A GIS-based variable source area hydrology model

Jane R. Frankenberger\textsuperscript{1}, Erin S. Brooks\textsuperscript{2}, M. Todd Walter\textsuperscript{2*}, Michael F. Walter\textsuperscript{3}
and Tammo S. Steenhuis\textsuperscript{3}

\textsuperscript{1}Assistant Professor, Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907-1146
\textsuperscript{2}Research Associate, Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853-5701
\textsuperscript{3}Professor, Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853-5701

Abstract:

Effective control of nonpoint source pollution from contaminants transported by runoff requires information about the source areas of surface runoff. Variable source hydrology is widely recognized by hydrologists, yet few methods exist for identifying the saturated areas that generate most runoff in humid regions. The Soil Moisture Routing model is a daily water balance model that simulates the hydrology for watersheds with shallow sloping soils. The model combines elevation, soil, and land use data within the geographic information system GRASS, and predicts the spatial distribution of soil moisture, evapotranspiration, saturation-excess overland flow (i.e., surface runoff), and interflow throughout a watershed. The model was applied to a 170 hectare watershed in the Catskills region of New York State and observed stream flow hydrographs and soil moisture measurements were compared to model predictions. Stream flow prediction during non-winter periods generally agreed with measured flow resulting in an average $R^2$ of 0.73, a standard error of 0.01 m$^3$/s, and an average Nash-Sutcliffe efficiency $R^2$ of 0.62. Soil moisture predictions showed trends similar to observations with errors on the order of the standard error of measurements. The model results were most accurate for non-winter conditions. The model is currently used for making management decisions for reducing non-point source pollution from manure spread fields in the Catskill watersheds which supply New York City’s drinking water. Copyright © 1999 John Wiley & Sons, Ltd.

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INTRODUCTION

An important watershed management strategy for controlling nonpoint source pollution is to minimize pollutant loading on runoff source areas; therefore, there is considerable need to accurately identify variable source areas. Saturated areas, which expand and contract seasonally, as well as during individual storms, have been shown to be the most important source areas of surface runoff in humid, well-vegetated areas (Dunne and Black, 1970; Hewlett and Nutter, 1970; Dunne, 1978). The term \textit{variable source areas} has been adopted for referring to these saturated areas which often form where subsurface lateral flow converges, where the slope changes, or where depth to the restricting layer decreases.

Simple lumped models or hydrograph analysis can be used to estimate the percent of the total watershed area that produces surface runoff. For example, Steenhuis \textit{et al.} (1995) presented a method consistent with the SCS curve number approach to predict the portion of a watershed contributing to runoff in shallow sloping soils.

\* Correspondence to: M. Todd Walter, Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853-5701, USA.

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In order to predict the spatial pattern of variable source areas, however, a distributed approach is needed. Many distributed, physically based models require large amounts of data and calibration, and have given mixed results (Bernier, 1985; Beven, 1989; Grayson et al., 1992; Wigmosta et al., 1994). Grayson et al. (1992) concluded that although complex process-based models are useful in research, models used for management decisions should be simple and unpretentious, with few data requirements and clearly stated assumptions.

One example of a simpler model which accounts for spatial variability is TOPMODEL (Beven and Kirkby, 1979; Beven, 1986), a semi-distributed model which falls between fully lumped and fully distributed models. TOPMODEL lumped hydrologically similar portions of a watershed based on a topographic index, \( \ln(a/\tan \beta) \), where ‘a’ is the up slope contributing area per unit length of contour and \( \tan \beta \) is the local slope. Assumptions of steady state soil moisture distribution and an exponential decline in saturated conductivity with depth are necessary for relating moisture content (or deficit) to the topographic-soil index. The first assumption of steady state conditions, meaning that the entire potential subsurface contributing area contributes to flow, has been shown by Burling et al. (1994) to be a limitation. The second assumption, that soil conductivities decline exponentially with depth, may not be appropriate in shallow soils where saturation arises from perched water tables above a restricting layer, rather than a water table underlying the entire watershed. TOPMODEL has no mechanism for predicting these 'subsurface infiltration excess' processes (Beven et al., 1994).

Although TOPMODEL provides some insight into spatial variability of runoff source areas, the inherent problems discussed above limit its applicability to watersheds which are hydrologically characterised by steep, shallow soils above a restricting layer. However, as an additional note, TOPMODEL is computationally very efficient due to its assumption of hydrologic similarity among areas with the same topographic index. This results in short model runtimes which can be an attractive feature. Nevertheless, faster computers and the widespread availability of digital geographic data, including elevation and soils, make the computational simplicity of lumped and semi-distributed models less advantageous.

The Soil Moisture Routing model (SMR), described here, is a simple distributed water balance model run on a daily time step, which predicts daily saturation-excess overland flow occurring at any point in a watershed. SMR’s simplicity allows a physical modelling basis without over parameterisation. SMR’s modest input requirements include: digital elevation data, soil parameters, and land use data for a distributed estimation of evapotranspiration and Hortonian flow. SMR was developed with the objective of aiding management decisions in potential runoff source areas of watersheds with steep hills and shallow soils. It was also equipped with routines for simulating the hydrologic impacts of diversions and subsurface drainage, two common water management practices. For applicability purposes, the model was designed to utilise readily available data and require essentially no calibration.

SMR development was initiated by a lack of reasonably parameterised, distributed models which could adequately describe the hydrology of the Catskills region of New York State. Interest in the area’s hydrology is acute due to the potential of contamination of New York City’s water supply reservoirs from agricultural non-point source pollution. SMR was developed specifically for topographically steep areas hydrologically characterised by relatively thin, permeable soil layers over a much less permeable fragipan, bedrock, or other restricting layer. This description is typical of upland soils in the glaciated region of New York State as well as many other places in the United States where a fragipan or bedrock limits root growth and water movement. The model is most effective where slopes are steep enough to be the main cause of lateral flow. SMR application is limited to regions fitting the description discussed above and should not be viewed as a general or universal hydrology model.

**SOIL MOISTURE ROUTING MODEL OVERVIEW**

The Soil Moisture Routing model is based on a hydrologic model for shallow soils of Steenhuis et al. (1986), adapted into the geographic information system (GIS), GRASS (U.S. Army CERL, 1991), by Caraco (1992) and Zolliweg (1994) who used a similar model to predict stream flow event hydrographs.
The model is 'tightly coupled' with the GIS (Stuart and Stocks, 1993), which means that it is written as a sequence of commands within GRASS. This coupling with a GIS simplifies data input and model calculations, as well as providing an efficient way to display and manipulate results. It also makes the processes clear for the user to understand and modify for different conditions. GRASS was chosen because it is public domain, widely available, and runs within the UNIX operating system on a variety of platforms. We have used the model on a SUN SPARC station as well as Linux running on a 386DX and Pentium PC.

SMR is based on a water balance at each time step for each cell of the watershed. Cells are typically of dimension 10 m to 30 m, so each square kilometer of watershed area is divided into 1100 to 10 000 cells, easily manipulated by the GIS. Soil moisture content for each cell is predicted, and any moisture above saturation results in surface runoff. Water inputs to each cell are daily precipitation and lateral flow from uphill cells, and outputs are lateral flow to downhill cells, percolation into the bedrock, evapotranspiration, and surface runoff (Figure 1). The calculations of the water balance and its individual elements are described later.

Below the soil layer is bedrock, which is often highly fractured. Since there is little hydrologic information concerning the bedrock, distributed modeling of percolated water is not feasible. In the model, water draining vertically out of the soil layer simply enters an uncharacterised 'bedrock reservoir', which eventually resurfaces as springs. Because the natural evolution of the landscape typically concentrates these springs near streams, the flow contribution from the bedrock reservoir is base flow for the stream. This base flow is assumed not to affect variable source areas. Though this assumption may be erroneous for some areas, especially near perennial streams, SMR is generally applicable to upland areas fitting the introductory hydrologic description. A lumped linear reservoir model, rather than a distributed model, is used to characterise the bedrock reservoir.

To predict variable runoff source areas, the input requirements for SMR are modest: elevation, soil, and land use maps (digital), six soil parameters, and three daily weather parameters: precipitation, potential evapotranspiration, and average air temperature. The six soil parameters are: depth to restrictive layer, type of restrictive layer (fragipan, bedrock, or impervious), saturated hydraulic conductivity, saturated moisture...
content, field capacity, and percent rock fragments. The land use map divides land uses among five categories: forest, grass, cropland, water, and farmstead. SMR uses the elevation map to estimate all topographic parameters, i.e., slope and flow direction. If stream flow estimates are desired, the only additional parameter needed is a linear bedrock reservoir coefficient to predict base flow. SMR automatically uses a coefficient based on the Catskills hydrology if a better estimate is not available. The effects of tiles and diversions may be incorporated into SMR simply by providing a digital map indicating the locations of these practices in a watershed.

**Water balance**

The water balance is calculated for each grid cell. GIS helps facilitate the water balance by providing a computational platform which simplifies the code for large array calculations. GIS stores input parameters such as soil data, slope, and flow direction for each cell. Soil moisture, for each cell, is updated for each time step using only simple GIS commands; for each cell:

\[
D_i \frac{d\theta_i}{dt} = P - ET_i + \frac{\Sigma Q_{in,i}}{A} - \Sigma Q_{out,i} - L_i - R_i
\]

where: \(i\) = cell address; \(D_i\) = depth to restrictive layer of the cell, (m); \(\theta_i\) = average moisture content of the cell, (m³/m³); \(P\) = precipitation (rain + snowmelt), (m); \(ET_i\) = actual evapotranspiration, (m); \(Q_{in,i}\) = lateral inflow from surrounding upslope cells, (m³); \(Q_{out,i}\) = lateral outflow to surrounding downslope cells, (m³); \(L_i\) = leakage out of the surface soil layer to bedrock, (m); \(R_i\) = surface runoff, (m); \(A\) = area of a cell, (m²).

These model components will each be examined in detail in the following sections. The model is run on a daily time step, a compromise between precision and speed for the model objectives of predicting variable source areas.

**Precipitation**

Precipitation consists of rainfall and snowmelt. Saturated hydraulic conductivities of soils in humid areas are generally higher than rainfall intensities, so all rainfall is assumed to infiltrate unless the soil is saturated or the area is disturbed or compacted.

When complete snow data is unavailable (depth and density), precipitation that occurs when the mean daily temperature is below 0°C is assumed to be snow, and remains in the snowpack until the mean daily temperature is above 0°C. A simple temperature index method is used to estimate snowmelt:

\[
M = m_i T + k_p, \quad \text{if } T > 0°C
\]

where: \(M\) = snowmelt (cm/day); \(T\) = average daily temperature (°C); \(m_i, k_p\) = melt factor (cm °C⁻¹ day⁻¹) and constant (cm/day) respectively. The snowmelt factor, \(m_i\), is 0.23 cm °C⁻¹ day⁻¹ in forested areas and 0.27 cm °C⁻¹ day⁻¹ in non-forested areas, while the constant, \(k_p\), is 0 cm/day in forested areas and 1.22 cm/day in non-forested areas (U.S. Army Corps of Engineers, 1960).

**Evapotranspiration**

Evapotranspiration is calculated for each cell using the relationship developed by Thornthwaite and Mather (1955) as a function of daily potential evapotranspiration, vegetation and stage of growth, and moisture content in the cell:

\[
ET_i = \begin{cases} 
    c_i PET \left( \frac{\theta_i - \theta_{wp}}{\theta_{fc,i} - \theta_{wp}} \right) & \text{for: } \theta_i < \theta_{fc,i} \\
    c_i PET & \text{for: } \theta_i \geq \theta_{fc,i}
\end{cases}
\]

where: PET = potential evapotranspiration, (m); \( c_i \) = a vegetation coefficient from Jensen (1973), which varies throughout the year depending on vegetation type which is determined by land use class; land use in SMR; \( \theta_{fc,i} \) = moisture content at field capacity as defined in the next section, (m\(^3\)/m\(^3\)); \( \theta_{wp,i} \) = moisture content at wilting point (m\(^3\)/m\(^3\)); \( \theta_i \) = average soil moisture content of cell \( i \), (m\(^3\)/m\(^3\)).

The actual evapotranspiration varies linearly between PET, when soil moisture content is at or above field capacity, and zero when soil moisture is below the wilting point. Determination of field capacity is discussed in the next section.

Subsurface lateral flow

Shallow subsurface lateral flow, or interflow, is a key component in the water balance. Lateral flow causes some areas, such as regions with convergent topographies, to be wetter than others, which often leads to the formation of saturated runoff source areas. The GIS, GRASS, is a convenient computational platform for routing subsurface lateral flow. Though subsurface lateral flow out of one cell and into an adjacent cell are physically coupled processes, SMR approximates each independently. The quantity of lateral flow leaving each cell is calculated and this flow is divided among all downhill neighbours as described below.

The quantity of lateral flow out of each cell is calculated from Darcy’s Law and the kinematic approximation; i.e. the hydraulic gradient is equal to the land slope at each cell:

\[
Q_{out,i} = w K_i D_i \left( \frac{dh}{dL} \right)_i
\]

(4)

where: \( Q_{out,i} \) = lateral flow out of cell \( i \), (m\(^3\)/d); \( (dh/dL)_i \) = land slope of cell \( i \), (m/m); \( w \) = width of each cell, (m); \( K_i \) = hydraulic conductivity of the soil profile, (m/day); \( D_i \) = depth to restrictive layer, (m). The hydraulic conductivity, \( K_i \), is dependent on soil moisture content, \( \theta_i \).

Because of the restricting layer at shallow depth, significant vertical water movement stops when the soil at the deepest part of the profile (i.e. directly above the restricting layer) becomes unsaturated. Field capacity of the soil layer above the restrictive layer is therefore defined as the average profile moisture content when the soil is just saturated at the fragipan interface (Steenhuis et al., 1988). When soil moisture is above field capacity, a saturated layer of thickness \( D_i (\theta_s - \theta_i)/ (\theta_s - \theta_{fc,i}) \) forms and the effective conductivity of the soil profile is:

\[
K_i = (K_s - K(\theta_{fc,i})) \left( \frac{\theta_i - \theta_{fc,i}}{\theta_s - \theta_{fc,i}} \right) + K(\theta_{fc,i}) \quad \text{for:} \quad \theta_s \geq \theta_i > \theta_{fc}
\]

(5)

where: \( \theta_{fc,i} \) = moisture content at field capacity as defined above, (m\(^3\)/m\(^3\)); \( \theta_i \) = soil moisture content for cell \( i \), (m\(^3\)/m\(^3\)); \( K_s \) = saturated hydraulic conductivity, (m/day); \( K(\theta_{fc,i}) \) = soil hydraulic conductivity at a field capacity, (m/day), (calculated with Equation (6) for \( \theta = \theta_{fc,i} \)).

If the average moisture content of the soil profile is less than field capacity, \( \theta_{fc,i} \), the effective hydraulic conductivity is the unsaturated conductivity, \( K(\theta) \). Based on the average moisture content of the profile, \( \theta \), unsaturated hydraulic conductivity is calculated using an exponential relationship:

\[
K(\theta) = K_i \exp \left[ \frac{\theta - \theta_i}{\theta_s - \theta_i} \right] \quad \text{for:} \quad \theta \leq \theta_{fc}
\]

(6)

where: \( \theta_i \) = residual moisture content, (m\(^3\)/m\(^3\)); \( \theta_s \) = saturated moisture content (assumed equal to porosity), (m\(^3\)/m\(^3\)); \( \theta_i \) = soil moisture content, (m\(^3\)/m\(^3\)); \( \alpha \) = a universal constant equal to 13 (Bresler et al., 1978; Steenhuis and Van der Molen, 1986).

