STUDY AREA AND SWAT MODEL
CHAPTER III
STUDY AREA AND SWAT MODEL

3.1 INTRODUCTION

This chapter includes description of study area, SWAT model and its features, data acquisition and theoretical consideration relating to SWAT model. Overview and brief description of the model operation and its limitations along with the description of input files used for evaluating the SWAT model are also included.

3.2 STUDY AREA

On scrutiny of several watersheds two watersheds of different locations had been chosen for the study. Chhokranala and Arang watersheds are gauged watershed and falls under small watershed category.

Chhokranala watershed: The Chhokranala watershed has been selected for the study, which is located between 81° 42' to 81° 46' E longitude and 21° 13' to 21° 14' N latitude and covers an area of 1731 ha. The altitude of the watershed varies from 290 to 310 m above MSL. The part of the research farm of the Indira Gandhi Krishi Vishwavidyalaya, Raipur comes under the selected watershed. The Chhokranala is third order watershed and comprises of 6 villages. Location map of Chhokranala watershed in Chhattisgarh along with contours and drainage lines is shown in Fig. 3.1.

The topography of the watershed is almost flat. The slope ranges from 1% to 2% and the weighted average slope of the watershed is 1.6%. The predominant soil of watershed is sandy clay loam. Sandy loam, loam and clay are also found in the watershed. The watershed receives an average annual rainfall of 1420 mm, out of which the monsoon season (June to October) contributes more than 90% rainfall. The monthly mean temperature ranges from a maximum of 37°C in the month of May to a minimum of 7°C in the month of December. The monthly mean relative humidity varies from a minimum of 38% in the month of April to a maximum of 83% in the month of August. Overall climate of the area can be classified as sub-humid tropical.
Major crops grown in the area are paddy, maize and vegetables in **kharif** season and gram, mustard and vegetables in **rabi** season.

**Arang watershed:** The Arang watershed is third order watershed and comprises of seven villages. Main channel of the Arang watershed is known as *Sanghari* nala. This watershed is located between 81°55' to 82°0' E longitude and 21°12' to 21°16' N latitude and covers an area of 5450 ha. The altitude of the watershed varies from 270 to 290 m above MSL. The watershed is 45 km away from the Indira Gandhi Krishi Vishwavidyalaya, Raipur towards east. Location map of Arang watershed in Chhattisgarh along with contours and drainage lines is shown in Fig. 3.2.

The average slope of the Arang watershed is 1.5 %. The predominant soil of watershed is loam associated with clayey soils. The characteristics of the major soil of the watershed includes deep, well drained on gentle sloping undulating plateau with mounds and valley with moderate erosion. The watershed receives an average annual rainfall of about 1350 mm out of which monsoon season contributes more than 80 % of annual rainfall. The daily mean temperature ranges from a maximum of 40.0°C to a minimum of 3.0°C. The daily mean relative humidity varies from a minimum of 40 % in the month of April to a maximum of 85 % in the month of July. Overall climate of the area can be classified as sub-humid tropical. Major crops grown during **kharif** season are paddy, maize and vegetables whereas during **rabi** season gram, mustard and vegetables are grown in the Arang watershed.
Fig. 3.1 Location map of the Chhokranala watershed

Fig. 3.2 Location map of the Arang watershed
3.3 THE SWAT MODEL AND ITS FEATURES

3.3.1 Overview

SWAT is the continuation of a long-term effort of nonpoint source pollution modelling by the USDA-Agricultural Research Service (ARS) at Temple Texas (U.S.A.). SWAT was obtained by adding a new routing structure of ROTO (Arnold et al., 1995) to the SWRRB (Williams et al., 1985; Arnold et al., 1990) so as to remove the restriction of only being able to simulate 10 sub-watersheds as in the case of SWRRB. SWAT allows considerable flexibility in watershed discretization. The watershed can be divided into a number of grid cells or sub-watersheds. Different parts of the watershed can be divided differently. The new routing structures of SWAT routes and add flows down through the basin reaches to the reservoirs. Apart from this, changes have been incorporated to simulate lateral flow, ground water flow, reach routing transmission losses, and sediment and chemical movement through ponds, reservoirs, streams and valleys. SWAT is capable of simulating hundreds of sub-watersheds for periods of 100 years or more. The major components of the model include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, ground water and lateral flow, and agriculture management.

3.3.2 Merits of the Model

SWAT is a distributed parameter model that operates on a daily time step. The major goal of the model development is to predict the impact of management measures on water, sediment and agricultural chemical yields in large ungauged basins. 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.
The SWAT model uses a command structure for routing runoff and chemicals through a watershed similar to the structure of HYMO model (Williams and Hann, 1973). Specific commands are there for routing flows through streams and reservoirs, adding flows and inputting measured data or point sources (Fig. 3.3). Using a routing command language, the model can simulate a basin subdivided into grid cells or sub-watersheds. Additional commands have been developed to allow measured and point source data to be input to the model and routed with simulated flows.

3.3.3 Limitations of the Model

The following are the limitations of the model (Arnold et al., 1998):

1. Daily precipitation is input to the model and curve number equation is applied to daily rainfall without accounting for its intensity for runoff estimation.

2. One of the major limitations of large area hydrologic 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 sub-watershed or even if an attempt is made to 'spatially weight' precipitation for a watershed.

3. SWAT does not simulate detailed event based flood and sediment routing. It was developed to predict agricultural management impacts on long term (100 years) erosion and sedimentation rates. The model operates on a daily time step, although a shorter and more flexible time increment would be a major enhancement to the model.

4. The sediment routing equations are relatively simplistic and assume that channel dimensions are static throughout the simulation period. This may be unrealistic since simulation may be made even for 100 years or more.

5. Another limitation is the simplistic way the channel bed is described. The erodibility factor should be replaced with more detailed models that account for cohesive, noncohesive and armored channels.

6. Reservoir routing was originally developed for small reservoirs and assumes well-mixed conditions. The reservoir outflow calculations are not accounted for controlled operation. To adequately simulate large reservoirs, these items need to be addressed.
Fig. 3.3 SWAT model operation flow chart
3.4 DATA ACQUISITION

3.4.1 Meteorological Data

A set of instruments consisting of automatic rain gauge, non-recording rain gauge, evaporimeter, maximum and minimum thermometer, wet bulb and dry bulb thermometer are installed at the outlet of both the watersheds. Rainfall intensity has been recorded using automatic rain gauge. One non-recording rain gauge is also installed at Nakti village, which comes under Chhokranala watershed. Daily rainfall data of five years (2001-2005) for Chhokranala watershed and four years (2002-2005) for Arang watershed are measured at the outlet of the watersheds by a non recording rain gauge are collected and analysed to find out the best fitting frequency distribution for mean monthly rainfall. Rainfall data recorded with the help of recording type rain gauge is also collected for the purpose of determining the 0.5 and 6.0 hours rainfall of 10 years frequency. Some of the weather data such as solar radiation and wind velocity are collected from the meteorological observatory, Raipur. An automatic water level stage recorder is installed at the outlet of Chhokranala watershed to record the water level of the main channel automatically. Monthly average values for five years (2001-2005) for the rainfall, temperature, relative humidity, wind velocity and solar radiation are given in Table A1 of Appendix A.

3.4.2 Hydrological Data

Besides rainfall, some more hydrological data are collected for the study. For Chhokranala and Arang watersheds daily surface runoff and sediment yield data are collected for the monsoon season. A Runoff and Sediment Observation Post (RSOP) at the outlet of Chhokranala watershed is being installed and used in the present study. Daily surface runoff at the outlet of Arang watershed is recorded using the traditional water level stage recording method. A silt sampler (USDH-48) is used for collection of runoff samples from the watersheds. Water quality samples are also collected for few storm events during monsoon season. These samples are analyzed to determine the sediment and nutrient losses from the watersheds.
3.4.3 Topographic and Soil Data

The Chhokranala and Arang watersheds are covered in the topographic map Nos. 64 G/12 and 64 G/16 on 1:50,000 scales and 64 G/15 and 64 G/16 on 1:50,000 scales respectively, which are collected from Survey of India. Soil texture and soil resources data (Table 3.1) for both the watersheds are collected from Department of Soil and Water Engineering, Indira Gandhi Krishi Vishwavidyalaya, Raipur.

