environmental sciences proceedings

MDPI

Proceedings

Evaluation of the Impacts of Land Use Land Cover Change on Hydrology—A Case Study of the Nashe Watershed †

Megersa Kebede Leta [1,2,*], Tamene Adugna Demissie [2] and Jens Tränckner [1]

1. Faculty of Agriculture and Environmental Sciences, University of Rostock, Satower Str. 48, 18051 Rostock, Germany; jens.traenckner@uni-rostock.de
2. Faculty of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University, Jimma 378, Ethiopia; tamene.adugna@ju.edu.et

* Correspondence: megersa.kebede@uni-rostock.de; Tel.: +4915210100572

† Presented at the 6th International Electronic Conference on Water Sciences (ECWS-6), Online, 15–30 November 2021.

Abstract: Changes in land use and land cover (LULC) have a significant impact on a watershed's hydrological processes. Investigating the impact of land use land cover change on hydrological components and the responses of watersheds to environmental changes is crucial for water resource planning, land resource utilization, and maintaining hydrological balances. The impacts of land use land cover on hydrological parameters in the Nashe watershed, Blue Nile River Basin, are explored in this study. Historical and future land use land cover change scenarios that represent baseline, current and future periods have been implemented into a calibrated Soil and Water Assessment Tool (SWAT) model using Digital Elevation Model (DEM), land use land cover maps, soil data, weather data, and hydrological data. The result showed the land use land cover changes analyzed for the time period of 2019 to 2035 reveal a decline in ground water flow, lateral flow, evapotranspiration, and increment of surface runoff, and water yield. This depicts that the land use land cover change will occur in the future by decreasing forest land and increasing agricultural land and urban area that will increase the vulnerability of the watershed.

Keywords: LULC change; surface runoff; SWAT model; water balance

Citation: Leta, M.K.; Demissie, T.A.; Tränckner, J. Evaluation of the impacts of land use land cover change on hydrology. A case study in Nashe watershed. *Environ. Sci. Proc.* **2021**.

Academic editor: Maurizio Polemio

1. Introduction

Land use land cover change effect on hydrology is revealed at different scales and has become a worldwide concern because of its varied environmental effects. Many hydrological processes such as rainfall, evapotranspiration, and runoff are significantly affected by LULC change. The most frequent analysis in hydrology is runoff estimation in a watershed depending on rainfall distribution [1]. The assessment of LULC change and the drivers that have direct consequences on the natural environment and human societies are the focus of the current scientific examination of scientists [2]. Therefore, it is important to investigate the impacts of LULC change on the hydrology of the catchment to address water resource operation and management issues.

Assessment of the historical, current, and potential future LULC change dynamics is essential to manage LULC and water resources efficiently in a watershed [3]. Analyzing and predicting the future watershed hydrology through advanced tools over a long period is significant to attain sustainable water resources at the catchment scale [4]. Soil and Water Assessment Tool (SWAT) is used to investigate the effects of LULC change on hydrological processes in small and large watersheds [5]. The model is also mostly used for modeling and analyzing hydrological processes in the context of changing LULC and land management with high efficiency. The findings of different studies that compared the

SWAT performance to other hydrological models conclude that the SWAT model simulates stream flow better than other hydrological models [2,6].

Therefore, based on the criteria specified for the Nashe watershed, the SWAT model has been adopted. Ethiopia experienced serious environmental problems including soil erosion, land degradation, loss of soil fertility, and deforestation due to LULC changes [7]. The investigations directed on the hydrological processes of watersheds dependent on LULC change show an increment of flow in the wet season and surface runoff potential that relates to the agricultural and urban area expansion at the expense of forest lands [8].

The Blue Nile River Basin is the most substantial and diverse water resource for the region and continent also serving as the largest catchment to the Nile River Basin. Human-induced land degradation has occurred in the Nashe watershed that subsidizes a large amount of water to the Blue Nile River Basin [7]. Furthermore, in the Nashe catchment, the agricultural land and urban expansion at the expense of range land, forest land, and grass land is the common problem and this will also be predictable to continue in the future [3].

