 1992 [16]; Duan et al. 1993 [17]; Duan et al. 1994) [18]. For the present study, simulation period (1993-2012) was divided in to calibration periods (1994-2005) and validation periods (2006-2012). One year period (1993) used for initiation to minimize the effects of the user`s estimate of initial value of state variables at the model start up by allowing the model to cycle a number of times. The model calibration and validation carried out by using daily and monthly scale of stream flow simulation. This involves calibrating and validating of the hydrological model using present conditions and running the model with parameters and input data corresponding to the proposed scenario conditions.

2.6. Model Performance Evaluation

Nesh and Sutcliffe (1970) [19] used to evaluate performance of the model on daily and monthly scales using standard model efficiency (E). This method is widely used in evaluating hydrologic models. The E value ranges from negative infinity to 1.0, with higher values showing good agreement between observed and simulated values equated as follows:

$$E = \frac{\sum_{1}^{N}(Qoi - Qo)^2 - \sum_{1}^{N}(Qoi - Qsi)^2}{\sum_{1}^{N}(Qoi - Qo)^2}$$

Where,

$E =$ Model goodness of fit efficiency

$Qoi =$ Observed stream flow for day or month i

$Qsi =$ Simulated stream flow for day or month i

$Qo =$ Mean observed daily or monthly stream flow

N= number of samples.0

2.6. Scenario Simulation

Different scenarios were simulated to identify the impacts of LU/LC changes on stream flow at GilgelAbay River basin. For simulating the hydrological response of stream flow to different scenarios, calibrated and validated hydrological model PRMS used for comparing present conditions with proposed scenarios. PRMS model ran by using parameters generated from GIS Weasel and time series input data corresponding to proposed scenarios.

2.6.1. Effects of land use /land cover and other changes on stream

To identify effect of changes in LU/LC, vegetation type and vegetation density on stream flow, different LU/LC, vegetation type and vegetation density data from 1990-2000 and 2001-2010 years were considered as shown in Figures 2.3 and 2.4. This different period LU/LC, vegetation type and vegetation density with soil data and DEM were given to GIS Weasel to generate different parameters for PRMS model. These generated parameters together with time series data (daily minimum and maximum air temperature, daily precipitation and daily stream flow) feed to PRMS model to simulate stream flow for the years 1993-2000 and 2001-2008. From the time series data, climate changes (daily maximum and minimum temperature and daily precipitations) were kept the same as baseline period (1993-2000). The stream flow of 2001-2008 compared with baseline period (1993-2000) and the effect of LU/LC, vegetation type and vegetation density was identified using calibrated and simulated PRMS model.