Table 3.1: Soil properties of different soil textures existing in both watersheds

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Bhata (Sandy Loam)</th>
<th>Matasi (Sandy clay loam)</th>
<th>Dorsa (Loam)</th>
<th>Khanar (Clay)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil depth (cm)</td>
<td>5-25</td>
<td>25-75</td>
<td>75-100</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>50-80</td>
<td>30-50</td>
<td>25-35</td>
<td>15-25</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>15-25</td>
<td>30-50</td>
<td>25-30</td>
<td>20-30</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>10-20</td>
<td>20-35</td>
<td>34-45</td>
<td>45-47</td>
</tr>
<tr>
<td>Bulk density (g/cc)</td>
<td>1.76-1.85</td>
<td>1.55-1.60</td>
<td>1.35-1.65</td>
<td>1.28-1.30</td>
</tr>
<tr>
<td>Infiltration (cm/hr)</td>
<td>4.0-6.0</td>
<td>0.6-2.9</td>
<td>2.0-3.0</td>
<td>1.0-2.5</td>
</tr>
<tr>
<td>Available water (cm)</td>
<td>2.15</td>
<td>8.67</td>
<td>17.5</td>
<td>16.8</td>
</tr>
<tr>
<td>pH</td>
<td>5.7-6.5</td>
<td>6.5-7.0</td>
<td>7.0-7.4</td>
<td>7.4-7.6</td>
</tr>
</tbody>
</table>

3.4.4 Satellite Data

The cloud free digital data of the study area has been obtained from National Remote Sensing Agency (NRSA), Hyderabad in CD ROM. The path 21, row 55, scenes of IRS-1C (LISS-III) satellite with date of pass 5th October 2002 is used for the study to prepare the land use/land cover maps of both the watersheds. The satellite data is in four electromagnetic spectral bands (band 1: 0.45-0.52 μm, band 2: 0.52-0.59 μm, band 3: 0.62-0.68 μm and band 4: 0.77-0.86 μm). Its sensor provided the data with 26.5 m spatial resolution. Standard False Colour Composite (FCC) for a sample date of pass (5th October 2002) is used for the preparation of different maps for both the watersheds.
3.4.5 Hardware and Software Used

The computer equipped with advanced image processing, GIS analysis facilities, scanner, digital camera and a laser printer are used for the study. The software available such as Arc GIS is used for terrain analysis and Geometica software is used for image processing. Extracted data is processed with the help of Excel package of Microsoft Office and the entire input data file are generated in DOS using UTIL programme which is built-up with the SWAT model (Arnold et al. 1996) used in the study.

3.5 THEORETICAL CONSIDERATION

The brief description of different components and the mathematical relationships used to simulate the processes and their interactions in the model as described by Arnold et al. (1996) are considered. First, the sub-basin components that include hydrology, weather, sediment yield, nutrients, pesticides, soil temperature, crop growth, tillage and residue, and agricultural management are described. This is followed by a description of the channel and reservoir routing components of the model.

3.6 SUBBASIN COMPONENTS

3.6.1 Hydrology

The hydrology model (Fig. 3.4) is based on the water balance equation:

\[ SW_t = SW + \sum_i (R_i + Q_i - ET_i - P_i - QR_i) \]  

(3.1)

where \( SW \) is the soil water content minus the 15-bar water content, \( t \) is time in days, and \( R, Q, ET, P, \) and \( QR \) are the daily amounts of precipitation, runoff, evapotranspiration, percolation and return flow, respectively; all units are in mm. Since the model maintains a continuous water balance, complex basins are subdivided to reflect differences in \( ET \) for various crops and soils. Thus, runoff is predicted separately for each sub-area (Fig. 3.5) and routed to obtain the total runoff for the basin. This increases accuracy and gives a much better physical description of the water balance.
Fig. 3.4 Component of the hydrologic balance simulated within the SWAT subbasin
Fig. 3.5 Hydrologic flow chart of SWAT model
3.6.1.1 Surface Runoff Volumes

The model simulates surface runoff volumes, given daily rainfall amounts. Runoff volume is estimated by the Soil Conservation Service (SCS) curve number technique (USDA, 1972). The SCS curve number equation used in the model is as follows:

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

\[
Q = 0.0, \quad R \leq 0.2s
\]  

(3.2)

where \( Q \) is the daily runoff, \( R \) is the daily rainfall, and \( s \) is a retention parameter. The retention parameter, \( s \), varies (a) among sub-basins because of the variation in soils, land use, management, and slope all vary and (b) with time because of changes in soil water content. The parameter \( s \) is related to curve number (CN) by the SCS equation (USDA, 1972):

\[
s = 254 \left( \frac{100}{CN} - 1 \right)
\]

(3.3)

The constant, 254, in equation (3.3) gives \( s \) in mm. Thus, \( R \) and \( Q \) are also expressed in mm. \( CN \) is the curve number for antecedent moisture condition (AMC) II.

Fluctuations in soil water content cause the retention parameter to change according to the equation:

\[
s = s_1 \left( 1 - \frac{FFC}{FFC + \exp \left( w_1 - w_2 (FFC) \right)} \right)
\]

(3.4)

where \( s_1 \) is the value of \( s \) associated with \( CN_1 \), \( FFC \) is the fraction of field capacity, and \( w_1 \) and \( w_2 \) are shape parameters. \( FFC \) is computed with the equation:
where \( SW \) is the soil water content in the root zone, \( WP \) is the wilting point water content (1,500 kPa for many soils), and \( FC \) is the field capacity water content (33 kPa for many soils). Values for \( W_1 \) and \( W_2 \) are obtained from a simultaneous solution of equation (3.4) according to the assumptions that \( s=s_2 \) when \( FFC=0.6 \) and \( s=s_3 \), when \( (SW-FC)/(PO-FC)=0.5 \):

\[
W_1 = \ln\left(\frac{60}{1-s_3/s_1} - 60\right) + 60 \cdot W_2
\]  

(3.6)

\[
W_2 = \frac{\ln\left(\frac{60}{1-s_3/s_1} - 60\right) - \ln\left(\frac{POFC}{1-s_3/s_1} - POFC\right)}{POFC - 60}
\]  

(3.7)

where \( s_3 \) is the \( CN_3 \) retention parameter and the porosity-field capacity ratio \( POFC \) is computed with the equation:

\[
POFC = 100 + 50 \left( \frac{\sum_{i=1}^{M} (PO_i - FC_i)}{\sum_{i=1}^{M} (FC_i - WP_i)} \right)
\]  

(3.8)

where \( PO \) is the porosity of soil layer \( i \). Equations (3.6) and (3.7) assure that \( CN_i \) corresponds with the wilting point and that the curve number cannot exceed 100.

The \( FFC \) value obtained in equation (3.5) 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. SWAT estimates water content of each soil layer daily, since the depth distribution is available. The effect of depth distribution on runoff is expressed in the depth weighting function:
where \( FFC^* \) is the depth weighted \( FFC \) value for use in equation (3.4), \( Z \) is the depth in m to the bottom of soil layer \( I \), and \( M \) is the number of soil layers. Equation (3.9) performs two functions: (a) it reduces the influence of lower layers because \( FFC_i \) is divided by \( Z_i \) and (b) it gives proper weight to thick layers relative to thin layers because \( FFC \) is multiplied by the layer thickness.

### 3.6.1.2 Peak Runoff Rates

There are two options for estimating the peak runoff rate, (a) the modified Rational formula and (b) the SCS TR-55 method (USDA, 1986). The SCS TR-55 method for estimating peak runoff rate has been described in detail (USDA, 1986). In this study the modified Rational formula method was used for estimating peak runoff rates. The modified Rational formula is described here in detail.

**Modified Rational Formula:** A stochastic element is included in this method to allow realistic simulation of peak runoff rates, given only daily rainfall and monthly rainfall intensity. The rational formula can be written in the form:

\[
q_p = \left( \frac{\rho}{360} \right) \left( \frac{r}{A} \right)
\]

(3.10)

where \( q_p \) is the peak runoff rate in m\(^3\)s\(^{-1}\), \( \rho \) is a runoff coefficient expressing the watershed infiltration characteristics, \( r \) is the rainfall intensity in mmh\(^{-1}\) for the watershed's time of concentration, and \( A \) is the drainage area in ha. The runoff coefficient can be calculated for each storm if the amount of rainfall and runoff are known:

\[
\rho = \frac{Q}{R}
\]

(3.11)
Since $R$ is input and $Q$ is computed with equation (3.11), $\rho$ can be calculated directly. Rainfall intensity can be expressed with the relationship:

$$ r = \frac{R_{tc}}{t_c} \quad (3.12) $$

where $R_{tc}$ is the amount of rainfall in mm during the watershed's time of concentration, $t_c$ in h. The value of $R_{tc}$ can be estimated by developing a relationship with total $R$. Generally, $R_{tc}$ and $R_{24}$ are proportional for various frequencies. Thus,

$$ R_{tc} = \alpha R \quad (3.13) $$

where $\alpha$ is a dimension less parameter that expresses the proportion of total rainfall that occurs during $t_c$.

