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The Effects of Land use Change on Hydrological Responses in the Choke Mountain Range (Ethiopia) - A new Approach Addressing Land Use Dynamics in the Model SWAT

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Abstract: Land use change (LUC) is a very important issue considering global dynamics and their responses to environmental and socio-economic drivers. Especially in fast changing developing countries, it is a scientific challenge to predict land use changes and their effects on water availability, flood risk and erosion rates. To address these issues, catchment models must be able to deal with land use dynamics. Unfortunately, many models handle land use in a static state way. The objective of this research is to investigate the effect of dynamic land use implementation into SWAT ("Soil and Water Assessment Tool") by developing the supportive tool "Land use Update and Soil Assessment" (LUPSA) and to improve the overall SWAT abilities to handle LUC. A catchment in the Choke Mountain Range (Ethiopia) was selected as test case where significant land use change occurred during the last decades. These dynamics were addressed by 5 land use maps based on interpretation of aerial photographs and satellite imageries, while several years of climate and discharge data were available. The available data for the test application were carefully analyzed and found to be limited in quantity and quality. LUPSA was applied to feed the SWAT model for the period of 1973 to 2003 with yearly land use updates. The annual LUC varied between -6% and +360% for different classes. The impact of land dynamics on the hydrological response was observed and shown at the daily discharge, the total annual runoff and the peakflow.. Also a higher proportion of low flow rates was found and caused more water stress. Considering the high uncertainties, SWAT was not able to produce reliable results due to the bad data quality. Nevertheless, the implementation of land cover dynamics in SWAT led to a significant change in the model outputs and demonstrated improved capabilities to handle their impacts on water resources. Further model testing is strongly recommended.

***Keywords**:* LUPSA; SWAT; Dynamic Land Use Change; Blue Nile; Ethiopia

1. INTRODUCTION

A major challenge in environmental research is to understand and describe the effects of climate change and land use change on the socio-economic structure and the environment (Vitousek 1994). Today, eighteen years after Vitouseks paper, we develop environmental management strategies to deal with related questions. To achieve this aim it is important to predict the impact of inter-scale changes on the hydrological cycle (Ott & Uhlenbrook 2004, Sivapalan 2003).

In 2001 Fohrer et al. showed the impact of LUC (land use change) on the annual water balance and temporal discharge variability in a meso-scale catchment using SWAT. They found the surface runoff the most sensitive variable effected by the considered change.
Meanwhile, Lahmer et al. (2001) concluded with an ArcEGMO model on meso- and macro-scale catchments a stronger impact on water availability rather than on water balance components based on land use change.
An application of the TAC^D Model (tracer aided catchment model, distributed) to quantify the effects of land use change on the hydrology for seasonal and event scale were carried out by Ott and Uhlenbrook (2004). They stated that a process-oriented catchment model was useful to describe LUC impacts on the hydrology in mountainous areas and argued that the physically based regionalization of the input data was as important as the parameterization of the vegetation.

Considering the research of land use change alone, the development of separate and very sophisticated land dynamic tools can be observed over the last two decades (Jones 2005). This is caused by the large number of variables from different scientific fields which influence the land use change (Weber et al 2001).Therefore, future development of land use change modeling related to river catchment modeling will probably remain a parallel process where a dynamic link would be the desired connection on a long term perspective. A basis for such a link is the ability of the addressed hydrological modeling tools to deal with dynamically changing land use input.

A widely used, highly sophisticated modeling tool which addresses many aspects of a catchment is SWAT. Its strength is the very supportive community, the easy and free availability including very good documentation and its small computational demand. Unfortunately, nearly all SWAT applications addressing the effect of LUC did scenario based predictions based on static land use. This is astonishing as the majority of SWAT applications have jet been focused on the impact of land use and management change as well as climate change dynamics (Arnold & Fohrer 2005). One step towards land use change implementation was realized with an update function in the most recent SWAT version (SWAT2009). Only that this lup.dat file is not much used yet due to its impractical set-up/use (any update must be made for any HRU one by one).

