Training Course

Climate Change and its Impact on Water Resources

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LECTURE - 6

CATCHMENT MODELLING USING SWAT

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CATCHMENT MODELLING USING SWAT

ABSTRACT

SWAT (Soil and Water Assessment Tool) is a conceptual, continuous time model that was developed in the early 1990s to assist water resource managers in assessing the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over a long period of time. The SWAT model was developed by merging Simulation for Water Resources in Rural Basin (SWRRB) and Routing Output to Outlet (ROTO) into one basin scale model. SWAT is the continuation of over three decades of model development within the US Department of Agriculture's, Agricultural Research Service and was developed to 'scale up' past field-scale models to large river basins. Model components include weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing and pond/reservoir routing. The model SWAT has been used in many countries all over the world. It is a flexible model that can be used under a wide range of different environmental conditions.

INTRODUCTION

Catchment scale planning of water resources development and management require an understanding of basic hydrologic processes and simulation capabilities. Current concerns that are motivating the development of large area hydrologic modeling include climate change, management of water supplies, large-scale flooding and offsite impacts of land management. Recent advances in computer hardware and software, including increased speed and storage, advanced software debugging tools and GIS software, have allowed large-area simulation to become feasible. The challenge then are to develop a basin-scale model that (1) is computationally efficient; (2) allows considerable spatial detail; (3) requires readily available inputs; (4) is continuous time; (5) is capable of simulating land-management scenarios; and (6) gives reasonable results. The model must reflect changes in land use and agricultural management on stream flow and sediment yield. Available models with these capabilities are generally limited by spatial scale. Also, most are single-event models. A number of hydrological and water quality models are being used for catchment modeling. These are broadly grouped into three categories viz. field scale, event based, watershed scale and continuous watershed scale. The classification of these models is presented on table 1.

Among the various models, SWAT model incorporates features of several ARS models and is a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins) (Williams *et al.*, 1985; Arnold *et al.*, 1990). The specific models that contributed significantly to the development of SWAT were CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard *et al.*, 1987) and EPIC (Erosion–Productivity Impact Calculator) (Williams *et al.*, 1984). The model SWAT is applicable for European Environmental Policy, such as the adoption of the European Water Framework directive in December 2000, demand tools for integrative river basin management.

Table 1 Classification of hydrologic and water quality models

Models acronym	Space domain		Time domain		Scale		Potential for integration with GIS
	Lum -ped	Distrib- uted	Contin -uous	Event based	Field	Watershed	
AGNPS		⊗	⊗	⊗		⊗	High
ANSWERS		⊗	⊗	⊗		⊗	High
CREAMS	⊗		⊗		⊗		Low
EPIC	⊗		⊗	⊗	⊗		Low
GLEAMS	⊗		⊗		⊗		Low
HSPF	⊗	⊗	⊗			⊗	High
NPS	⊗		⊗			⊗	Very low
NLEAP	⊗		⊗		⊗		High
ROTO	⊗		⊗			⊗	Moderate
RUSLE	⊗			⊗		⊗	High
SHE		⊗	⊗	⊗		⊗	High
SPUR	⊗		⊗		⊗		Moderate
STORM	⊗		⊗			⊗	Moderate
SWAT		⊗	⊗			⊗	High
SWMM	⊗		⊗		⊗	⊗	Low
SWRRB	⊗		⊗	⊗		⊗	Moderate
TOPMODEL		⊗	⊗	⊗		⊗	High
WEPP	⊗	⊗	⊗	⊗	⊗	⊗	Moderate

⊗ Features applicability indicator

SWAT is an operational or conceptual model that is developed to assist water resource managers in assessing water supplies and non-point source pollution on large river basins. The primary considerations in model development were to stress (1) climate and management impacts; (2) water quality loadings and fate; (3) flexibility in basin discretization; and (4) continuous time simulation. The model simulates the major hydrologic components and their interactions as simply and yet as realistically as possible. Upland components include hydrology, weather, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, and land and water management. Stream processes considered in the SWAT include channel flood routing, channel sediment routing, and nutrient and pesticide routing and transformation. The ponds and reservoirs component contains water balance, routing, sediment settling, and simplified nutrient and pesticide transformation routines. Water diversions into, out of, or within the basin can be simulated to represent irrigation and other withdrawals from the system.

