A REVIEW ON SOIL AND WATER ASSESSMENT TOOL (SWAT) AND ITS APPLICATIONS

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ABSTRACT: SWAT is the Soil and Water Assessment Tool, a river basin model developed originally by the USDA Agricultural Research Service (ARS) and Texas A&M University that is currently one of the world's leading spatially distributed hydrological models. SWAT is a continuous time model that operates at sub-basin and watershed scale to predict long-term impacts from management, agricultural practices, pollution, and environmental changes. SWAT can analyze the impacts of climate change on hydrology with stream flow simulations. In this study, an overview of SWAT hydrological model is presented which includes Introduction and background of swat model, Historical Development, Theoretical Description of SWAT model, Key process and algorithm used in SWAT, Important SWAT modules and resources, Capabilities, SWAT Components, Strengths and limitations, General applications of the SWAT model are discussed. This study will be helpful in developing an insight to the growing application of hydrological models.

Index Terms – SWAT, Soil and Water Assessment Tool, river basin, watershed, Model.

INTRODUCTION AND BACKGROUND OF SWAT MODEL

The SWAT model is a river basin and watershed model that was developed in the early 1990s by the US Department of Agriculture-Agricultural Research Service (USDA-ARS) and Texas A&M University AgriLife Blackland Research Center. The model was developed to investigate and simulate hydrology of water in complex river basins where water resources are impacted by land use, land management, and climate change over long periods of time (Kankam-Yeboah et al., 2013). SWAT is open-sourced and is a Physically-based model which requires specific information for soil, land-use, weather, and management of a watershed. Benefits of this approach allow for simulations of missing data such as stream or temperature gauging, and the quantification of input changes such as climate. SWAT uses daily and sub-daily time steps, that are time continuous and manipulated in a GIS interface (Kankam-Yeboah et al., 2013; Xu et al., 2013; Jha, 2011; Setegn et al., 2010; Jha et al., 2004). The continuous model allows for long-term watershed monitoring and does not limit the timescale of future simulations. These daily and sub-daily time steps consist of average mean precipitation measurements, minimum and maximum temperature, and mean stream flow measurements.

SWAT uses a high level of spatial detail. This detail includes the use of upland processes to capture the heterogeneity of the watershed. Interconnected processes incorporated by SWAT are weather, hydrology, sedimentation, plant growth, nutrient cycling, pesticide dynamics, and management. Spatial details of hydrology include canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds and wetlands, and transmission losses. SWAT is computationally efficient, it can process an unlimited number of watershed subdivisions, and can simulate future scenarios based on environmental inputs (Jha, 2011). SWAT is a widely used model and was chosen by the Environmental Protection Agency (EPA) as one of the models to include in the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) model packages (Jha, 2011). The current SWAT model has been part of the ongoing model services provided by the USDA-ARS throughout the last 30 years and there are many components of SWAT that originated in other models. The models include Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model, the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model, and the Environmental Policy Integrated Climate (ERIC) model. These three models represent the early trials of hydrologic modelling by the USDA. Components from each model were combined to form the Simulator for Water Resources in Rural Basins (SWRRB) model. Early versions of SWAT were renditions of the

SWRRB model that included components from the Routing Outputs to Outlet (ROTO) model and the Enhanced Stream Water Quality Model (QUAL2E). Later modifications in the early 2000s included carbon cycling inputs from the C-FARM model as well as including the ArcGIS platform to create ArcSWAT that can be downloaded into GIS.

As an open sourced model, SWAT development has benefited from a community of users and developers to create calibration and validation tools for SWAT modelling. SWAT-CUP is one of these tools available for SWAT users. SWAT-CUP allows users to choose from a variety of algorithms to enable sensitivity analysis, calibration, validation, and uncertainty analysis of the model. SWAT-CUP4 links together GLUE, ParaSol, SUFI2, MCMC, and PSO algorithms and procedures for this application. The most current edition of SWAT is SWAT2012 rev. 664 was released December 23, 2016. To be run with the ArcGIS and being distributed in SWAT website: (http:// swat.tamu.edu/). Fig. 1 shows the history and development of the SWAT model.