There are many cases where SWAT models have been used to predict the impact of land use change on environmental cycles. Although their solutions vary in terms of the effect magnitude, most of them show that land use change can be an important variable in SWAT models as well as they state that SWAT would be a useful tool for further investigation of land use dynamic implementation. A common weak point of these models is the fact that the land use application was always non-dynamic (steady state land use) and without regard to the spatial variability of the changes.
Demissie et al. (2004) applied the influence of LUC on the hydrology, erosion and sediment yield in the Legedad Reservoir watershed in Ethiopia and found that there was a considerable impact on water quantity, erosion and sediment yield. The authors stated that due to the intensification of agricultural land use, also water quality had decreased continuously.

Within another study in Ethiopia, Tibebe, T. et al. (2010) argued that based on reasonable model results, SWAT turned out to be sensitive to land use changes and would be a good tool to assess soil erosion and the effects of best management practices in Ethiopia.
Alibuyog et al. (2009) showed with a SWAT application in the Philippines that the impact of LUC on the hydrology and sediment yield varied between 3 % to 14 % and 200 % to 273 %, respectively.
A SWAT case study in the Nzoia catchment in Kenya was conducted by Faith Githui et al. in 2009. They stated that high land use alterations towards agricultural land led to an increase of runoff between 16% and 30%.

The objective of this paper was to draw attention on a topic (LUC in SWAT) which seems to be improperly addressed in comparison to its importance. Moreover it is to demonstrate a possible approach (LUPSA) and some preliminary results to investigate the potential impact. As the Gedeb Catchment turned out to be difficult as test case due to the data availability, the detailed results must rather be seen as tendencies instead of facts. Nevertheless might the a method be applicable and supportive for further investigations.

2. CASE STUDY CATCHMENT

The Gedeb catchment as part of the upper Blue Nile river basin covers an area of about 290 km² and is situated between 37°30'00'' E to 37°50'00'' E and 10°24'00'' N to 10°40'0'' N in the Choke Mountain range of Ethiopia. The average altitude is 2703 m and the mean slope is high with 16 %. The topological profile is very heterogeneous. The longest distance to the outlet amounts to 40 km and the longest flow path is ~50 km. Average annual precipitation and discharge are 1392 mm/a and 752 mm/a, respectively. Administratively, the catchment lies within the region of Amhara and is part of East Gojam. There are four villages within the catchment with fewer than a few hundred inhabitants each. The nearest city is Debre Markos with ~50,000 inhabitants. The catchment geology is dominated by Termaber Basalt (TTB2) upstream and the stronger eroded Termaber Basalt (TTB1) downstream. Due to the deeper weathered downstream formation, the corresponding area is rather useful for agriculture and provides better water capacities. At the very downstream end of the catchment, an alluvial formation (QALL) starts with more wetlands, especially in the transfer areas.
The Ethiopian Meteorological Survey (NMSA) divides the local climate of the upper Blue Nile basin into three seasons. The dry season "Bega" (October-January), the short rain season "Belg" (February-May / which contributes to about 10 % of the annual rainfall) and "Kiremt", the rain season from (June-September).

3. MATERIAL AND METHODS

Several time series and point data were available for the SWAT catchment model. Nine rainfall stations, one discharge monitoring point, five land use maps (refer to Teferi et al 2010), one soil map (FAO world soil map) and one temperature data set have been implemented in this study. For the topological analysis the SRTM 90x90 data has been used.
It turned out that the temporal data distribution significantly varies in availability and quality. Long term (> 16 month) rainfall observation was available only on two stations out of the nine. Those stations were used for the assessment of the rainfall distribution only, which were found very heterogenic on a daily scale. As no other relationship could have been carried out, the data scattering was simply done by an IDW interpolation. Temperature data was available as further regional climate data at Debre Markos.
Many years of daily discharge measurements were collected at the catchment outlet (>39a) and opened the opportunity to select the simulation period based on

other temporal restricted data sets. The overall flow was dominated by high variations due to the seasonal effects in the region. The analysis of the flow duration curve showed the significance of the base flow (base flow index = 0.56).
The strong land use change was accessed by 5 land cover maps based on satellite images between 1957 and 2009. The analysis showed well the dynamics towards artificial land use on cost of the natural landscape while the whole catchment is rural dominated. Ten land use types have been taken into account which are: Grass Land, Afroalpine Grasland, Shrubs and Bushes, Cultivated Land, Riverine Forest, Wood Land, Plantation Forest, Marsh Land, Barren Land and Ericaceous Forest.