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Each cell, potentially, has eight neighbouring cells. Lateral flow is divided among all neighbouring cells that are downhill from a particular cell. Allowing flow to divide into multiple flowpaths is particularly important in areas where topography may diverge. Some automatic drainage path algorithms route all downslope flow to one neighbouring cell, even though there may be two descending directions of equal slope (Tribe, 1992). This tends to lead to downslope accumulation of moisture into channels or gullies much more quickly than is actually seen in the field. Quinn et al. (1991) showed that TOPMODEL gave a more realistic prediction of wetness distribution when multiple flowpaths were allowed. The multiple flowpath division allocates to each neighbour a portion of the total flow, depending on the elevation difference between it and cell \( i \), as well as on the distance between the cells. For any downslope neighbour \( j \) of cell \( i \):

\[
P_j = \frac{(Z_i - Z_j)/L_j}{\sum_{j=1}^{n}((Z_i - Z_j)/L_j)} \quad \text{for: } Z_i > Z_j
\]

where: \( P_j \) = the portion of the total flow out of cell \( i \) that is routed to neighbour \( j \); \( Z_i, Z_j \) = elevations of cell \( i \) and its downslope neighbour \( j \), respectively; \( L_j \) = the distance from the center point of cell \( i \) to neighbour \( j \); \( n \) = the number of downslope neighbours of cell \( i \) (\( n \leq 8 \)).

**Leakage out of the root zone layer**

If a saturated layer is present, water can percolate into fractures or cracks in the bedrock or fragipan. An 'effective conductivity' of the bedrock and fragipan is specified which limits the rate at which water can leak out of the root zone. The bedrock in the Catskills is highly fractured. Flow takes place through the fractures in the bedrock and, to a lesser degree, in the dense fragipan (Soren, 1963). Though values vary widely, literature provides estimates of fragipan and bedrock conductivities (Theil and Bornstein, 1965; McCarty, 1980; Dabney and Selim, 1987; Smith and Wheeler, 1993). Typical reported fragipan conductivities range between 0.1 and 7 mm/day; SMR uses a value of 1 mm/day which is equal to the geometric mean of the extremes. Similarly, the SMR effective bedrock conductivity is 2 mm/day which is within the range of reported conductivities for bedrock similar in composition to the Catskills.

If the SMR is used to predict stream flow, an estimate must be made of flow from the bedrock reservoir into the stream for each time step. Since little is known about the bedrock, the simple concept of a linear reservoir is used to estimate discharge. The reservoir coefficient is found from recession portions of stream flow hydrographs. Based on 168 recession events from three sub-basins in the Catskills' Cannonsville watershed over ten years, the SMR linear reservoir coefficient is 0.1 day\(^{-1}\) (mean \( r^2 = 0.96 \)) (Weiler, 1997).

**Artificial drainage and compacted areas**

The hydrologic impacts of diversions, tile drains, and ditches, common features on farms, can be simulated by SMR. These human-caused changes to the natural drainage may have a significant impact on watershed output and soil moisture distribution, particularly in locations adjacent to the drain. Although diversions are often constructed for the purpose of intercepting surface runoff in shallow soils, channels, as well as subsurface drains, intercept subsurface lateral flow from uphill. Lateral flow is assumed to be completely intercepted by the diversion or drain, and flow downslope starts as if there were a new watershed. Runoff from diversions and flow from tiles are summed over the watershed each day and added to daily stream flow.

Disturbed or compacted areas of the farm may generate Hortonian or infiltration-excess overland flow and are modeled by SMR as impermeable areas with surface detention storage as estimated by Miner (1967). These areas may include barnyards, other parts of farmsteads, or intensively cropped fields where infiltration has been reduced by growing continuous row crops or other poor field practices.
APPLICATION TO A SMALL WATERSHED

Location, climate, and land use

The model was tested on the Crowe Road Watershed, located in the northern Catskills region of the Appalachian plateau physiographic province. It has generally shallow soils and rolling topography, typical of upland watersheds in the region. Elevation in the 170 hectare watershed ranges from 580 to 732 m. The main stream draining the Crowe Road Watershed is an unnamed tributary of Wright Brook, which flows into the west branch of the Delaware River. This stream has been gauged since 1993 by the New York State Department of Environmental Conservation. A total of 23 months of 10 minute stream flow data were available. Average stream flow during the monitoring period was 0.030 m³/s, with flows ranging from 0 to 0.5 m³/s. Watershed location, elevation, and the main stream and pond can be seen in Figure 2.

The climate can be characterised as northern humid continental. The latitude is approximately 42°30' North. Average yearly temperature is 8°C, with cold winters and warm summers. Average annual precipitation is 1123 mm and yearly stream flow for streams in the region averages 600 mm. Precipitation generally exceeds potential evapotranspiration except for four months in the growing season.

The entire watershed is owned by dairy farmers although, due to an abundance of steep rocky upper slopes with very shallow soil, more than 65% is forested. The lower slopes are mainly rotated corn and hay, with 2% in corn and 20% in hay during the 1994 growing season. The wetter, rockier areas are primarily permanent pasture (10% of the watershed). The remaining area is the farmstead (0.7%) and pond (0.8%). Land use for the watershed can be seen in Figure 3.

Geology and soils

The bedrock is of sedimentary origin, consisting of flat fractured layers of sandstone, siltstone, and shale (Soren, 1963). Glaciers have modified the landscape, rounding and smoothing the hills and depositing glacial till through much of the valley. Till, an unsorted mixture of particle sizes deposited by the glaciers, is the parent material for most soils in the watershed. Soil is generally very thin on hilltops and upper slopes, while in the lower slopes have deeper soils. A dense, brittle fragipan is found at a shallow depth in much of this area, roughly parallel to the land slope and relatively impervious to water. Soils have formed fairly recently in the glacial till, all soils being classified as inceptisols or entisols. The surface layer of most soils in the watershed is shallow and permeable, with a high percentage of rock fragments. Roughly half of the watershed consists of soils that overlie fractured bedrock and are well drained, while half overlie a dense fragipan layer and often have perched water tables during wet periods. A complete description of soils is given in Frankenberger (1996). Soils of the watershed can be found in Figure 4.

Soil data interpretation

Input data for the model were primarily obtained from the soil survey and other published literature and supplemented with field measurements. Although soil surveys are the best data source generally available, they were not developed with hydrologic modeling as an objective and, therefore, the parameters that determine soil moisture flow are not those that are emphasised in the soil survey (McKeague et al., 1984; Bouna, 1986; Soil Survey Staff, 1993). Depth and nature of the restricting layer were obtained from the typical pedon for that series in the soil survey and the volume occupied by rock fragments was obtained from the midpoint of the estimated range. Soil types and values used are shown in Figure 4 and Table I. Saturated conductivity, saturated moisture content (approximately soil porosity), and field capacity were obtained from field measurements. Using the auger hole method, the average measured saturated hydraulic conductivity was 2 m/day, somewhat higher than the permeability range of the soil survey (0.4 to 1.2 m/day for all soils). The differences are probably due to macropores which are not taken into account in the soil survey data. Porosity averaged 0.6 cm³/cm³ without rocks, and 0.45 cm³/cm³ when rock fragments were included. Field capacity, measured on soils draining to bedrock at a depth of 70 cm after a period of low rainfall.
in January, averaged 0.37 cm³/cm³ without rocks and 0.28 cm³/cm³ when rocks were included. Field capacity was assumed to vary linearly with depth to the restricting layer in other soils.

Weather data

The weather data needed by SMR are: daily precipitation, potential evapotranspiration, and average temperature. Precipitation was measured every 10 minutes with two recording gauges at the watershed outlet by the New York State Department of Environmental Conservation, and aggregated into daily values. During the growing season, pan evaporation was measured at a site approximately 30 km away and potential evapotranspiration was estimated from pan evaporation multiplied by a pan factor of 0.8. During the rest of the year, no local pan evaporation data was available so potential evapotranspiration was
approximated from Hamon's (1961) method of calculating potential evapotranspiration which utilises potential hours of sunshine (from basic astronomical relationships) and saturated water vapor density at the daily mean temperature (from a psychrometric chart). Temperature was measured every 10 minutes near the watershed outlet after 8 December, 1993 and, before 8 December temperature was measured at a site 15 km from the watershed.
Results and Discussion

A comparison between observed and predicted runoff source areas throughout the watershed would be the ideal demonstration of its adequacy. Unfortunately, making this comparison is technologically very complicated due to difficulty in identifying and monitoring source areas. In lieu of methods for comparing predicted and observed runoff source areas, comparisons between measurements and predictions for integrated outflow and distributed soil moisture along a transect were used to confirm SMR. While not ideal, the combination of these comparisons gives good insight into SMR's adequacy as a variable source hydrology model.

Integrated results: stream flow

Although predicting hydrographs is not the primary objective of SMR, stream flow integrates hydrologic response from across the watershed and, can therefore, be used in assessing the overall predictions of the model. Hydrograph generation was based on daily stream flow, which is the sum of surface runoff generated anywhere in the watershed, subsurface lateral flow into the stream, diversions, or tile drains, and a portion of the water stored in the bedrock reservoir each day. Figure 5 shows predicted vs. measured stream flow for 1993 and 1994 and Table II summarises statistical comparisons. Winter and summer results are segregated to isolate snow and other winter-time factors.

From Figure 5, predictions show good visual agreement with measured flow trends during periods without snowmelt. The Nash-Sutcliffe efficiency $R^2$ (Nash and Sutcliffe, 1970) were 0.59 and 0.64 for daily stream flow during summer 1993 (23 June to 30 November, 1993) and summer 1994 (1 May to 15 November, 1994), respectively. In other words, SMR predicted measured values 59% and 64% better than simply using the average stream flow value during these periods. The average correlation coefficient, $r^2$, for the summer periods was 0.73. Considering the absence of any major calibration, this correlation is good. Comparing the mean, maximum, and minimum stream flows also shows good statistical agreement between predicted and measured stream flows (Table II). During the summer, the standard error was about one order of magnitude less than the range of measured stream flows, indicating good predicted stream flow. One way to investigate

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Figure 5. Predicted and measured streamflow with Nash-Sutcliffe efficiency for summer 1993, winter 1994, and summer 1994.
Figure 2. Watershed location and topography

- 580-620 m
- 621-640 m
- 641-680 m
- 681-732 m
primary soil types, and two main land uses (cropland and pasture). The area upslope of the transect was forest.

A summary of statistical comparisons between predicted and measured soil moisture along the transect is presented in Table III. The sampling transect had considerable spatial variability in topography and, consequently, in moisture content under wet conditions. Steeper areas became much drier than flat areas when conditions were wet enough for a saturated layer to form over the bedrock or fragipan (6 May, 1994 and 18 January, 1995), while topography had little effect during drier times (28 October, 1994). The model correctly predicted the general pattern of soil moisture, particularly the increase in soil moisture from the top to the bottom of the slope. 6 May, 1994 showed particularly good agreement in downslope wetting; SMR simulated a 31% increase from 330 m to the bottom of the slope which was relatively close to the 26% increase measured (Figure 7). 28 October, 1994 showed the least statistical correlation between predicted and measured results because the total downslope change in measured soil moisture was only slightly higher than the standard error and almost all the change occurred in the bottom 30 m. The standard error gives a better indication of model and measurement agreement, 0.009 cm³/cm³, which is an order to magnitude lower than the measurement error.

Table III. Summary of soil moisture statistics: predicted vs. measured

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<th>Observed</th>
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<td>Min</td>
<td>Mean</td>
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<td>0.29</td>
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<tr>
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<td>0.34</td>
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</table>

Note: The units of Mean, Max, Min are cm³/cm³.
1Standard error of the predicted to measured soil moisture; cm³/cm³.
2Correlation coefficient between predicted soil moisture and the moving average of the measured soil moisture.
Table II. Summary of stream flow statistics: predicted vs. measured

<table>
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<th>Observed</th>
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<th></th>
<th>r^2(a)</th>
<th>sta(b)</th>
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<tbody>
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<td>Min</td>
<td>Mean</td>
<td>Max</td>
<td>Min</td>
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<tr>
<td>Winter 1994</td>
<td>0.068</td>
<td>0.35</td>
<td>0.011</td>
<td>0.061</td>
<td>0.052</td>
<td>0.008</td>
<td>0.54</td>
<td>0.049</td>
</tr>
<tr>
<td>Summer 1994</td>
<td>0.015</td>
<td>0.16</td>
<td>&lt;10^-3</td>
<td>0.014</td>
<td>0.18</td>
<td>0.002</td>
<td>0.66</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Note: The units of Mean, Max, Min are m^3/s.

a Correlation coefficient.
b Standard error of the predicted to measured stream flow; m^3/s.
c Nash-Sutcliffe efficiency R^2 (Nash and Sutcliffe, 1970).

The accuracy of SMR is to see if its stream flow predictions are comparable to other accepted models. Even though, as discussed earlier, TOPMODEL is overly simplified in many respects, it was used, after calibration, to simulate the summer 1994 stream flow. TOPMODEL predicted flow with an efficiency of 0.59, similar to, but somewhat worse than, SMR for the same period. The similarity of results is not surprising because the lateral flow components of the two models are based on the same assumptions.

As expected, winter-time stream flows were not predicted well due to the absence of soil frost simulation and an overly-simplified snowmelt model. The Nash-Sutcliffe efficiency was 0.50 for winter 1994 (November 1993 through April 1994). During winter conditions, errors in precipitation measurements, and in snowmelt especially, accentuated errors in stream flow predictions. An early or late prediction in snowmelt results in poor stream flow correlation on both the day of the erroneously simulated melt and the day of the actual melt. This problem can be seen in Figure 5 by comparing the period around day 82, when SMR badly over-estimated flow due to premature snowmelt in the simulation, to the period around day 98, when SMR under-predicted flow because of a melt event at the site. SMR might have predicted the snowmelt event around day 98 if it had not already predicted that all the snow melted around day 82.

Distributed results: soil moisture

Because the integrated output measured at the outlet of the watershed provides ambiguous information about the detailed hydrology within the watershed (Steenhuis et al., 1998), an effort was also made to assess distributed model predictions. Soil moisture, a state variable of the model which is updated at every time step, was measured in order to assess the distributed predictions of the model. During 1994 and 1995, soil moisture was sampled on sites representing a variety of soil types, land uses, and average moisture contents found in the watershed. Each cell's soil moisture was characterised by gravimetric sampling at three locations within the cell. For further details on sampling methods and results see Frankenberger (1996).

Due to variability within a 30 m² area, there is difficulty in characterising the soil moisture of a cell with a single value. In an attempt to account for this microvariability, two cells representing different moisture were sampled at thirteen locations and average soil moisture at each location was estimated by averaging. gravimetric soil moisture from two depths. The average standard deviation of measured soil moisture for the two cells was 0.07 cm³/cm³, representing both spatial variability and sampling error. Assuming 0.07 cm³/cm³ is a good approximation of the spatial variability of soil moisture content in a cell, 0.04 cm³/cm³ is the standard error of the mean obtained with three samples per cell. This provides some guidance in assessing the performance of SMR in predicting soil moisture, i.e., predictions within 0.04 cm³/cm³ are within errors in measured mean cell soil moisture.