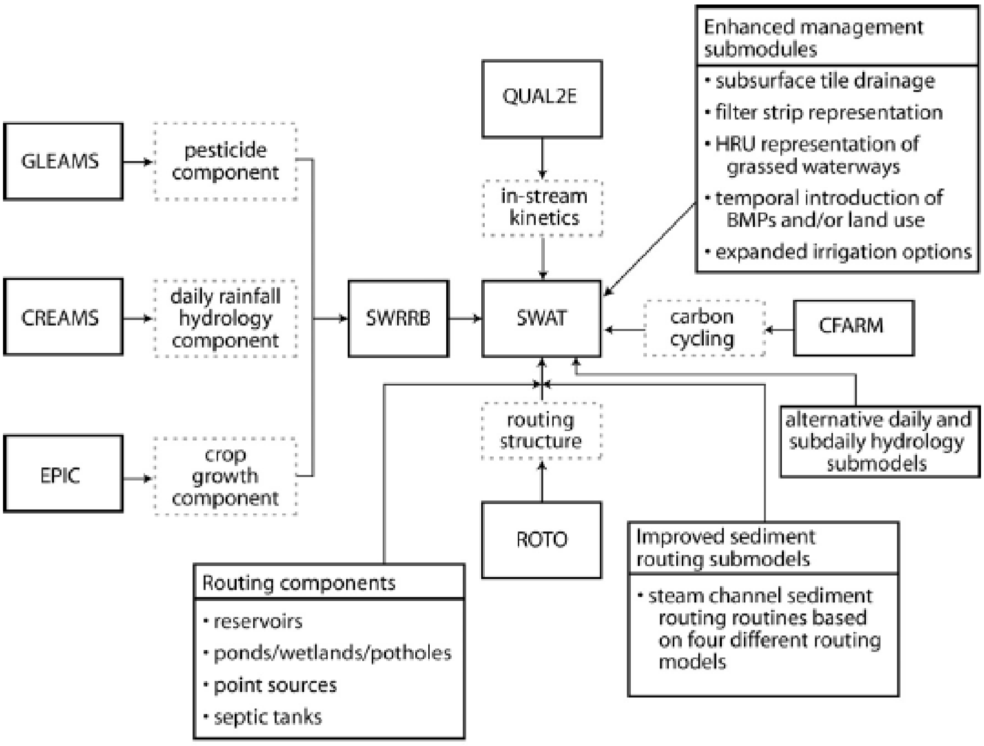

Fig. 1: The history and development of the SWAT model from Arnold et al., (2012) originally adapted from Gassman et al., (2002).

AN OVERVIEW OF SWAT HISTORICAL DEVELOPMENT

SWAT has undergone some significant improvement since its creation in 1990s. Neitsch et. al. (2008) and Philip W. Gassman, et al. (June, 2015) outlined some of these improvements as:

- ☆ **SWAT94.2:** Multiple hydrologic response units (HRUs) were incorporated; Development of groundwater component; EPIC crop growth model added; routing command language added; Interface of SWRRB and ROTO models.
- ☆ **SWAT96.2:** Auto-fertilization and auto-irrigation added as management options; canopy storage of water; crop growth CO_2 routine; Penman–Monteith potential ET option; soil lateral flow of water based on kinematic storage model; QUAL2E in-stream nutrient water quality equations & in-stream pesticide routing added.
- ☆ **SWAT98.1:** Snow melt routines improved; in-stream water quality improved; nutrient cycling routines expanded; grazing, manure applications and tile flow drainage options added; model modified for use in Southern Hemisphere.
- ☆ **SWAT99.2:** Nutrient cycling routines improved, rice/wetland routines improved, reservoir/pond/wetland nutrient removal by settling added; bank storage of water in reach added.
- ☆ **SWAT2000:** Bacteria transport routines added; Green & Ampt infiltration added; weather generator improved; Muskingum routing method unlimited number of reservoirs added; all potential ET methods updated; elevation band processes improved; dormancy calculations modified for proper simulation in tropical areas; all daily climate inputs can be read in or generated.

- ✫ **SWAT2005:** Bacteria transport routines improved; weather forecast scenarios added; sub-daily precipitation generator added; forest growth to mature stand, SWAT-CUP software &new option for simulating perched water; ET-based runoff curve number method; improved sediment transport routines, continuous manure application option.
- ✫ **SWAT2009:** Bacteria transport routines improved; weather forecast scenarios added; subdialy precipitation generator added; the retention parameter used in the daily CN calculation may be a function of soil water content or plant evapotranspiration; update to vegetative filter strip model; wet and dry deposition of nitrate and ammonium improved; modelling of on-site wastewater system.
- ✫ **SWAT2012:** Incorporated routing of flow and sediment across landscapes within a subwatershed; sediment-filtration basins and other types of urban practices; management operations to remove crop residues; improved algorithms to remove crop residues; improved representation of miscanthus and switchgrass growth processes; algorithms depicting glacier melt and other glacier processes; extension of one-reservoir baseflow approach by adding a slow-reacting reservoir; a second more physically-based subsurface tile drainage component; improved soil and in-stream phosphorus cycling routines; tropical conditions and senescence modifications and improved tree growth algorithms.

