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Watershed Modeling Using Swat for Hydrology and Water Quality : A Review

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ABSTRACT

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According to World health Organization Global health Observatory, 600 million Indians are facing extreme water stress and about two lakh people die every year due to inadequate access to safe water. This scenario indicate that many parts of the country will soon face a crisis in both water quantity and water quality unless management of water resources planned in a sustainable way. Many major rivers are polluted as a result of urbanization and industrialization, thereby quality parameters also violating the standards. In India, more than 50% of population depends on agriculture and many farmers use fertilizers, consists of harmful chemicals. The Nitrogen and phosphorous are the two nutrients originating from inorganic and organic fertilizers, that affect the water quality due to intensive agricultural farming and livestock grazing. Water availability in a catchment is necessary to plan/allocate the water resources in an equity manner. This can be estimated using a hydrologic model, which is designed to simulate the rainfall-runoff processes of watershed systems. An ArcGIS-based user interface could be used to model hydrologic and water quality parameters. SWAT is a continuous simulation-based model and is developed through a distributed hydrological modeling approach, which is one of the few hydrologic models with water quality coupling capability. This review mainly focuses on the broad aspects related to the execution and applicability of SWAT for various catchments to simulate the runoff and other quality parameters with various calibration techniques, thereby to make policies for best management practices and to promote sustainable development.

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I. INTRODUCTION

Water resources are very important renewable resources that are the basis for the survival and development of any society. Water plays vital role, not only in agriculture but also in industry, navigation and production of energy. As per June 2018 Niti aayog report, by 2020 India will be formally categorized as a “water stressed” country. 70% of water in India is contaminated and India is ranked

120 among 122 countries in the water quality index [12]. According to Sustainable Development Goal-6 (SDG 6), set by United Nations General Assembly in 2015, this aims to ensure availability and sustainable management of water for everyone by 2030. Therefore, attention must be paid to preserve water quality and towards conservation of water resources. The Soil and Water Assessment Tool (SWAT) model is a non-proprietary hydrologic/water quality tool developed by the United States Department of Agriculture-Agriculture Research Service (USDA-ARS) ([1, 3, 26, 31]; and has been continuously updated (currently SWAT version 2012 with ArcGIS10.5 interface is available) in response to advancing technology and improving its capabilities for its application all over the world. The SWAT model is developed to evaluate the effects of alternative decisions on water resources and non-point source pollution in river basins. It is also necessary to test the model accuracy for built confidence interval on the simulated results. Also, several studies focused on calibration and validation approaches used for verifying the accuracy of the SWAT model for the simulated conditions [2]. In India, very little research has been carried out in the field of water quality modeling using SWAT. Therefore, the main objective of this review article is to provide (a) overview of SWAT development history, (b) summarize the research carried out in estimating the runoff and water quality using SWAT and (c) to present general overview of calibration and validation in order to reduce uncertainties.

II. THE SWAT MODEL

A large number of hydrological models are available for different aspects of water resources management, such as flood forecasting, water supply, and demand analysis and water quality evaluation. Among all, the Soil and Water assessment Tool [1] has proven its capability to model water fluxes in regions with limited data availability [11,13]. SWAT is a distributed parameter, deterministic, continuous watershed model that operates on a daily time step. It is developed from the digital elevation model, land use, soil type and slopes as the key inputs. SWAT model is used to address various environmental issues at a range of geographic and temporal scales. SWAT is used to simulate water quality responses such as sediment, Total phosphorous (TP), Total Nitrogen (TN) and inorganic nitrogen [8]. It is a process-oriented model [1,3], which incorporate the understanding of linkages between watershed properties and water quality responses. SWAT has already been utilized in large scale hydrologic studies in India [14, 18, 19]. SWAT has been successfully used for simulating runoff, sediment yield and water quality of small watersheds for Indian conditions [28, 30, 33]. This model could be calibrated and sensitivity analysis can also be performed based on the data availability for point and non-point sources.