This paper aimed to assess different features of LULC change impacts on hydrological parameters at various Spatio-temporal scales and to develop LULC scenarios to explore the change of LULC effect on hydrological parameters of the watershed. Therefore, analyzing the impacts of LULC on the hydrological processes at different periods and prioritization of the sub-basins will contribute to identifying strategies of hydrological responses of the watershed.

2. Materials and Methods

2.1. Study Area

The study was conducted in the upper Blue Nile River Basin, Nashe catchment in Oromia Regional State, Ethiopia. Nashe catchment lies in 9°35′ to 9°52′ North latitude and 37°00′ and 37°20′ East longitude covering 94578 Ha areas (Figure 1). The Nashe watershed is the major tributary of Blue Nile River Basin of Ethiopia which is situated about 300 km from Addis Ababa. The watershed area varies in elevation from 1600 m in the lower plateau under the escarpment to the hills and ridges of the highland climbing to over 2500 m.

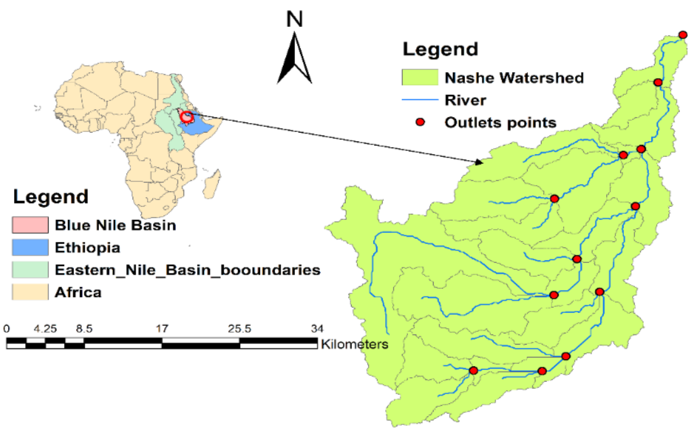

Figure 1. Location map of the study area.

2.2. Data

The main data used for the study to characterize the basin was weather data, Digital Elevation Model, land use land cover maps, soil data, and hydrological data. The historical LULC images were obtained from Landsat images and classified using supervised classification in Earth Resource Data Analysis System (ERDAS) imagine model [3]. The future LULC was predicted based on the classified historical satellite images using Land Change Modeler (LCM) integrated TerrSet model (Figure 2 b). The historical (1990, 2005, and 2019) and future (2035 and 2050) LULC maps developed by Leta et al. [3] were used.

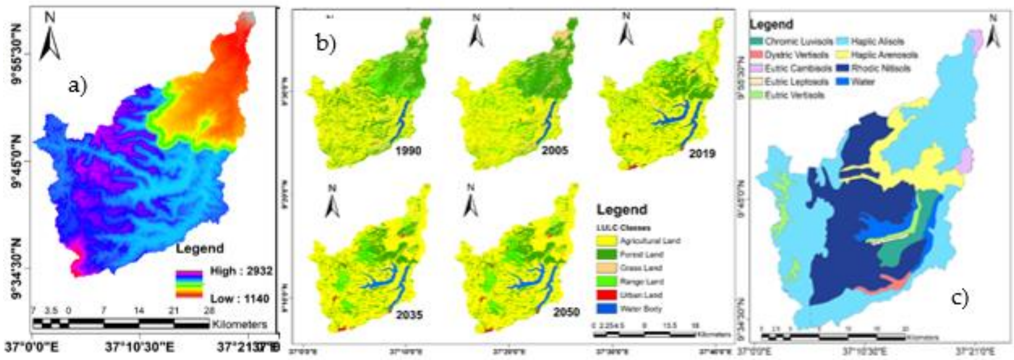

Figure 2. Nashe watershed a) DEM b) LULC c) Soil.