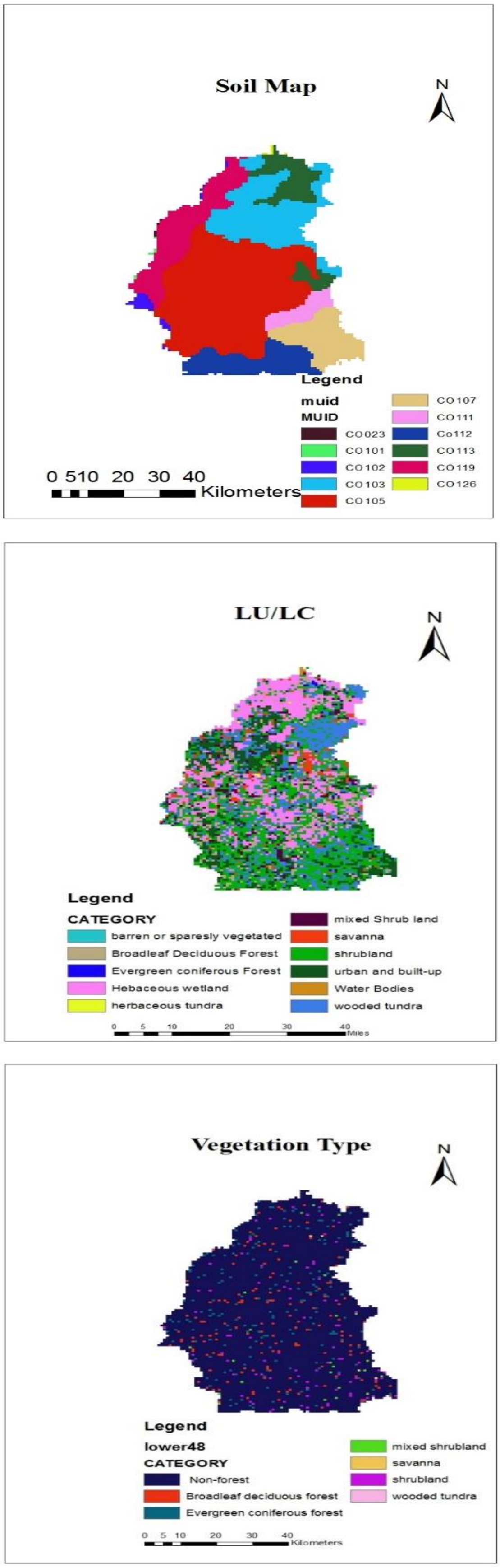

***Figure.2.3.** LU/LC, Vegetation type and soil map of 1990-2000*

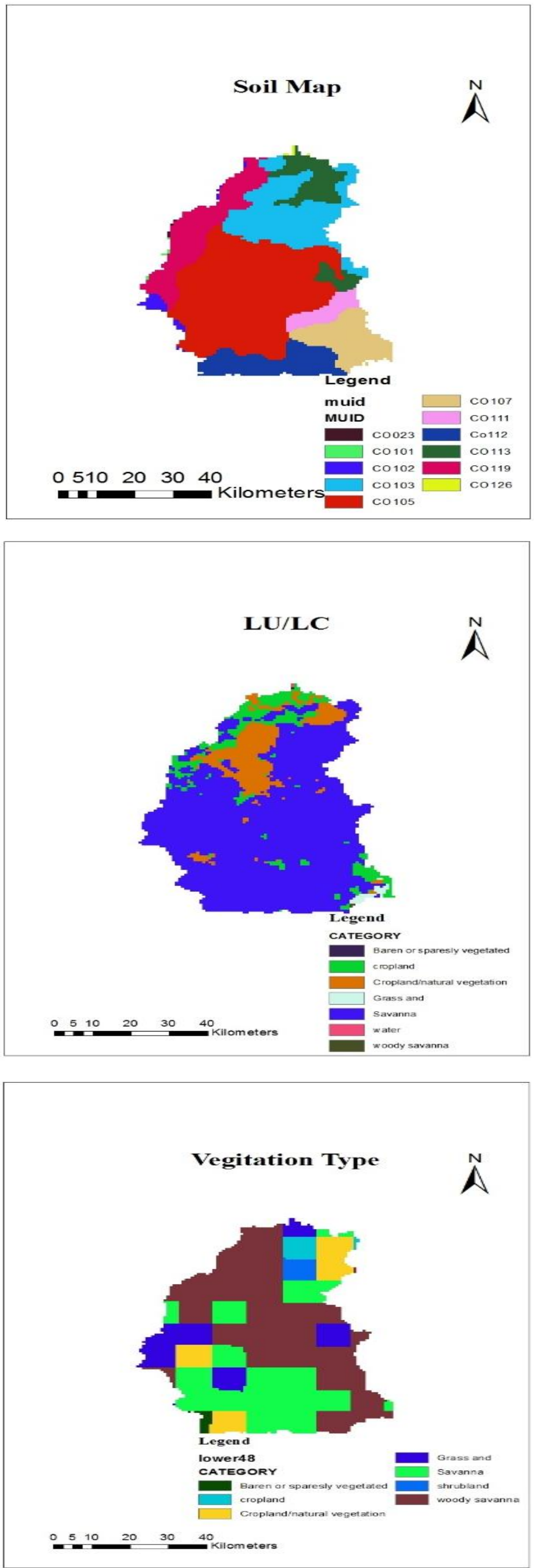

Figure.2.4. *LU/LC, Vegetation type and soil map of 2001-201*

3. Results and Discussion

3.1 Model calibration and validation at daily and monthly modes

For the area of interest which has 26 number of Hydrological Response Units there is a good agreement between daily simulated and measured stream flow during calibration and validation periods with average E values 0.71 and 0.70 respectively. For monthly stream flow average E values for calibration and validation are 0.91 and 0.90 respectively. The monthly observed and simulated stream flow showed better agreement between observed and simulated stream flow than daily observed and simulated stream flow. This indicates that model is more compatible for monthly stream flow simulation than daily stream flow simulation at GilgelAbay River Basin. It is also clear that the model simulated stream flow very well in daily mode of simulation.

3.2 Effect of land use/land cover change on stream flow

To identify effect of changes in LU/LC, vegetation type and vegetation density on stream flow, different LU/LC, vegetation type and vegetation density data are considered with cover periods of 1990-2000 and 2001-2010.Analysis have been done by considering baseline period (1993-2000) and simulating stream flow for 2001-2008 periods using input parameters generated from LU/LC, vegetation type, vegetation density of 2001-2010 year with the time series data of daily maximum and minimum air temperature and daily precipitation using PRMS model. Finally, simulated stream flow and ET for 2001-2008 periods compared with baseline period (1993-2000) and evaluated as follows. As LU/LC, vegetation type and vegetation density changed from 1993-2000 period to 2001-2010 period, stream flow increased from 7.8% (1284 Mm^3) to 25.3% (432 Mm^3) and ET decreased from4.2% (75 Mm^3) to 20% (524 Mm^3) from baseline period. For the whole simulation periods (2001-2008) stream flow increased by 10.9% (784 Mm^3), but ET decreased 6.7% (43 Mm^3) related to baseline periods. Hence as LU/LC, vegetation type and vegetation density changed from 1990-2000 period to 2001-2010 period, there is an increase in stream flow by decreasing ET.

4. Conclusions

For the entire GilgelAbay River Basin PRMS performed reasonably well in simulating monthly and daily stream flow with the model fit efficiency (E) value of 0.9 and 0.7 respectively. LU/LC, vegetation type and vegetation density changes have an effect on stream flow, that is as LU/LC, vegetation type and vegetation density changed from 1993-2000 period to 2001-2010 period, stream flow increased by 10.9% (784 Mm^3), but ET decreased by 6.7% (43 Mm^3) related to baseline periods (1993-2000) for GilgelAbay River basin.

5. Acknowledgements

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