

Land Use Change and Suitability Assessment in the Upper Blue Nile Basin Under Water Resources and Socio- economic Constraints: A Drive Towards a Decision Support System

Seleshi Yalew^{1,2}, Ermias Teferi^{1,2,4}, Ann van Griensven^{1,3}, Stefan Uhlenbrook^{1,2}, Marloes Mul¹, Johannes van der Kwast¹, Pieter van der Zaag^{1,2}

1. UNESCO-IHE Institute of Water Education, Delft, The Netherlands

(s.yalew@unesco-ihe.org, m.mul@unesco-ihe.org,
p.vanderzaag@unesco-ihe.org)

2. Delft University of Technology, Delft, The Netherlands

(s.uhlenbrook@unesco-ihe.org)

3. Vrije Universiteit Brussel, Brussels, Belgium

(a.griensven@unesco-ihe.org)

4. Addis Ababa University, Addis Ababa, Ethiopia

(e.teferi@unesco-ihe.org)

Abstract: The Upper Blue Nile is home to a large human and livestock population that live in diverse biophysical and socio-economic environment. The basin is increasingly experiencing multi-dimensional pressures including population growth, climate change and variability, deforestation, land/soil degradation, as well as increasing upstream-downstream tension on water use rights. Understanding the dynamic interactions of land use and water resources in the basin comes at the forefront of any effort to improving the livelihood and sustainability in the basin. As part of a study to develop a decision support system for an integrated natural resources management for the Upper Blue Nile basin, methods and techniques are developed to identify land use suitability based on various biophysical and socio-economic factors, and water resources availability in the basin. Possible biophysical and socio-economic land use change drivers on a mesoscale catchment, Jedeb, were identified using historical remote sensing data as well as primary data sources such as field observations, questionnaires and interviewing key stakeholder informants. Then, major land use change drivers were ranked using regression analysis (PCA). A hydrological model was setup using the Soil and Water Assessment Tool (SWAT) for the Jedeb catchment. Based on the identified high impact land use change drivers and additional factors such as agro-ecological zones and water resources availability (output from the hydrological model), a land use suitability analysis for the catchment was developed using the SITE (Simulation of Terrestrial Environments) generic land use change modeling framework. The land use and hydrological models exchange yearly simulation results to determine land use suitability analysis and impacts of land use change on components of the basin's hydrology, and vice-versa. Land use scenario was analyzed by assuming a 20% increase in population in the catchment. Preliminary results indicate a clear shift mainly from grassland land use type to cultivation land use type. It is concluded that the techniques and methodologies used in this study especially for integrating the two models can be

used for a more realistic and thorough analysis of land use suitability and water resources dynamics and assessment study. Outputs of this study are used as inputs to develop a spatial decision support system for an integrated assessment and management of land use and water resources in the basin.

Keywords: Land use change, land cover dynamics, Nile, SDSS, Integrated Modelling.

1. INTRODUCTION

There is an immense potential of land and water resources in the Upper Blue Nile (Abbay) basin. However, small and fragmented land holding, soil/land degradation, declining crop yield, increasing population, climate variability, desertification, and increasing upstream-downstream water use tensions have created enormous pressure in the basin. A number of descriptive studies have been produced in the past on the hydrology and/or land use change in the basin [Bewket and Sterk 2002, Legesse et al. 2003, Hurni et al. 2005, Setegn et al. 2008, Easton et al. 2010, Tebebu et al. 2010, Teferi et al. 2010, Tekleab et al. 2010, Gebrehiwot et al. 2011, Rientjes et al. 2011]. These studies demonstrated the trends and current dynamics of hydrology and land use change. However, the studies focus on either the hydrology or the land use in isolation, and often only on biophysical aspects of the basin. Land use suitability assessment and scenario analysis that integrates land use and water resources assessment in the basin by incorporating the biophysical as well as the socio-economic dynamics would be an essential addition for resource management and decision making efforts in the basin. The objective of this study is to identify major land use change drivers, to produce future environmental and socio-economic scenarios and to analyze their impacts on land use change dynamics. The study produces and discusses land use scenario and suitability maps based on various socio-economic as well as biophysical factors (including water resources availability).

