

# Performance Evaluation of SWAT Model for Land Use and Land Cover Changes in Semi-Arid Climatic Conditions: A Review

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## Abstract

Evaluation of land use land cover changes on the hydrological regime of river basins is one of the concerns in the global climate change. With plethora of tools available in the literature choosing of an appropriate tool that can quantify and analyze the impact of land use land cover changes on the hydrological regime in a systematic and planned manner is important. Soil and Water Assessment Tool (SWAT) integrated with Geographic Information System (GIS) based interfaces and its easy linkage to sensitivity, calibration and uncertainty analysis tools made its applicability more simple and has great potential in simulation of the past, present and future scenarios. A number of standards were used to appraise the model set-up, model performances, physical representation of the model parameters, and the accuracy of the hydrological model balance to assess the models that are defined in journal papers. On the basis of performance indicators, the mainstream of the SWAT models were categorized as providing satisfactory to very good. This review debates on the application of SWAT in analyzing land use land cover changes in semi-arid environment. Application of SWAT and land use land cover simulation models for impact assessment in semi-arid region improves accuracy, reduces costs, and allows the simulation of a wide variety of conservation practices at watershed scale. It is also observed that different researchers and/or model versions bring about in different outcomes while a comparison of SWAT model applications on similar case study was applied. This review determines the interactive role of SWAT and GIS technologies in improving integrated watershed management in semi-arid environments.

**Keywords:** Impact assessment; Land use land cover changes; Semi-arid environment

**Abbreviations:** SWAT: Soil and Water Assessment Tool; GIS: Geographic Information System

## Introduction

To study sustainable water resources and land use planning and development understanding the consequences of changes in land use and land cover scenarios is required. Human activities can affect the integrity of natural resources and the output of goods and services in the ecosystem. The development of new patterns of land use and land cover conditions can be enhanced by careful planning for the well-being of people [1]. The scientific framework for the analysis of land use systems have changed by the modelling tools which can addresses both spatial and temporal dynamics. It is a universal concern the changes in land use and land cover in river basins resulted in flooding events that has increased sediment loads [2-6]. There are some proportional alterations in the basin condition and hydrological response as a result of changes in land cover and land use scenarios. This is appropriately becoming one of the main existing land management issues [7].

The response of hydrological processes of river basins influenced by human activities and climate changes have been widely studied [8-12] [2,3]. In recent years, understanding the occurrences of natural processes at the watershed scale by the application of the model became an essential tool [13]. Geographic Information System (GIS) based spatial modeling has grown into an important tool to assess the effect of land use land cover changes on runoff and soil erosion studies and, consequently in advancement of suitable soil and water conservation strategies. Among several models SWAT linked with GIS has been extensively used in earlier studies.

Gassman et al. [14] investigated that the historical development, application and future research directions using SWAT model for a

wide range of scales and environmental conditions across the globe and over a long period of time. The Soil and Water Assessment Tool (SWAT) model [15] has been proved to be an effective tool for assessing land use land cover changes, water resources and nonpoint-source pollution problems. This paper aims to review performance evaluation of SWAT model for land use and land cover changes in Semi-arid environments. An overview on the efficiency analysis of SWAT and its integration with land use and land cover simulation models are also presented.

## SWAT Model

SWAT is readily applicable through the development of geographic information system (GIS) based interfaces and is attributed to the fact that the tool is freely available and easy linkage to sensitivity, calibration and uncertainty analysis tools makes it a very popular model. In data-scarce areas the online and free availability of basic GIS data made SWAT model applicability more straightforward [16]. Conservation practices such as riparian buffers and vegetative filter strips can be adequately simulated whilst SWAT is being altered to account for landscape spatial positioning [15]. One of the main advantages of SWAT is that it can be used to model watersheds with less monitoring data. For simulation, SWAT needs digital elevation model (DEM), land use and land cover

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map, soil data and climate data of a specific study area. These data are used as an input for the analysis of hydrological simulation of surface runoff and groundwater recharge.