The peak runoff equation is obtained by substituting equations (3.11), (3.12), and (3.13) into equation (3.10):

$$ q_p = \frac{(\alpha)(Q)(A)}{360(t_c)} \quad (3.14) $$

The time of concentration can be estimated by adding the surface and channel flow times:

$$ t_c = t_{cc} + t_{cs} \quad (3.15) $$

where $t_{cc}$ is the time of concentration for channel flow and $t_{cs}$ is the time of concentration for surface flow in h. The $t_{cc}$ can be computed by using the equation:

$$ t_{cc} = \frac{L_c}{3.6 V_c} \quad (3.16) $$
where $L_c$ is the average channel flow length for the watershed in km and $V_c$ is the average channel velocity in ms$^{-1}$. The average channel flow length can be estimated by using the equation:

$$L_c = \sqrt{(L)(L_{oa})} \quad (3.17)$$

where $L$ is the channel length from the most distant point to the watershed outlet in km and $L_{oa}$ is the distance from the outlet along the channel to the watershed centroid in km.

Average velocity can be estimated by using Manning's equation and assuming a trapezoidal channel with 2:1 side slopes and a 10:1 bottom width/depth ratio. Substitution of these estimated and assumed values give:

$$t_{cc} = \frac{\sqrt{(L)(L_{oa})} (n)^{0.75}}{0.489 \left(\frac{q_c}{A}\right)^{0.25} (\sigma)^{0.375}} \quad (3.18)$$

where $n$ is Manning's $n$, $q_c$ is the average flow rate in m$^3$s$^{-1}$, and $\sigma$ is the average channel slope in m m$^{-1}$. Assuming that $L_{oa}=0.5L$ and converting units ($L$ from m to km, $t_{cc}$ from s to h, and $q_c$ from m$^3$s$^{-1}$ to mmh$^{-1}$) gives the equation:

$$t_{cc} = \frac{1.75 (L^*)(n)^{0.75}}{\left(\frac{q_c^*}{A}\right)^{0.25} (\sigma)^{0.375}} \quad (3.19)$$

where $L^*$ is the channel length in km and $q_c^*$ is the average flow rate in mmh$^{-1}$.

The average flow rate is obtained from the estimated average flow rate from a unit source in the watershed (1 ha area) and the relationship is given as:

$$q_c^* = q_o^* A^{-0.5} \quad (3.20)$$
where \( q_o \) is the average flow rate from a 1.0 ha area in mm h\(^{-1}\). The unit source flow rate is estimated with the equation:

\[
q^* = \frac{Q}{DUR} \quad (3.21)
\]

where \( DUR \), the rainfall duration in h, which is calculated using the equation:

\[
DUR = \frac{4.605}{-2\ln(1-\alpha_S)} \quad (3.22)
\]

where \( \alpha_S \) is computed with equation (3.13) using \( R_S \) instead of \( R_{tc} \). Equation (3.22) is derived assuming that rainfall intensity is exponentially distributed.

Substituting equation (3.21) into equation (3.19) gives the final equation for \( t_{ce} \):

\[
t_{ce} = \frac{1.75}{(q^*)^{0.25} (\lambda)^{0.25} (\nu)^{0.75} (\sigma)^{0.25}} \quad (3.23)
\]

A similar approach is used to estimate \( t_{cs} \):

\[
t_{cs} = \frac{\lambda}{\nu} \quad (3.24)
\]

where \( \lambda \) is the surface slope length in m and \( \nu \) is the surface flow velocity in ms\(^{-1}\).

Applying Manning's equation to a strip 1 m wide down the slope length, assuming that flow is concentrated into a small trapezoidal channel with 1:1 side slopes and 5:1 bottom width-depth ratio gives the velocity equation:

\[
\nu = \frac{0.8375d^{0.666}s^{0.5}}{n} \quad (3.25)
\]

50
where \( v \) is the flow velocity in \( \text{m}^3\text{s}^{-1} \), \( d \) is flow depth in \( \text{m} \), \( s \) is the land surface slope in \( \text{mm}^{-1} \), and \( n \) is Manning's roughness coefficient for the surface. The average flow depth, \( d \), can be calculated from Manning's equation as a function of flow rate:

\[
d = \left( \frac{q_0 n}{5.025 s^{0.5}} \right)^{0.375}
\]

(3.26)

where \( q_0 \) is the average flow rate in \( \text{m}^3\text{s}^{-1} \). Substituting equations (3.25) and (3.26) into equation (3.24) gives:

\[
l_{\alpha} = \frac{0.0216}{q_0} \left( \frac{A. n}{s} \right)^{0.75} \left( \frac{q_0 n}{5.025 s^{0.5}} \right)^{0.375}
\]

(3.27)

To properly evaluate \( \alpha \), variation in rainfall patterns must be considered. For some short duration storms, most or all the rain occurs during \( t_c \) causing \( \alpha \) to approach its upper limit of 1.0. Other storms of uniform intensity cause \( \alpha \) to approach minimum value. All other patterns cause higher \( \alpha \) values than the uniform pattern, because \( r_c \) is greater than \( r_24 \) for all patterns except the uniform. By substituting the products of intensity and time into equation (3.13), an expression for the minimum value of \( \alpha \), \( \alpha_{mn} \), is obtained:

\[
\alpha_{mn} = \frac{t_c}{24}
\]

(3.28)

Thus, \( \alpha \) ranges within the limits \( \frac{t_c}{24} \leq \alpha \leq 1.0 \)

Although confined between limits, the value of \( \alpha \) is assigned with considerable uncertainty when only daily rainfall and simulated runoff amounts are given. Thus, \( \alpha \) is generated from a triangular distribution with the base ranging from \( t_c/24 \) to 1.0. The peak of the \( \alpha \) distribution changes monthly because of seasonal differences in rainfall intensities.
3.6.1.3 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 the equation:

\[ SW_i = SW_{oi} \exp \left( - \frac{\Delta t}{TT_i} \right) \tag{3.29} \]

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

\[ O_i = SW_{oi} \left[ 1 - \exp \left( - \frac{\Delta t}{TT_i} \right) \right] \tag{3.30} \]

where \( O \) is the percolation rate in mm d\(^{-1}\).

The travel time, \( TT_i \), is computed for each soil layer with the linear storage equation:

\[ TT_i = \frac{SW_i - FC_i}{H_i} \tag{3.31} \]

where \( H_i \) is the hydraulic conductivity in mm h\(^{-1}\) and \( FC \) is the field capacity minus wilting point water content for layer \( i \) in mm. The hydraulic conductivity is varied from the saturated conductivity value at saturation to near zero at field capacity.

\[ H_i = SC_i \left( \frac{SW_i}{UL_i} \right)^{\beta_i} \tag{3.32} \]

where \( SC_i \) is the saturated conductivity for layer \( i \) in mm h\(^{-1}\), \( UL_i \) is soil water content at saturation in mm mm\(^{-1}\). \( \beta_i \) is a parameter that causes \( H_i \) to approach zero as \( SW_i \) approaches \( FC_i \). The equation for estimating \( \beta \) is
\[ \beta_i = \frac{-2.655}{\log_{10} \left( \frac{FC_i}{U/L} \right)} \]  

(3.33)

The constant (-2.655) in equation (3.33) is set to assure \( H_i = 0.002SC_i \) at field capacity. Upward flow may occur when a lower layer exceeds field capacity. The soil water to field capacity ratios of the two layers regulates 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, no percolation is allowed from that layer.

### 3.6.1.4 Lateral Subsurface Flow

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

\[ q_{\text{lat}} = 0.024 \frac{2SK_x \sin(\alpha)}{\Theta_d L} \]  

(3.34)

where \( q_{\text{lat}} \) is lateral flow (mmd\(^{-1}\)), \( S \) is drainable volume of soil water (mh\(^{-1}\)), \( \alpha \) is slope (mm\(^{-1}\)), \( \Theta_d \) is drainable porosity (mm\(^{-1}\)), and \( L \) is flow length (m). If the saturated zone rises above the soil layer, 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.

### 3.6.1.5 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 the shallow aquifer. The water balance for the shallow aquifer is
\[ V_{sa_i} = V_{sa_{i-1}} + Rc - revap - q_{rf} - perc_{gw} - WU_{SA} \] (3.35)

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

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

\[ q_i = q_{i-1} e^{-\sigma \Delta t} + Rc \left( 1.0 - e^{-\sigma \Delta t} \right) \] (3.36)

where \( \sigma \) is the constant of proportionality or the reaction factor.

The relationship for water table height is (Arnold et al., 1993)

\[ h_i = h_{i-1} e^{-\sigma \Delta t} + \frac{Rc}{0.8 \mu \alpha} \left( 1.0 - e^{-\sigma \Delta t} \right) \] (3.37)

where \( h \) is the water table height (in m above stream bottom) and \( \mu \) is the specific yield.