2.3. Modeling

SWAT is physically based, a spatially semi-distributed, daily time step hydrological model designed to simulate a range of various parameters such as lateral flow, ground water, surface runoff, and soil water. Similarly, the SWAT model was developed to predict the impact of land use and management on water, sediment, and agricultural chemical yields at catchment scale at daily, monthly, and annual time increments.

The major model components include DEM, weather, hydrology, soil properties, and land management. Depending on the extent of the watershed and detail of available geographical input data, the SWAT model splits a watershed into several sub-basins, which are further divided into smaller areas denoted as hydrologic response units (HRUs) [9,10]. As a result, depending on the topographical information data, the SWAT divides the Nashe catchment into 23 sub-watersheds that are then divided into a total of 321 HRUs based on their soil type, land use land cover, and slope.

$$SWt = SWo + \sum_{i=1}^{n}(Rday - QSurf - Ea - Wseep - Qgw) \quad (1)$$

where: *SWt* is the final soil water content(mm), *SWo* is the initial water content (mm), *t* is the time (days), *Rday* is the amount of precipitation on day *i* (mm), *Qsurf* is the amount of surface runoff on day *i* (mm), *Ea* is the amount of evapotranspiration on day *i* (mm), *Wseep* is the amount of water entering the vadose zone from the soil profile on day *i* (mm) and *Qgw* is the amount of return flow on day *i* (mm).

2.4. Sensitivity Analysis, Calibration and Validation

Due to a large number of flow parameters in SWAT, ascertaining the most sensitive parameters is crucial to improve the calibration of the hydrological model. The Sequential Uncertainty Fitting (SUFI-2) integrated in the SWAT-CUP (Calibration and Uncertainty Program) has been used to achieve sensitivity analysis, calibration and validation [11]. The process of estimating hydrological model parameters by comparing the model prediction with the observed data is known as Calibration. Whereas, testing the calibrated model without further parameter adjustments with an independent dataset is known as validation. The observed stream flow of 1985–2008 was divided into a warm-up (1985–1986), calibration period (1987–1999), and validation period (2000–2008).

The simulation of the model fitness with the observed stream flow was expressed by statistics like coefficients of determination (R^2), Nash-Sutcliffe efficiency (NSE), and percent bias (PBIAS). The performances of the model ratings were: R^2 varies between 0 and 1, where higher value shows less error. NSE ranges from negative infinity to 1, where 1 indicates the best. PBIAS varies from negative infinity to positive infinity. Where the value close to 0 shows the best simulation, a negative and positive value indicates overestimation, and underestimation respectively. The two measurements used to assess the quality of uncertainty analysis are the p-factor and the r-factor. The p-factor is a proportion of measured data bracketed by the 95PPU that varies from 0 to 1, with 1 being the optimal result. The r-factor ranges between 0 to infinity, and it is the average thickness of the 95PPU band to the standard deviation of the corresponding measured data.

The calibrated and validated model with the historical (1990, 2005, 2019) and future (2035, 2050) LULC maps were used to reveal the effects of LULC variations on watershed hydrology. In this study five LULC scenarios were developed, representing baseline, current, and future LULC conditions. The first two scenarios (1990 and 2005) are considered as a baseline. The third scenario corresponds to 2019 represents the current LULC. The 2035 and 2050 projected under Business as Usual Scenario represents the fourth and fifth scenarios representing the future LULC change. Correspondingly, to develop linear correlations between dependent variables and independent variables the pair-wise Pearson correlation matrix was implemented.