The Simulation of the hydrology of a watershed is done in two separate divisions. One is the land phase of the hydrological cycle that controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin [17]. Hydrological components simulated in land phase of the hydrological cycle are canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds, tributary channels and return flow. The second division is routing phase of the hydrologic cycle that can be defined as the movement of water, sediments, nutrients and phase of hydrological cycle. SWAT simulates the hydrological cycle based on the water balance equation.

$$SW_t = SW_o + \sum_{i=1}^t (R_{day} + Q_{surf} - E_a - W_{seep} - Q_{qw})_i \quad (1)$$

Where  $SW_t$  is the final soil water content (mm),  $SW_o$  is the initial soil water content on day  $i$  (mm  $H_2O$ ),  $t$  is the time (days),  $R_{day}$  is the amount of precipitation on day  $i$  (mm  $H_2O$ ),  $Q_{surf}$  is the amount of surface runoff on day  $i$  (mm),  $E_a$  is the amount of evapotranspiration on day  $i$  (mm  $H_2O$ ),  $W_{seep}$  is the amount of water entering the vadose zone from the soil profile on day  $i$  (mm  $H_2O$ ) and  $Q_{qw}$  is the amount of return flow on day  $i$  (mm  $H_2O$ ).

Surface runoff occurs whenever the rate of precipitation goes beyond the rate of infiltration. SWAT suggests two methods for estimating surface runoff: the SCS curve number procedure [18] and the Green & Ampt infiltration method [19]. Using daily or sub daily rainfall, SWAT simulates surface runoff volumes and peak runoff rates for each HRU. In most cases, the SCS curve number method was used to estimate surface runoff because of the unavailability of sub daily data for Green & Ampt method.

The SCS curve number equation is:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)}, \text{ if } R_{day} > 0.2S; Q_{surf} = 0 \text{ otherwise} \quad (2)$$

Where:  $Q_{surf}$  is the accumulated runoff or rainfall excess (mm),  $R_{day}$  is the rainfall depth for the day (mm);  $S$  is the retention parameter (mm). The retention parameter is defined by equation 3.

$$S = 25.4 \left( \frac{100}{CN} - 10 \right) \quad (3)$$

Where;  $CN$  is the curve number for the day.

Erosion caused by rainfall and runoff is computed using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by [20]. It calculates the average annual gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor is substituted with a runoff factor which advances the sediment yield prediction and permits the equation to be applied to discrete storm events. This advances sediment yield prediction because runoff is a function of antecedent moisture condition as well as rainfall energy [21].

$$Sed = 11.8 * (Q_{surf} * q_{peak} * area_{hru})^{0.56} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG \quad (4)$$

Where  $Sed$  is the sediment yield on a given day (metric tons),  $Q_{surf}$  is the surface runoff volume (mm  $H_2O$ /ha),  $q_{peak}$  is the peak runoff rate ( $m^3/s$ ),  $area_{hru}$  is the area of the HRU (ha),  $K_{USLE}$  is the soil erodibility factor (0.013 metric ton  $m^2hr/(m^3\text{-metric ton cm})$ ),  $C_{USLE}$  is the cover

and management factor,  $P_{USLE}$  is the support practice factor,  $LS_{USLE}$  is the topographic factor and  $CFRG$  is the coarse fragment factor. The details of the USLE factors and the descriptions of the different model components can be found in [15].

## Impact Analysis of LUCC by SWAT Model

Hydrologic response is an integrated indicator of watershed condition, and significant changes in land cover may affect the overall health and function of a watershed. [7] used SWAT model for evaluating the effects of land cover change and rainfall spatial variability on watershed response of the Walnut Gulch experimental watershed encompassing approximately 150  $km^2$  located in southeastern Arizona, USA. The authors evaluated the impact of land cover change on the runoff depth of different land cover classes. The simulation results showed that the runoff responses of the watershed due to changes of land use and land cover.

Mango et al. [22] analyzed the sensitivity of model outputs to land use change for a sub-basin (700  $km^2$ ) on the Nyangores tributary of the Mara River basin, Kenya, used three hypothetical scenarios: partial deforestation, complete deforestation to grassland, and complete deforestation to agriculture. Simulations under all land use change scenarios indicated that various land use pattern should have various impacts on rainfall-streamflow interactions. For example, the conversion of forest land to agricultural land indicated an increased overland flow and a decreased subsurface flow and average flow over the period of simulation, while evapotranspiration shows a small positive increase. These outcomes are disagreed to the results achieved by [23], where a reduction in forest cover directed to a decrease in evapotranspiration, an increase in both surface and sub subsurface flow and a large increase in water yield.