REVIEW OF WORK

Among the various models reviewed, Srinivasan et al. (1998) used the SWAT model to simulate the hydrology, soil erosion and sediment transport in the Richland-Chambers watershed of the Trinity River basin in Texas. The stream flow and sediment yield was calibrated and validated for the watershed. The calibration conducted in the study was minimal and in general the monthly stream flow rates predicted by the SWAT corresponded very well with the observed values. Tripathi et al. (1999a and b) calibrated the SWAT model for runoff and sediment yield estimation for the Nagwan watershed, India. The predicted runoff and sediment yield compared well with their observed counterparts giving high values (0.87) and (0.92) of Nash-Sutcliffe coefficient. The results showed that the calibrated SWAT model adequately describes rainfall-runoff and sediment yield process of the Nagwan watershed. Arnold et al. (1999) integrated GIS with a distributed parameter, continuous time, model SWAT (Soil and Water Assessment Tool) for the management of water resources. This integration has proven to be effective and efficient for data collection and to visualize and analyze the input and output of simulation models. The SWAT-GIS system is being used to model the hydrology of eighteen major river systems in the United States (HUMUS). Tripathi et al. (2006) presented the effect of watershed subdivision on simulated water balance components using the thoroughly tested SWAT model. The model was evaluated for the Nagwan watershed in eastern India. They claimed a perfect water balance for the Nagwan watershed when computed with the SWAT model. Although some variations occurred in the other water balance components (i.e. in ET, percolation and soil water content) of the Nagwan watershed with change in the subdivision pattern. Schilling et al. (2008) used SWAT model to evaluate potential impacts from future LULC change on the annual and seasonal water balance of the Raccoon River watershed in west-central Iowa. Three primary scenarios for LULC change and three scenario variants were evaluated, including an expansion of corn acreage in the watershed and two scenarios involving expansion of land using warm season and cool season grasses for ethanol bio-fuel. Results indicated that future LULC change will affect the water balance of the watershed, with consequences largely dependent on the future LULC trajectory. Shimelis et al. (2008) applied the SWAT2005 model to the Lake Tana Basin for modeling of hydrological water balance. The model was calibrated and validated on four tributaries of Lake Tana; Gumera, Gilgel Abay, Megech and Ribb rivers using SUFI-2, GLUE and ParaSol algorithms. They also suggested that calibrated model can be used for analysis of the effect of climate and land use change as well as other different management scenarios on stream flow and soil erosion.

THE SWAT MODEL

Descriptions of the Model Input /Output Files

SWAT input files can be splitted into separate files by subbasin and data type. SWAT reads a file name, opens that file, reads and stores the input data, and then closes the file. This eliminates the problem of having more files open than the operating system will allow. A brief description of input output files are given below.

General input files

The input control code (.cod) file contains the number of years of simulation, beginning year of simulation, number of subbasin, weather generation control codes, print codes, and several others. All the inputs are common to the entire basin and not subbasin dependent. There is a provision to take output on daily, monthly or annual basis by providing different codes.

The measured rainfall (.pcp) input file contains daily rainfall values in mm. Each day is stored on one line. The measured temperature (.tmp) input file contains daily maximum and minimum temperature values in Degree Celsius. Each day's maximum and minimum temperature is stored on one line.

The general basin (.bsn) input file contains inputs for the entire basin. It includes drainage area, base flow factor and initial soil water content.

The crop.dat is a crop database input file contains crop specific parameters. When a crop is specified to be planted in the management (.mgt) file, the crop parameters for that crop are taken from crop.dat file. The crop parameters include biomass conversion factor, harvest index, optimum and base temperatures, maximum leaf area, maximum root depth and several others. One crop data file namely CROPPARM.DAT was provided in the model that contains information for 66 crops (Arnold *et al.*, 1996).