3.6.1.6 Evapotranspiration

The model offers three options for estimating potential evapotranspiration (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, while 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).
The Penman-Monteith method requires solar radiation, air temperature, wind speed, and relative humidity. The Penman-Monteith equation is expressed as

\[
E_o = \frac{\delta(h_o - G) + 86.7 AD(e_o - e_d)}{AR \left( \delta + \gamma \left( \frac{CR}{AR} \right) \right)}
\] (3.38)

where \( E_o \) is the evaporation \((\text{gm}^2\text{s}^{-1})\), \( h_o \) is the net radiation \((\text{MJ/m}^2)\), \( \delta \) is the slope of the saturation vapour pressure curve \((\text{kPa}^{{\circ C}^{-1}})\), \( G \) is the soil heat flux \((\text{MJ/m}^2)\), \( e_o \) is the saturated vapour pressure at mean air temperature \((\text{kPa})\), \( e_d \) is the vapour pressure at mean air temperature \((\text{kPa})\), \( H \) is the latent heat of vaporization and \( \gamma \) is the psychrometer constant \((\text{kPa}^{{\circ C}^{-1}})\), and \( AR \) is the aerodynamic resistance for heat and vapour transfer in \(\text{sm}^{-1}\), and \( CR \) is the canopy resistance for vapour transfer \((\text{sm}^{-1})\).

The Priestley-Taylor method provides estimated of potential evaporation based only on temperature and radiation:

\[
E_o = 1.28 \left( \frac{h_o}{HV} \right) \left( \frac{\delta}{\delta + \gamma} \right)
\] (3.39)

where \( E_o \) is the potential evaporation in mm, \( \delta \) is the slope of the saturation vapour pressure curve in \(\text{kPa}^{{\circ C}^{-1}}\), \( \gamma \) is a psychrometer constant in \(\text{kPa}^{{\circ C}^{-1}}\), \( h_o \) is the net radiation in \(\text{MJm}^2\), and \( H \) is the latent heat of vapourization in \(\text{MJkg}^{-1}\). The latent heat of vapourization, saturation vapour pressure and slope of the saturation vapour pressure curve all estimated with the temperature function (Arnold et al., 1996).

The Hargreaves method estimates potential evapotranspiration as a function of extraterrestrial radiation and air temperature. Hargreaves method was modified for use in SWAT by increasing the temperature difference exponent from 0.5 to 0.6. Also,
extraterrestrial radiation is replaced by RAMX (maximum possible solar radiation at the earth's surface) and the coefficient is adjusted from 0.0023 to 0.0032 for proper conversion (Arnold et al., 1996). The modified equation is

$$E_o = 0.0032 \left( \frac{RAMX}{HV} \right) (T + 17.8)(T_{mx} - T_{mn})^{0.6}$$

(3.40)

where $T_{mx}$ and $T_{mn}$ are the daily maximum and minimum air temperatures in °C.

The model computes evaporation from soils and plants separately, as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential ET and leaf area index (LAI). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential evaporation and leaf area index.

3.6.1.7 Transmission Losses

Many semiarid watersheds have alluvial channels that abstract considerable quantities of streamflow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volumes, as water is lost as the flood wave travels downstream. Lane's method described in USDA (1983) is used to estimate transmission losses. Channel losses are a function of channel width, length and flow duration. Both runoff and peak rate are adjusted when transmission losses occur.

3.6.1.8 Ponds

Farm ponds are small structures that occur within a subbasin. Pond storage is simulated as a function of pond capacity, daily inflows and outflows, seepage and evaporation. Ponds are assumed to have only emergency spillways. Required inputs are capacity and surface area. Surface area below capacity is estimated as a non-linear function of storage.
3.6.2 Weather

The weather variables for driving hydrology balance are precipitation, air temperature, solar radiation, wind speed, and relative humidity. If daily precipitation and maximum and minimum air temperature data are available, they can be input directly to the model. If not, the weather generator can be used to simulate daily rainfall and temperature. Solar radiation, wind speed, and relative humidity are always generated by the weather generator and used by the model. One set of weather variables may be simulated for entire basin, or different set of weather variables may be simulated for each subbasin. Weather generators can be extremely useful when measured data is unavailable and management scenarios are being compared.

3.6.2.1 Precipitation

The precipitation model developed by Nicks (1974) is a first-order Markov chain model. Input for this model includes monthly probabilities of receiving precipitation if the previous day was dry and if the previous day was wet. Given the wet-dry state, the model determines stochastically if precipitation occurs or not. A random number (0-1) is generated and compared with the appropriate wet-dry probability. If the random number is less than or equal to the wet-dry probability, precipitation occurs on that day. Random numbers greater than the wet-dry probability give no precipitation. Since the wet-dry state of the first day is established, the process can be repeated for the next day and so on throughout the simulation period. If wet-dry probabilities are not available, the average monthly number of rainy days may be substituted (Arnold et al., 1996). The probability of a wet day is calculated directly from the number of wet days:

\[ PW = \frac{NWD}{ND} \]  \hspace{1cm} (3.41)

where \( PW \) is the probability of a wet day, \( NWD \) is the number of rainy days, and \( ND \) is the number of days, in a month. The probability of a wet day after a dry day can be estimated as a fraction of \( PW \).
\[ P(W/D) = \beta \, PW \]  
(3.42)

where \( P(W/D) \) is the probability of a wet day following a dry day and where \( \beta \) is a fraction usually in the range of 0.6 to 0.9. For many locations, \( \beta = 0.75 \) gives satisfactory estimates of \( P(W/D) \). The probability of a wet day following a wet day \( P(W/W) \) can be calculated directly by using the equation:

\[ P(W/W) = 1.0 - \beta + P(W/D) \]  
(3.43)

When precipitation event occurs, the amount is generated from a skewed normal daily precipitation distribution

\[
R_i = \left( \left( \frac{SND_i \, SCF_i}{6.0} \right) \left( \frac{SCK_k}{6.0} \right) + 1 \right)^3 - 1 \left( RSDV_k + \bar{R}_k \right)
\]  
(3.44)

where \( R \) is the amount of rainfall on day \( i \), in mm, \( SND \) is the standard normal deviate for day \( i \), \( SCF \) is the skew coefficient, \( RSDV \) is the standard deviation of daily rainfall in mm, and \( R \) is the mean daily rainfall in month \( k \).

If the standard deviation and skewness coefficient are not available, the model simulates daily rainfall by using a modified exponential distribution.

\[
R_i = \left( - \ln \left( \mu \right) \right) R \bar{R}_k \int_{\ln(2)}^{\ln(\mu)} (- \ln(\chi))^\zeta \, d\chi
\]  
(3.45)

where \( \mu \) is a uniform random number (0.0-1.0) and \( \zeta \) is a parameter usually in the range of 1.0 to 2.0. The modified exponential is usually a satisfactory substitute and requires
only the monthly mean of daily precipitation as input. Amount of daily precipitation is partitioned between rainfall and snowfall using average daily air temperature.

3.6.2.2 Air Temperature and Solar Radiation

Daily maximum and minimum air temperature and solar radiation are generated from a normal distribution corrected for wet-dry probability state. The model developed by Richardson (1981) is used because it simulates temperature and radiation, which are mutually correlated with rainfall. The correction factor is used to provide more deviation in temperatures and radiation when weather changes on rainy days. Conversely, deviations are smaller on dry days. The correction factors are calculated to insure that long-term standard deviations of daily variables are maintained.

The temperature model requires monthly means of maximum and minimum temperatures and their standard deviations as inputs. The model estimates standard deviation as 0.25 of the difference between the extreme and the mean for each month. The solar radiation model uses the extreme approach extensively. Thus, only the monthly means of daily solar radiation are required as inputs.

3.6.2.3 Wind Speed and Relative Humidity

Daily wind speed is simulated using a modified exponential equation given the mean monthly wind speed as input. The modified exponential equation is as follows:

\[ V_i = b_{1,k} V_k \left[ - \ln (RN) \right]^{b_{2,k}} \]  

(3.46)

where \( V_k \) is the mean wind speed for month \( k \), \( RN \) is a random number, \( b_1 \) and \( b_2 \) are parameters for month \( k \). The value of \( b_1 \) can be closely approximated with the equation:

\[ b_1 = 1.5567 (b_2)^{0.1128} \exp(-0.4336b_2) \]  

(3.47)

The relative humidity model simulates daily average relative humidity from the monthly average by using a triangular distribution. As with temperature and radiation,
the mean daily relative humidity is adjusted to account for wet- and dry-day effects. The assumed relation between relative humidity on wet and dry days is

\[ RHW_k = RHD_k + \Omega_H (1.0 - RHD_k) \]  

where \( RHW \) is the daily mean relative humidity on wet days for month \( k \), \( RHD \) is the daily mean relative humidity on dry days, and \( \Omega_H \) is a scaling factor ranging from 0.0 to 1.0. An \( \Omega_H \) value of 0.9 seems appropriate for many locations. The appropriate value \((RHW \text{ or } RHD)\) is used as the peak of a triangular distribution to generate daily relative humidity. The model determines long-term average relative humidity for month \( k \) using the continuity equation.