In addition, there are many models developed based on SWAT (see overview in Gassman et al. 2014a), which are adapted to more specific applications, including parameterization for some other components, and using different input data formats. Among them are: the SWIM model (Krysanova et al. 1998, 2000), based on SWAT-93 and aiming mainly at climate and land-use change impact assessment; the SWAT-G model (Lenhart et al. 2002) based on SWAT99.2 and focused on flow prediction for low mountain ranges in Germany; the Extended SWAT model (ESWAT; Van Griensven and Bauwens 2005) with a number of adjustments for the hourly time step; the coupled watershed and groundwater model (SWAT-MODFLOW; Kim et al. 2008); a version of SWAT with a modified plant growth module for improved simulation of perennial vegetation in the tropics (Strauch and Volk 2013); a grid-based version of the SWAT landscape model for an improved spatial representation of hydrological and transport processes (Rathjens et al. 2014); and SWAT3S with a multi-storage groundwater concept implemented to emphasize nonlinear groundwater dynamics in lowland catchments (Pfannerstill et al. 2014).

THEORETICAL DESCRIPTION OF SWAT MODEL

Source: (http://wiki.sdstate.edu/User:Todd.Trooien/SP14ABE721%3AModels/SWAT)

For modelling purpose in SWAT, the watershed is divided into a number of subwatershed or sub-basins. Input information for each sub-basin is grouped into following categories: climate; hydrologic unit response units (HRUs), ponds/wetlands; groundwater, and main channel. HRUs are lumped land areas within the subbasin that are comprised of a unique land cover, soil, and management combinations. SWAT model operates on a daily time step for each hydrologic unit based on water balance equation Eq (1). Simulation of hydrology or hydrologic cycle is divided into two phases: land phase and water or routing phases. Land phases control the loading of the amount of water, sediment and nutrients and second phase defines the movement of water, sediments, and nutrients through the channel of the HRUs or watershed outlets. Fig. 2 represents the Schematic of hydrologic processes simulated in SWAT.
The hydrologic cycle simulated by SWAT is based on the water balance equation as below (on daily basis):

$$S_{Wt} = S_{W0} + \Sigma\, R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \qquad \text{Eq (1)}$$