3. Results and Discussions

3.1. Sensitivity Analysis, Calibration and Validation

Sensitivity analysis (r__CN2.mgt, v__GW_DELAY.gw, r__SOL_K (...).Sol, v__ALPHA_BF.gw, v__CH_N2.rte, v__GWQMN.gw, r__SOL_AWC (...).Sol, r__SLSUBBSN.hru, r__RCHRG_DP.gw) was conducted and the top three most sensitive parameters are CN.mgt, GW_DELAY.gw, and SOL_K(..).Sol. The parameters include those governing sub-surface and surface hydrological processes and stream routing. The simulated and observed graphical and statistical comparison shows a good agreement both in calibration and validation periods (Figure 3). The evaluation of simulated and observed stream flow computed through the statistical values of objective functions are in the recommended range based on the performance assessment criteria. Therefore, the performance indices obtained indicates a good performance rate of the model in simulating the impacts of LULC changes [7].

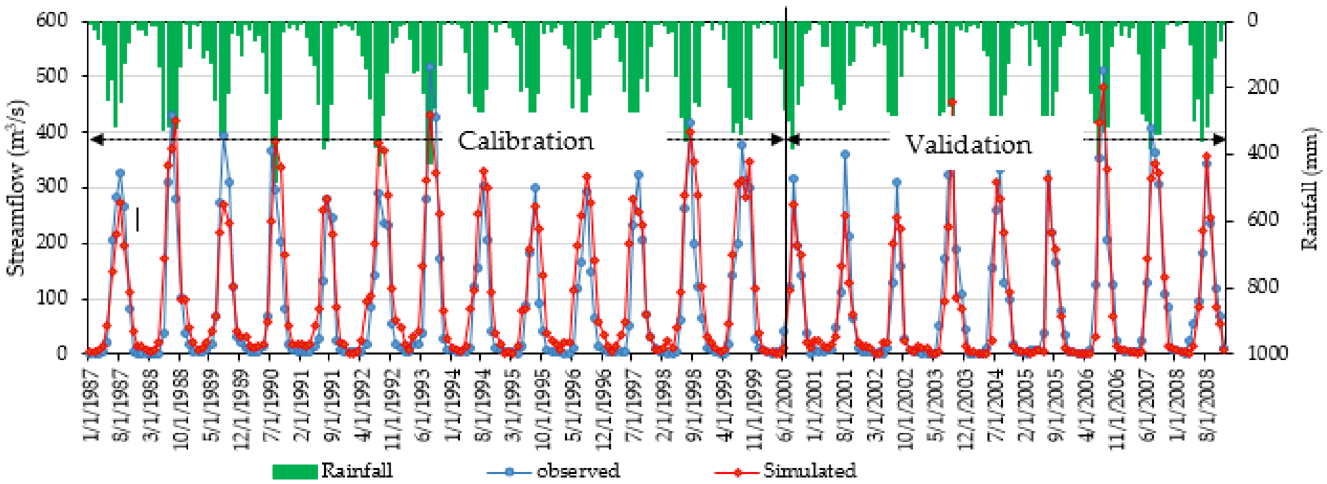

Figure 3. Calibration and validation of average monthly stream flow.

3.2. Land Use Land Cover Change Effects on Hydrological Responses

The effect of LULC change on hydrological parameters of the Nashe watershed was assessed based on the LULC classes of different periods. The seasons in Ethiopia are categorized into three in the year based on the rainfall magnitudes. The wet season is from June to September, the season of short rain (February to May), and the dry season from October to January. The hydrological parameter variability due to LULC change was assessed based on these three rainfall seasons. The findings revealed that above 80% and 40% of the surface runoff and ground water happens throughout the wet season, whereas less than 10% of the surface runoff happens in the dry and short rainy season.

The surface runoff in the wet season was increased by 2.15% from 2019 to 2035 LULC change (Figure 4). The extraction of forest land, range land, grass land, and agricultural coverage and urban area expansion highly influence surface runoff, peak flow, and base flow following rainfall events [9]. The reduction in forest land decreases infiltration and evapotranspiration rates, resulting in a decrease of base flow and an increase in impervious surface covers. Evapotranspiration has reached a minimum from October to January and maximum in the period of February to May. The urban area expansion increases high stream flow and decreases low stream flow.