2. STUDY AREA

With an area of 296.6 km², Jedeb is a mesoscale catchment in the Upper Blue Nile basin (Figure 1). It lays between 10° 23' to 10° 40' N and 37° 33' to 37° 60' E. It has elevation that extends from 2172 to 4000m above sea level and precipitation that ranges from 1400 to 1600 mm per year. The catchment is part of the head water region of the Nile which is composed of rugged topography that drives torrential floods carrying fertile top soil cover from the highlands of the basin. As one of the severely eroded and degraded parts of the basin, the Jedeb catchment has attracted a lot of attention from organizations and researchers who have undertaken various environmental and water resources studies there [Hurni et al. 2005, Teferi et al. 2010, Tekleab et al. 2010].

3. DATA AND METHODS

From a number of primary and secondary data sources, various environmental and socio-economic datasets are collected and organized. Spatial datasets are computed from other environmental/biophysical dataset layers. Then a number of analyses are performed based on the conceptual framework of the study.

3.1 Conceptual Framework

The conceptual framework of this study is based on the theory that land use and water resources dynamically interact in a basin or a catchment, and that the change in location or magnitude of either land use or water resources, or their components affects the other. Furthermore, it is assumed that land use change is

affected not only by environmental or biophysical components but also with various socio-economic factors, which makes the understanding of it rather complex. In this study, a land use change model (SITE) is used to analyze land use based on various socio-economic and biophysical constraints (including water resources availability) on the Jedeb catchment. The water resources part of the input for the land use model, however, are computed using a semi-distributed hydrological model (SWAT). Since SWAT itself in return requires land use as its input, this value is provided to it from the SITE model. Dynamic linking/feedback between the two models results in a more realistic representation of the interaction between land use and water resources assessment.

3.2 Data Types and Data Sources

In addition to environmental datasets such as digital elevation, soil, precipitation, temperature and agro ecological zones, environmental/biophysical datasets were collected (and spatial datasets were derived) from various data sources (Table 1).

Table 1. Data layers (maps) used in this study

Variable	Description	Source
Socio-economic data	population density, livestock density, average house hold income, literacy level,	Central Statistical Agency, IFPRI, FAO-SDRN
Biophysical data	land cover, woody biomass, agro climatic zones, major crops, avg. rainfall, avg. temperature, current and potential crop yields, roads, rivers, urban centers	EMA, CSA, ERA, Meteorological Agency, Ministry of Water Resources, IFPRI, FAO-SDRN, USGS/NASA
Spatial data	distance to roads, distance to water sources/river, distance to market, distance to towns	Computed from biophysical inputs

*EMA=Ethiopian Mapping Agency, CSA=Central Statistical Agency of Ethiopia, ERA=Ethiopian Roads Authority, IFPRI=International Food Policy Research Institute, FAO-SDRN= FAO Environmental and Natural Resources Service, USGS=United States Geological Survey

3.3 Methods

Black and white aerial photographs of 1957 and Landsat images of 1972, 1986, 1994 and 2009 were analyzed to produce the major land use types of the catchment. The analysis of the Landsat images resulted in 10 major land use classes in the study area (Table 2). Overall classification accuracies of 89.25% (khat value 0.84), 87.67% (khat value 0.81), 91.47% (khat value 0.89), 94.17% (khat value 0.91), and 95.65% (khat value 0.94) were achieved for the 1957, 1972, 1986, 1994, and 2009 image classifications, respectively. Further details of the aerial photographs and Landsat images analysis are reported on a separate paper [Teferi et al. 2012]. Of the 10 land use classes, 'Cultivated land' was further analyzed to determine the dominant land use type in the catchment. A land use model for the Jedeb catchment was built using the SITE land use modelling framework by incorporating various socio-economic and biophysical inputs.