Figure 6 shows predicted and measured soil moisture for all the samples throughout the watershed. The standard error was 0.044 cm³/cm³, approximately the same as the errors in measuring mean soil moisture for a cell. Figure 7 shows SMR predicted and measured soil moisture for three sampling dates along a transect: 6 May, 1994, was moderately wet; 28 October, 1994, relatively dry; and 18 January, 1995, was very wet (although the soil was not frozen). The transect ran uphill with a 14% average slope, intersected three
Figure 7. Predicted and measured soil moisture along a transect for three sampling dates: 6 May 1994 (wet), 28 October 1994 (dry), and 18 January 1995 (wet-winter). O = observed; △ = predicted with SMR; — = moving average of observations.
SMR also correctly predicted the observed dip in soil moisture between 204 m and 120 m from the slope bottom. On all three dates, the dip was evident in both the predicted and measured soil moistures, although the predicted results underestimated the magnitude of the dip. This may be due to scaling issues. Large cell sizes will tend to remain wetter because cell slope will decrease, thus decreasing the rate of subsurface lateral flow out of a cell (Kuo et al., 1998).

Some localised variations were not consistently predicted by SMR, such as the rapid change in moisture content between 90 m and 120 m. This observed trend may be due to a localised anomaly such as a ‘trench’ in the underlying bedrock or fragipan which, as McDonnel et al. (1996) showed, may have significant impacts on hydrologic predictions over small areas on the same order of magnitude as a SMR cell. In general, the SMR model predicted a smoother transition in soil moisture along the transect than was measured, although the standard error of predicted values for all three days were below the error in measured average cell moisture content, 0.04 cm$^3$/cm$^3$. Using a moving average to moderate the localised effects of microtopography on soil moisture gives good correlations, as shown in Figure 7 and Table III. 28 October 1994’s correlation coefficient, $r^2$, is low even with the moving average because, as stated earlier, changes in moisture content along the slope are on the same order as errors in measurement.

CONCLUSIONS

The widespread availability of digital geographic data, particularly digital elevation models, opens new opportunities for using distributed models in watershed planning. At the same time, variability of soils, as well as lack of subsurface data, makes the use of complex models unrealistic in the field. The Soil Moisture Routing model uses elevation, soil, and land use data in a simple way to estimate soil moisture and runoff in watersheds with shallow soils. Its use of GIS to keep track of all parameters and state variables makes it easy to use and modify for different conditions. Results from the integrated output (stream flow) and the distributed output (soil moisture) show that it adequately predicted stream flow (runoff) and soil moisture distribution in the Crowe Road Watershed.

Despite its promise for use as a management tool, many sources of uncertainty exist in SMR predictions. Beven and Binley (1992) have listed the sources of error in hydrologic models as: (1) deficiency of model structure, (2) input data or boundary condition error, and (3) error associated with measurements used in model calibration. Deficiencies in model structure include the simplification of soil moisture relationships, infiltrated precipitation instantaneously distributed through the soil profile, no re-infiltration of runoff generated upslope, deficient snowmelt algorithm, absence of soil frost model, and the simplification of the bedrock hydraulics. Uncertainty in input data is a large source of error in the model, however, we believe that the simplified structure of the model is in balance with the level of data available for most watersheds. The greatest source of uncertainty lies in measuring distributed hydrology in a way that allows for meaningful comparisons between predicted and measured values. Though it was only briefly discussed in this paper, scale issues may be a significant source of model error and are definitely an uncertainty at this point.

Although refinements and further research are needed, SMR, in its present form, has proved useful in assisting with management decisions in the Catskills region, such as location and timing of manure spreading on farms to minimise contamination of the New York City reservoirs. It is also being used to evaluate the most effective ‘best management practices’.

ACKNOWLEDGEMENTS

The authors thank the Robertson family for allowing us to sample on their farm, Mike Rafferty of the New York State Department of Environmental Conservation for streamflow data, and John Kick of the Natural Resources Conservation Service for GIS data.
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Chapter 12

HYDROLOGICAL SIMULATION PROGRAM - FORTRAN (HSPF)

A. S. Donigian, Jr.
B. R. Bicknell
J. C. Imhoff

12.1. INTRODUCTION

In the mid-1970's, the U.S. EPA Environmental Research Laboratory in Athens, Georgia was in the beginning stages of model development and testing efforts that focused on tools and procedures for quantifying nonpoint sources (NPS) of pollution. Initiated by legislative mandates that required assessment of both urban and agricultural NPS contaminants, the Laboratory was supporting development and field testing of mathematical models (along with companion data collection programs) to be used to estimate these NPS loadings and, ultimately, to evaluate potential management and control alternatives. However, EPA scientists realized that although these field-scale models could provide loading values, they alone would not be sufficient to evaluate water quality impacts at the larger watershed, or regional scale. Thus began an extensive, comprehensive watershed model development effort to integrate the field-scale models with instream hydraulic and water quality process models, within a flexible, modular framework, to allow continuous simulation of complex watersheds with multiple land uses, both point and nonpoint contaminant sources, networked channels and drainage patterns, and lakes and reservoirs. The HSPF model produced by this development effort has been applied throughout North America and numerous countries and climatic regimes around the world. It enjoys the joint sponsorship of both the U.S. Environmental Protection Agency and the U.S. Geological Survey, and continues to undergo refinement and enhancement of its component simulation capabilities along with user support and code maintenance activities.

In this chapter we provide an overview of the HSPF model, along with background on its historical development, current ongoing and planned enhancements, selected examples of model applications to demonstrate the
12.1. Overview

The Hydrological Simulation Program-FORTRAN, known as HSPF, is a mathematical model developed under EPA sponsorship for use on digital computers to simulate hydrologic and water quality processes in natural and man-made water systems. It is an analytical tool with application in the planning, design, and operation of water resources systems. The model enables the use of probabilistic analysis in the fields of hydrology and water quality management. HSPF uses such information as the time history of rainfall, temperature, evaporation, and parameters related to land use patterns, soil characteristics, and agricultural practices to simulate the processes that occur in a watershed. The initial result of an HSPF simulation is a time history of the quantity and quality of water transported over the land surface and through various soil zones down to the groundwater aquifers. Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other quality constituent concentrations can be predicted. The model uses these results and stream channel information to simulate instream processes. From this information, HSPF produces a time history of water quantity and quality at any point in the watershed.

HSPF is a valuable tool to water resource planners. Because it is more comprehensive than most systems, it permits effective planning. Benefits to the user include:

- Flexibility in solving a wide range of water quantity and quality problems using a single model
- Convenient data management features that save time and money
- Modular program structure which facilitates program changes and additions for special applications

HSPF is currently one of the most comprehensive and flexible models of watershed hydrology and water quality available. It is the only available model that can simulate the continuous, dynamic event, or steady-state behavior of both hydrologic/hydraulic and water quality processes in a watershed, with an integrated linkage of surface, soil, and stream processes. The model is also unusual in its ability to represent the hydrologic regimes of a wide variety of streams and rivers with reasonable accuracy. It has been applied to such diverse climatic regimes as the tropical rain forests of the Caribbean, arid conditions of Saudi Arabia and the Southwestern U.S., the humid Eastern U.S. and Europe, and snow covered regions of Eastern Canada. The potential applications and uses of the model are comparatively large including:

- Flood control planning and operations
- Hydropower studies
- River basin and watershed planning
- Storm drainage analyses
- Water quality planning and management
- Point and nonpoint source pollution analyses
- Soil erosion and sediment transport studies
- Evaluation of urban and agricultural best management practices (BMPs)
- Fate, transport, exposure assessment, and control of pesticides, nutrients, and toxic substances
- Time-series data storage, analysis, and display

HSPF is designed so that it can be applied to most watersheds using existing meteorologic and hydrologic data; soils and topographic information; and land use, drainage, and system (physical and man-made) characteristics. The inputs required by HSPF are not different than those needed by most other simpler models. The primary difference in data needs is that long, rather than short time-series records are preferred. Typical long time-series records include precipitation, waste discharges, and calibrations data such as streamflow and constituent concentrations.

12.1.2. Background

HSPF is an extension and improvement of three previously developed models: 1) The EPA Agricultural Runoff Management Model - ARM (Donigian and Davis, 1978), 2) The EPA Nonpoint Source Runoff Model - NPS (Donigian and Crawford, 1979), and 3) The Hydrologic Simulation Program (HSP), including HSP Quality (Hydrocomp, 1977), a privately-developed proprietary program. In the late 70's EPA recognized that the continuous simulation approach contained in these models would be valuable in solving many complex water resource problems. Thus, a fairly large investment was devoted to developing a highly flexible non-proprietary FORTRAN program which contains the capabilities of these three models, plus many extensions.
HSPF incorporates the field-scale ARM and NPS models into a watershed-scale analysis framework that includes the capabilities needed to model fate and transport in one-dimensional stream channels. It is the only comprehensive model of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with instream hydraulic and sediment-chemical interactions.

HSPF was first released publicly in 1980, as Release No. 5 (Johanson et al., 1980), by the U.S. EPA Water Quality Modeling Center (now the Center for Exposure Assessment Modeling); since its initial release, the model has maintained a reputation as perhaps the most useful watershed-scale hydrology/water quality model that is available within the public domain. Fig. 12.1 is a timeline of the development activities of HSPF and its predecessor models beginning about 1971 and extending through the current time. The development of HSPF in the late 1970's represented an integration of a variety of EPA-sponsored model development and testing efforts associated with the ARM and NPS models, and the WEST (Watershed Erosion and Sediment Transport) model (Leytham and Johanson, 1979); the basic watershed modeling approach embodied in HSPF was chosen, a highly modular code design and structure was developed, and all the individual models were redesigned and recoded into FORTRAN to make the resulting package widely useable and available to potential model users.

Throughout the 1980's and early 1990's, HSPF underwent a series of code and algorithm enhancements producing a continuing succession of new releases of the code, culminating in the recent release of Version No. 10 in 1993 (Bicknell et al., 1993). Table 12.1 lists some of the key enhancements and changes for the various HSPF releases since 1980, along with a preview of potential enhancements expected for the next release (Version No. 11) in the 1994-95 time period. The capabilities and changes for the various versions are discussed as part of the model capabilities overview in Section 12.2.

Since 1981, the U.S. Geological Survey has been developing software tools to facilitate watershed modeling by providing interactive capabilities for model input development, data storage and data analysis, and model output analysis including hydrologic calibration assistance. The ANNIE, WDM, Scenario Generator, and HSPEXP designations in Fig. 12.1 are USGS products that have greatly advanced and facilitated watershed model applications, not only for HSPF but also for many other USGS models. For example, the WDM (Watershed Data Management) file has effectively replaced the Time Series Store (TSS) file used in the earlier versions of HSPF due to the expanded data analysis and graphical capabilities of the ANNIE software (Lumb et al., 1990). These products are discussed in greater detail in Section 12.3.

HSPF applications since its initial release in 1980 have been world-wide and number in the hundreds; on the order of 50 current active applications...
# Historical Progression of HSFP Releases

<table>
<thead>
<tr>
<th>Year</th>
<th>Version</th>
<th>Comments/Enhancements</th>
<th>Document</th>
</tr>
</thead>
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<tr>
<td>1980</td>
<td>5</td>
<td>Initial public release</td>
<td>Johnson et al. (1980)</td>
</tr>
<tr>
<td>1981</td>
<td>6</td>
<td>Performance and portability enhancements</td>
<td>Johnson et al. (1981)</td>
</tr>
<tr>
<td>1984</td>
<td>7</td>
<td>GQUAL-SED, TWIN, MUTSIN enhancements</td>
<td>Johnson et al. (1984)</td>
</tr>
<tr>
<td>1988</td>
<td>8</td>
<td>WDM implementation</td>
<td>CEAM publication</td>
</tr>
<tr>
<td>1993</td>
<td>9</td>
<td>Special Actions enhancements</td>
<td>HSPF Rel. 10 Manual</td>
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<tr>
<td>1994</td>
<td>10</td>
<td>Sediment-nutrient interactions</td>
<td>DOE publication</td>
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<tr>
<td>1994(?)</td>
<td>11</td>
<td>Enhanced special actions</td>
<td>Updated documentation</td>
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**TABLE 12.1**

12.1.3. Chapter Contents

The purpose of this chapter is to provide a comprehensive overview of the HSFP, its development, and its applications. This chapter begins with an overview of the HSFP's history, including its development and evolution. The chapter then discusses the current status of the HSFP, including its application in various locations and the challenges and opportunities associated with its use. Finally, the chapter concludes with a discussion of the future of the HSFP and its potential for continued development and improvement.

The HSFP is a comprehensive hydrologic simulation program that is used to model the interaction of water, sediment, and nutrients in natural and urbanized watersheds. The program is designed to help researchers and managers understand and manage the impacts of human activities on water quality and quantity.

The HSFP is based on a series of model components that are linked together to form a comprehensive simulation system. The components include models for rainfall, runoff, infiltration, evapotranspiration, surface and groundwater flow, and nutrient and sediment transport.

The HSFP has been used in a variety of applications, including the assessment of the impacts of urban development on water quality, the evaluation of the effects of climate change on water resources, and the development of water management strategies.

The HSFP is a powerful tool for hydrologic analysis, but it also has limitations. These include the complexity of the models, the need for high-quality input data, and the potential for model errors.

The HSFP is an ongoing project, and it is expected to continue to evolve and improve as new data and technologies become available.
watershed scale, is leading to increased interest in model applications. To support this increased interest and potential usage, the final section identifies and explores areas of current model enhancements, and future research and model development. In addition to potential algorithm enhancements, we explore future needs for databases and user interaction capabilities that will be required to keep pace with changing software/hardware capabilities.

12.2. OVERVIEW OF CAPABILITIES

HSPF contains three application modules and five utility modules. The three application modules simulate the hydrologic/hydraulic and water quality components of the watershed. The utility modules are used to manipulate and analyze time-series data. Table 12.2 summarizes the constituents and capabilities of the HSPF modules. A brief description of each of the modules follows.

<table>
<thead>
<tr>
<th>Application Modules</th>
<th>Utility Modules</th>
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<tr>
<td>PERLND</td>
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<td>Plot data</td>
</tr>
<tr>
<td>Water</td>
<td>Data transfer</td>
</tr>
<tr>
<td>Sediment</td>
<td>DURANL</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>Duration</td>
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<tr>
<td>Quality</td>
<td>Analysis</td>
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<td>Pesticide</td>
<td>GENER</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>TRANSFORM or</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>COMBINE time</td>
</tr>
<tr>
<td>Tracer</td>
<td>SERIES data</td>
</tr>
<tr>
<td>Snow</td>
<td>RCHRES</td>
</tr>
<tr>
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<td>Hydraulics</td>
</tr>
<tr>
<td>Solids</td>
<td>Conservatives</td>
</tr>
<tr>
<td>Quality</td>
<td>Temperature</td>
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<td>Sediment</td>
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<td>Carbon/pH</td>
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<tr>
<td>Nitrogen</td>
<td>Radiation</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>plankton</td>
</tr>
<tr>
<td>Tracer</td>
<td>Tabulate, summarize</td>
</tr>
</tbody>
</table>

The three application modules within HSPF, and their primary functions are as follows:

1. PERLND - Simulates runoff and water quality constituents from pervious land areas in the watershed.
2. IMPLND - Simulates impervious land area runoff and water quality.
3. RCHRES - Simulates the movement of runoff water and its associated water quality constituents in stream channels and mixed reservoirs.