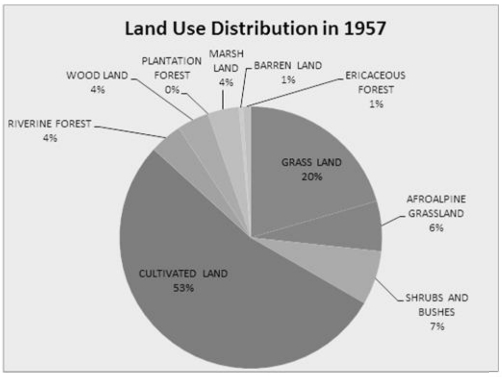

Figure 1: Land Use Distribution 1957

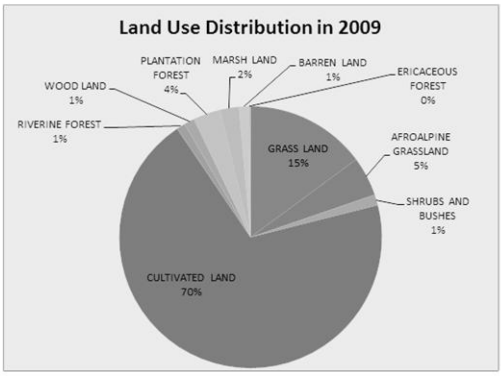

Figure 2: Land Use Distribution 2009

SWAT (Arnold et al., 1998) is a watershed simulation tool which works on a daily basis. It is (semi-) distributed and time continuous. SWAT addresses interactive matters of land management practice, climate variations, sediment movement, water supply and chemical yields. SWAT is capable of being implemented at meso- and macro-scale basins. The central elements of watershed simulations implemented into the model are: Hydrology, Weather, Erosion, Plant Growth, Nutrients, Pesticides, Land Management and Stream Routing. SWAT is a script-based model which provides graphical interfaces with ESRI ArcGIS (AVSWAT2000, DiLuzio et al., 2002) and MapWindow (a very capable open source GIS software -http://www.mapwindow.org/). Whereby ArcSWAT is the most commonly used tool.
Spatial heterogeneity is represented by SWAT in three hierarchic classes. The whole basin (1) and subbasins (2) which are further discretized into hydrological response units (HRUs) (3). A HRU is defined by a unique combination of land use, soil and slope classes. In this way, all SWAT areas covering a specific combination within a subbasin are lumped together. Any calculation in SWAT is conducted on the basis of HRUs and is later aggregated. Climate data and other physical characteristics such as stream network properties and stream slope are set on the basin scale. The flow components (water, sediment, nutrients, etc.), which are calculated for each subbasin, are routed to and within the stream network using the Muskingum method. Hydrological processes are handled in four blocks. The deep aquifer, shallow aquifer, the root zone and the soil surface, whereby the root zone is again subdivided into sub layers depending on the soil input.

LUPSA – “Land Use Update and Soil Assessment” is able to generate a new SWAT setup out of two existing setups based on different land use (or soil) inputs. Additionally, it will create monthly or annually update files (lup.dat) for the (new) HRU fractions and slopes. As LUPSA considers the land use change as a linear function between two inputs, the update numbers are correspondingly determined. More available land use input could be implemented using a step-by-step approach. The tool is also able to extrapolate future land use while it is preventing the total area of a subbasin from exceeding/fall below 100%.
It must be underlined that all possible HRUs as they occur in setup one and two will be taken into account for the new setup (scenario) but some of them may be

given an initial area of nearly 0 in case they do not exist when the simulation starts. LUPSA is changing the HRU slopes too, since changing land use causes HRU fraction change and leads therefore to a new average HRU slope. Furthermore, LUPSA is redefining the following: The number of HRUs (in total and subbasin-wide), HRU file names and descriptions within files, the simulation period (I/O master file), the number of land use updates, the files containing new HRU fractions and slopes.