Table 2. Jedeb land use classes and descriptions

Code	Land cover class	Description
1	Grassland	Where grass is the dominant vegetation
2	Afroalpine grassland	High altitude (>3700m) herbaceous vegetation
3	Shrubs & bushes	Low woody plant (<3m high)
4	Cultivated land	Areas covered by temporary crops, bare after harvest
5	Riverine forest	Trees and shrubs along the banks of water bodies
6	Woodland	Continuous strand of trees with crown density of 20-80%
7	Plantation forest	Composed of transplanted trees (e.g. Eucalyptus tree)
8	Marshland	Periodically or continuously flooded wetland
9	Barren land	Bare soil/rock with little or no vegetation cover
10	Ericaceous Forest	Acidic Soil forests between 1800m and 2400 m.a.s.l

Various spatial datasets were computed/derived from combinations of biophysical dataset layers on a GIS platform; for example, 'distance to road' is derived from roads and settlement or from roads and land use type layers, 'distance to rivers', is derived from river networks and settlement or land use type.

Based on altitude, annual rainfall, soil type, temperature, and length of growing season, four agro ecological zones (Wurch, Dega, Woyna Dega, and Kola) exist in the catchment. Dominant crops in each of these zones were identified. Current and potential yield dataset layers are collected for the different crops in each of the zones. Climate data such as average annual precipitation and temperature is associated with the agro ecological zones. An aerial photograph from 1957 (Figure 2a) is used as a base map for land use analysis. The same map was simulated for 52 years (until 2009) land use change analysis by associating various environmental and socio-economic variables mentioned in Table 1. Then, the output land use map is compared (that is, historical calibration) to an independent 2009 land use map with the same land use classes which is derived from Landsat images. The factor of major local, regional and national historical socio-economic and environmental events such as rapid economic growth in the 1960s and in the 1970s, land nationalization policies, enforced resettlements, and failure of rain up to 2009 are taken into account for impacts for the land use change analysis. The SITE generic land use modelling framework, which includes two major modules, SUIT and ALLOC, for calculating suitability assessment and for allocating land use based on suitability and demand, respectively, are employed for the land use analysis in this study. The SUIT module is subdivided into functions computing biophysical suitability (e.g. elevation, terrain slope, soil fertility and precipitation) and suitability based on socio-economic factors, such as gross margins, accessibility and farmers' preferences to produce land use suitability maps [Priess et al. 2007]. The suitability analysis involves randomness, and hence, is probabilistic. The set of maps calculated by SUIT serve as the basis for the land use decisions implemented in the allocation module (ALLOC). ALLOC includes a set of functions allocating land use such as for settlements, crops and forest following certain hierarchical priorities based on the case under study.

A grid-based hydrological model using the semi-distributed Soil and Water Assessment Tool (SWAT) [Arnold et al. 1998] for the same catchment was setup with equal spatial resolutions to the land use model grid cells. Since, generally, land use input in hydrological models, and particularly, in SWAT, is implemented to change with statistical factors on the biophysical inputs (irrespective of specific socio-economic realities of a catchment or watershed), dynamic coupling of the land use and the hydrological models is proposed and implemented in this study. Two levels of model coupling were identified: a loose coupling and a strong coupling.

The loose coupling of the two models, which is implemented for this report, enables each of the two models to execute one time step at a time, set a flag to show that they have finished executing that one time step, and recursively check back and wait if the other model didn't finish executing one time step of its own yet. The output of every time step from one model is an input to the other model for the next time step. The time steps setup for each of the models here are different: for the land use model, one time step is one year (and, hence, yearly simulation) whereas for the hydrological model, one time step is one day (that is, daily simulation). The hydrological model, therefore, executes 365 'internal' simulations before it presents its outputs to the land use model as results of one ('external') simulation time step. By the same token, the hydrological model uses the same land use value for 365 'internal' simulations which is provided from results of one simulation time step of the land use model. Yearly average simulation results from the hydrological model are directly stored in a database shared by both the land use and the hydrological models. An external python program triggers the simulation of the land use model, where by, after each simulation time step, the land use model in return initiates the hydrological model to simulate for the next time step. The hydrological model triggers back the land use model to continue simulating after it finishes the current time step and writes back results to the common database. This loose coupling (data exchange) continues until both the land use and the hydrological models read a 'finished' flag which they set in a commonly accessible file.