Subbasin input files

Files such as sub, rte, chm, sol, mgt, mco, gw and wgn are required for each sub basin. These files contain inputs that are specific to each subbasin. Brief description about these files is given as follows:

The general subbasin (.sub) input file, which contains general inputs specific to each subbasin such as area, curve number, carbon dioxide (CO_2) concentration, land and channel slopes and lengths, USLE P factor, and initial residue cover. The runoff curve numbers for the Indian conditions can be used as input to the model. CO_2 concentrations (ppm) are used in ET and biomass calculations. If CO_2 value is left blank, default of 330 ppm is assumed in the SWAT model. The soil (.sol) input file contains soil data including bulk density, available water capacity, saturated conductivity, particle sizes, organic carbon, and maximum rooting depth. Available water holding capacity and saturated conductivity for sandy loam, sandy clay loam, loam and clay soils can determine using the standard procedures described by Arnold *et al.* (1996) and Tripathi (1999), respectively. The weather generator (.wgn) input file contains monthly parameters that are required for generating daily amounts of precipitation, maximum and minimum air temperatures, soil temperature and solar radiation. The management (.mgt) input file contains input data for management operations such as planting, harvesting and tillage operations; and irrigation, pesticide and nutrient applications. There is facility to schedule the operations by month and day or by heat units. Inputs in this file include dates, tillage code, crop code and pesticide code and application amounts.

Output files

The main SWAT output files are the .std and .sbs files. The .std file is described in user's manual (Arnold *et al.*, 1990). The subbasin (.sbs) output file reports output for over 50 variables related to water, sediment, nutrients, and crops. More than 100 output variables could be written on daily, monthly, or annual basis for each subbasin in output files. The output variables that were used to evaluate the model performance for the watershed include surface runoff (mm).

MODEL COMPONENTS

Water Balance of the Study Area

The first issue that should be studied in the effort of achieving sustainable water management is, understanding the water balance in the basin. This means finding out how much water comes into the system and then finding out where that water goes. Either infiltrates to the ground renewing underground water bodies or runs off to end up to the sea while a significant percentage evaporates and returns to the atmosphere. It has to be linked with raster based GIS to facilitate the input of spatial data such as land use, soil map and digital elevation model. The SWAT model itself based on the water balance equation:

$$SW_t = SW + \sum_{t-1}^{t} (R - Q - ET - P - QR) \quad (1)$$

Where SW_t = final soil water content,mm, SW = initial soil water content (mm), t is the time (days), R = amount of precipitation,mm, Q = amount of surface runoff,mm, ET = amount of evapotranspiration,mm, P = percolation,mm and QR = amount of return flow,mm.

Surface runoff volumes

The model simulates surface runoff volumes, by giving daily rainfall amounts as input. Runoff volume is estimated by the SCS CN technique (USDA, 1972). The SCS CN equation used in the model is as follows:

$$Q = \frac{(R-0.2)^2}{R+0.8s} \quad R > 0.2\,s \quad (2)$$

$$Q = 0.0 \quad R \leq 0.2s \quad (3)$$

Where Q = daily runoff, R = daily rainfall, and s = a retention parameter. The retention parameter s varies (a) among subbasins, because of the variation in soils, land use, management, and slope, and (b) with time, because of changes in soil water content. The parameter s is related to CN by the SCS equation (USDA, 1972):

$$s = 254\left(\frac{100}{CN}\right) - 1 \quad (4)$$

The constant, 254, in above equation gives s in mm. Thus, R and Q are also expressed in mm. The term AMC refers to the water content present in the soil at a given time. The AMC value is intended to reflect the effect of infiltration on both the volume and rate of runoff. The SCS developed three soil moisture conditions and labelled them as I, II and III. AMC I and III refer to dry and wet soil conditions, whereas AMC II is the average condition. Fluctuations in soil water content cause the retention parameter to change according to:

$$s = s_1\{1 - \frac{FFC}{FFC + \exp[w1 - w2(FFC)]}\} \tag{5}$$

Where s_l is the value of s associated with CN1, FFC is the fraction of field capacity, and w1 and w2 are shape parameters.