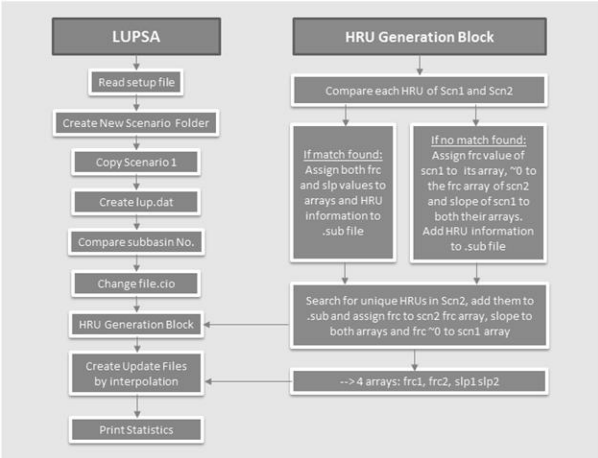

Figure 3: LUPSA workflow (Scn = Scenario, lup.dat = SWAT land use update file, frc = fraction, slp = slope)

For anything LUPSA is not changing, the setup remains as given in scenario 1. The general workflow of the tool is presented in figure 4.

To run the tool a setup file (interface) must be provided including simulation time and specific input scenario information (land use collection time, scenario location etc.).

4. RESULTS AND DISCUSSION

The SWAT model for the Gedeb catchment was found to be the most sensitive to the CN curve number and to the Manning roughness coefficient. Table 1 shows further sensitivities in ranked order. The model was calibrated at the catchment outlet on a rating curve. For that process the tool SWAT-Cup was used (Abbaspour et al 2007) applying the SUFI-2 method and the Nash-Sutcliffe-Efficiency (NSE) as objective function, which was combined with a manual calibration based on plotting the simulations against the observations.

The model was calibrated and validated for several periods. Due to the poor data, the uncertainty band width was set to a threshold of 45 % of the objective function. It turned out to be very difficult to represent extreme flows and the average flow together due to the strong hydrological heterogeneity and the data availability. The best parameterization led to a NSE of 0.39 which is acceptable for the difficult region. On the applied daily time scale the model was able to represent the catchment behaviors with acceptable results while on the monthly scale the model represented the catchment very good with a NSE of >0.80. The validation of the model showed NSEs of 0.24 on the daily time scale and 0.71 on the monthly scale respectively.

Table 1: Parameter Sensitivity (ranked) on the Observed Data (1973 - 1974) and Model Parameterization (fitted value).

Rank (Sens.)	Parameter	Description	Fitted Value	Lower Bound	Higher Bound
1	Ch_N2	Channel Manning	0.272	0.013	0.400
3	Cn2	CN Curve Number	0.082	0.010	0.400
4	Alpha_Bf	Baseflow Factor	0.023	0.020	0.040
7	Sol_K	Saturated Hydraulic Conductivity	0.074	-1.149	0.349
8	Revapmn	Shallow Water Aquifer Threshold	196.8	0.000	200.0
9	Sol_Awc	Soil Layer Water Capacity (mm)	0.244	-0.092	0.352
10	Gwqmn	Shallow Aquifer Threshold (mm)	114.8	0.000	150.0

11	Gw_Delay	Groundwater Delay Time (Days)	20.84	0.000	78.06
12	Surlag	Surface Runoff Lag Coefficient	11.87	0.000	24.00
16	Esco	Soil Evap. Compensation Factor	0.229	0.010	1.000

LUPSA was applied for the period of 1972 – 2003 with the same parameterisation as used for the model without the LUC implementation. The land use update were applied annually and two setups were calculated, one with and one without additional slope change.
While the “normal” setup (without LUC) had 337 HRUs when applying the LU (land use) from 1972, the number of HRUs after the LUPSA setup generation had increased to 418 HRUs. Meaning that 81 HRUs were uniquely in the 1972 based setup, 58 were uniquely in the 2003 setup and 279 HRUs have been derived for both setups. As the standard land use update file (lup.dat) generation, as applied in ArcSWAT, can consider only HRUs from one land use input, only the 279 “common” HRUs could have been considered in SWAT without using the LUPSA tool. Therefore, the LUPSA application optimized the update function here by 33%.

Comparing the model without LUC and the one applying LUPSA led to the following conclusions.
There was no difference on the first year, which proves the functionality of the tool (the first update would have been after one year). Intentionally, it might be expect that the amplitude of the output difference would increase in time, but this was not observed.
Comparing the outlet flows of the LUPSA setups including slope change and excluding it, shows very small impact of slope change in general. This might be explained with the relatively small proportion of the surface runoff component which was necessary during the model calibration by means of the existence of a strong baseflow component to realize the dry season flows. As the slope mainly has an impact on the surface flow component, the small corrections for the slope do not affect the overall flow significantly. Another reason might be the rough DEM input raster with 90x90m.
The LUC implementation shows higher peak runoffs with a difference of about 1.4 % to the simulated one from the basic model. Although the mean and median values are higher for the LUPSA application models and the maximum temporal runoff difference is 8 m³/sand its average 0.14 m³/s. Table 2 represents the annual average of water components. It is shown that the LUC implementation causes higher overland flows which leads to higher sediment loads as a consequence. The basic model displays higher evapotranspiration which is also logical since the top soil and plant storage would be suspected to be higher. Considering the total discharge volumes there is a significant difference observed which accounts for 2.9% of the total flow within the whole period of 30 years.