Data exchange between the two models in this manner (that is, recursive flag check and wait, and database access time) consumes simulation time. Thus, a more direct and strong coupling of the two models is proposed for implementation. This uses the Open Modelling Interface (OpenMI) standard which allows time-dependent models to exchange data at run-time [Gregersen et al. 2007]. When the standard is implemented, existing models can be run simultaneously and share information at each time step, exchanging memory-based data in a predefined way and in a predefined format [Fortune et al. 2008]. This method can be especially interesting because SWAT is already modified and it is an OpenMI compliant model. In this paper, however, only loose coupling is implemented.

Once a satisfactory level of comparisons between the simulated and the independently processed land use map is reached (see Figure 2 b and c), a major objective in land use modelling is often to produce potential consequences of future land use options, or development pathways [Alcamo et al. 2008, Schweitzer et al. 2011] by coding/incorporating foreseeable socio-economic and environmental dynamic variables. Land use map comparisons are carried out by various algorithms, such as the Kappa [Gregersen et al. 2007], the Figure of Merit [Fortune et al. 2008] and the Moving Window [Kuhnert et al. 2005], which are built in the SITE land use modelling framework. A 'what if' scenario (Figure 3a) by increasing human population variable in the catchment with the rate of growth for the national population prediction, *ceteris paribus*, and a future land use scenario (Figure 3b) by assuming the same environmental and socio-economic dynamics is produced based on the same simulated land use map of Figure 2b). For this report, average annual precipitation, discharge, surface runoff and distance to water body aspects of the hydrology or water resources of the catchment at a grid level are taken into account for the land use suitability assessment. Other important considerations such as lateral flow exchange between grid cells is not implemented yet.

4. RESULTS

Results of this analysis indicate that out of the biophysical as well as socio-economic land use change drivers identified in the Jedeb catchment, population, resettlement, distance to roads, distance to markets, crop prices, livestock population and livestock prices are major controls of the land use change. Unlike the conventional wisdom, distance to water sources has shown little significance on land use change until late on the simulation matchup for the 1994 land use map, and, for a bigger extent, for the 2009 land use simulation map. This might have to do with the fact that farmers are lately practicing more small scale irrigation using small capacity water pumping generators in the basin, encouraged either by the sudden availability of such technology, or by variability and less reliable rainfall seasons. The rugged topography of the catchment might have hindered the practice of irrigation, and hence making the 'distance from rivers' on land use change irrelevant prior to 1994 without such small capacity water pumping generators. As a preliminary test, a scenario of a 20% increase in population in the catchment is simulated. The result shows a state where land use shifts mainly from grassland into cultivated land. Of particular interest is the results of the loose integration of the land use and the water resources/hydrological (SITE and SWAT) models. The simulation of the land use model alone (without inputs from SWAT about the water budget of each land grid cell) represents a land use type such as a wet land or marsh land in this study, simply as wet land or marsh land and does not allocate them to any other land use such as for certain crop types or settlement areas, because a wetland is suitable for neither of them. However, simulation feedback from the hydrological model shows that certain wetland/marsh land grid cells, in fact, hold less and less water budget during the simulation periods, thereby putting themselves as a good candidate for being picked by the SUIT module and being allocated to other land use types. The same way, a measure in the land use aspect shows changes in runoff and sedimentation levels in SWAT model outputs which will be discussed in a detailed paper. In this study, the presented preliminary population increase scenario demonstrates that population growth continues to be a major pressure on the future land use dynamics in the catchment.