3.6.3 Sedimentation
3.6.3.1 Sediment Yield

Sediment yield is computed for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977).

\[ Y = 11.8 \left( V q_p \right)^{0.46} (K)(C)(PE)(LS) \]  

where \( Y \) is the sediment yield from the subbasin in t, \( V \) is the surface runoff column for the subbasin in m\(^3\), \( q_p \) is the peak flow rate for the subbasin in m\(^3\)s\(^{-1}\), \( K \) is the soil erodibility factor, \( C \) is the crop management factor, \( PE \) is the erosion control practice factor, and \( LS \) is the slope length and steepness factor.

The \( LS \) factor is computed with the equation (Wischmeier and Smith, 1978)

\[ LS = \left( \frac{A}{22.1} \right)^{0.5} \left( 65.41S^2 + 4.465S + 0.065 \right) \]
The exponent $\xi$ varies with slope and is computed using the equation:

$$\xi = 0.6[1 - \exp(-35.835S)]$$  \hspace{1cm} (3.51)

The crop management factor, $C$, is evaluated for all days when runoff occurs using the equation:

$$C = \exp\left[-0.2231 - CVM\exp(-0.00115CV) + CVM\right]$$  \hspace{1cm} (3.52)

where $CV$ is the soil cover (above ground biomass + residue) in $\text{kg ha}^{-1}$ and $CVM$ is the minimum value of $C$. The value of $CVM$ is estimated from the average annual $C$ factor using the equation:

$$CVM = 1.463\ln(CVA) + 0.1034$$  \hspace{1cm} (3.53)

The value of $CVA$ for each crop is determined from tables prepared by Wischmeier and Smith (1978). Values of $K$ can be estimated for each subbasin using standard procedure. $PE$ factors can be estimated for each subbasin using information contained in Wischmeier and Smith (1978).

### 3.6.3.2 Soil Temperature

Daily average soil temperature is simulated at the centre of each soil layer for use in hydrology and residue decay. The temperature of the soil surface is estimated using daily maximum and minimum air temperature and snow, plant and residue cover for the day of interest plus the four days immediately preceding. Soil temperature is simulated for each layer using a function of damping depth, surface temperature and mean annual air temperature. Damping depth is dependent upon bulk density and soil water.
3.6.4 Nutrients

Subbasin nutrient yield and nutrient cycling were taken from the EPIC model (Williams et al., 1984) and modified as necessary for inclusion into the SWAT model (Arnold et al., 1996). The SWAT model allows for simultaneous computations on each subbasin and routes the water, sediment, and nutrients from the subbasin outlets to the basin outlet.

3.6.4.1 Nitrogen

The amount of NO$_3$-N contained in surface runoff is estimated for each subbasin by considering the first layer (10mm thickness) only. The total amount of water leaving the layer is the sum of runoff, lateral subsurface flow, and percolation.

\[ QT = Q + O_1 + QR_1 \]  (3.54)

where $QT$ is the total water lost from the first layer in mm, $Q$ is the runoff volume in mm, $O_1$ is the percolation from the first layer in mm, and $QR_1$ is the lateral flow from the first layer in mm.

Amounts of NO$_3$-N contained in runoff, lateral flow, and percolation are estimated as the products of the volume of water lost and the average concentration of NO$_3$-N.

\[ VNO_3 = (QT)(C_{NO3}) \]  (3.55)

where $VNO_3$ is the amount of NO$_3$-N lost from the first layer and $C_{NO3}$ is the concentration of NO$_3$-N in the first layer. Leaching and lateral subsurface flow in lower layers is treated with the same approach used in the upper layer except surface runoff is not considered.

A loading function developed by McElroy et al., (1976) and modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic N transport by sediment. The loading function estimates the daily organic N
runoff loss based on the concentration of organic N in the topsoil layer, the sediment yield and enrichment ratio. The loading function:

$$YON = 0.001(Y)(CON)(ER)$$

(3.56)

where $YON$ is the organic N runoff loss at the subbasin outlet in kg ha$^{-1}$, $CON$ is the concentration of organic N in the topsoil layer in g t$^{-1}$, $Y$ is the sediment yield in t ha$^{-1}$, and $ER$ is the enrichment ratio.

The value of $CON$ is input to the model and is constant throughout the simulation. Enrichment ratios are logarithmically related to sediment concentration as described by Menzel (1980). The logarithmic equation estimating enrichment ratio is

$$ER = x_1 c_a^{x_2}$$

(3.57)

where $c_a$ is the sediment concentration in g m$^{-3}$ and $x_1$ and $x_2$ are parameters set by the upper and lower limits. The enrichment ratio to approach 1.0, the sediment concentration would be extremely high.

The technique used to estimate the denitrification rate is described in the user's manual of the SWAT model (Arnold et al., 1996). The N mineralization model is a modification of the PAPRAN mineralization model (Seligman and Keulen, 1981). The daily amount of immobilization is computed by subtracting the amount of N contained in the crop residue from the amount assimilated by the microorganisms. Immobilization may be limited by N availability. If the amount of N available is less than the amount of immobilization predicted the decay rate constant is adjusted. To estimate the N contribution from rainfall, SWAT uses an average rainfall N concentration of 8 ppm for all locations for all storms. The amount of N in rainfall is estimated as the product of rainfall amount and concentration. This concentration corresponds to 6 lb/acre for 30 inches of rainfall.
Crop use of N is estimated using a supply and demand approach. The daily (day i) crop N demand can be computed using the equation:

\[ \text{UND}_i = \left( C_{NB} \right)_i B_i - \left( C_{NB} \right)_{i-1} B_{i-1} \]  \hspace{1cm} (3.58)

where \( \text{UND}_i \) is the N demand of the crop in kg ha\(^{-1} \), \( C_{NB} \) is the optimal N concentration of the crop, and \( B \) is the accumulated N in kg ha\(^{-1} \).

The crop is allowed to take N from any soil layer that has roots. Uptake starts at the upper layer and proceeds downward until the daily demand is met or until all N has been depleted. If the soil cannot supply the daily N demand for legumes, the deficit is attributed to N fixation. The simulated nitrogen cycle is presented in Fig. 3.6 and is a simplification of the actual soil nitrogen cycle.

Fig. 3.6 Nitrogen forms and transformations simulated with the SWAT subbasin
3.6.4.2 Phosphorus

The SWAT approach is based on the concept of partitioning pesticides into the solution and sediment phases (Knisel, 1980). Because P is mostly associated with the sediment phase, the soluble P runoff equation can be expressed in the simple form

\[ Y_{SP} = \frac{0.01(C_{LPP})(Q)}{k_d} \]  

(3.59)

where \( Y_{SP} \) is the soluble P in kg ha\(^{-1} \) lost in runoff volume \( Q \) in mm, \( C_{LPP} \) is the concentration of soluble P in soil layer P in g\( \cdot \)t\(^{-1} \), and \( k_d \) is the P concentration in the sediment divided by that of the water in m\(^3\)t\(^{-1} \). The value of \( C_{LPP} \) is input to the model and remains constant. The value of \( k_d \) used in SWAT is 175.

Sediment transport of P is simulated with a loading function. The P loading function is

\[ Y_P = 0.01(Y)(C_P)(ER) \]  

(3.60)

where \( Y_P \) is the sediment phase of P loss in runoff in kg ha\(^{-1} \) and \( C_P \) is the concentration of P in the topsoil layer in g\( \cdot \)t\(^{-1} \).

The P mineralization model developed by Jones et al. (1984) is similar in structure to the N mineralization model. The P immobilization model, also developed by Jones et al. (1984), is similar in structure to the N immobilization model. The daily amount of immobilization is computed by subtracting the amount of P contained in the crop residue from the amount assimilated by the microorganisms.

3.6.5 Crop Growth Model

The crop model is a simplification of the EPIC crop model (Williams et al., 1984). SWAT uses EPIC concepts of phenological crop development based on daily accumulated heat units, harvest index for partitioning grain yield, Monteith's approach
(Monteith, 1977) for potential biomass, and water and temperature stress adjustments. However, the detailed EPIC root growth and nutrient cycling models are not included. A single model is used for simulating all the crops considered SWAT is capable of simulating crop growth for both annual and perennial plants. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop.