SWAT model subdivides the watershed into a number of subwatersheds based on topography and user-defined threshold drainage area (minimum area required to begin a stream) or predefined subwatershed and reach delineation supplied by the user. Each subwatershed is further divided into hydrologic response units (HRUs), which are unique combinations of soil, land use, slope, and land management. The HRU is the smallest landscape component of SWAT used for simulating hydrologic processes. The size of an HRU depends on the resolution of inputs, including digital elevation model, soils, land use, and slopes, and user-defined thresholds that define and refine the HRU distribution. Simulation could be performed at HRU level. The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) [37] to estimate sediment yield at HRU level. The SWAT model calibrations are performed on an HRU basis, and flow and water quality variables are routed by HRUs and subbasins to the basin outlet. The SWAT model simulates hydrology as a two-component system, comprised of land phase, which controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin and in-stream or routing phase, which is the movement of water, sediments etc., through the channel network of the watershed to the outlet. The land portion of the hydrologic cycle is based on a water mass balance. Soil-water balance is the primary consideration by the model in each HRU, which is represented as [1] (see Fig.1).

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where SW_t is the final water content, SW_0 is the initial soil water content of the day I, t is the time in days, R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i, w_{seep} is the amount of water entering the vadose zone from the soil profile on day i and Q_{gw} is the amount of return flow on day i (mm of H_2O).

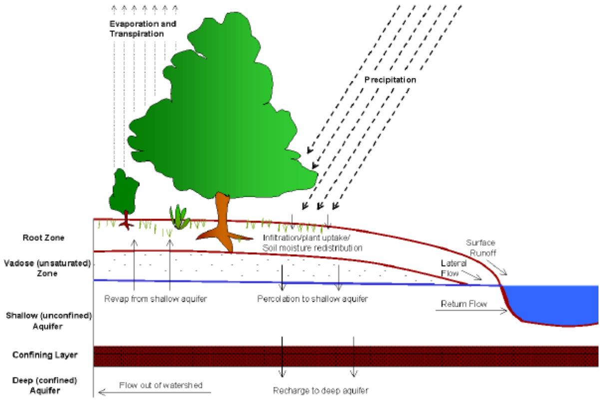

Figure 1. Hydrologic cycle representation in SWAT model (source: Neitsch et al. 2005a; http://swatmodel.tamu.edu/documentation

Precipitation inputs for hydrologic calculations can be either measured data or simulated with the weather generator available in the SWAT model. Surface runoff is estimated using the Soil Conservation Service (SCS) Curve Number (CN) or the Green-Ampt infiltration equation. Potential evapotranspiration can be calculated using Hargreaves, Priestly-Taylor or Penman-Monteith method [1]. Loadings of flow, sediment, nutrients, pesticides, and bacteria from the upland areas to the main channel are routed through the stream network similar to hydrologic model (HYMO) [36]. The soil nitrogen (N) sis simulated in the SWAT model and is partitioned into five N pools, with two being inorganic (ammonium-N[NH_4-N] and nitrate-N [NO_3-N]) and three being organic (active, stable and fresh). All soil N processes are simulated in the SWAT model using relationships described in the model's theoretical documentation. The algorithms used to describe N transformations in channel flow were adapted from QUAL2E model [26]. phosphorous(P) is divided into soluble P and organic P. The model simulates transformation of nitrogen (N) and phosphorus (P) between organic and inorganic pools in the nutrient cycle as shown in Fig. 2.

III. APPLICABILITY OF SWAT FOR HYDROLOGY AND WATER QUALITY

The SWAT model has been extensively applied for issues ranging from hydrology, climate change, pollutant load assessment, and best management practices evaluation in various spatial and temporal scales [33]. Flow, sediment, nutrients, pesticide and bacteria from all HRUs are summed to the sub watershed level and then routed through the channels, ponds, reservoirs, and wetlands to the watershed outlet. Flow is routed using either variable-rate storage method [35] or Muskinghum method [27]. SCS Curve Number method is the only available in the model suitable for use with daily data. Variable storage routing method may be used if the calibration of parameters is not required [23].

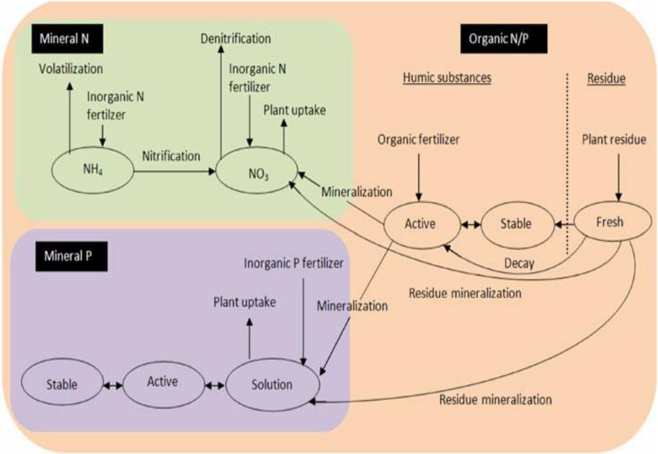

Figure 2. Nitrogen and phosphorus transformation simulated in SWAT (source: Neitsch et al. 2005a; http://swatmodel.tamu.edu/documentation)