Pikounis et al. [24] investigated that the hydrological effects of specific land use changes in a catchment of the river Pinios in Thessaly (Ali Efenti catchment, 2976  $km^2$ ), Greece, through the application of the SWAT model on a monthly time step. It should be noted that although the model was run for 23-years (1970 to 1993), the first 5 years of simulated output were disregarded in the calibration process, since they are required by the model as a warm-up period. This period was essential for the stabilization of parameters, as the results sometimes vary significantly from the observed values. The authors investigated the effect of land use change by using three land use scenarios which are: expansion of agricultural land, complete deforestation and expansion of urban area in the Trikala sub-basin. All the three scenarios resulted in an increased in streamflow during wet season and decreased during the dry season. Thus, the final calibration period was from April 1975 to December 1993. The result can be quite satisfactory.

SWAT application for assessing LUCC impacts on sustainable development and watershed hydrological status is gaining momentum worldwide due to enormous anthropogenic activities on the natural systems of river basins [25-32]. In a case study at the Little Miami Watershed, USA, it was recognized that there is significant reduction in flow, sediments, and nutrients were detected as the land use in the watershed shifts from predominantly agricultural to mixed rural and residential lands [33]. To simulate the main components of the hydrological cycle, SWAT model was also used in order to study the effects of land use changes in 1967, 1994 and 2007, in the Zanjanrood Basin, Iran [11]. The results indicated that the hydrological response was nonlinear and exhibited a threshold effect to overgrazing and changing of rain-fed agriculture and bare ground from rangelands where more than 60% of the rangeland was removed, the runoff increased considerably.

Singh and Gosain [34] used SWAT model for the valuation of the total amount of available water, as well as prediction of the impact of changes in the land management practices on the availability of water in Cauvery basin, India. Nine reservoirs in the basin where data was available were also modeled as impoundments structures in this study. When monthly streamflow values were considered, the values of NSE and R2 was 0.934 and 0.936, respectively, which reveals that the model had captured the system and there was no need to calibrate the model. These authors produced a series of scenarios for the participants to analyze the above-mentioned categories of changes in land use and land cover. This paper reported that as the percentage of forest decreases, the water yield increases in the basin. Similar scenario generation approach was made in Kaneri basin, Maharashtra by [35]. Four scenarios were considered in model simulations. The first one was the base scenario; second with sensitive parameters flow was calibrated to advance the outcomes. Each sub-basin was provided with pond in the third scenario and the impact was studied. For the fourth condition, the Best management practices (BMP's) like farm terracing, contouring, residue management and generic conservation practices were included and the impact was studied. The BMP's provided results in the reduction of surface runoff in the range of 62% to 75%, decrease of water yield in the range of 33% to 53% and reduction of sediment yield to nearly 98%. In four time periods (1973, 1986, 1992, and 1997) in the upper San Pedro watershed, USA another application of SWAT, hydrological modeling was conducted for each of the land use map [36]. Results verified that major environmental stressors affecting local water resources were urbanization and mesquite invasion. In the Chi River basin, Thailand in another place land use change were evaluated in five scenarios [37]. These scenarios have incorporated conversion of farmland to rice and sugarcane plantation and three scenarios involving a conversion of forested area, expansion of farmland, switching of rice paddy fields to energy crops. Results have shown that not worth mentioning changes shown on water flows and evapotranspiration (ET) due to the conversion of forested area and farmland. In the dry season there is reduced water flows and increased ET when paddy fields are substituted by sugarcane plantation. Predominantly, small changes occur on annual flow and ET but more significant effects occur on seasonal flows in case of expansion of rice paddy fields to farmland. In the dry season period the results showed there is an increase of water yield as a result of decreasing ET leading to a significant effect on seasonal ET showed as the conversion of farmland to sugarcane plantation for bio-fuel production, but small changes on water yields.