Phenological development of the crop is based on daily heat unit accumulation. It is computed using the equation:

\[
HU_i = \left(\frac{T_{mx,i} + T_{mn,i}}{2}\right) - T_b, \quad HU_i \geq 0
\]  

(3.61)

where \( HU \), \( T_{mx} \) and \( T_{mn} \) are the values of heat units, maximum temperature, and minimum temperature in °C on day \( i \) and \( T_b \) is the crop-specific base temperature in °C (no growth occurs at or below \( T_b \)) of crop \( j \). A heat unit index (HUI) ranging from 0 at planting to 1 at physiological maturity is computed as follows:

\[
HUI_i = \frac{\sum_{k=1}^{i} HU_i}{PHU_j}
\]

(3.62)

where \( HUI \) is the heat unit index for day \( i \) and \( PHU \) is the potential heat units required for maturity of crop \( j \). The value of \( PHU \) is calculated by the model from normal planting and harvest dates.

3.6.5.1 Potential Growth

Interception of solar radiation is estimated with Beer's law equation (Monsi and Saeki, 1953)

\[
PAR_i = 0.02092 (RA_i) \left[1 - \exp\left(-6.05 LAI_i\right)\right]
\]

(3.63)
where $\text{PAR}$ is photosynthetically active radiation in MJm$^{-2}$, $RA$ is solar radiation in Laly, LAI is the leaf area index, and subscript $i$ is the day of the year. Using Monteith's approach (Monteith, 1977), potential increase in biomass for a day can be estimated with the equation:

$$\Delta B_{pi} = (BE_i)(\text{PAR}_i)$$

(3.64)

where $B_p$ is the daily potential increase in total biomass in kg ha$^{-1}$ and $BE$ is the crop parameter for converting energy to biomass in kg m$^{-2}$ ha$^{-1}$ MJ. Potential biomass is adjusted daily due to stresses caused by water, nutrients and temperature.

LAI is simulated as a function of heat units and biomass. LAI is estimated with the equations:

$$LAI_i = \frac{(LAI_{mx})(B_{AG})}{B_{AG} + \exp(9.5 - 0.0006 \cdot B_{AG})}, \quad HUI_i \leq DLAI$$

(3.65)

$$LAI_i = (16)(LAI_{mx})(1 - HUI_i)^2, \quad HUI_i > DLAI$$

(3.66)

where $LAI_{mx}$ is the maximum LAI potential for the crop, $B_{AG}$ is above ground biomass (kg ha$^{-1}$), and $DLAI$ is the fraction of the growing season when LAI starts declining ($\approx 0.75$).

The fraction of total biomass partitioned to the root system normally decreases from 0.3 to 0.5 in the seedling to 0.05 to 0.20 at maturity (Jones, 1985). The model estimates the root fraction to range linearly from 0.4 at emergence to 0.2 at maturity. Thus, the daily root fraction is computed with the equation:

$$RTW_i = (0.4 - 0.2 \cdot HUI_i)$$

(3.67)

where $RTW$ is the fraction of total biomass partitioned to the root system on day $i$. Thus, $B_{AG}$ is calculated from the equation:
where \( B_{TO} \) is total biomass in kg ha\(^{-1} \) on day \( i \).

### 3.6.5.2 Crop Yield

Crops have a variety of mechanisms, which insure that their production is neither too great to be supported by the vegetative components nor too small to insure survival of the species. As a result, harvest index (economic yield/above-ground biomass) is often a relatively stable value across a range of environmental conditions.

Crop yield is estimated using the harvest index concept.

\[
YLD_i = (HI_i) (B_{AO})
\] (3.69)

where \( YLD \) is the amount of the crop removed from the field in kg ha\(^{-1} \), \( HI \) is the harvest index at harvest, and \( B_{AO} \) is the aboveground biomass in kg ha\(^{-1} \) for crop \( j \). Harvest index increases non-linearly from zero at planting using the equation:

\[
HIA_i = HIO_j \left( HUFH_i - HUFH_{i-1} \right)
\] (3.70)

where \( HIA \) is the harvest index on day \( i \), \( HIO \) is the harvest index under favourable growing conditions, and \( HUFH \) is the heat unit factor that affects harvest index on day \( i \) and on the previous day \( i-1 \).

The harvest index heat unit is computed with the equation:

\[
HUFH_i = \frac{HUI_i}{HUI_i + \exp(6.50 - 10.0 HUI_i)}
\] (3.71)

The constants in equation (3.71) are set to allow \( HUFH \) to increase from 0.1 at \( HUI = 0.5 \) to 0.92 at \( HUI = 0.9 \).
Most grain crops are particularly sensitive to water stress from shortly before until shortly after anthesis, when major yield components are determined (Doorenbos and Kassam, 1979). An optimum condition for growth may reduce harvest index slightly if dry matter accumulation is large and economic yield is limited by sink size. The harvest index is affected by water stress using the equation:

\[ HIA_i = \frac{HIA_i}{1 + (WSYF_i)(FHU_i)(0.9 - WS_i)} \]  

(3.72)

where \( HIA \) is the adjusted harvest index, \( WSYF \) is a crop parameter expressing drought sensitivity, \( FHU \) is a function of crop stage, and \( WS \) is the water stress factor for day \( i \). Notice that harvest index may increase slightly on days with \( WS \) values greater than 0.9. The crop stage factor, \( FHU \), is estimated with the equation:

\[ FHU_i = \sin \left( \frac{\pi}{2} \left( \frac{HUI_i - 0.3}{0.3} \right) \right), \quad 0.3 \leq HUI_i \leq 0.9 \]

(3.73)

\[ FHU_i = 0, \quad HUI < 0.3 \text{ or } HUI > 0.9 \]

Thus, water stress only affects harvest index between 0.3 and 0.9 of maturity with the greatest effect occurring at 0.6.

### 3.6.6 Agricultural Management

The agricultural management component provides submodels that simulate tillage systems, application of irrigation water, fertilizer and pesticides and grazing systems.

#### 3.6.6.1 Tillage

The SWAT tillage component is designed to incorporate surface residue into the soil. The user inputs the day of the tillage operation and selects the tillage implement from the database (over 100 implements are listed and each implement has an associate mixing efficiency).
\[ RSD = RSD_0 (1 - EF) \] (3.74)

where \( RSD_0 \) is the residue on the surface before tillage, \( RSD \) is the residue after tillage, and \( EF \) is the mixing efficiency. Once the residue is incorporated, it has no impact on the model. Also, no adjustments are made to bulk density due to tillage.

### 3.6.6.2 Fertilization

Fertilizer applications can also be scheduled by the user or automatically applied by the model. The user-scheduled option requires the user to input the application date, total amount of N and P, fraction of organic and inorganic N and P, and the soil layer of application. The model adds the amount of fertilizer to the proper nutrient pool (organic and inorganic) and to the specified soil layer. The automatic fertilization option requires the user to input the plant nitrogen stress level (0-1) to trigger fertilization, the amount of NO\(_3\) in the soil profile after fertilization, the soil layer of the application, the maximum amount of NO\(_3\) that can be applied in one year, and the minimum time between fertilizer applications.

When the plant N stress level reaches the specified trigger level, the model automatically applies fertilizer to the NO\(_3\) storage of the specified soil layer to bring the entire profile to the specified level.

\[ ANO3 = FNMX - \sum_{i=1}^{nl} WNO3_i \] (3.75)

\[ WNO3_{jl} = WNO3_{jl} + ANO3 \] (3.76)

where \( ANO3 \) is the amount of NO\(_3\) applied, \( FNMX \) is the amount of NO\(_3\) in the soil after fertilization, \( nl \) is the number of soil layers, and \( jl \) is the soil layer of the application. Organic N is also added according the amount of NO\(_3\) applied and the fraction of organic N (input).
\[ ON = ON + AN03 \left( \frac{forn}{1 - forn} \right) \] (3.77)

where \( forn \) is the fraction of organic N in the total N application (0-1). Automatic P fertilization also occurs when the N stresses level is reached. The user inputs a low, medium, or high level of P management and the model automatically restores the upper two soil layers to 10, 20, and 30 ppm of soluble P, respectively. Organic P is added like organic N in the previous equation.

3.6.6.3 Irrigation

SWAT users have the option to simulate dry land or irrigated agricultural areas. The user-scheduled option requires the user to input application dates, amounts, and application efficiencies. Irrigation water is added to fill the upper layer to field capacity and then added to fill the successive lower layers to field capacity until all of the water is applied. If automatic irrigation is specified, the user must input the application efficiency and a plant water stress level to trigger irrigation. The plant water stress factor ranges from 0 to 1.0 (1 means no stress and 0 means no growth) and is in the Crop Growth section. When the user-specified stress level is reached, water is applied according to the equation:

\[ AIR = FC - FW \frac{1 - EFI}{1 - EFI} \] (3.78)

where \( FC \) is the root zone field capacity in mm, \( SW \) is the root zone water content before irrigation in mm, \( EFI \) is the efficiency ratio, and \( AIR \) is the volume of irrigation water applied in mm.