12.2.1. PERLND Module

As PERLND simulates the water quality and quantity processes that occur on pervious land areas, it is the most frequently used part of HSPF. To simulate these processes, PERLND models the movement of water along three paths: overland flow, interflow, and groundwater flow. Each of these three paths experiences differences in time delay and differences in interactions between water and its various dissolved constituents. A variety of storage zones are used to represent the processes which occur on the land surface and in the soil horizons. Snow accumulation and melt are also included in the PERLND module so that the complete range of physical processes affecting the generation of water and associated water quality constituents can be represented. Some of the many capabilities available in the PERLND module include the simulation of:

- water budget and runoff components
- snow accumulation and melt
- sediment production and removal
- nitrogen and phosphorus fate and runoff
- pesticide fate and runoff
- movement of a tracer chemical

Figure 12.2 defines the structure and contents of the PERLND module. The module features individual compartments for modeling air temperature as a function of elevation (ATEMP), snow accumulation and melting (SNOW), hydrologic water budget (PWATER), sediment production and removal (SEDMNT), soil temperature (PTEMP), surface runoff water temperature and gas concentrations (PWTGAS), generalized water quality constituents (PQUAL), solute transport (MSTLAV), pesticides (PEST), nitrate (NITR), phosphorous (PHOS), and conservatives (TRACER).
ATEMP modifies the input air temperature values from the weather station record assigned to each land segment to account for elevation differences between the station and the land segment. SNOW uses meteorologic data (precipitation, air temperature, solar radiation, dewpoint, wind movement) to determine whether precipitation is rain or snow, to simulate an energy balance for the snowpack, and to determine the effect of heat fluxes on the snowpack. A combination of physical and empirical formulations are used to model such processes, fluxes and variables as snowfall accumulation; snowpack dullness; snowpack compaction; pan evaporation; atmospheric heat exchange; snow, ice and water occurrence, and melt from ground heat.

PWTGAS estimates the water temperature for surface, shallow subsurface (interflow) and groundwater outflows. The temperature of each outflow is considered to be the same as the soil temperature of the layer from which it originates. PWTGAS also computes the dissolved oxygen and carbon dioxide concentrations of overland flow using empirical formulations; concentrations are assumed to be at saturation.

PQUAL simulates generalized water quality constituents in the outflows (surface and subsurface) from a pervious land segment using simple relationships with water and/or sediment yield. The behavior of a constituent in surface outflow is considered more complex and dynamic than...
the behavior in subsurface flow. The code allows quantities in surface outflow to be simulated by one, or both, of two methods. Either (1) a constituent can be modeled using "potency factors" to indicate constituent strength relative to the sediment removal computed by SEDMNT, or (2) storage of a constituent on the land surface can be modeled, considering accumulation and depletion/removal, and a first-order washoff rate of the available constituent can be removed by overland flow, as computed by PWATER. In addition, both formulations can be used for representing the washoff behavior of particulate and dissolved components of an specific pollutant.

The remaining five code compartments in PERLND are used together to model detailed behavior of soil nutrients (i.e. nitrogen and phosphorus) and non-reactive tracer chemicals (e.g. chloride). These five code sections have been referred to as the AGCHEM module because their primary use to date has been for modeling the mass balance and runoff of agricultural chemicals. MSTLAY estimates the storages and fluxes of moisture in the four soil layers -- surface, upper, lower, groundwater -- which define soil layers used by the remaining four code compartments. MSTLAY is required because the moisture storages and fluxes computed by PWATER must be modified to effectively simulate solute transport through the soil. Estimates of solute flux are computed based on the assumption that the concentration of solute being transported is the same as that for storage; uniform flow through the layers and continuous mixing of solutes is also assumed. Leaching retardation factors are computed to modify the solute fluxes from the top three soil layers based on user-defined model parameters.

PEST simulates pesticide behavior in the soil and runoff from pervious land segments in three forms: dissolved, adsorbed and crystallized. The PEST code utilizes time series data generated by other compartments of PERLND (i.e., PWATER, SEDMNT, MSTLAY) to compute transport (runoff and leaching), adsorption/desorption and degradation. Pesticide transport is modeled as a function of water flow and/or association with transported sediment. Chemicals in solution move to, through, and from storages according to the fractions calculated in MSTLAY. Computations are performed that compute the movement of adsorbed pesticide associated with removal of sediment from the surface layer via scour and washoff. Adsorption/desorption is a function of both chemical and soil layer characteristics; several options for characterizing sorption are offered, including a first-order kinetic approach and the use of two different Freundlich isotherm methods. Degradation from all processes is modeled as a lumped rate in each of the four soil layers.

The NITR code section simulates the transport and soil reactions of nitrate, ammonia and organic nitrogen. Figure 12.3 shows the nitrogen and phosphorus transformations performed by the NITR and PHOS code sections for each soil layer. Nitrogen species are transported by the same methods used for pesticides. Nitrate and dissolved ammonium are transported as a function of water flow; organic nitrogen and adsorbed ammonium are removed from the surface layer storage by association with sediment scour and washoff; nitrate and ammonium in the soil water are transported according to the fractions calculated in MSTLAY; and computations are performed that compute the movement of adsorbed organic nitrogen and ammonium associated with removal of sediment from

Fig. 12.3. Nutrient Transformations Simulated by the AGCHEM Module.
the topsoil surface layer. First-order kinetics or a Freundlich isotherm can be used to model adsorption/desorption. Nitrogen transformation processes (denitrification, nitrification, plant uptake, immobilization, mineralization) are modeled using temperature-corrected, first order kinetics with separate rate constants defined for each soil layer.

PHOS simulates the transport and reaction of phosphate and organic phosphorus using methods parallel to those used for nitrogen species in NITR. Transport mechanisms for phosphate parallel those modeled for ammonium, and those for organic phosphorus parallel organic nitrogen. Like ammonium, phosphate adsorption/desorption can be modeled using either first-order kinetics or a Freundlich isotherm. Phosphorus transformation processes (plant uptake, immobilization, mineralization) are modeled using temperature-corrected, first order kinetics with separate rate constants defined for each soil layer.

Typically, the TRACER code is applied to chloride (or bromide) to calibrate solute movement through the soil profile. This involves adjustment of leaching retardation factors until good agreement with observed soil chloride concentrations has been obtained. Once appropriate retardation values have been determined, they are used in PEST, NITR and PHOS to simulate solute transport.

12.2.2. IMPLND Module

IMPLND is used for impervious land surfaces, primarily for urban land categories, where little or no infiltration occurs. However, some land processes do occur, and water, solids, and various pollutants are removed from the land surface by moving laterally downslope to a pervious area, stream channel, or reservoir. IMPLND includes most of the pollutant washoff capabilities of the commonly used urban runoff models, such as the STORM, SWMM, and NPS models.

Figure 12.4 defines the structure and contents of the IMPLND module. The module shares much of its code with PERLND, but is simplified since infiltration and other interactions with the subsurface cannot occur. The module features individual compartments for modeling air temperature as a function of elevation (ATEMP), snow accumulation and melting (SNOW), hydrologic water budget (IWATER), solids accumulation and removal (SOLIDS), surface runoff water temperature and gas concentrations (IWGTGAS), and generalized water quality constituents (IQUAL). Since IMPLND is only used to model impervious areas, the code is not concerned with detailed simulation of agri-chemicals, and hence has no capabilities parallel to those contained in MSTLAY, PEST, NITR, PHOS or TRACER.
12.2.3. RCHRES Module

RCHRES is used to route runoff and water quality constituents simulated by PERLND and IMPLND through stream channel networks and reservoirs. The module simulates the processes that occur in a series of open or closed channel reaches or a completely mixed lake. Flow is modeled as unidirectional. A number of processes can be modeled, including:

- hydraulic behavior
- heat balance processes that determine water temperature
- inorganic sediment deposition, scour, and transport by particle size
- chemical partitioning, hydrolysis, volatilization, oxidation, biodegradation, and generalized first-order (e.g., radionuclides) decay, parent chemical/metabolite transformations
- DO and BOD balances
- inorganic nitrogen and phosphorus balances
- plankton populations
- pH, carbon dioxide, total inorganic carbon, and alkalinity

Figure 12.5 defines the structure and contents of the RCHRES module. The module features individual compartments for modeling hydraulics (HYDR), constituent advection (ADCALC), conservatives (CONS), water temperature (HTRCH), inorganic sediment (SEDDRN), generalized quality constituents (GQUAL), specific constituents involved in biochemical transformations (QUAL), and acid mine drainage phenomena (ACIDPH). Because the ACIDPH code section has not been fully field-tested, it is not a documented feature of Release 10 and is not shown in Fig. 12.5 (see Section 12.3.3).

HYDR simulates the processes that occur in a single reach of an open channel or a completely mixed lake. Hydraulic behavior is modeled using the kinematic wave assumption. All inflows to a reach are assumed to enter at a single upstream point. The outflow of a reach may be distributed across several targets that might represent normal outflows, diversions, and multiple gates of a reservoir. In HSPF, outflows can be represented by either, or both, of the methods:

1. Outflow can be modeled as a function of reach volume for situations where there is no control of flows or gate settings or only a function of water level.

2. Outflow can be modeled as a function of time to represent demands for municipal, industrial, or agricultural use. To do so, the modeler...
must provide a time series of outflow values for the outflow target
that is time-dependent and independent of reach volume.

If an outflow demand has both volume-dependent and time-dependent
components, the modeler can, and must, specify how the components are
combined to define the resulting outflow demand. HSPF allows the modeler
to define the resulting demand in one of three manners: (1) as the minimum
of the two components, (2) as the maximum of the two components, or (3)
as the sum of the two components.

HSPF makes no assumptions regarding the shape of a reach; however,
the following assumptions are made:

(1) There is a fixed, user-defined, relation between water depth, surface
area, volume, and discharge. This is specified in a Function Table
(or FTABLE) defined for each reach by the user.

(2) For any outflow demand with a volume-dependent component, the
relation between the above variables is constant in time. (This
assumption presumes modeling flow reversals.)

In addition to calculating outflow rates and reach water volumes, HYDR
computes the values for additional hydraulic parameters that are used in
the other code sections of RCHRES including depth, stage, surface area,
average depth, top width, hydraulic radius, bed shear stress and shear
velocity.

ADCALC calculates values for variables that are necessary to simulate
longitudinal advection of dissolved and entrained constituents. These
variables are all dependent upon the volume and outflow values computed in
the hydraulics compartment (HYDR). CONS simulates constituents which,
for all practical purpose, do not decay with time or leave the reach by any
other mechanism than advection. Typical constituents that are modeled as
conservatives include chlorides, total dissolved solids, and hydrophilic
chemicals which decay very slowly.

In HTRCH temperature is simulated using a heat-balance approach. Five
time series of meteorologic data are required to simulate the temperature
balance within a reach. These are solar radiation, cloud cover, air
temperature, dewpoint temperature and wind speed. HTRCH considers two
major processes: heat transfer by advection and heat transfer across the air-
water interface. Heat transfer by advection is accomplished by treating
water temperature as a thermal concentration, and using the standard
advection computations contained in CONS. The net transport of heat
across the air-water interface is computed as the sum of a number of
mechanisms, each of which is evaluated individually. Sources of heat that
are computed include absorption of shortwave solar radiation, absorption of

longwave radiation, and conduction-convection. Sinks of heat that are
computed are emission of longwave radiation, conduction-convection, and
evaporation.

The approach taken by the SEDTRN code compartment to compute
transport of channel sediment is based on the SERATRA model developed
by Battelle Laboratories (Onishi and Wise, 1979). Both noncohesive (sand)
and cohesive (silt, clay) sediments are simulated in SEDTRN; migration of
each sediment fraction between suspension in water and the bed is modeled
by balancing deposition and scour computations. The code allows the
modeler to compute the deposition or scour of noncohesive sediment by
selecting one of three empirical formulations:

(1) A user-defined power function of streamflow velocity,

(2) A relationship (Toffaleti method) dependent upon median sand
    particle diameter, average stream velocity, reach hydraulic radius,
    reach slope, settling velocity for sand (user-specified), and water
    temperature,

(3) A relationship (Colby method) dependent upon median sand
    particle diameter, average stream velocity, reach hydraulic radius,
    fine sediment load concentration, and water temperature.

The simulation of cohesive sediment transport consists of two steps.
First, advective transport is calculated; then deposition and scour is
calculated based on the calculated bed shear stress. To evaluate deposition,
the modeler is required to provide values for settling velocity and critical
shear stress for deposition for each fraction (silt, clay) of cohesive sediment
that is modeled. To evaluate resuspension, or scour, the modeler must
provide values for the erodibility coefficient and critical shear stress for
scour for each fraction.

The focus of the GQUAL code development was to allow simulation of
agricultural pesticides and other synthetic organic chemicals. Given the
diversity of pesticides that might be modeled, the code provides the user
with the capability to model any subset of the following generalized
processes: advection of dissolved material; decay of dissolved material by
hydrolysis, oxidation by free radical oxygen, photolysis, volatilization,
biodegradation, and/or generalized first-order decay; production of one
modeled constituent as a result of decay of another constituent; advection of
adsorbed suspended material; deposition and scour of adsorbed material; and
adsorption/desorption between dissolved and sediment-associated phases.
Using the GQUAL section in conjunction with the sediment transport code
(SEDTRN), adsorbed chemicals may settle or resuspend during each
simulation time step, depending on hydrodynamic conditions.
Decomposition of adsorbed chemicals may be simulated, both in suspended materials and in the bed, by using a first-order, temperature-corrected decay formulation.

The RQUAL code provides detailed simulation of constituents involved in biochemical transformations. Included are dissolved oxygen, BOD, ammonia, nitrite, nitrate, phosphate, phytoplankton, benthic algae, zooplankton, refractory organics, and pH. The primary dissolved oxygen and biochemical oxygen demand balances are simulated with provisions for decay, settling, benthal sinks and sources, reaeration, and sinks and sources related to plankton. The primary nitrogen balance is modeled as sequential reactions from ammonia through nitrate. Ammonia volatilization, ammonification, denitrification, and ammonium adsorption/desorption interactions with suspended sediment fractions are also considered. Both ammonium and phosphate adsorption/desorption to suspended sediment fractions are modeled using an equilibrium, linear isotherm approach. Both nitrogen and phosphorus species are considered in modeling three types of plankton—phytoplankton, attached algae and zooplankton. Phytoplankton processes that are modeled include growth, respiration, sinking, zooplankton predation, and death; zooplankton processes include growth, respiration and death; and benthic algae processes modeled are growth, respiration and death. Hydrogen ion activity (pH) can be calculated by two independent code sections. The first, named PHCARB, is contained within the RQUAL section and computes pH by considering carbon dioxide, total organic carbon and alkalinity. In doing so, the code considers the effects on the carbon dioxide-bicarbonate system of carbon dioxide invasion, zooplankton respiration, BOD decay, net growth of algae, and benthic releases.

ACIDPH is a general module for performing user-defined instream chemical computations. Its intended application is primarily to model acid mine drainage and acid rain affected waters, where the pH computations in the PHCARB module, which are based solely on carbonate system equilibria, cannot adequately represent the processes which determine pH (see Section 12.3.4 for further details).

### 12.2.4. Utility Modules

The five utility modules are used to access, manipulate, and analyze time series information stored in the user in HSPF’s TSS (Time Series Store) and WDM (Watershed Data Management) files. These time series, such as hourly precipitation, daily evaporation, daily streamflow, are used by the application modules and are often a valuable resource in the analysis of a watershed’s characteristics. The five utility modules and their functions are as follows:

1. **COPY** - Copies data in the TSS or WDM to another file. The user can change the time step of the time series during the COPY operation; for example, a five-minute rainfall record can be aggregated to an hourly time interval.

2. **PLTGEN** - Generates a specially formatted ASCII file for subsequent data display on a plotter, or input to other software.

3. **DISPLY** - Creates data display tables. Aggregated values, as well as summary information, can be generated.

4. **DURANL** - Performs frequency, duration, and excursion analyses; computes statistics; and performs toxicity/lethality analysis. DURANL can be used to answer such questions as: "How often does dissolved oxygen stay below 4 mg/l for 4 consecutive hours?"