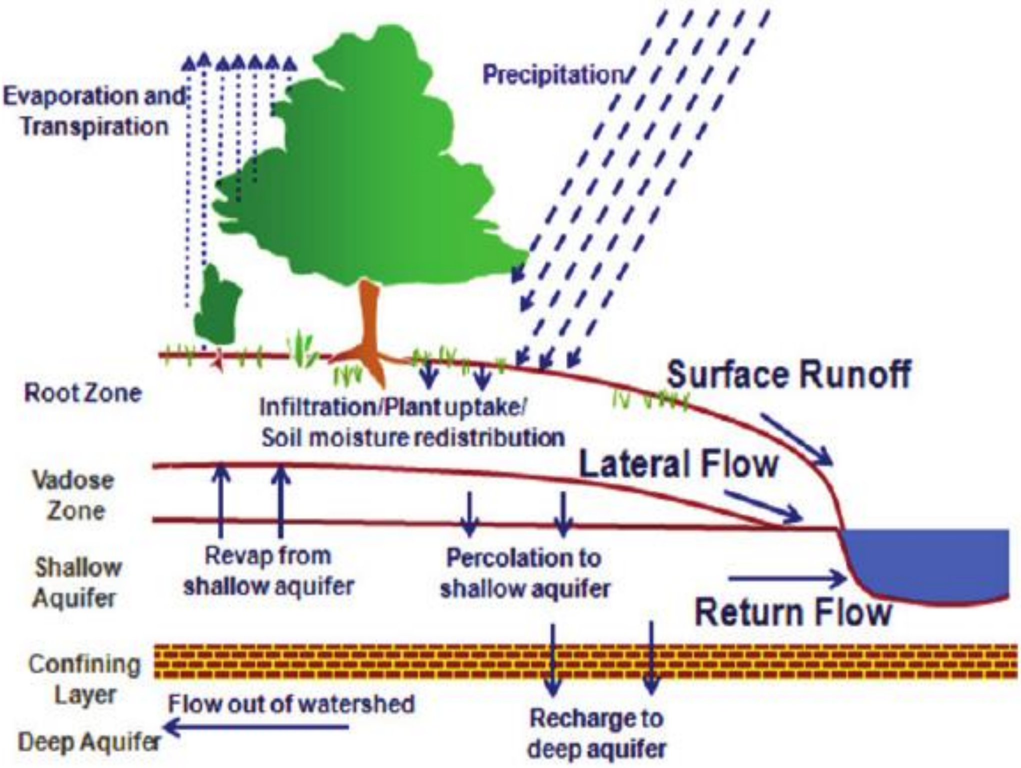

Fig. 2: Schematic of hydrologic processes simulated in SWAT

Where, S_{Wt} and S_{Wo} is final soil water content and initial water content, t is the time in day, R_{day} is the amount of rainfall, Q_{surf} is amount of surface runoff/discharge, E_a is amount of evapotranspiration (ET), Wseep is amount of water entering Vadose zone, and Q_{gw} is amount of return flow (all component in day i). Several other inputs are required to calculate the components mentioned on E_{qn} 1. Minimum input data required to run the model are DEM, land use/land cover, soils, daily precipitation, max. and min. temperature, solar radiation, relative humidity, wind speed, daily discharge, sediment, nutrient delivery, fertilizer and pesticides application data, point source of pollution and management practices.

KEY PROCESS AND ALGORITHM USED IN SWAT

Key process and algorithm used in swat are as follows:

- **Climate:** Weather generator WXGEN or user's input
- **Hydrology:** Canopy interception, runoff (SCS curve number, infiltration (Green-Ampt),
- **Evapotranspiration** (Penman-Monteith, Priestley-Taylor, or Hargreaves Samani)
- **Land Cover/Plant growth:** MRLC,NLCD or user define, water and nutrient uptake, crop and plant growth database
- **Erosion:** MUSLE using peak runoff rate
- **Nutrient:** Nitrogen and phosphorus cycle
- **Agricultural management:** planting, tillage, irrigation, fertilization, pesticide management, grazing, and harvesting. SWAT also handles auto fertilization and auto irrigation.
- **Urban management:** Build up and wash off approach
- **Routing:** Variable routing or Muskingum routing methods
- **Sediment Transport:** Based on stream flow and various equation are used to calculate sediment concentration and sediment transport

SWAT MODULES AND RESOURCES

Important SWAT modules and resources are:

☆ **ArcSWAT**: ArcGIS-ArcView extension and graphical user input interface for SWAT.

- ☆ **Global Weather Data for SWAT:** Allows to download daily Climate Forecast System Reanalysis (CFSR) data (precipitation, wind, relative humidity, and solar) in SWAT file format for a given location and time period.
- ☆ **QSWAT:** A GIS interface linking SWAT to the public domain GIS software QGIS.
- ☆ **SWAT-CUP:** It enables sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT models.
- ☆ **SLEEP:** A tool to help SWAT users generate a soil database at sub-catchment level from point field observations, or legacy soil maps.
- ☆ **SWAT201**2: The SWAT Input/output File Documentation reviews all processes simulated with the model. And provides definitions for all input variables. It is absolutely essential for beginning to work with SWAT.
- ☆ **SWAT-MODFLOW:** An integrated hydrological model that couples SWAT land surface processes with spatially-explicit groundwater flow processes.
- ☆ **MWSWAT:** Open source interface to SWAT, consisting of the GIS system MapWindow and the Map Window-SWAT interface.
- ☆ **VIZSWAT:** A GIS-based data visualization and analysis tool that animates time series and spatial data over GIS maps with impressive display speed. Analysis functions include time series aggregation, basic statistics, and correlation, frequency, base flow and flow duration analyses.
- ☆ **AVSWAT:** (ArcView SWAT) is a complete pre-processor, interface and post processor of SWAT. User friendly tool for the watershed scale assessment and control of the agricultural and urban sources of water pollution.
- ☆ **SWAT Output Viewer:** A tool to quickly view and analyze the outputs of a SWAT model on-the-fly.
- ☆ **SWAT Check:** It reads model output from a SWAT project and performs many simple checks to identify potential model problems.
- ☆ **Baseflow Filter Program**: Estimates baseflow and groundwater recharge from stream flow records.
- ☆ **Potential Heat Unit Program**: Estimates the number of heat units requires to bring a plant to maturity.