3.6.6.4 Pesticide Applications

The user inputs the pesticide number, the date, and the amount of pesticide applied. The user must also input the application efficiency factor to account for losses to the atmosphere. The amount of pesticide reaching the ground (added to the upper soil layer) and the amount intercepted by plants is computed as a function of LAI.
3.6.6.5 Grazing

Livestock grazing is simulated as a daily harvest operation. Users specify a daily grazing rate in kg·ha$^{-1}$ and the date grazing begins and ends.

$$B_{AG} = D_{AG} - BMEAT$$

(3.79)

where $BMEAT$ is the daily amount of biomass removed by livestock in kg·ha$^{-1}$.

3.6.6.6 Heat Unit Scheduling

In addition to specifying an exact date of an operation or application, the user can schedule an operation or application using heat units. If an operation is scheduled before a crop is planted, heat units are accumulated from January 1 with a base temperature of zero.

$$HUSC = \sum_{k=1}^{t} \frac{HU_k}{PHUY}$$

(3.80)

where $HUSC$ are the accumulated base zero heat units, $HU_k$ are the heat units on day $k$, $PHUY$ are the total heat units for the year with a base temperature of zero. Average monthly maximum and minimum temperatures are used to estimate $PHUY$ at the beginning of simulation.

$$PHUY = \frac{12}{n-1} \left( \frac{T_{mx,m} + T_{mn,m}}{2} \right)$$

(3.81)

When $HUSC$ exceeds the user-specified heat units, the operation occurs. After a crop is planted, heat units are reset to zero and are then computed as a function of the crop's base temperature and the heat units required for maturation (according to equations (3.61) and (3.62)). $PHU$ is allowed to accumulate after maturity ($PHU>1$). For example, harvest may be scheduled at 1.2, which occurs after the plant reaches maturity.
3.6.6.7 Biomass and Harvest Index Override

The biomass and harvest index override provides the user the flexibility to set biomass and yield at a specified level. The model disregards all environmental stress and forces the above ground biomass override that is specified by the user.

\[ \Delta B_{p,j} = \Delta B_{p,i} \left( \frac{B_{AGT} - B_{AG}}{B_{AGT}} \right) \]  

(3.82)

where \( B_{AGT} \) is the target above ground biomass in kg ha\(^{-1}\). The harvest index override is then multiplied by the above ground biomass at harvest to estimate crop yield.

\[ YLD_j = (HIT_j)(B_{AG}) \]  

(3.83)

where \( HIT \) is the target harvest index for crop \( j \).

3.7 ROUTING COMPONENT

3.7.1 Channel Flood Routing

Reach routing operates on a daily time step and requires no iteration. This makes the model efficient enough for long-term simulations (50-100 years) on large basins. Also, the need for detailed channel cross-section data has been eliminated. Channel input includes the reach length, channel slope, channel depth, channel top width, channel side slope, flood plain slope, channel "n", and flood plain "n". Flow rate and average velocity are calculated using Manning's equation. Travel time is computed by dividing channel length by velocity. These calculations are computed for full channel depth and a depth of 0.1 times the full depth.

\[ TT = \chi_1 qr^{\chi_2} \]  

(3.84)

where \( TT \) is the travel time in h, \( qr \) is the flow rate in m\(^3\)h\(^{-1}\), and \( \chi_1 \) and \( \chi_2 \) are parameters determined for each reach when flow is within the channel.
The procedure is repeated for a depth of 1.5 times the full depth. When the flow rate exceeds full channel depth during routing, the relationship becomes

\[ TT = \chi_3 qr^{2\lambda} \]  

(3.85)

where \( \chi_3 \) and \( \chi_4 \) are parameters determined for each reach when flow exceeds full channel flow.

The storage coefficient, \( SC \), is estimated using the equations (Williams and Hann, 1973):

\[ SC = \frac{48}{2TT + 24} \]  

(3.86)

Outflow from the reach is determined by

\[ O_j = SC \left( I_j + S_{j-1} \right) \]  

(3.87)

where \( O \) is outflow in \( m^3 \), \( I \) is inflow in \( m^3 \), and \( S_{j-1} \) is storage in the reach from the previous day in \( m^3 \). Outflow is then adjusted for transmission losses, evaporation, diversions, and return flow.

Storage in the reach is calculated from the balance equation:

\[ S_j = S_{j-1} + I_j - O_j - TL - EV + dv + rt \]  

(3.88)

where \( TL \) is channel transmission losses in \( m^3 \), \( EV \) is evaporation in \( m^3 \), \( dv \) is diversions in \( m^3 \), and \( rt \) is return flow in \( m^3 \).
3.7.2 Transmission Losses

Many semiarid watersheds have alluvial channels that abstract large quantities of streamflow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volumes and peak rates as the flood wave travels downstream. Transmission losses are estimated with the equation:

\[ t_l = (k)(DUR)(wp)(CHL) \]  

(3.89)

where \( t_l \) is channel transmission losses in \( m^3 \), \( k \) is the effective hydraulic conductivity of the channel alluvium in \( mh^{-1} \), \( DUR \) is the flow duration in h, \( wp \) is the wetted perimeter in m, and \( CHL \) is the channel length in m.

A short cut method is also developed to determine \( wp \) for a given flow rate to eliminate the need for iteration. Again, a non-linear relationship was used.

\[ wp = 1.02q_p^{0.565} \]  

(3.90)

The parameters values (1.02 and 0.565) are determined by running several hypothetical channels for various flow depths.

3.7.3 Evaporation Losses

The volume of water in the reach lost to evaporation is

\[ ev = \eta (ev_p)(sa_{rch})(DUR) \]  

(3.91)

where \( \eta \) is an evaporation coefficient, \( ev_p \) is potential evapotranspiration in \( mh^{-1} \), \( sa_{rch} \) is the surface area of the reach in \( m^2 \), and \( DUR \) is the flow duration in hour. The surface area is simply:

\[ sa_{rch} = (CHL)(w) \]  

(3.92)

where \( CHL \) is the channel length and \( w \) is the channel width at flow depth.
3.7.4 Impoundment Routing

This component of SWAT is designed to account for the effects of reservoirs, farm ponds, and wetlands on water yield. The relationships used to estimate evaporation and seepage are identical for all three types of impoundment. The water balance equation is

\[ VM = VM_0 + QI - QO - EV - SEP \]  

(3.93)

where \( VM_0 \) is the volume of the water stored in all impoundment within a subbasin at the beginning of the day, \( VM \) is the volume at the end of the day, \( QI \) is the inflow during the day, \( QO \) is the outflow, \( EV \) is the evaporation, \( SEP \) is the seepage, and all units are \( m^3 \). The inflow, \( QI \) is composed of surface runoff from the total impoundment drainage area and rainfall on the water surface area.

The evaporation is computed with the equation:

\[ EV = 10(\eta)(E_a)(SA) \]  

(3.94)

where \( \eta \) is an evaporation coefficient (0.6) and \( SA \) is the surface area of the impoundment.

Seepage from the impoundment is computed with the equation:

\[ SEP = 240(SC)(SA) \]  

(3.95)

where \( SC \) is the saturated conductivity of the impoundment bed in \( mm \cdot h^{-1} \).

Surface area can be calculated with the equation:

\[ SA = \omega_1 VM^n \]  

(3.96)
where $\omega_1$ is a parameter ($1.3 \times 10^{-4}$) and $\omega_2$ is a fairly constant parameter (0.9). The SWAT model assumes $\omega_2 = 0.9$ and determines $\omega_1$ for each subbasin using $SA_{nx}$ and $VM_{mx}$.

For larger reservoirs, the method for estimating $\omega_1$ and $\omega_2$ is slightly different. Since the surface areas and volumes for the principal and emergency spillway crest elevations are generally readily available, those values can be used for a simultaneous solution of equation (3.96). The resulting equations are

$$\omega_2 = \frac{\log SA_F - \log SA_S}{\log VR_F - \log VR_S}$$  \hspace{1cm} (3.97)

$$\omega_1 = \frac{SA_F}{VR^{\omega_2}}$$  \hspace{1cm} (3.98)

where $SA$ is the reservoir surface area and subscripts $F$ and $S$ refer to emergency and principal spillway crest elevations, respectively.

Although the relationships used to estimate evaporation and seepage are identical for all impoundment, methods for determining outflow vary considerably. Wetlands may not have outflow. Farm ponds have only permanent pool storage, while small flood control reservoirs have principal and emergency spillway volumes and surface areas with a given release rate at volumes above the principal spillway.

For farm ponds, outflow occurs when the volume exceeds the permanent pool storage capacity and is described with the equation:

$$Q_O = VM - VM_{nx}, \hspace{1cm} VM > VM_{nx}$$

$$Q_O = 0, \hspace{1cm} VM \leq VM_{nx}$$  \hspace{1cm} (3.99)

where $VM_{nx}$ is the maximum permanent pool storage of all ponds in the subbasin in $m^3$. 