5. **GENER** - Transforms one or two time series to produce a new, or different time series. GENER is a powerful tool that allows the user to perform any of 22 optional transformations (e.g., absolute value, truncation, division, logarithm).

### 12.3. RECENT IMPROVEMENTS

Recently Release 10.0 of HSPF (Bicknell et al., 1993) was published and made available through the U.S. EPA. This most current release of HSPF reflects recent improvements in database and input management, as well as improved algorithms for such processes as instream sediment-nutrient interactions and acid mine drainage. In addition to improvements to the batch version of HSPF, a stand-alone expert system for hydrologic calibration using the HSPF water budget computations in the PERLND module has been developed by the U.S. Geological Survey and made available to the public.

#### 12.3.1. ANNIE/WDM

The United States Geological Survey has sponsored the development of interactive pre- and post-processing capabilities to facilitate applications of HSPF and other hydrologic models. ANNIE (Lumb et al., 1990) is an interactive computer program written in FORTRAN and designed for portability to mainframe computers, minicomputers, and microcomputers (i.e., PCs and workstations). ANNIE helps users interactively store, retrieve, list, plot, check, and update spatial, parametric, and time-series data for hydrologic models and model analyses. A binary, direct-access file is used to store data in a logical, well-defined structure and is called a
12.3.3. Sediment-Nutrient Interactions

By the late 1980's, it became evident that the instream nutrient algorithms contained in the RQUAL module of Release 9.0 of HSPF had deficiencies that, under certain conditions, precluded effective modeling of nutrient loadings to endpoint receiving waters. Perhaps the process representation deficiency of greatest concern was the inability of HSPF to account for instream sediment-nutrient interactions such as adsorption/desorption and advection with sediment. To correct these model deficiencies, the EPA Chesapeake Bay Program sponsored a model enhancement project in 1990-1991.

The enhanced RQUAL module that resulted from the effort for the Chesapeake Bay Program is included in HSPF Release 10.0. The module now simulates the exchange of phosphate and ammonium between the dissolved state and adsorption on sediment suspended in the water column; adsorption/desorption in bed sediment is not modeled. The sorbents considered are the sand, silt and clay fractions of instream sediment that are simulated in the SEDTRN module. The adsorption/desorption process for each sediment fraction is represented with an equilibrium linear isotherm. The advective processes for phosphate and ammonium adsorbed to each sediment fraction are:

1. Inflow to the reach of nutrient attached to suspended sediment.
2. Migration from suspension to the bed as a result of deposition of the sediment to which the nutrient is adsorbed.
3. Migration from the bed into suspension as a result of scour of the bed sediments to which the nutrient is adsorbed.
4. Outflow from the reach of nutrient attached to suspended sediment.

The following modeling assumptions are used for inorganic nutrients in the bed:

1. The phosphate and ammonia storages in the bed are infinite as long as the bed sediment storage is non-zero.
2. Phosphate and ammonia that is deposited to the bed is assumed to be lost from the reach.
3. The scoured sediment is assumed to have a constant (user-specified) adsorbed concentration for each of the nutrients. Thus, the scoured nutrient fluxes are limited only by the storage of sediment in the bed.
These enhancements provide a more realistic means of representing phosphate and ammonia behavior in streams and lakes, and allowed a more accurate estimation of nutrient loadings, especially for phosphate, as part of the Chesapeake Bay HSPF application (discussed in Section 12.5.1).

12.3.4. Acid Mine Drainage

To address the needs within the USGS for modeling acid mine drainage from Pennsylvania coal mines, a new module, called ACIDPH, was designed and implemented in Release 10 of HSPF. ACIDPH is a general module for performing user-defined in-stream chemical computations. Its intended application is primarily to model acid mine drainage and acid rain affected waters, where the pH computations in the PHCARB module, which are based solely on carbonate system equilibria, cannot adequately represent the processes which determine pH.

The chemistry and methods used in the ACIDPH module were adapted from an earlier computer code called PHCALC (Gherini, 1984), and were specifically designed to represent the conditions exhibited by streams in the Pennsylvania coal mining regions. The code implemented in HSPF is comprised of computations that consider the effects on pH of aluminum and carbonate equilibria; extended alkalinity; and the possible effects of iron complexation and competition with aluminum. Three solution options were coded based on the PHCALC methods. These routines perform the following computations:

1. Compute pH and extended alkalinity assuming Gibbsite (Al(OH)_3) saturation; includes interactions from aluminum and ferric complexes of fluoride, sulfate, and water.

2. Compute pH and extended alkalinity assuming ferric hydroxide (Fe(OH)_3) saturation; includes interactions from aluminum and ferric complexes of fluoride, sulfate, and water.

3. Compute pH from alkalinity assuming saturation of Al^3+ and Fe^3+ complexes of fluoride, sulfate, and water.

ACIDPH simulates the following seven chemical species: total aluminum (Al^3+ and Al complexes), free Al^3+, total Fe (Fe^3+ and Fe complexes), free Fe^3+, H^+, total inorganic carbon, and alkalinity. The CONS section of HSPF is used to represent sulfate and fluoride.

To date, the ACIDPH module has had limited testing and use. Its only application has been performed in the district office of the USGS at Pittsburgh, Pennsylvania. The applicability of the module to other mine drainage areas is uncertain, and may require the user to develop customized, situation-specific algorithms within the HSPF framework; the module has been designed to accommodate this need with a minimum of programming effort. Due to the minimal field-testing of the module, ACIDPH is currently an undocumented feature in HSPF Version 10.

12.3.5. HSPEXP

A stand-alone version of the HSPF land surface hydrologic computations has been developed as an expert system for calibrating watershed models for drainage basins. The resulting product, called HSPEXP (Lamb and Kittle, 1993), represents an effort to make the knowledge of experienced surface hydrology modelers available to general model users. The knowledge consists of the statistical representation of the observed hydrograph in terms of the system parameters that drive the precipitation-runoff process. The estimation procedure consists of a set of hierarchical rules designed to guide the calibration of the model through a systematic evaluation of the model parameters.

To date, the system has been tested on watersheds in Washington and Maryland, and the developers report encouraging results. In each instance, the system correctly identified the model parameters to be adjusted and the adjustments led to an improved calibration. It is anticipated that HSPEXP will serve as a major component in future calibration efforts for watershed models.

12.4. MODEL DISTRIBUTION, MAINTENANCE EXPERIENCE, USER SUPPORT/TRAINING, SOFTWARE/HARDWARE ISSUES

Since its initial release in 1980, HSPF has undergone a number of corrections, revisions, and enhancements; more than 300 copies of the code have been distributed to users throughout the world. To enable the widespread use of a complex model that has continued to evolve over many years, various methods of user support have been provided by both private parties and government agencies. The purpose of this section is to identify model distribution requirements and to share our experiences over the past thirteen years in attempting to support model users and improve their HSPF modeling opportunities.

12.4.1. Model Distribution and Hardware Requirements

Over the years, general distribution of HSPF has been the responsibility of the U.S. EPA Environmental Research Laboratory in Athens, Georgia. The model distribution activities are carried out by the Center for Exposure
12.4.1. Support for Model Users

Although a few current model users have successfully applied HSPF without any formal training and little or no user assistance, most potential users will greatly benefit from attending a training workshop (discussed above) and will need some degree of application assistance or support. Thus, the U.S. EPA Center for Exposure Assessment Modeling (CEAM), and its predecessor, the EPA Water Quality Modeling Center, located in Athens, GA, has been the primary center for model distribution and user support activities for HSPF since its initial release. These activities have included code distribution, model updates, and limited phone consultation. Since about 1988, the U.S. Geological Survey’s Water Resources Division has provided support for both model enhancements and user assistance and has also sponsored workshops for providing HSPF application support. Currently, model support is limited to local state and federal workgroups, and phone consultations are available from CEAM.

12.4.2. Model Maintenance

Software maintenance of HSPF has been supported by the EPA Athens Laboratory,olic Laboratory, and since the late 1980's, cooperatively by the U.S. Geological Survey, Water Division. Since the initial release in 1980, almost all of the major enhancements have been performed by two firms: Anderson, Nichols, Inc. and its successor, AQUA Consultants. The maintenance activities have included maintaining a list of software errors, correcting errors, implementing improvements, adapting the code to new computer environments, providing authors and users with new versions to EPA and USGS for distribution to users.

12.4.3. Training Workshops

Workshops and seminars on the theory, structure, application, and operation of HSPF have been held on a periodic basis since 1981. These have included in-depth discussions sponsored by model developers and users, focusing on the new capabilities and case studies provided with HSPF. The U.S. EPA has also sponsored workshops (with EPA) on the past few years on HSPF, and has held annual training sessions over the past few years on HSPF. Workshops have covered a wide range of topics, including operational implementation, software capabilities and model operation, and had hands-on computer work sessions focusing on model quality control and certification. The U.S. Geological Survey has also sponsored and co-sponsored (with EPA) a number of training sessions focusing on the new capabilities and case studies provided with HSPF.
12.5. SELECTED APPLICATIONS

As was previously mentioned, applications of the HSPF model have numbered in the hundreds. Many applications have utilized a straightforward approach and a limited subset of the model's capabilities to evaluate watershed problems that require a continuous simulation approach. Other applications have featured more comprehensive and/or innovative approaches to using HSPF that demonstrate the power of the model and the breadth and complexity of problems to which it can be successfully applied. Five examples of such model applications are described briefly below.

12.5.1. Chesapeake Bay Watershed Model

The EPA Chesapeake Bay Program uses the HSPF model as the framework for the Chesapeake Bay Watershed Model to determine total watershed contributions of flow, sediment and nutrients (and associated constituents such as water temperature, DO, BOD, etc.) to the tidal region of the Chesapeake Bay (Donigian et al., 1986a; 1991). The Watershed Model represents pollutant contributions from an area of more than 68,000 sq. mi., and provides input to drive a fully dynamic three-dimensional, hydrodynamic/water quality model of the Bay. The watershed drainage area is divided into land segments and stream channel segments; the land areas modeled include forest, agricultural cropland (conventional tillage, conservation tillage, hay), pasture, urban (pervious and impervious areas), and uncontrolled animal waste contributions. The stream channel simulation includes flow routing and oxygen and nutrient biochemical modeling in order to account for instream processes affecting nutrient delivery to the Bay.

At the onset of the study, buildup/washoff type algorithms were used for urban impervious areas, potency factors for all pervious areas, and constant (or seasonally variable) concentrations for all subsurface contributions and animal waste components. Subsequently, detailed process (i.e. agri-chemical modules) simulation was performed for cropland areas to better represent the impacts of agricultural BMPs. The Watershed Model is currently being used to evaluate nutrient management alternatives for attaining a 40 percent reduction in nutrient loads delivered to the Bay, as defined in the 1987 Chesapeake Bay Agreement signed by the governors of the member states, the EPA Administrator, and the District of Columbia. Figure 12.6 shows the Watershed Model estimates of Total Nitrogen loads to the Chesapeake Bay from the major subbasins under a range of alternative scenarios or conditions, including base conditions for 1984-87, progress made through 1991, load reductions required by the Bay Agreement, 'limit of technology' controls on both point and nonpoint sources, and expected loads for the year 2000 conditions. This type of analysis is being used to evaluate both the feasibility of the 40% reduction goal, the nature of the controls required, and the distribution of the needed load reductions among the Bay tributaries and the member states.

![Fig. 12.6. Chesapeake TN Loads by Scenario.](image)

12.5.2 Patuxent River Study and Scenario Generator

The Maryland Department of the Environment is conducting a study of the Patuxent River to quantify nonpoint source contributions and evaluate alternative means of improving downstream water quality in the Patuxent River Estuary. The study includes a multi-year monitoring program that involves observations of runoff quality at both field size (single land use) locations and instream, multi-land use sites. HSPF is being applied to calculate nonpoint loadings from the forest, agriculture, and urban land areas of the watershed, and the instream water quality throughout the river system. The Patuxent is a microcosm of the larger Chesapeake Bay, a complex watershed with multiple land uses, point and nonpoint sources, and reservoirs draining to a tidal estuary. Like the larger Chesapeake Bay study, both simple and complex nonpoint runoff algorithms are being used to represent the various land uses and effects of potential management practices.
Use of HSPF for applications such as the Patuxent study has traditionally involved using a text editor to build a series of input sequences that describe the physical conditions resulting from various management alternatives or scenarios. Each of these input sequences might comprise thousands of lines, and hence, the process of making changes has been time consuming and complex. In order to facilitate the process of evaluating the likely effects of potential management decisions in the Patuxent basin, a scenario generator was developed. The scenario generator provides the modeler with the ability to change an input sequence, run HSPF, and view graphical results interactively within a multi-window environment. When a user makes a change to an existing input sequence, the change is immediately checked via a set of programmed rules to see if it makes sense. Changes which are incomplete or inconsistent are indicated to the user, so that further refinement can be made. When changes to the input sequence are complete, the HSPF model is executed. After execution completes, the user may view results on the display screen or on printed output. Selection of locations at which results are to be reported can be achieved by using a built-in map of the study watershed with a 'point-and-click' capability. The multi-window graphics capability allows users to view comparisons of results for numerous watershed scenarios and management alternatives.

The Patuxent scenario generator interface screen typically contains three concurrently visible windows: 1) the interaction window, 2) the map window, and 3) a window for viewing graphical model output. In the user interface window, the user interacts with menu screens (using the keyboard) to select the various map and graphics options, as well as perform the model simulations. In the map window, the user operates a mouse to select locations for data display and zoom on specific areas. The graphics window is used to display the data plots that are selected in the interface window. The user can also interactively control the sizes and locations of the different windows on the screen.

The Patuxent basin scenario generator has proved itself a powerful tool for dealing with the literally thousands of input/output time series datasets that have been developed to represent possible watershed management scenarios (Lumb, 1993). Additional scenario generators are currently being developed for the USGS for use at other geographical locations, including the Carson-Truckee River basin in California and Nevada, and small urban basins in the Seattle, Washington area (Lumb, personal communication, 1994).

12.5.4. Seattle Regional Parameter Approach

A "Runoff Files" implementation of HSPF has been developed as a hydrologic modeling tool for western King County, Washington (Jackson, personal communication, 1994). The method produces results (design flows, detention pond sizing, etc.) comparable to those obtained by direct use of the HSPF model, but with significantly less effort. This is achieved by providing the user with a set of time-series files of unit area land surface runoff (i.e., "runoff files") pre-simulated using HSPF for the range of land cover conditions and soil types found within several regions of King County. Estimation of design flows and design detention facilities is then accomplished by directly accessing and manipulating the runoff file data by means of supporting software.
The runoff files consist of runoff values generated from 8 representative years of a 40-year record of hourly meteorological data; the runoff files represent simulated unit area land surface runoff for six rainfall stations and eight land use classifications (forest till, pasture till, grass till, forest outwash, pasture outwash, grass outwash, wetlands, impervious areas). For each land use classification, a characteristic set of parameter values that satisfy the input requirements of the PERNLD module of HSPF was developed. Taking advantage of the resulting 48 runoff files requires software which scales up and combines unit area runoff from a mix of land use types to represent the total runoff to specific design facility locations. King County has developed a software package, named KCRTS, with which to perform the manipulations necessary to use the runoff files to design stormwater detention facilities. The County has subsequently performed tests comparing the Runoff Files/KCRTS software implementation versus routing a full 40-year time-series of HSPF-simulated hourly flows through the facility. These analyses demonstrated that most designs using the simplified method met, or came close to meeting, their performance standards when tested using HSPF (Jackson, personal communication, 1994).