FFC is computed using

$$FFC = \frac{SW - WP}{FC - WP} \tag{6}$$

Where SW is the soil water content in the root zone, WP is the wilting point water content (1500 kPa for many soils) and FC is the field capacity water content (33 kPa for many soils). Values for w1 and w2 are obtained from a simultaneous solution of Equation (5) according to the assumptions that $s = s_2$

When FFC = 0.6, and $s = s_3$ when (SW-FC)/(PO-FC) =0.5

$$w1 = \ln\left(\frac{60}{1 - \frac{s_2}{s_1}} - 60\right) + 60\, w_2 \tag{7}$$

$$w_2 = \frac{\ln\left(\frac{60}{1 - \frac{s_2}{s_1}} - 60\right) - \ln\left(\frac{POFC}{1 - \frac{s_3}{s_1}} - POFC\right)}{POFC - 60} \tag{8}$$

Where s3 is the CN3 retention parameter and the porosity–field capacity ratio POFC is computed thus:

$$POFC = 100 + 50\left[\frac{[\sum_{l=1}^{M}(PO_l - FC_l)]}{\sum_{l=1}^{M}(FC_l - WP_l)}\right] \tag{9}$$

Where PO is the porosity of soil layer l. Equations (7) and (8) assure that CN1 corresponds with the wilting point and that CN cannot exceed 100.

The FFC value obtained in Equation (6) represents soil water uniformly distributed through the top 1.0 m of soil. Runoff estimates can be improved if the depth distribution of soil water is known. The SWAT model estimates water content for each soil layer daily, since the depth distribution is available. The effect of depth distribution on runoff is expressed in the depth weighting function:

$$FFC^* = \sum_{l-1}^{M} FCC_l \frac{Zl - Zl - 1}{Zl} \qquad Z_l \leq 1.0\ m \tag{10}$$

Where FFC* is the depth-weighted FFC value for use in Equation (5), Z (m) is the depth to the bottom of soil layer l, and M is the number of soil layers. Equation (10) performs two functions: (a) it reduces the influence of lower layers, because FFC_l is divided by Z_l; (b) it gives proper weight to thick layers relative to thin layers, because FFC is multiplied by the layer thickness.

Percolation

The percolation component uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer. Once water percolates below the root zone, it is lost from the watershed (becomes groundwater or appears as return flow in downstream basins). The storage routing technique is based on

$$SW_i = SW_{oi} \exp\left(\frac{-\Delta t}{TT_i}\right) \tag{11}$$

Where SWo (mm) and SW (mm) are the soil water contents at the beginning and end of the day, Δt is the time interval (24 h), and TT (h) is the travel time through layer i. Thus, by subtracting SW from SWo, percolation can be computed:

$$O_i = SW_{oi}\left[1 - \exp\left(\frac{-\Delta t}{TT_i}\right)\right] \tag{12}$$

Where O (mm day^{-1}) is the percolation rate.

The travel time TTi is computed for each soil layer with the linear storage equation:

$$TT_i = \frac{SW_i - FC_i}{H_i} \tag{13}$$

Where Hi (mm h^{-1}) = hydraulic conductivity in and FC (mm) = field capacity minus wilting point water content for layer i. The hydraulic conductivity varies from the saturated conductivity value at saturation to near zero at field capacity.

$$H_i = SC_i \left(\frac{SW_i}{UL_i}\right)^{\beta_i} \tag{14}$$

where SCi (mm h^{-1}) = saturated conductivity for layer i, ULi (mm mm^{-1}) = soil water content at saturation. i =a parameter that causes Hi to approach zero as SWi approaches FCi. The equation estimating β is

$$\beta_i = \frac{-2.655}{\log_{10}\frac{FC_i}{UL_i}} \tag{15}$$

The constant -2.655 in Equation (15) was set to assure Hi = 0.002SCi at field capacity. Upward flow may occur when a lower layer exceeds field capacity. The soil water/field capacity ratios of the two layers regulate movement from a lower layer to an adjoining upper layer. Percolation is also affected by soil temperature: if the temperature in a particular layer is 0 °C or below, then no percolation is allowed from that layer.