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Although this component was mainly designed to simulate flow through small reservoirs, it can also be used on larger reservoirs. The reservoir water balance component is similar to the pond component except it allows flow from principal and emergency spillways. The reservoir outflow function is expressed in the equation:

\[
Q_{OR} = VR - VR_{E}, \quad VR > VR_{E}
\]

\[
Q_{OR} = (RR)(\Delta t), \quad VR_{E} < VR \leq VR_{F}
\]

\[
Q_{OR} = 0, \quad VR < VR_{E}
\]

where \(Q_{OR}\) is the daily outflow in \(m^3\), \(VR\) is the volume of water in the reservoir in \(m^3\), \(VR_{E}\) is the reservoir capacity at the emergency spillway crest in \(m^3\), \(RR\) is the principal spillway release rate in \(m^3s^{-1}\), and \(VR_{F}\) is the reservoir capacity at the principal spillway crest in \(m^3\).

For large, regulated flood control reservoirs, a simplistic approach is used to simulate outflows (Arnold et al., 1996), which tries to mimic general release rules that may be used by reservoir operators. Although the model cannot account for all decision criteria, it can realistically simulate major outflows and low flow periods.

Additional operation rules can be added to model specific reservoirs or reservoir systems. For this situation, the principal or normal spillway volume corresponds to maximum flood control reservation, while the emergency spillway volume corresponds to no flood control reservation. The model requires the beginning and ending month of the flood season. The model uses a target storage approach based on flood season and the hydrologic condition of the watershed.

\[
Q_{O} = \left(\frac{VR - VR_{T}}{ND_{T}}\right) + Q_{R_{mo}}, \quad VR > VR_{T}
\]

\[
Q_{O} = Q_{R_{mo}}, \quad VR < VR_{T}
\]
where $VR_T$ is the target storage in m$^3$, $ND_T$ are the number of days to return to the target storage, and $QR$ is the daily minimum reservoir release for month in m$^3$.

In the non-flood season, no flood control reservation is required, and the target storage is set at the emergency spillway volume. The flood control reservation for wet ground conditions (field capacity) is set at the maximum and for dry ground conditions (wilting point) the flood control reservation is set at one-half the maximum.

$$VR_T = VR_s + 0.5(1-SWF)VR_s - VR_f$$  \hspace{1cm} (3.103)$$

where $SWF$ is the soil water factor and is defined with the equation:

$$SWF = \frac{SW_w}{f_{cw}}$$  \hspace{1cm} (3.104)$$

where $SW_w$ is the soil water content in mm and $f_{cw}$ is the field capacity of the watershed drainage area in mm.

### 3.7.5 Channel Sediment Routing

The sediment routing model consists of two components operating simultaneously (deposition and degradation). Deposition in the stream channel is based on the fall velocity of the sediment particles (Arnold et al., 1990). With a temperature of $22^\circ C$ and a sediment density of $1.2$ t·m$^3$, Stokes' Law for fall velocity becomes

$$V_f = 411(d^2)$$  \hspace{1cm} (3.105)$$

where $V_f$ is the fall velocity in m·h$^{-1}$ and $d$ is the sediment particle diameter.

The depth ($y_f$) that sediment of particle size $d$ will fall during time, $TT$, is

$$y_f = (V_f)(TT)$$  \hspace{1cm} (3.106)$$
The sediment delivery ratio (DR) through the reach is estimated with the equations:

\[
DR = \frac{1 - 0.5y_f}{d_q} \quad y_f \leq d_q
\]  
(3.107)

\[
DR = \frac{0.5(d_q)}{y_f} \quad y_f > d_q
\]  
(3.108)

where \(d_q\) is the depth of flow.

Finally, deposition is calculated with the equation:

\[
DEP = SED_{in}(1 - DR)
\]  
(3.109)

Stream power is used to predict degradation in the routing reaches. Williams (1980) used Bagnold's (1977) definition of stream power to develop a method for determining degradation in channels. Bagnold defined stream power, \(SP\), with the equation:

\[
SP = \gamma q_s S_w
\]  
(3.110)

where \(\gamma\) is the density of the water, \(q\) is the flow rate, and \(S_w\) is the water surface slope. By applying stream power to bed load predictions (Bagnold, 1977) and estimating model parameters (Williams, 1980), the equation for sediment reentrained, \(DEG_{in}\), is

\[
DEG_{in} = \alpha_p \gamma^{1.5} (dur) (w) (d_q S_w V_e)^{1.5}
\]  
(3.111)

where \(\alpha_p\) is a parameter dependent on maximum stream power for the reach and \(V_e\) is the velocity in the channel.
The parameter \( \alpha_{a,p} \) can be estimated with the equation:

\[
\alpha_{a,p} = (y_q S_{c_m})^{0.5} \tag{3.112}
\]

where \( S_{c} \) is the slope of the channel and the subscript \( m_x \) refers to the maximum flow expected in the reach for extreme events. The value of \( q \) is assumed to equal some maximum rainfall intensity (250 mm/hr) and \( \alpha_{a,p} \) becomes

\[
\alpha_{a,p} = (69.44 y DAS_{m})^{-0.5} \tag{3.113}
\]

where \( D_A \) is the drainage area into the reach in km².

All of the stream power is used for reentrainment of loose and deposited material until all of the material has been removed. When this occurs, degradation of the bed material, \( DEG_B \), begins and is calculated by

\[
DEG_B = K C DEG_R \tag{3.114}
\]

where \( K \) and \( C \) are MUSLE (Williams and Berndt, 1977) factors for the stream channel. Total degradation, \( DEG \), is the sum of the reentrainment and bed degradation components. This amount is also allowed to be redepositing before reaching the basin outlet.

\[
DEG = (DEG_R + DEG_P)(1 - DR) \tag{3.115}
\]

Finally, the amount of sediment reaching the basin outlet, \( SED_{out} \), is

\[
SED_{out} = SED_{in} - DEP + DEG \tag{3.116}
\]

where \( SED_{in} \) is the sediment entering the reach.
3.7.6 Nutrient Routing

3.7.6.1 Nitrate

Once NO$_3$-N enters a stream it is considered a conservative material for the duration of an individual runoff event (Williams, 1980). Thus, NO$_3$-N routing is simply a matter of adding the yields from all subbasins to determine the basin yield.

3.7.6.2 Organic N Routing

The loading function approach is also used in routing organic N from the subbasin outlets to the basin outlet.

$$YON_B = 0.01\left(Y_b \right)_j \left(CONSB \right)_j \left(ER_R \right)_j$$  \hspace{1cm} (3.117)

where $YON_B$ is the organic N runoff loss at the basin outlet in kg ha$^{-1}$, $Y_b$ is the sediment yield reaching the basin outlet from subbasin $j$ in t ha$^{-1}$, $CONSB$ is the concentration of organic N in the sediment reaching the subbasin $j$ outlet in g t$^{-1}$, and $ER_R$ is the enrichment ratio for the channel routing from subbasin $j$ to the channel outlet.

The delivery ratio for the channel routing calculated from

$$DR = \frac{\left(Y_{sb} \right)_j}{\left(Y_B \right)_j}$$  \hspace{1cm} (3.118)

where $Y_{sb}$ is the sediment yield at the subbasin outlet in t ha$^{-1}$, and $Y_B$ is that sediment yield from subbasin $j$ after it has been routed to the basin outlet in t ha$^{-1}$.

3.7.6.3 Soluble P Routing

As with NO$_3$-N routing, once soluble P enters a stream it is considered a conservative material and routing is accomplished by adding the yields from all subbasins to determine the basin yield.
3.7.6.4 P Routing

Again, the loading function approach is used in routing P from the subbasin outlets to the basin outlet.

\[ YP_q = 0.01(\gamma_j)(C_{PSB})(ER_p) \]  \hspace{1cm} (3.119)

where \( YP_q \) is the P yield at the basin outlet in kg ha\(^{-1}\), and \( C_{PSB} \) is the P concentration in the sediment reaching the subbasin \( j \) outlet in g t\(^{-1}\).

3.7.6.5 Pesticide

Soluble pesticide in runoff is considered conservative in the stream channels and no decay or volatilization is considered. Absorbed pesticides are allowed to be deposit if sediment deposition occurs. The delivery ratio approach used for nutrient routing is also used for adsorbed pesticides in the stream channel.

3.8 CONCLUDING REMARK

In this Chapter the description of study area, SWAT model and its features, model merits and its limitations are discussed. Different types of data relating to SWAT model like, meteorological data, hydrological data, topographic and soil data, satellite data are collected for further processing. Also the brief description of different components and the mathematical relationships used to simulate the processes and their interactions in the model. In the Chapter to follow all the collected data has been processed for the model and utilized as input parameters for the model.