Using land use maps in the upper Huaihe River, China over three phases the 1980s, 1990s and 2000s the effect of land use change on the sediment yield characteristics were explored [38]. The results have shown that there is increasing rate for sediment yield and the sensitivity of rainfall-sediment yield relationship to rainfall changes move down by woodland, paddy field and farmland under the same condition of soil texture and terrain slope in the area. [39] assessed impact of two small scale Slovenian watersheds by using historical land use maps from 1787, 1827, 1940, 1984 and 2009 land use map depicting present situation for LUCC. Results showed statistically insignificant for both watersheds the influence of land use change on total and green water quantity, but would have considerable effects on the seasonal flow. Shao Y, Lunetta R, et al. [40] investigated in the Laurentian Great Lakes Basin, USA including the conversion of all "other" row crop types to corn and hay/pasture to corn they considered two future agricultural scenarios compared with the current baseline condition. Significant increases in average annual sediment yields were noticed when compared with the baseline condition.

Several researchers have investigated several studies on the combined impact of land use change with climate change. In the Loess

Plateau of China, [10] among others, quantified the influences of the land use change and climate variability by comparing the SWAT outputs of the four scenarios, i.e., S1 (1985 land use and 1981–1990 climate), S2 (2000 land use and 1981–1990 climate), S3 (1985 land use and 1991–2000 climate), and S4 (2000 land use and 1991–2000 climate). Results revealed that the surface hydrology is influenced more significantly by the climate variability than the land use change within the watershed during the period 1981–2000. In the Be River Watershed, Vietnam through climate change scenarios three land use scenarios were considered in examining the impact of land use change on streamflow and sediment yield [41]. All current shrub lands were converted into perennial cropland, and the remaining land use types were kept constant as shown in the first scenario. The second scenario assumed that shrub land substituted all productive forest lands. All shrub land and productive forest land were replaced by perennial cropland while using the third scenario. Generally, Streamflow, sediment load, and water balance components response to the separate impacts of climate and land use changes were offset by one another. On the other hand, surface runoff and few components of subsurface flow were less sensitive to climate change than to land use change. However, surface runoff and few components of subsurface flow were more sensitive to land use change than to climate change. In addition, the results underlined increased soil erosion during the wet season and water scarcity during the dry season [42] showed that for runoff variations the climate conditions, especially precipitation, played an important role while land use change during the period 1970–2000 was secondary across the Taoyerhe River basin, China. Furthermore, monthly runoff was larger in the wet season due to the effects of changes in land use land cover conditions. In the Biliu River basin, China [43] generalized the characteristics of the human activities to forecast future runoff using land use land cover change conditions. The Results indicated that under normal human activities and future land use land cover change scenarios; there will be approximately 10% future increase in annual flow from 2011 to 2030, as suggested by land use land cover change scenarios with a particularly wet year in the next 20 years.

SWAT results showing improved tillage practices could result in reduced sediment yields of almost 20% within the Rock River in Wisconsin, USA, [44]. In the Walnut Creek watershed in central Iowa, USA, [45] found that adoption of no tillage, changes in nitrogen application rates, and land use changes could greatly impact nitrogen losses. Large sediment reductions could be obtained, depending on the choice of Best Management Practice as indicated by [46] on their analysis of Best Management Practices for the Walnut Creek and Buck Creek watersheds in Iowa. The impacts of Best Management Practices of three 25-year SWAT scenario simulations for two small watersheds in Indiana, USA, were studied [28], and indicated that for streamflow, sediment, and total phosphate Best Management Practices in varying conditions, and best management practices in good conditions are reported. [47] reported that within the 3000 km<sup>2</sup> Delaware River basin in northeast Kansas, USA in response to simulated shifts of cropland into switch grass production large nutrient and sediment loss reductions are occurred.