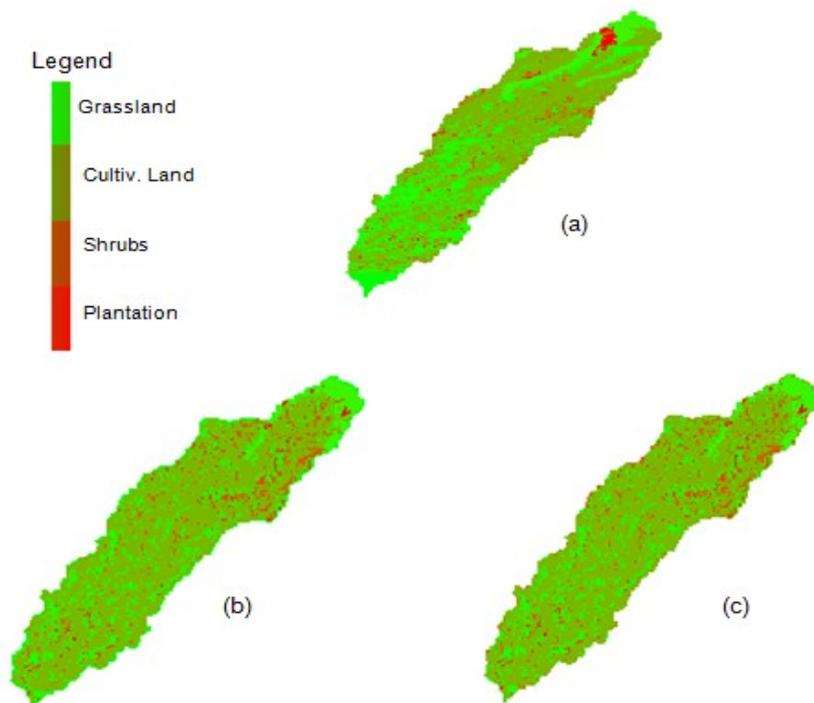


Figure 2. Baseline land use map of aerial photograph from 1957 (a), simulated land use map of 2009 (b) and historical (Landsat derived) land use map of 2009 (c).

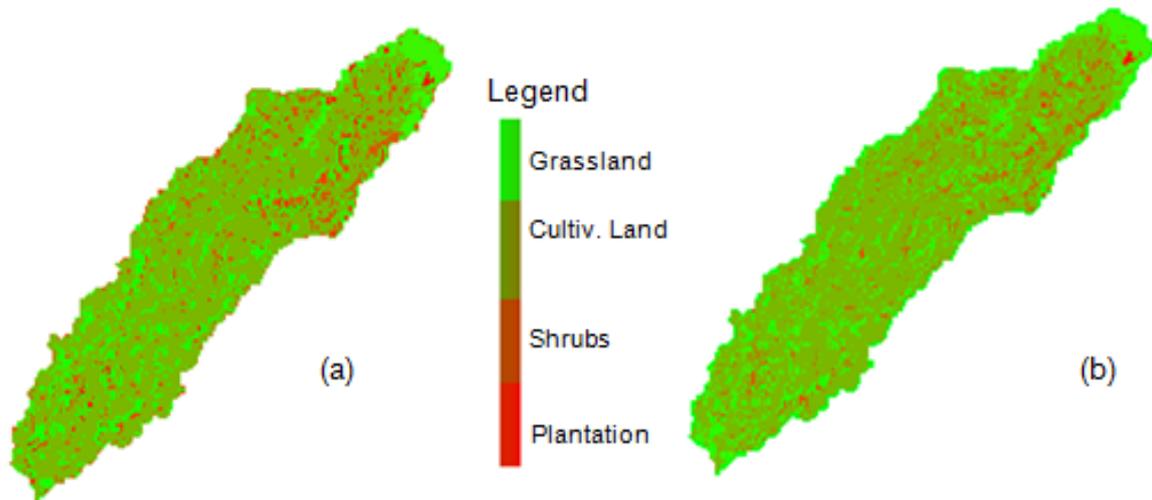


Figure 3. Historical (a) vs. simulated land use map of 2009 with '+20% population' scenario (b).

5. CONCLUSIONS

The approach discussed in this paper demonstrates plausible methods of land use suitability and scenario assessment. The study also highlights the importance of integrating water resource and land use analysis tools in environmental modelling endeavours. The study demonstrated with a scenario that population is a major land use change driver in the Jedeb catchment. On a next step, further scenario building and strong dynamic coupling of the two models (without the need for the intermediary database for data exchange rather than for data storage) is envisioned.

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