The loss of both Nitrogen and Phosphorous from the soil system of each HRU is accounted for by plant uptake, their transport via surface runoff, eroded sediment, lateral flow and percolation below the soil profile, and by volatilization to the atmosphere [13, 22]. Excessive nutrients to water body can come from a various source, such as nutrient-enriched runoff from agricultural fields, lawns and discharges from waste water treatment plants. In order to restore the water quality, total maximum daily loads (TMDLs) have to be developed for many nutrient impaired water bodies. The water quality observations along with spatially distributed watershed model SWAT has extensively used for developing TMDLs by simulating the hydrology, sediment, nutrient and pollutant loading of large basins [25]. Sediment transport is simulated, using modified Bagnold's equation [4], as a function of peak channel velocity. Sediment is either deposited through channel erosion depending on the sediment load entering the channel. The QUAL2E model [6] can be coupled into SWAT model to process in-stream nutrient dynamics [22]. In addition, the model is also linked to GIS packages like GRASS (Geographic Resources Analysis Support System) via the SWAT-GRASS interface [1]. The SWAT model could be applied to any region, if the datasets are available to set up the model and the real-time data availability to evaluate the model outcomes.

IV. CALIBRATION AND VALIDATION

Several studies present systematic strategies for performing stream flow and/or pollutant calibration and validation [2]. The most commonly calibrated SWAT output is stream flow, which is especially at annual and monthly time steps. Stream flow is calibrated more often than water quality because it is essential for the other water quality components of the model [17] and also because observed flow data are relatively abundant. On the other hand sediment and nutrient parameters are not calibrated and validated as often especially at the daily time scale [2, 15, 34]. Calibration and validation of water quality parameters (sediment and nutrients) of SWAT at coarser time scales is mainly attributed to scarcity of observed water quality data at finer time scales [38]. For water quantity and quality analysis in SWAT, there are three groups of parameters: Flow, Sediment, and Nutrients, which could be calibrated either separately [7, 20, 17, 24] or simultaneously [21, 32, 38]. The first step in the calibration and validation process in SWAT is the determination of the most sensitive parameters for a given watershed. It is necessary to identify key parameters and the parameter precision required for calibration. When the number of parameters used in the manual calibration is large, especially for complex hydrologic models, manual calibration becomes labor-intensive [5] and automated calibration methods are preferred. Automatic calibration could be performed using SUFI-2 and can be performed at daily, monthly and annual time scales [34]. Automatic calibration and uncertainty analysis capability is now directly incorporated in SWAT2012 [15, 16,18] via the SWAT-CUP software [10]. An extensive array of statistical techniques can be used to evaluate SWAT hydrologic and pollutant predictions [9],which describe nearly 20 potential statistical tests that can be used to judge SWAT predictions, including coefficient of determination(r2), NSE, root mean square error (RMSE), non-parametric tests, t-test, objective functions, autocorrelation, and cross-correlation.

V. CONCLUSION

The model SWAT is widely used as the best hydrologic model in India and world-wide. Also, it is used to address various environmental issues and has identified specific model improvements to better address these issues. From the literature, the simulation performance of the SWAT could be improved by coupling with other water quality models. Application of SWAT for fate and transport, water footprint estimation, economic implications due to climate change and land use change, and simulation of concentrated flow sources of sediment and nutrients are some of the important topics. Nutrient loading from channels should be considered while developing the watershed management plans. Based on the spatially distributed watershed model, sub basins that contribute sediments and nutrients could be identified. Several best management practices also can be assessed with SWAT. The cost-effective watershed management practices that will reduce the watershed load in terms of total nitrogen and phosphorous, which can be identified from the sub basins in the watershed. Uncertainty can be achieved by training the model with different training sets and initialization conditions, whereas in the SWAT model uncertainty can be estimated through the several algorithms and expressed in terms of parameter uncertainty. Very few studies focused on water quality modeling coupled with hydrological simulations using SWAT model in India [19, 29]. So, it is utmost important to focus more on the water quality and quantity aspects for the effective utilization of water resources in a sustainable manner.

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Conflict of Interest. Nil.

VII. REFERENCES

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