In east Africa watersheds, [48] investigated that the net influence of land cover conversion was as estimated an overall slight increase in water yield, articulated as the total streamflow from the outlet of the river resulting from both overland flow and subsurface flow that happened when the soil is comparatively well inundated. Although the overall impact on water yield was relatively small, the amount of water yield resulting from overland flow increased considerably at the expense of soil water flow. Overland flow increased while lateral flow



was reduced significantly. The increase in surface water was offset by an appropriate decline in groundwater recharge. In addition, these changes are due to two reasons: (1) declines in evapotranspiration due to the reduction in vegetation cover, and (2) greater fraction of rainfall actuality transformed into overland flow instead of going down into the soil and drifting to the aquifer and concluded that hydrologic changes were highly inconstant both spatially and temporally, and the streams in the uppermost of the forested highlands were most considerably affected and these variations have negative consequences for the environmental health of the river system.

### Application of SWAT Model in Semi-arid Environments

Numerous studies have been conducted in the past two decades that pointed out the application of the SWAT model and has been used widely. Examples of studies carried out include those of [49-53] who studied and predict the potential impacts of climate change on water resources and yields. To predict various impacts of land management on water quantity [54,55]; assess the watershed response impact to land use/cove changes on the annual water balance and temporal runoff dynamics [32,24,56,57]; to predict streamflow which were compared favorably with measured data for a variety of watershed scales [58-61]. All these studies have shown varied results due to the different regions considered, and also have employed different methodologies to construct land use/cover change and scenarios on the impacts on the hydrological responses. However, most of these studies concluded that SWAT is suitable for long-term simulations (monthly, seasonal and yearly) have been preferred for use in impact assessment and that daily flows are simulated with lower efficiencies.

Van Griensen et al. [16] stated that researchers in the Nile countries are adopting SWAT for several integrated water resources studies such as erosion modeling, land use and climate change impact modeling and water resources management. The majority of the studies were focused on locations in the tropical highlands of Ethiopia and around Lake Victoria. The majority of the SWAT models were categorized with results satisfactory to very good on the basis of performance indicators. On the other hand, the hydrological mass balances as reported in a number of articles controlled losses that might not be acceptable.

Mengistu et al. [62] investigated the sensitivity of SWAT simulated streamflow to climatic changes within the three major sub-basins of Abbay (Blue Nile), Baro- Akobo and Tekeze in Eastern Nile River basin. Those sensitivity parameters ranking were CN2, SOL\_AWC, Sol\_K and ESCO. Calibration and validation periods used for model simulations were 1990-1996 and 1997-2004 respectively. However the curve number (CN2) was the main sensitive parameter for all the outlets. This is due to the fact that the curve number depends on several factors including soil types, soil textures, soil permeability and land use properties etc., Good agreements between simulated and observed flows in both of daily and monthly time scale were also noticed.

Easton et al. [63] used a modified version of SWAT model (SWAT Water Balance) tool to quantify the hydrologic and sediment fluxes in the Blue Nile Basin, Ethiopia. They modeled SWAT to simulate runoff and erosion in the Blue Nile basin with source of runoff from Ethiopia. The model was initialized for eight sub basins ranging in size from 1.3 km<sup>2</sup> to 174,000 km<sup>2</sup>. This new version of SWAT, SWAT-WB, calculates runoff volumes based on the available storage capacity of a soil and distributes storages across the watershed using soil topographic wetness index [64]. In place of CN for each HRU to predict runoff losses, SWAT-WB model used water balance. To obtain good hydrologic predictions the model requires very little direct calibration. The authors selected

the most sensitive parameters controlling erosion in the watershed were those used for calculating the maximum amount of sediment that can be entrained during channel routing. The channel properties, channel erodibility factor (CH\_EROD), channel cover factor (CH\_COV), channel manning's *n* (CH\_N) and channel saturated hydraulic conductivity (CH\_K). The model prediction showed reasonable accuracy of NSE 0.53-0.9.