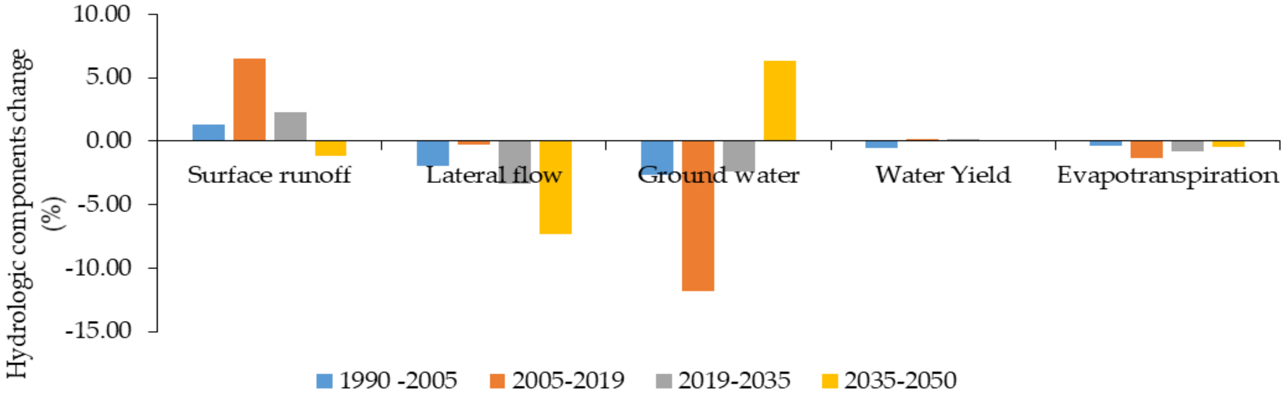

Figure 4. Average annual hydrological components change (%) under land use land cover scenarios.

The average surface runoff of the catchment was increased by 7.94%, 10.45%, and 9.17% in 2019, 2035, and 2050 respectively, compared to the baseline scenario (1990). In contrast, the average annual lateral flow of the watershed declined by 2.27%, 5.55%, and 18.24% in 2019, 2035, and 2050 with the baseline scenario (1990). The surface runoff will decrease by 1.41 % from 2035 to 2050 due to the gradual increase of grass land and range land starting from the year 2035. Gyamfi et al. [12] and Leta et al. [9]indicated that the surface runoff, groundwater, and base flow parameters were affected by LULC changes. It was also observed from the result a strong positive Pearson correlation factor was found between agricultural land and surface runoff. Similarly, a strong negative correlation has also happened between forest land and surface runoff.

In hydrological components, changes in rainfall are the dominant factor that induces changes in water balance components. Evapotranspiration is the foremost water availability determinant in the watershed since it negatively influences surface runoff. The decrease in forest land, grass land, and range land combined with an increase in slope length and steep slopes cause surface runoff increment [9]. The monthly peak flows happened in July and August and the maximum monthly discharges occurred in 2050, while the minimum flow occurred in 1990. Generally, the increase of surface runoff in wet seasons may result in flooding and a decline in the dry season may affect water scheme practices.

4. Conclusions

The SWAT hydrological model was used to simulate historical and future continuous fluctuations in stream flow through time. The relation of LULC categories and hydrological components revealed that the surface runoff was highly attributed to change in the agricultural land with a higher correlation coefficient. Similarly, it was observed that the increment of surface runoff and decline of ground water observed during the rainy season in the Nashe watershed of the Blue Nile River Basin may lead to increasing extreme weather events, sedimentation, runoff, siltation, and water shortages may occur during the dry season and obstruct socio-economic development in Ethiopia. The suitable management policy should be prepared depending on the usually LULC change of the watershed. Additionally, appropriate conservation measures of water and soil are extremely essential and should be flexible and adaptable to changing insights on the impacts.