12.5.5. Interactive Water Resource and Reservoir Management Tools

Using the hydrology process algorithms of HSPF, Hydrocomp Inc. has developed a number of customized forecast/analysis models to simulate water resources within specific watersheds or geographic regions (Crawford, personal communication, 1994). These software packages enable interactive modeling of natural and anthropogenic hydrologic processes, including reservoirs, hydroelectric plants and irrigation projects. Process algorithms are identical to HSPF, but are coded in Pascal and C programming languages. The components of the water resources management systems include real-time data networks; historic hydrometeorologic databases; watershed, channel and reservoir characteristics; modeling software; and interactive graphical modeling using engineering workstations. The packages feature a graphical user interface (GUI) developed for the X-Windows environment, using Xt Intrinsic and the Motif Widget Set. The software runs on engineering workstations.

The increased speed and excellent graphics of engineering workstations, equivalent to having desktop "Cray" super computers, prompt re-examination of traditional methods used for operation of multi-purpose water resource reservoirs. The Hydrocomp forecast/analysis models enable advanced techniques for reservoir operation and design; the use of current watershed state and real-time data to forecast future water supplies; and the use of "alternate futures", "exceedance probabilities" and "sensitivity analysis" for reservoir operation.

12.5.6. Other Recent Model Applications

Table 12.3 lists a number of recent and/or current HSPF applications to provide a brief summary of the many types of watershed hydrology and

TABLE 12.3.

Selected Recent and/or Current HSPF Applications

- Chesapeake Bay Watershed Model of nutrient loadings and management alternatives
- Seattle Metropolitan Area watershed and urban drainage studies
- Metropolitan Washington, DC urban nonpoint and water quality studies
- U.S. EPA Office of Pesticide Programs assessment of alachlor surface water concentrations
- Sydney Water Board (Australia) assessment of water supply quality and nonpoint pollution
- Maryland Department of the Environment Patuxent River nonpoint source study
- Numerous Florida applications for hydrologic assessments, nutrient loadings and water quality simulation
- Flooding and Water Resource Development studies for Saudi Arabian Ministry of Agriculture
- Upper Grande Ronde (OR) temperature TMDL
- Walnut Creek (IA) MSEA/MASTER surface water exposure assessment
- Minnesota River Nonpoint Source Assessment Project
- Water Management for the Humber River, South Africa
water quality assessments that can be, and have been, performed with HSPF. In addition to the studies mentioned above, the Washington metropolitan area, the Seattle metropolitan area, and Florida have been regions with numerous model applications by county and local agencies, often focusing on stormwater management. Foreign applications have included modeling studies in Australia for nonpoint and water quality assessment, in Saudi Arabia for flooding and water resources development, and in South Africa for water management. The Minnesota River Assessment Project is a comprehensive assessment with the ultimate goal of implementation of a watershed-based nonpoint source control program to improve water quality conditions related to low dissolved oxygen and high levels of turbidity, fecal coliform and ammonia. Current research-oriented applications include the Walnut Creek (Iowa) exposure assessment for surface/subsurface interactions related to agricultural BMPs, and the Upper Grande Ronde (Oregon) water temperature modeling study to evaluate impacts of riparian forest buffers on stream shading.

12.6. FUTURE DIRECTIONS

The recent resurgence of government concern for nonpoint source issues and problems, as catalyzed by various sections and amendments to the Clean Water Act in the United States, has renewed interest in nonpoint source modeling and assessments at the watershed scale. The comprehensive nature of HSPF, and its flexibility in allowing consideration of the combined impacts of both point and nonpoint source pollutants, is leading to increased interest in model applications. To support this increased interest and potential usage, this section identifies and explores areas of ongoing model and algorithm development, many of which will be implemented in the upcoming Version 11 of HSPF, and future research areas where additional development efforts are needed. In addition to potential algorithm enhancements, we explore future needs for databases and user interaction capabilities that will be required to keep pace with changing software/hardware capabilities.


As shown in Table 12.1, HSPF has experienced a flurry of model development activity during the past five years, primarily related to needed improvements identified through selected model applications. This section describes the major improvements and added capabilities that users can expect in HSPF Version 11, planned for release in 1994-95.

Atmospheric Deposition

It has become apparent that atmospheric transport and deposition of nitroglycerine and other pollutants can contribute a significant fraction of the total load delivered to surface waters. Therefore, the ability to represent these inputs in water quality models is important. Currently, atmospheric deposition inputs are difficult or impossible to model with HSPF, especially to the land surface; and these inputs generally require extensive use of the Special Actions section. Consequently, the next release of the program will contain significant improvements in this area. These enhancements are also designed to facilitate linkage of the model with atmospheric transport models, such as EPA's Regional Acid Deposition Model (RADM) (Chang et al., 1987).

HSPF has been enhanced to accept atmospheric deposition inputs to all water quality constituent state variables, both on land surfaces and in water bodies. The deposition can consist of wet deposition, computed from user-specified concentrations in rainfall, and dry deposition, which is specified as areal loading rates. The input concentrations and loading rates can be in the form of time series or monthly averages. Also, the program's output contains summaries of the deposition inputs.

Plant Uptake and Forest N Cycling

The nitrogen (NITR) subroutines of the AGCHEM module are currently being enhanced to improve the ability to represent plant uptake for agricultural crops and nitrogen cycling in forested watersheds. The current first-order representation for plant uptake makes the model extremely sensitive to nutrient application rates (i.e., fertilizers and manure); to evaluate the impacts of changes in these application rates the user is required to re-calibrate the plant uptake rates whenever the application rates are significantly changed, such as under a nutrient reduction or management plan. To eliminate the need for re-calibration under these conditions, the plant uptake algorithms are being modified to be a function of crop needs and expected yields, in addition to available site nitrogen. These changes will be incorporated and tested as part of the ongoing Chesapeake Bay Watershed Model refinement effort (Linker, personal communication, 1994), and are planned for inclusion in Version 11 of HSPF in late 1994.

The EPA Athens Laboratory is currently sponsoring a review of the AGCHEM module with specific focus on the applicability of the soil nitrogen (NITR) algorithms and structure to represent nitrogen cycling and discharge to streams from forested watersheds (Barnwell, personal communication, 1994). Because forests are a dominant fraction of watersheds in many parts of the country, a mass-balance, deterministic approach to modeling nitrogen on forest lands provides a more accurate means of determining nitrogen loads from various sources, including
atmospheric deposition contributions (discussed above). In addition, improving estimates of nitrogen loads from forests will result in more accurate loads from other sources in the watershed, many of which are more controllable and affected by management alternatives. Scientists at Oak Ridge National Laboratory are currently reviewing the NTR subroutines and algorithms to identify appropriate changes to nitrogen storages, rate constants, and flux pathways for forested conditions. Some of the changes being considered include, (1) addition of nitrogen fixation by plants and microbes, (2) return of plant nitrogen to soil organic nitrogen, and (3) partitioning of organic nitrogen into labile, refractory, and soluble forms. Many of these improvements will also provide expanded capabilities applicable to non-forested areas (e.g. croplands, rangelands). The changes will be incorporated into the NTR subroutines by AQUA TERRA Consultants, and tested on primarily forested subbasins of the Chesapeake Bay drainage, and are planned for inclusion in HSPF Version 11.

Water Allocation/Ownership

In many river basins in the western U.S., the entire flow is allocated to various owners, such as municipal suppliers, farmers, ranchers, and industrial facilities, who can utilize their allocations at specific times of the year. In order to improve our ability to analyze such basins, the HSPF RCHRES module has been enhanced to keep track of the ownership of water within the reach network. This capability has been implemented as a set of water "categories" that represent ownership. A user can assign the ownership of water inflows and outflows from each stream segment. The ownership of outflowing water can be defined in the form of specified priorities or percentages, or they can be proportional to the current mixture in the stream segment. The initial application of this feature is the Carson-Truckee River system in California and Nevada, where the U.S. Geological Survey is developing allocation and water quality models of the basins.

Impacts of Riparian Forests on Instream Water Temperature

The EPA Office of Water, Assessment and Watershed Protection Division, is sponsoring a riparian characterization and water temperature modeling study of the Upper Grande Ronde (UGR) River in Northeastern Oregon U.S. EPA, 1994). The focus of the study is to assess the causes of elevated summer water temperatures in the UGR River that impair its ability to sustain a healthy coldwater ecosystem for annual salmon runs and resident adult salmon populations; reduced shading of the stream channel and riparian zone are the suspected causes. A TMDL (Total Maximum Daily Load) is being developed under authority of section 303(d) of the Clean Water Act to determine the temperature reductions needed to sustain a viable salmon habitat.

HSPF is being applied to the watershed, along with code enhancements to better represent the seasonal and directional aspects of both topographic and vegetal shading, to evaluate alternative management approaches for reducing the summer water temperatures. A GIS is being used to determine critical stream and riparian parameters -- such as stream direction and orientation; topographic variation; riparian zone forest density, height, crown, etc. -- for segments of the stream throughout the channel system (U.S. EPA, 1994). These parameters will then be used to evaluate the impacts of stream shading on water temperature, as impacted by diurnal shading variations, seasonal shading changes, and riparian forest characteristics. These changes in solar radiation impinging on the stream surface will then lead to changes in the energy input to the heat-balance equations used in the HTRCH section of HSPF and produce the resulting water temperature changes. Changes to existing forest buffers, or development of buffers where none existed, can then be evaluated as potential management alternatives for improving the coldwater ecosystem habitat. The study is a coordinated effort among the EPA Office of Water and the Athens Environmental Research Laboratory, the Oregon State Department of Environmental Quality, the Columbia River Tribes, the U.S. Forest Service, the Northwest Power Planning Council, and others.

Increased Limit on HSPF Operations

As HSPF has been used to model larger and more complex river basins, it has become obvious that the limit on the number of discrete operations (i.e., PERLND's, RCHRES's, PLTGEN's, etc.) in a single run must be increased. This limitation on the number of operations has forced simulations of basins that consist of many land segments and stream reaches to be divided into multiple runs that are executed sequentially from upstream to downstream. For example, the Susquehanna River portion of the Chesapeake Bay Watershed Model (Donigian et al., 1991) consists of six separate runs. This results in significant computational overhead in the form of disk space and execution time to transfer the results between successive runs. It is expected that the current maximum of 75 operations in a run will be increased to 200 or more in Version 11 of the program.

Enhancements to SPECIAL ACTIONS

Addition of chemicals to the soil in HSPF requires use of the SPECIAL ACTIONS section in which each application of a chemical to a PERLND requires a separate instruction. In large basins containing multiple PERLND's representing different crops, soil types, and meteorologic regions, the number of these SPECIAL ACTIONS can easily grow into the thousands. Several enhancements have been added to the program to
significantly reduce the number of SPECIAL ACTIONS instructions required in complex basins where agricultural operations are simulated. These enhanced capabilities are briefly discussed below.

Repeat -- Each SPECIAL ACTION can now be "repeated" at regular time intervals. This facilitates application of chemicals several times per year and each year of the simulation.

Distribution -- A SPECIAL ACTION can be "distributed" over time (equal time increments) with a user-defined pattern that is based on fractions of the total amount. This is useful in representing the activities of multiple farmers applying chemicals on different days when all of the farms are represented by a single PERLND.

User-defined -- Several SPECIAL ACTIONS can be combined as a single "user-defined" action which can be invoked multiple times for different PERLNDs and at different times. This reduces the number of actions required to represent incorporation of chemicals in two or more soil layers as a result of plowing, and application of multiple chemical species.

Conditional -- In addition to the enhancements designed to reduce the user-input requirements of SPECIAL ACTIONS, conditional SPECIAL ACTIONS are now possible in which an action can be dependent on the value of some other variable in the model. This can be useful for deferring agricultural operations that are dependent on rainfall or soil moisture, and for reservoir operations that are dependent on river flow or reservoir volume.

12.6.2. Future Algorithm/Computation Enhancements

The requirements of the process modeling capabilities of a model such as HSPF fall into five categories:

- Provide capability to define the physical setting of the modeling effort
- Represent important environmental state variables and processes
- Represent man-made effects on environmental state variables and processes
- Use process algorithms that utilize available data
- Provide a spectrum of analysis level capabilities

While HSPF provides capabilities to perform all these functions, there is room for significant improvement. In this section, possible enhancements to process algorithms and computational techniques are noted, first in general terms. Then specific capabilities of particular interest to the authors are elaborated.

Capability to Define Physical Setting of Modeling Effort

Developing and verifying model input that defines the physical setting of the modeling effort and specifies spatially-referenced materials properties can be confusing and time-consuming. A graphical approach to performing these tasks would be a highly useful enhancement to HSPF. Performance of these tasks is best performed within a GIS environment. GIS capabilities can be used effectively to accomplish the following tasks:

- Insert, delete and move rows and columns to define cells or segments
- Zoom, pan and window capabilities for detailed design
- Overlay a digitized map to aid in visualization or assign parameter values
- Rotate and offset a site schematic relative to a digitized base map
- Establish connectivity between cells or segments
- Compute segment-dependent data volumes and interfacial areas
- Assign parameter values (global, spatially variable, time dependent) depicting natural and anthropogenic conditions
Process Algorithms that Utilize Available Data

HSPF was developed prior to the proliferation of a new generation of data and data generation techniques that offer refined spatial detail for a number of parameters critical to watershed modeling. In some cases these new data are best used to support existing process algorithms that are solved for a higher resolution grid. However, the potential also exists to replace or enhance certain process algorithms to improve the simulation of natural processes by taking advantage of new data. For example, satellite data, GIS and digital elevation models (DEMs) have made it possible to compute the aspect (i.e., the direction toward which a slope faces) for watersheds or watershed segments at a high level of detail. The availability of techniques to reliably compute aspect invites the incorporation of improved process algorithms for snowmelt, soil temperature, and water temperature in areas of significant topographical relief.

The two technologies that offer the greatest body of new data that could be used to refine process algorithms are satellite remote sensing data and the transformation of remote sensing data, by use of GIS and related capabilities, to derive other useful data types.

The remote sensing data available from current and future satellites offer an opportunity to develop new process algorithms that could improve representation of precipitation, surface runoff, soil moisture, groundwater, and water quality variables including thermal pollution, erosion, sediment load, and trophic state of receiving waters. An immediate need of watershed-scale models are algorithms using radar imaging data to represent thunderstorms.

Future Modeling Research Areas

Every modeler has one's own views and opinions as to the most important areas of future modeling research. These are often the result of modeling applications and experiences where obvious deficiencies have been identified, and no satisfying resolution has been developed. Below we discuss a few of the areas we feel deserve attention in future model research and development, borne from our experiences with HSPF and other models.

Wetlands - Modeling of wetlands is an issue that arises in many watershed modeling studies, to varying degrees, and not only in the humid, coastal plain areas of the southeastern U.S. The beneficial effects of wetlands on flood retention, sediment filtration, and nutrient and toxics processing are well known, but not adequately understood. HSPF has been used to approximate the impacts of wetlands, and various code modifications have been proposed (Nichols and Timpe, 1985); however, these approaches have been primarily 'stop-gap' measures due to lack of resources and alternative models. Coordinated data collection and modeling...
research efforts (i.e. algorithm development) are needed to improve our ability to represent the complex water quality impacts of wetlands on the watershed system.

**Fish** - Fish share all zooplankton processes including growth, respiration, death and predation; additional important processes for fish include exposure to environmental stresses such as high temperatures, low dissolved oxygen, toxic chemicals, and sedimentation. Models of various fish species exist, but few are appropriate for inclusion within a comprehensive watershed modeling framework.