Lateral subsurface flow

Lateral subsurface flow in the soil profile (0–2 m) is calculated simultaneously with percolation. A kinematic storage model developed by Sloan *et al.* (1983) is used to predict lateral flow in each soil layer:

$$q_{lat} = 0.024 \frac{2 S K_s \sin(\alpha)}{\theta_d L} \tag{16}$$

where q_{lat} (mm day^{-1}) is lateral flow, S (m h^{-1}) is drainable volume of soil water, α (mm^{-1})

is slope, Θd (mm^{-1}) is drainable porosity, L (m) is flow length and Ks is saturated hydraulic conductivity. If the saturated zone rises above the soil layer, then water is allowed to flow to the layer above (back to the surface for the upper soil layer). To account for multiple layers, the model is applied to each soil layer independently, starting at the upper layer.

Groundwater flow

The main role of the groundwater model is to predict the impact of management changes on total water supplies (Arnold *et al.*, 1993). A simple and realistic model is used to simulate groundwater contribution to total stream flow by creating shallow aquifer storage. The percolate from the soil profile is assumed to recharge a shallow aquifer. A shallow aquifer or unconfined aquifer is a permeable bed only partly filled with water and overlying a relatively impervious layer. The water balance for the shallow aquifer is

$$V_{sai-1} + R_c - revap - q_{rf} - perc_{gw} - WU_{SA} \quad (17)$$

where V_{sa} (mm) is the shallow aquifer storage, Rc is the recharge, revap is the water flow from the shallow aquifer back to the soil profile, q_{rf} (mm) is the return flow, $perc_{gw}$ (mm) is the percolate to the deep aquifer, WU_{SA} (mm) is the water use (withdrawal) from the shallow aquifer, and i is the day.

Return flow from the shallow aquifer to the stream is estimated with the equation of Arnold *et al.* (1993):

$$q_i = q_{i-1}e^{-\alpha\Delta t} + Rc\,(1.0 - e^{-\alpha\Delta t}) \quad (18)$$

where α is the constant of proportionality or the reaction factor.
The relationship for water table height according to Arnold *et al.* (1993) is

$$h_i = h_{i-1}e^{-\alpha\Delta t} + \frac{Rc\,(1.0 - e^{-\alpha\Delta t})}{0.8\mu\alpha} \quad (19)$$

Where h (m) is the water table height (above stream bottom) and μ is the specific yield.

Evapotraspiration

The model offers three options for estimating potential ET: Penman–Monteith (Monteith, 1965), Hargreaves (Hargreaves and Samani, 1985), and Priestley-Taylor (Priestley and Taylor, 1972). The Priestley–Taylor method requires solar radiation and air temperature as input, whereas the Hargreaves method requires air temperature only. The Hargreaves or Priestley–Taylor methods provide an option that gives realistic results in most cases (Arnold et al., 1996). Penman-Monteith method is generally used for computing potential ET. Studies have shown that the Penman-Monteith method is more reliable than methods that use less climatic data (Jensen et al., 1990). Moreover this method is widely recommended because of its detailed theoretical base and its accommodation of small time period so in the present study. The Penman–Monteith method requires solar radiation, air temperature, wind speed, and relative humidity.