CAPABILITIES OF SWAT

Basins of several thousand square miles can be studied, but must be divided to account for difference in soils, land use, crops, topography, weather, etc. SWAT accepts outputs from APEX (Agricultural Policy/Environmental eXtender) as well as measured data and point sources. Watersheds with no monitoring data can be modeled and impacts of changes in management and climate can be generated.

SWAT COMPONENTS

Weather Inputs

- Precipitation, solar radiation, temperature, relative humidity, and wind speed
- Can be measured or generated.

Hydrology

- Simulates canopy interception of precipitation, partitioning of precipitation, and snowmelt water.
  - Simulates partitioning water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, return flow from shallow aquifers, and deep aquifer recharge.

Plant Growth

- Inputs: soil properties, management operations, and weather variables
- Estimates crop yields and biomass output for a wide range of crop rotations, grassland/pasture systems, and trees
- Simulates forest growth from seedling to mature stand
- Simulates planting, harvesting, tillage passes, nutrient applications, and pesticide applications for each cropping system with specific dates or with a heat unit scheduling approach

Bacteria and Pathogens

- Simulates bacteria and pathogen loads through surface runoff in both the solution and eroded phases

Nutrient and Pesticide Simulations

- Residue and biological mixing in response to each tillage operation
- Nitrogen and phosphorous applications in the form of inorganic fertilizer and/or manure inputs
- Biomass removal and manure deposition for grazing operations
- Continuous manure application for confined feeding operations
- Type, rate, timing, application efficiency, and percentage of application to foliage versus soil pesticide applications
- Accounts for pesticide fate and transport by degradation/losses by volatilization and leaching

- Routes sediment, nutrient, pesticide, and bacteria loadings/concentrations through channels, ponds, wetlands, digressional areas, and/or reservoirs to the watershed outlet

Land Management Simulations

- Conservation practices such as terraces, strip cropping, contouring, grassed waterways, filter strips, and conservation tillage
- Irrigation water on cropland from sources such as stream reach, reservoir, shallow aquifer, or a water body source external to the watershed

STRENGTHS OF SWAT MODEL

- Physically based
- Well documented
- Can be used on GIS interface
- Computationally efficient
- Most of the input data are easily available
- Enables users to study long-term impacts
- Watersheds with no monitoring data can be modelled

LIMITATIONS OF SWAT MODEL

- Not intended for single storm event
- Only for simulating conservative metal species from the point source input
- Only route one pesticide each time through the stream network
- Cannot specify actual areas to apply fertilizers
- A large watershed can be divided into hundreds of HRUs which might be difficult to manage.

GENERAL APPLICATIONS OF THE SWAT MODEL

General SWAT Scenario applications includes assessment of

- The effectiveness of conservation practices within the USDA Conservation Effects Assessment Program (CEAP) initiative.
- *The impacts of climate change on*:
    - Plant development and transpiration from increased atmospheric carbon dioxide concentrations
    - Plant growth, stream flow, and other responses from changes in climatic input shifts
- The impacts of historical climate trends versus future climate change projections on hydrology, erosion, and pollutant loss
- The effects of land use and land management on recharge estimates at the watershed scale
- The impact of changes in land use on hydro-sedimentologic characteristics of rivers
- The economic and environmental benefits of conservation practices
- Watershed-scale bacteria fate and transport
- Hydrological modelling of watersheds
- Flow and chemistry variables for development of ecological indicators in stream ecosystems
- Soil and water patterns in small watersheds
- Cumulative winter stream flow and spring base flow estimates
- Conversions to wetlands
- Sediment load predictions at different watershed scales
- Pesticide and nutrient movement predictions
- Alternative land use, best management practices, and other factors on removing pollutants
- Stream flow impacts in response to historical land use shifts versus hypothetical land use change

CONCLUSION

This paper emphasizes that swat is one of the most versatile ecohydrological models currently Available for addressing watershed-scale hydrological and water quality problems. SWAT is very strong and flexible tool used to simulate different kinds of land management problems in heterogeneous catchments with various land cover and climatic conditions over long periods of time. SWAT is a potential and powerful model once calibrated and validated effectively used for wide range of applications. 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 the simulation of the past, present and future scenarios.

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