**Habitat Suitability** - As a group, habitat state variables (e.g., velocity, channel gradient, flow, depth, % pools and riffles, streambank vegetation and shading, substrate character, turbidity, salinity, pH, temperature, dissolved oxygen) characterize the physical or chemical setting in which biotic communities live. The physical state variables are tied to considerations of topographical relief, runoff, erosion, sedimentation, channel characteristics and thermal inputs. To a large extent, the habitat state variables that characterize the chemical setting need to be modeled irrespective of whether modeling goals include habitat analysis. A watershed modeling system, like HSPF, is ideally suited to include assessment of habitat variables.

**Ecosystem Modeling** - The goal of ecological modeling is to determine self-sustainability. To do this, modeling may focus on system elements or components (i.e., species), system structure/organization, system function (based on physical, chemical, and/or biological principles), system dynamics (material and energy transport), or the integration of one or more of these system characteristics, habitat features, and biotic communities. Relative to the other categories described above, habitat and ecological modeling are in their infancies; consequently, it is not possible to identify the important processes in a rigid manner. However, the need exists to integrate these areas into the watershed modeling arena to allow consideration of the full extent of human impacts on the watershed system and its component ecosystems.

### 12.6.2. User Interaction

User interaction, or more accurately the lack thereof, is a major weakness of HSPF and a significant stumbling block to many new model users. However, at the time of its initial release in 1980, interactive water resources and environmental models were non-existent, and many of the popular menu-driven, business and word processing programs (e.g. Lotus, WordPerfect) did not emerge until the mid-1980’s. Although HSPF was developed as a state-of-the-art model, with respect to both software and model algorithms, advances in ‘useability’ features and interactive software packages quickly aged these aspects of the code. Today it remains a batch program, with interactive features reserved for its ancillary and related programs (i.e. ANNIE/WDM, HSPEXP, Scenario Generators), largely due to the lack of resources to bring it up to current 1990’s standards of user interaction.

Many sophisticated users have developed a variety of software tools to automate specific functions needed to facilitate model application, data manipulation, and results analysis. Possible tools that could improve HSPF user interaction can be categorized into five categories of functionality:

- Data exploration/visualization
- Model support before processing
- Model support during processing
- Model support after processing
- Decision support

Potential enhancements for each of the categories are noted below.

### Data Exploration/Visualization

- Basic display of data spatial and/or temporal variation (e.g., superimpose model results on location maps; time series plot of user-defined model variables; 2-dimensional and 3-dimensional plots, contour plots).
- Graphical comparison of different data types at common locations or times to make preliminary assessments of cause and effect.

The primary source of the list of capabilities to support modeling support activities (i.e., pre-processing, processing, post-processing) is the GEO-WAMS effort (DePinto, 1993).

### Model Support Before Processing

- Site specification and problem definition. Provide an interactive graphical site schematic configuration and manipulation system with sophisticated capabilities (e.g., insert, delete and move rows and columns to define cells or segments; global and zonal modification; zoom, pan and window capabilities for detailed design; overlay of multiple information types).
Graphical assignment of parameter values (global, spatially variable, time dependent)

Hooks to retrieve raw data. Integrate custom programs to automate retrieval of data from commonly-used external databases (archival or commercial).

Data transformation tools. Provide automated techniques for aggregating or disaggregating data. The modeling system should automatically transform data to meet process model requirements, and hence should be transparent to the user.

Data derivation tools. When commonly accepted relationships of either an empirical or physical nature are available to estimate data needed by the component process models, the modeling system should include tools that enable automated value estimation based on available data.

Computation of segment-dependent data volumes, interfacial areas

Graphical prescription of initial conditions and boundary conditions

**Model Support During Processing**

- Spatial and temporal animation of results
- Model interrupt/restart capability

**Model Support After Processing**

- Basic display of primary variable spatial and/or temporal variation (e.g., superimpose model results on location maps, 3-dimensional plots, contour plots)
- Sensitivity analysis
- Segment/system mass balance diagrams
- Uncertainty analysis
- Data export for use in other modeling systems. The modeling system needs a full library of tools designed to expedite data export from the application data base.

**Decision Support**

- Improve on-line model capabilities to assist users developing model input: estimating parameter values, selecting appropriate distr-

12.7. **CLOSURE**

In this chapter, we've attempted to summarize the historical development of HSPF, its current capabilities, selected model applications, near-term future enhancements, and potential areas for future model development and research. At the time of its initial release in 1980, the original model developers felt that HSPF would have about a five-year 'useful life' before it would need to be replaced with more advanced technology. Now, almost 15 years later, HSPF continues to enjoy a growing user community both in the U.S. and abroad, a renewal of interest from governmental agencies awakening to the need for watershed-scale assessments, and the joint sponsorship of the U.S. EPA and the U.S. Geological Survey. This longevity can be attributed to the foresight and vision of the original developers, who provided the framework and flexibility needed to withstand the test of time, and to the sponsoring agencies for their continuing code and user support. It remains unique in its comprehensive capabilities for watershed hydrology and water quality modeling, and its framework and structure is sufficiently flexible to accommodate many advances in process science and understanding.

Clearly, HSPF will continue to exist and evolve over the foreseeable future. Whether or not it provides the basis for the 'next generation' of watershed models depends on the availability of continuing support and resources to adapt it to current standards of usability and interactions with current and future technology (i.e. GIS, remote sensing, computerized databases). The inertia inherent in the current HSPF user community and ongoing development efforts, in addition to its ability to satisfy the specific niche for comprehensive watershed-scale assessments, will sustain its evolution and popularity for many years, likely through the end of this century.
REFERENCES


Chapter 13

THE HBV MODEL

S. Bergström

It is now more than 20 years since the first presentation of results from the HBV model. Since then the use of hydrological models has grown dramatically, and today they are standard tools for an increasing number of applications. The HBV model has followed this trend, and there are examples of applications in some 30 countries. The span of applications has also widened and covers today hydrological forecasting, spillway design, studies of effects of climate change, synoptic water balance mapping, simulations of groundwater response among others. The chapter describes the structure of the most widely used version of the HBV model and summarizes Swedish and international experiences from its application.

13.1. INTRODUCTION

When the first steps in hydrological modelling were taken at the Swedish Meteorological and Hydrological Institute (SMHI) in early 1972 no one could foresee the development. Today, more than 20 years later, we can look back at a tremendous expansion of the use of hydrological models. These models are now everyday tools for many of the Swedish hydrologists. The best known model is the HBV model which exists in a number of versions in Sweden and abroad. Applications have been found in some 30 countries (Bergström, 1992). The PULSE model is a modified HBV model, used for environmental applications, which also exists in several versions.

The SMHI is concentrating on applied research and the use of models for practical purposes. Therefore the models developed by the institute belong to the conceptual family. The following general, and rather simple, principles in model development were identified when the work started:

The models must be based on a sound physical description but must not be so complex that they have higher data demand than can be met by our standard climatological and hydrological network.
Chapter 23

MIKE SHE

J. C. Refsgaard and B. Storm

23.1. INTRODUCTION

MIKE SHE is a comprehensive deterministic, distributed and physically-based modelling system for the simulation of all major hydrological processes occurring in the land phase of the hydrological cycle. It simulates water flow, water quality and sediment transport.

MIKE SHE is a further development based on the SHE modelling concept developed by a European consortium of three organizations: the Institute of Hydrology (UK), the French consulting firm SOGREGA and DHI (Abbott et al. 1986).

MIKE SHE is a fourth-generation, user-friendly modelling package comprising a number of comprehensive pre- and post-processors including digitizing, graphical editing, contouring, grid-averaging and graphical-result presentation with options for display of animations. It has been designed for efficient application on relatively low-cost, high-performance workstations.

MIKE SHE is applicable to a wide range of water resources and environmental problems related to surface water and groundwater systems and the dynamic interaction between these. Typical areas of application are:

- river basin planning
- water supply
- irrigation and drainage
- contamination from waste disposal sites
- impacts of farming practices (including the use of agrochemicals and fertilisers)
- soil and water management
- effects of changes in land use
effects of changes in climate
ecological evaluations, including those associated with wetland areas.

MIKE SHE is applicable on spatial scales ranging from a single soil profile (for infiltration studies) to large regions, which may include several river catchments. It has been tested and proved in a large number of research and consultancy projects. The experience record covers a wide range of climatological and hydrological regimes.

23.2. INTEGRATED MODULAR STRUCTURE

The basic MIKE SHE Module is MIKE SHE WM for the description of water movement in the area under study. The WM Module itself has a modular structure with one component dedicated to each hydrological process. Several components include alternative options for describing certain specific processes.

The user can produce his own model configuration adapted specifically to the local hydrological conditions and the purpose of the study.

The following add-on modules are available for water quality, soil erosion and irrigation studies:

- MIKE SHE AD - advection and dispersion of solutes
- MIKE SHE GC - geochanical processes
- MIKE SHE CN - crop growth and nitrogen processes in the root zone
- MIKE SHE SE - soil erosion
- MIKE SHE DP - dual porosity
- MIKE SHE IR - irrigation

In this presentation only the WM module is described in detail, while a brief introduction is given to the AD module.

23.3. WATER MOVEMENT MODULE (MIKE SHE WM)

23.3.1. Programme Structure

The overall model structure is illustrated in Fig. 23.1. MIKE SHE WM has been designed with a modular programme structure comprising six process-oriented components, each describing the major physical processes in individual parts of the hydrological cycle and in combination describing the entire hydrological cycle:

- Interception/evapotranspiration (ET)
- Overland- and Channel Flow (OC)
- Unsaturated Zone (UZ)
- Saturated Zone (SZ)
- Snow Melt (SM)
- Exchange between Aquifer and Rivers (EX)

Fig. 23.1. Schematic representation of the components of the MIKE SHE.

The modular form of system structure, or architecture, ensures a great flexibility in the description of the individual physical processes. Data availability or specific hydrological conditions may favour one model description compared to another. By ensuring that the data flow between components are unchanged, alternative methods which are generally accepted in a certain geographical region or a country can be included in the MIKE SHE WM system if required.
The governing partial differential equations for the flow processes are solved numerically by efficient and stable finite difference methods in separate process components. All process descriptions operate at time steps consistent with their own most appropriate temporal scales. Hence the processes may be simulated using different time steps which may be updated during the simulation and coupled with the adjoining processes as and when their time steps coincide. The facility allows for a very efficient operation, making it possible to carry out simulations extending over long periods of time.

Individual components can also be operated separately to describe a single process. This may be relevant in a range of applications, where only rough estimates of data exchange from other parts of the hydrological cycle are required. An example could be a groundwater study where only approximate recharge estimates may be required and a full coupling to the unsaturated zone above the groundwater table is unimportant.

The ability to provide an integrated description of the various processes, despite different time scales, is the most important feature of MIKE SHE WM. This integration has probably been the largest problem encountered during its development and provides a unique feature. Perhaps the most difficult coupling is the one between the unsaturated zone and the groundwater components, which is described in Storm (1991).

### 23.3.2. Frame Component

A FRAME component coordinates the parallel running of the process components by selecting their different time scales and organizing their data interchanges. Its primary functions include:

1. Controlling the sequence in which each component is called to perform its computations. For some components there may be different time steps as well as changes in the time steps during a simulation, depending on the rate of hydrological response. If the time steps differ between components, it is necessary to accumulate calculated values over a period before they are transferred to another. In general, the larger time steps are used in the saturated zone component compared to the other components.

2. Controlling which components are included in the simulation. Dummy versions, which simply provide the necessary boundary variables for the other components may substitute process components if the concerned processes are irrelevant for the application.

3. Controlling which option of each process description is used if more than one method is available for a component.

4. Controlling the exchange of data between components. The results provided by one component will in some cases need to be processed into a different form for input to another component.

5. Controlling the output variables to be stored on disk for postprocessing and the time interval with which each variable is stored.

The data flow between components is illustrated in Fig. 23.2.

![Fig. 23.2. Data flow between the components of the MIKE SHE WM.](image)
23.3.3. Interception and Evapotranspiration Component

During rainfall, part of this will be intercepted by the vegetation and subsequently lost by evaporation.

It is assumed that the interception is either depending on the rainfall rate and/or the interception capacity. The importance of interception depends very much on vegetation type, development stage, density of vegetation and the climatic conditions. Dense forest canopies may account for a considerable interception loss, whereas for shorter and sparser vegetation, such as grass and agricultural crops, the evaporation loss may be much smaller and often insignificant.

Evapotranspiration involves the transfer of large quantities of water. In temperate areas approximately 70% of the annual precipitation is returned to the atmosphere, while under arid conditions it almost equals the rainfall. For this reason the prediction of the actual evapotranspiration plays a key role in many water resources studies.

The evapotranspiration is the total process of evaporation from soil and water surfaces and transpiration, the water uptake by plant roots that is transpired from the leafy parts of the plant. The spatial and temporal variation in the evapotranspiration rate in a catchment depends on multiple factors such as water availability in the rootzone, the aerodynamic transport conditions, plant physiological factors etc.

At present, two alternative formulations of the interception/evapotranspiration process are available in MIKE SHE WM.

(a) The Rutter Model/Penman-Monteith Equation

The interception is modelled by a modified Rutter model (Rutter et al., 1978). This calculates the evaporation, the actual storage on the canopy, and the net rainfall reaching the ground surface as canopy drainage and throughfall.

The actual evapotranspiration rates are calculated by the Penman-Monteith equation using canopy resistances. The potential evapotranspiration is calculated directly using climatological and vegetation data.

(b) The Kristensen-Jensen Model

The interception storage is calculated based on actual leaf area index and an interception capacity coefficient. The net rainfall is calculated by a simple water balance approach.

The actual evapotranspiration is calculated on the basis of potential rate and the actual soil moisture status in the root zone (Kristensen and Jensen 1975).

EQUATIONS

(a) The Rutter model/Penman-Monteith equation

Interception

The Rutter model is essentially an accounting procedure for the amount of water stored on the canopy. The rate of change in storage is given by

$$\frac{\partial C}{\partial t} = Q - Ke^{b(C-S)}$$  \hspace{1cm} (23.1)

where

$$Q = \begin{cases} \frac{P}{P_2} \left( P - E_p \right) / S & \text{when } C \leq S \\ \frac{P}{P_2} \left( P - E_p \right) & \text{when } C \leq S \end{cases}$$  \hspace{1cm} (23.2)

with the notation as given at the end of this section.

Evapotranspiration

The Penman-Monteith equation (Monteith, 1965) for predicting the actual evapotranspiration rates is

$$E_a = \frac{\Delta R_n + \rho C_p \delta e}{\lambda \left[ \Delta + \gamma \left( 1 + r_s / r_a \right) \right]}$$  \hspace{1cm} (23.3)

The total actual evapotranspiration calculated for each grid square depends on the wetness of the canopy and the degree of ground covered by the canopy:

$$E_t = P_1 P_2 E_p C / S + E_a \left( 1 - C / S \right) P_1 P_2 + E_s \left( 1 - P_1 P_2 \right)$$  \hspace{1cm} (23.4)
(b) The Kristensen-Jensen model

Interception

The intercepted water storage capacity is calculated by:

\[ S = S_{\text{int}} \cdot \text{LAI} \quad (23.5) \]

The evaporative demand constraint is first applied to the intercepted water and if this is not satisfied the remaining part is applied for transpiration and soil evaporation. If the interception storage capacity is exceeded during rainfall, the surplus of rain will be calculated as throughfall.

Evapotranspiration

The evaporative demand is only met if the soil moisture content in the rootzone is sufficient. For lower moisture contents the actual transpiration is calculated according to a procedure illustrated in Fig. 23.3.

The soil evaporation demand is reduced below the potential value for moisture contents below field capacity, according to the procedure illustrated in Fig. 23.4.