The Penman–Monteith equation is expressed as

$$E_0 = \frac{[\delta\,(h_o - G) + 867\,AD\,(e_a - e_d)]/AR}{HV\,[\delta + \gamma\,(1 + \frac{CR}{AR})} \quad (20)$$

where Eo ($g\ m^{-2}\ s^{-1}$) is the evaporation, h_o ($MJ\ m^{-2}$) is the net radiation, δ ($kPa\ °C^{-1}$) is the slope of the saturation vapour pressure curve, G (MJ m^{-2}) is the soil heat flux, e_a (kPa) is the saturated vapor pressure at mean air temperature, e_d (kPa) is the vapour pressure at mean air temperature, HV is the latent heat of vaporization, γ (kPa °C^{-1}) is the psychrometric constant, AD (g m^{-3}) is the air density, AR (s m^{-1}) is the aerodynamic resistance for heat and vapour transfer, and CR (s m^{-1}) is the canopy resistance for vapour transfer. The Routing structure of SWAT model is given in Figure 1.

Model Evaluation

Model evaluation is the adjustment of model parameters, within recommended ranges, to optimize the agreement between observed and simulated results. The evaluation tool of the SWAT provided different parameters for adjustment through user intervention. Different data of various scenarios have been used for the calibration of the model.

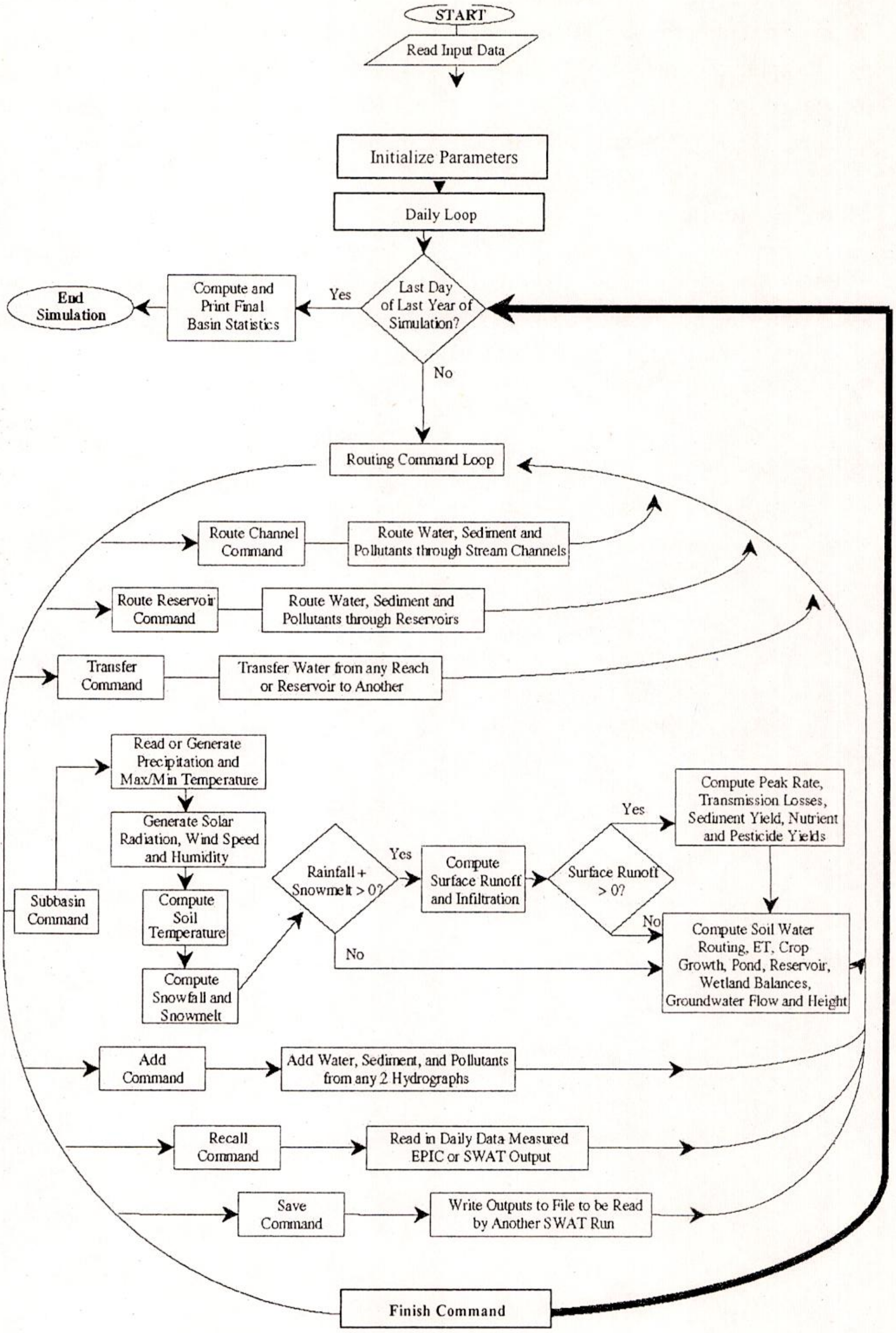

Figure 1. Routing structure of SWAT Model (Arnold and Fohrer, 2005)

Criteria for Model Evaluation

There is no unique criterion that defines a good evaluation of the model performance. However, if the verification is for only one watershed at one stream gauges location, the graphical displays can be easily interpreted (Hann *et al.*, 1982). Out of many advisable verification aids graphical comparisons are extremely useful. Continuous time series plot of the recorded and simulated series and a scattergram of recorded data plotted against simulated flows were therefore used in this study.

Several types of statistics provide useful numerical measures of the degree of agreement between models simulated and recorded quantities. The numerical and graphical performance criteria described below were used in this study:

Martinec and Rango (1989) recommended that the criteria should be as simple as possible. The deviation of runoff volumes, D_V, is one goodness-of-fit criterion.

$$D_V(\%) = \frac{V - V'}{V} 100 \quad (21)$$

Where V is the measured yearly or seasonal runoff volume; V' is the model computed yearly or seasonal runoff volume. D_V can take any value; however, smaller the number better the model results are. D_V would equal zero for a perfect model. The use of D_V provided an immediate compliment to a visual inspection of the continuous hydrographs.