Bertie et al. [65] set up the SWAT model to simulate spatial distribution of soil erosion/sedimentation processes at daily time step and to assess the impact of three Best Management Practice (BMPs) scenarios on sediment reductions in the upper Blue Nile River basin in an area of 184,560 km<sup>2</sup>. They found the most sensitive parameters for surface flow prediction were the surface flow parameters CN2, ESCO, SOL\_AWC, SOL\_K, SULAG, SLSUBBSN; baseflow parameters were ALPHA\_BF, GW\_DELAY, GWQMN, GW\_REVAP, REVAPMIN, RCHRG\_DP; channel routing parameters were CH\_K2 and CH\_N2. Taking different scenarios for best management practices at sub-basins scale and revealed that a wide-ranging spatial variability on sediment decrease. The sediment reduction was varied from 29% to 68% by buffer strip (Scenario-1), 9% to 69% by stone-bund (Scenario-2) and 46% to 77% by replantation of trees (Scenario-3) applying the Modified Universal Soil Loss Equation (MUSLE) which is embedded in the model SWAT. However, their results did not show the effects of gully erosion.

### Integration of SWAT with LULC Simulation Models

Based on different coherent scenarios land use models have a common objective of simulating landscape dynamics in the future at multiple scales [66]. Within land use patterns they improve understanding and sensitivity of key processes [67]. Consideration of socio-ecological dynamics and performance has been facilitated by scenarios building based on land use models [68]. Therefore, it is new and thoughtful way for hydrological assessment of future and hypothetical land use and land cover scenarios by integrating of SWAT with land use simulation models. In a case study, to estimate the impact of land cover change on runoff in a tropical watershed in Kenya, [23] integrated the SWAT with Conversion of Land Use and its Effects at Small-regional-extent (CLUE-S) model. Sensitivity of the basin's hydrological system attributable to alterations in land cover and this study offers a practical insight. In the upstream watershed of Miyun Reservoir in Beijing, China, SWAT coupled with CLUE-S to simulate pollution loads under different land use scenarios [69].

A dynamic combination of land use changes with a hydrologic model offers a more truthful representation of the progressive development of land use changes, is probable to advance the temporal predictive ability of the model [70], and permits for a temporally categorical analysis of hydrologic impacts emphasized that a close-fitting temporal assimilation of the dynamics of land use change and hydrology is needed to accurately represent the interfaces between land use, climate, and hydrology. A measureable investigation on the multi-scale land use changes in space specifically predicting probable changes under land use conditions in the forthcoming, and taking into account vicinity factors, driving forces and land suitability associated to land use condition design by the dynamic land use simulation model of CLUE-S [71]. The consolidation of CLUE-S and SWAT can provide complete play to the benefits of model coupling, which both improves the rationality and accurateness of the model for land use scenario simulation and successfully appraises non-point source pollutions under different conditions.

Even though more sophisticated methodologies to describe land use change conditions by using land use change models are available, these are rarely dynamically incorporated with hydrologic impact assessments. Land use change scenarios may be derived as a result of simple assumptions [72-74]. Therefore, they provide a basis to predict land use change in a more complex technique. Several land use change models have been developed and are used for several purposes, comprising empirical-statistical, stochastic, optimization, process-based, and integrated modeling approaches [67]. A thorough review of land use change models and their specific characteristics is provided by [72]. However, the significance of a dynamic representation of land use changes has been acknowledged [57] a dynamic combination of spatially categorical models of land use change and hydrologic models is seldom found in the literature.

## Conclusion

This paper emphasizes that SWAT is a very flexible and strong tool that can be used to simulate a variety of land management problems in different catchments with various climatic and land cover conditions. SWAT model is a potential and powerful model once calibrated and validated effectively for wide range of applications. The development of GIS-based interfaces, which provide a simple means of translating digital land use, topographic, and soil data into model inputs, has greatly facilitated the process of configuring SWAT for a given catchment. Furthermore, advancement of a new era in SWAT application for LUCC simulation with the highest possible accuracy as a result of the new facilities for SWAT auto-calibration and uncertainty analysis was presented. Simulation of hypothetical, real and future scenarios in SWAT has proven to be an effective method of evaluating alternative land use effects on runoff and sediment losses which made the SWAT robust and flexible framework that allows the simulation of a wide variety of conservation practices. This capability via the integration of SWAT with LULC simulation models has been strengthened to the best of possible. Therefore, the successful evaluation of SWAT model in semi-arid environments as demonstrated in this review provides the opportunity for expanding the model application to other similar climatic locations where there is limited number of gauge stations.

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