Author Contributions: Conceptualization, M.K.L.; methodology, M.K.L.; software, M.K.L.; validation, M.K.L., T.A.D., and J.T.; formal analysis, M.K.L.; investigation, M.K.L.; data curation, M.K.L.; writing original draft preparation, M.K.L.; writing—review and editing, M.K.L., T.A.D., and J.T.; visualization, M.K.L.; supervision, T.A.D., and J.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was part of the DAAD-EECBP Home Grown PhD Scholarship Program under (EECBP Homegrown PhD Program-2019).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study can be available from the authors on reasonable request.

Acknowledgments: Acknowledgments: The first author thanks the German Academic Exchange Service (DAAD) for providing a scholarship during the study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pang, S.; Wang X.; Melching, C.S.; Feger, K.H. Development and testing of a modified SWAT model based on slope condition and precipitation intensity. *J. Hydrol.* **2020**; 588, 125098, doi:10.1016/j.jhydrol.2020.125098.
2. Waseem, M.; Kachholz, F.; Tränckner, J. Suitability of common models to estimate hydrology and diffuse water pollution in North-eastern German lowland catchments with intensive agricultural land use. *Front Agric. Sci. Eng.* **2018**; 5, 420–431.
3. Leta, M.K.; Demissie, T.A.; Tränckner, J. Modeling and prediction of land use land cover change dynamics based on land change modeler (LCM) in Nashe watershed, Upper Blue Nile Basin, Ethiopia. *Sustain.* **2021**; *13*.
4. Anand, J.; Gosain, A.K.; Khosa, R. Prediction of land use changes based on Land Change Modeler and attribution of changes in the water balance of Ganga basin to land use change using the SWAT model. *Sci Total Environ.* **2018**; 644, 503–519, doi:10.1016/j.scitotenv.2018.07.017.
5. Saddique, N.; Mahmood, T.; Bernhofer, C. Quantifying the impacts of land use/land cover change on the water balance in the afforested River Basin, Pakistan. *Environ. Earth Sci.* **2020**, *79*, 1–13, doi:10.1007/s12665-020-09206-w.
6. Gassman, P.W.; Sadeghi, A.M.; Srinivasan, R. Applications of the SWAT Model Special Section: Overview and Insights. *J. Environ. Qual.* **2014,** *43*, 1–8.
7. Megersa, K.L.; Tamene, A.D.; Sifan, A.K. Impacts of Land Use Land Cover Change on Sediment Yield and Stream Flow; *Int. J. Eng. Sci. Technol.* **2017**, *6*, 763–781.
8. Khadr, M. Forecasting of meteorological drought using Hidden Markov Model (case study: The upper Blue Nile river basin, Ethiopia). *Ain Shams Eng. J.* **2016,** *7*, 47–56, doi:10.1016/j.asej.2015.11.005.
9. Leta, M.K.; Demissie, T.A.; Tränckner, J. Hydrological Responses of Watershed to Historical and Future Land Use Land Cover Change Dynamics of Nashe Watershed, Ethiopia. *Water* **2021**, *13*, 2372.
10. Arnold, J.G.; Moriasi, D.N.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, D.R.; Griensven; A. van.; Van, Liew. W.M.; Kannan, N.; Jha, M.K. SWAT: MODEL USE, CALIBRATION, AND VALIDATION; *Trans. ASABE* **2012,** *55*, 1491–1508.
11. Aduah, M.S.; Jewitt, G.P.W.; Toucher, M.L.W. Assessing impacts of land use changes on the hydrology of a lowland rainforest catchment in Ghana, West Africa. *Water* **2017**, *10*, 9.
12. Gyamfi, C.; Ndambuki, J.M.; Salim, R.W. Hydrological responses to land use/cover changes in the Olifants Basin, South Africa. *Water* **2016**, *8*, 588.