Table 2: Annual water balance comparison.

	LUPSA - NoSlope	**LUPSA - Slope**	**Basic Model**
Precipitation	1313.9	1313.9	1313.9
Surface Runoff	137.12	137.11	132.99
Lateral Flow	113.48	113.73	106.45
Groundwater Flow	442.86	442.65	438.05
REVAP	9.66	9.65	9.77
Deep Aquifer Recharge	24.06	24.05	23.57
Evapotranspiration	592.3	592.3	604.9

A comparison of flow duration curves (FDC) from the basic model and the LUPSA implementation (Figure 4) shows that the impact is even higher in the dry season where low flows dominate the regime. The FDC shows that the land use change causes a higher portion of low flows in comparison to the steady state land use model. Therefore, it can be stated that the considered land use change would cause temporal higher flood peaks but be most responsible for lower flows in the dry season which may lead to droughts and water supply shortages due to the also increasing agricultural land use and irrigation technics.

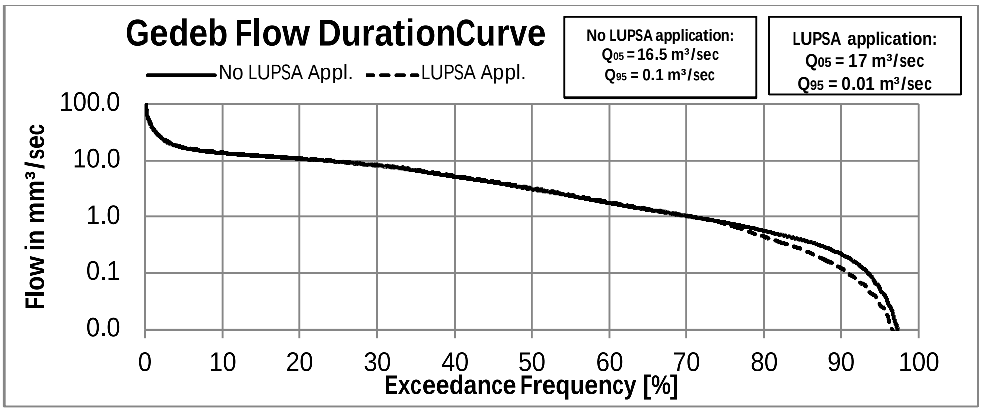

Figure 4: LUPSA application impact on the flow duration curve

5. CONCLUSIONS

The demand of supportive tools to implement LUC in the model SWAT can be covered with LUPSA as it is able to represent all land use dynamics in a catchment. The way SWAT addresses land use change with the lup.dat file proved to be unsatisfactory due to its difficult manual setup and the disability to cover future hydrological units. Both fundamental problems are solved with LUPSA which opened a better possibility to discover LUC impacts.

The Gedeb catchment turned out to be a difficult test case for two reasons. The poor input data challenges the reliability of the model results what is demonstrated by the relatively low NSE. Additionally the strong seasonality was difficult to be simulated with SWAT. In that regard it was problematic to represent both, the higher surface flows in the wet season and continuous subsurface flows in the dry season.

The data availability proved to be the most limiting factor for the reliability of the model output. Therefore the results presented here must be seen as an initial assessment of the potential impact of land use dynamics on SWAT applying LUPSA. The effect of the LUC implementation on the hydrological response of the model is substantial, showing significant changes in the flow dynamics. Still the model outcomes must be treated carefully. In order to produce more reliable results, further applications are needed. It is recommended to apply LUPSA in another test case where satisfactory data is available. Another aspect which wasn’t investigated here is the impact of the LUPSA application in SWAT on the model calibration efficiency. This might demand some changes in the (open source) code of LUPSA.

6. ACKNOWLEDGEMENT

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