The second basic goodness-of-fit criterion recommended by ASCE Task Committee (1993) is the Nash-Sutcliffe coefficient or coefficient of simulation efficiency (COE) (Nash and Sutcliffe, 1970):

$$COE = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_i)^2}{\sum_{i=1}^{n}(Q_i - Q)^2} \quad (22)$$

where Q_i is the measured daily discharge; Q'_i is the computed daily discharge; Q is the average measured discharge values. The COE values can be varies from 0 to 1, with 1 indicating a perfect fit. A value of COE = 0 indicates that the model was simulating no better than using the average of the observed data

Validation and Sensitivity Analysis

Validation of the calibrated model is essential to test its simulation performance. Calibrated model should be validated using a different set of data recorded during the given time period of the data. The simulated values of specified location should be compared with the observed values for validation of the model. Besides such comparison, validation can also been tested using different established indices.

To perform the sensitivity analysis, first of all data file can be established and base output variables will bedetermined. Each variable will be varied within the prescribed range keeping others constant. The output values then analyze to determine their variation with respect to the base values. As each variable varied about the base value, the mean output can be compared with the mean of the base value prediction as a measure of sensitivity.

Merits of the SWAT Model

The merits of the model are as follows (Arnold *et al.*, 1998):

1. It is comparatively simple, user friendly and physically based distributed model which uses readily available inputs.
2. It is computationally efficient to operate on large basins in a reasonable time.
3. It is a continuous time scale model, capable of simulating long term effects of management change.
4. It has got high potentiality to integrate with GIS.

Limitations of the SWAT Model

The major limitation of catchment modelling is the spatial variability associated with precipitation. Precipitation can cause considerable errors in runoff estimation if only one rain gauge is used to represent an entire catchment or even if an attempt is made to 'spatially weight' precipitation for a watershed.

CONCLUSION

Every component of the SWAT model is a simplification of the natural process and thus could be improved. It is important that each component is as simple and yet realistic as possible, interacts properly with other components, and uses readily available inputs.

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