![Fig. 23.3. Relationship between actual transpiration and soil moisture content in the Kristensen-Jensen model.](image)

![Fig. 23.4. Relationship between actual soil evaporation and the actual soil moisture content in the Kristensen-Jensen model.](image)

Symbol List

- \( E_t \) - total evapotranspiration rate
- \( E_a \) - actual evapotranspiration
- \( E_{aw} \) - actual transpiration
- \( E_p \) - potential evapotranspiration
- \( E_s \) - soil evaporation
- \( C \) - actual water depth on canopy (mm)
- \( S_{\text{int}} \) - interception storage coefficient (mm)
- \( S \) - canopy storage capacity (mm)
- \( P \) - rainfall rate (mm/s)
- \( P_1 \) - proportion of ground planview hidden by vegetation
- \( P_2 \) - ratio of total leaf area to area of ground covered by vegetation
- \( K \), \( b \) - canopy drainage parameters
- \( t \) - time (s)
\( R_a \) - net radiation minus energy flux into the ground (W/m²)

\( \Delta e \) - slope on specific humidity - temperature curve (mb/C°)

\( \rho \) - density of air (Kg/m³)

\( C_p \) - specific heat capacity of air (J/kg/C°)

\( \delta_p \) - vapour pressure deficit (mb)

\( r_a \) - aerodynamic resistance (s/m)

\( r_s \) - canopy resistance (s/m)

\( \lambda \) - latent heat of vaporization (J/kg)

\( \gamma \) - psychometric constant (mb/C°)

LAI - leaf area index

\( \theta_F \) - soil moisture content at field capacity

\( \theta_W \) - soil moisture content at wilting point

\( \theta_M \) - irreducible soil moisture content

**Solution Technique**

The Rutter model is solved by analytical integration. All other equations are solved directly.

The transpiration is calculated as sinks at each computational node in the rootzone and the total transpiration is found as a weighted average according to the actual root mass distribution. For the top node, the additional loss due to soil evaporation is also considered.

**Examples of Output**

The ET component calculates, at each grid square where calculation are performed with the UZ component, time series of e.g. evaporation from interception storage and ponded water, soil evaporation, and transpiration. This is illustrated in Fig. 23.5.

![Graphs of Rainfall and Evapotranspiration](image)

Fig. 23.5. Example of output from ET calculations for a four year period in a single grid square.

**23.3.4. Overland - and Channel Flow Component**

Water accumulated on the soil surface during heavy rainfall or when the groundwater table rises to the ground surface responds to gravity by flowing down-gradient over the land surface enroute to the stream channel system. From here it discharges through the channels (rivers) to the outlet of the catchment.

During its journey to the streams, the flowing water may diminish because of evaporation or infiltrate in areas with more permeable soils.

The stream channel system is assumed to run along the boundaries of the grid squares.
EQUATIONS

The overland flow process is described by solving the equations of continuity and conservation of momentum in two horizontal directions (the Saint Venant equations). In the latter the diffusive wave approximation is applied.

\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x_i} + \frac{\partial (vh)}{\partial x_j} = q
\]

\[
\frac{\partial h}{\partial x_i} = S_{oi} - S_{fi} \quad x_i - \text{direction}
\]

\[
\frac{\partial h}{\partial x_j} = S_{oj} - S_{fj} \quad x_j - \text{direction}
\]

(23.6)

The Strickler/Manning-type law for each friction slope is used giving the following relations between velocities and flow depths.

\[
u h = K_{xi} I_{xi}^{1/2} h^{5/3}
\]

\[
v h = K_{xj} I_{xj}^{1/2} h^{5/3}
\]

(23.7)

The channel flow is calculated by an equivalent set of equations, but in one dimension only.

\[
\frac{\partial A}{\partial t} + \frac{\partial (Au)}{\partial x} = Q
\]

and

\[
\frac{\partial h}{\partial x} = S_{ox} - S_{fx}
\]

(23.8)

Important Parameters

The Strickler roughness coefficients used both in the overland flow and the river flow descriptions influence the timing and shape of the simulated hydrograph simulations. In particular for the overland flow part these parameters may be subject to calibration.

Solution Technique

Implicit finite difference techniques are used for both the overland flow (Thomas, 1973) and the channel flow (Preissman and Zaoui, 1979). The former uses a modified Gauss-Seidel iterative solution scheme, analogous to that often used for the groundwater flow.

Examples of Output from the OC Component

The OC component calculates the temporal and spatial ponding depths and flows on the ground surface. In the river system the temporal and spatial variations in water levels and discharge are produced. A snapshot from a simulation is shown in Fig. 23.6. The figure illustrates the ponded water on the land surface in a fence diagram of the water level in the channel system.

23.3.5. Unsaturated Zone Component

The unsaturated zone is a crucial part of the hydrological system in a catchment. It plays an important role in many modelling applications, e.g. for recharge estimation, surface-groundwater interaction and agricultural pollution. The unsaturated zone refers here to the mostly-unsaturated soil.
EQUATIONS

In its most comprehensive mode, MIKE SHE WM solves Richards equation for one-dimensional vertical flow, which includes the effects of:

- gravity
- soil suction
- soil evaporation
- transpiration

in the form:

$$C \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial \psi}{\partial z} \right) + \frac{\partial K}{\partial z} - S$$  \hspace{1cm} (23.9)

The equation is solved over all representative grid squares in the model area.

In many soils pronounced macropore flow is observed. In addition to Richards equation, which only considers the water flow in the micropores (soil matrix), an empirical bypass function is introduced, which calculates a direct instantaneous groundwater recharge as a certain percentage of the net rainfall and the actual soil moisture conditions in the root zone.

Symbol list

- \( \psi(z, t) \) - pressure head (m)
- \( t \) - time (s)
- \( z \) - vertical space coordinate (m)
- \( C \) - soil water capacity (m\(^{-1}\))
- \( K(\theta, z) \) - hydraulic conductivity (m/s)
- \( \theta \) - soil moisture content
- \( S(z, t) \) - source/sink term (e.g. root extraction) (s\(^{-1}\))

Important Parameters

Two non-linear functional relationships are required to solve Richards' equation: the unsaturated hydraulic conductivity function \( K(\theta) \) and the soil moisture retention curve, describing the \( \theta - \psi \) relation. Both functions should be known for any soil type included in any soil profile within the model area.
In applications made on the catchment scale, these functions are not known in detail. Usually representative values can be obtained for the soil types. The parameters may therefore be subject to calibration.

Solution Technique

Richards' equation is solved numerically by an implicit finite difference technique using the double-sweep algorithm. The variables are defined at every computational node in the vertical.

The time-varying upper boundary at the land surface can shift between a flux-controlled boundary (net rainfall) and a soil-controlled head boundary during ponding. The time-varying lower boundary is usually the groundwater table, specified by a positive value of \( \psi \) at the computational node just below the groundwater table. If unsaturated conditions develop in the entire soil profile a zero-flux boundary is used at the impermeable interface until saturated conditions build up from the bottom.

A coupling procedure between the unsaturated and the saturated solutions is included to compute the correct soil moisture and the water table dynamics in the lower part of the soil profile. This overcomes any problems arising from the parallel running of the individual components.

Example of Output

The UZ component computes the temporal variation in soil moisture in all nodes above the groundwater table. The infiltration and recharge rate is also calculated. The temporal variation in soil moisture for two distances to the groundwater table is illustrated in Fig. 23.7.

23.3.6. Groundwater Component

Saturated subsurface flow plays a significant role in the hydrological cycle. During drought periods it provides and sustains streamflow through baseflow, while during storm events it may contribute significantly to the stormflow as well as influence the magnitude of overland flow provided by the rising water table.

Aquifers in catchments can contain large water resources storage which, besides natural changes, may be subject to abstraction for water supply and irrigation. The influence of this human activity may influence the natural recharge and discharge properties and thereby change the flow regime in the catchment.

\[
\frac{\partial}{\partial x_i} \left( K_{ij} \frac{\partial h}{\partial x_j} \right) = S_s \frac{\partial h}{\partial t} + R \quad i, j = 1, 2, 3 \tag{23.10}
\]

The equation is applicable both for a single-layered aquifer as well as a multi-layered aquifer system.

For applications on single aquifer systems, where a two-dimensional flow solution is adequate, the equation may degenerate to two dimensions by integrating over the saturated depth.
Symbol list

- \( h(x_i) \) - hydraulic head (m)
- \( x_i \) - space coordinate (m)
- \( K(x_{ij}) \) - hydraulic conductivity tensor (m/s)
- \( S_s(x_{ij}) \) - specific storage
- \( R(x_{ij}) \) - volumetric flow rate via sources or sinks per unit volume (m³/s/m²)

The source/sink term \( R \) includes:
- flow exchange with the unsaturated zone
- river exchange rates
- abstraction/injection rates
- evaporation losses
- flow through drain pipes

Important Parameters

A MIKE SHE WM generated model which includes the groundwater component will require information about the hydrogeology in terms of the hydraulic conductivity \( K \) (in vertical and horizontal directions), and the storage coefficient for unconfined and confined conditions. Based on a hydrogeological model for the aquifer system, parameter values for each computational node is generated by interpolation with the pre-processor.

Solution Technique

The equation is solved numerically by a finite-difference method using a modified Gauss-Seidel implicit, iterative scheme (Thomas, 1973) providing a value for the hydraulic head in time at each computational node. The discretization may either be a rigid network for fully three-dimensional flow or following the geological layering for a quasi-three-dimensional flow as illustrated below. In the latter case, each layer (aquifer and aquitard) is represented by one computational node only, and the vertical variations in the groundwater head within each layer is neglected.

Examples of models for a single unconfined aquifer (Karup Å) and a multilayer aquifer system (Langvad Å) respectively, are shown in Fig. 23.8.
The main characteristics of the SZ component and the type of regimes for which it is valid are described in Table 23.1.

**TABLE 23.1.**
The main characteristics of the SZ component of the MIKE SHE WM

<table>
<thead>
<tr>
<th>Soil/Rock Characteristics</th>
<th>Fluid Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confined aquifers</td>
<td>Single fluid</td>
</tr>
<tr>
<td>Aquitards</td>
<td></td>
</tr>
<tr>
<td>Watertable aquifers</td>
<td></td>
</tr>
<tr>
<td>Multiple aquifer</td>
<td></td>
</tr>
<tr>
<td>Heterogeneous</td>
<td></td>
</tr>
<tr>
<td>Anisotropic</td>
<td></td>
</tr>
<tr>
<td>Single soil layer</td>
<td></td>
</tr>
<tr>
<td>Layered soils</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow Conditions</th>
<th>Boundary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsaturated *</td>
<td></td>
</tr>
<tr>
<td>Transient</td>
<td></td>
</tr>
</tbody>
</table>

**Geometry**

- 1-dimensional
  - horizontal
  - vertical

- 2-dimensional
  - horizontal
  - vertical

- 3-dimensional

*Internal grid squares:*
- Time-varying point source
- Time-varying line source
- Time-varying distributed limited area (infiltration to top-layer)

*At the model boundary:*
- Specified time-varying distributed head
- Specified constant flux
- Specified constant head gradient

---

**Examples of Outputs**

The SZ component provides information on the hydraulic heads and flows in time and space. An example of different maps to illustrate simulated hydraulic heads is shown in Fig. 23.9.

**Spatial Distribution:**

- Depth to Water Table
- Water Table Elevation

**Time series:**

A (Shallow groundwater table)

B (Deep groundwater table)


---

Fig. 23.9. Example of output from the SZ component illustrating both the temporal and spatial variation of ground water tables for an unconfined aquifer.

**23.3.7. Aquifer-River Exchange Component**

The river system usually influences a large part of the groundwater system at its traverse of the catchment in many directions. The river will control the
groundwater head in both the horizontal and vertical directions, defining the recharge and discharge areas.

Since the river surface area is often small compared to the total catchment area, it can in many applications be represented in a separate node system running along the boundaries of the grid squares acting as a line source/sink.

The interaction between river and groundwater is assumed to take place in the middle of the intermediate river links connecting adjacent river computational nodes at the corners of the grid squares.

**EQUATIONS**

The EX component includes two options for describing the river/groundwater exchange:

1. The river is in full contact with the groundwater aquifer (but not necessarily fully penetrating the aquifer)
2. A riverbed lining of low permeability separates the river from the groundwater aquifer.

In both options, Darcy’s law is applied taking the additional head loss around the river bottom approximately into account.

If option (1), assuming the degree of river penetration is the limiting factor for the flow exchange, only the low area between the groundwater table and the river bed is taken into account. In option (2) the flow exchange is calculated as two resistances in series, one in the aquifer and one situated across the riverbed lining.

**23.3.8. Snow Melt Component**

The SM component includes two options:

1. An energy balance approach accounting for the energy and mass flux and for changes in the structure of the snow pack (Morris, 1982)
2. A simple degree-day approach

**23.3.9. Parameters and Data Requirements**

The application of distributed, physically-based models such as MIKE SHE requires the provision of large amounts of parametric and input data. Some of these may be time-dependent.

It is important to notice that MIKE SHE allows the user to utilize a large quantity of data, but it does not necessarily restrict the use of MIKE SHE if not all data are available. A model that is set up, or "instantiated", using MIKE SHE can be simplified according to its users conceptualization of the natural system and the data availability. Although MIKE SHE is an advanced modelling system, it is easy to apply and provides a greater flexibility as compared to many simpler models when describing natural systems.

No matter which mathematical model approach is used, the user should emphasize the reliability of the model output in view of the limiting factors for describing the natural system.

It is important to recognize that MIKE SHE WM requires calibration if it is applied on a different scale from that for which the equations have been developed and the parametric data are representative. In this connection it is important to realize the representativeness of model output compared to measured values.

Table (23.2) describes the parametric and input data for MIKE SHE WM.

**TABLE 23.2.**

Data and parameter requirements for each grid square or channel link

<table>
<thead>
<tr>
<th>Frame</th>
<th>Horizontal discretization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input data</td>
<td>Ground surface elevation</td>
</tr>
<tr>
<td></td>
<td>Distribution codes for rainfall and meteorological stations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interception</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model parameters</td>
</tr>
<tr>
<td>(Rutter Model)</td>
</tr>
<tr>
<td>(for each crop type)</td>
</tr>
<tr>
<td>Canopy drainage parameters</td>
</tr>
<tr>
<td>Canopy storage capacity</td>
</tr>
<tr>
<td>(time varying)</td>
</tr>
<tr>
<td>Ground cover indices (time varying)</td>
</tr>
<tr>
<td>Leaf area index (time varying)</td>
</tr>
<tr>
<td>Interception capacity coefficient</td>
</tr>
<tr>
<td>Rainfall rate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Evapotranspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model parameters</td>
</tr>
<tr>
<td>(P-M equation)</td>
</tr>
<tr>
<td>Canopy resistance</td>
</tr>
<tr>
<td>Aerodynamic resistance</td>
</tr>
<tr>
<td>Ground cover indices (time varying)</td>
</tr>
<tr>
<td>Ratio between actual and potential evapotranspiration as a function of soil moisture</td>
</tr>
<tr>
<td>Root distribution with depth</td>
</tr>
<tr>
<td>Empirical constants describing the ration between actual and potential evapotranspiration as function of soil moisture</td>
</tr>
<tr>
<td>Leaf area index (time varying)</td>
</tr>
<tr>
<td>Rooting depth (time varying)</td>
</tr>
<tr>
<td>Root distribution coefficient</td>
</tr>
<tr>
<td>Input data</td>
</tr>
<tr>
<td>Meteorological data</td>
</tr>
</tbody>
</table>

Table 23.2 Continued.
TABLE 23.2. Continued.

Overland and channel flow
Model parameters
Strickler roughness coefficients for overland and river flows
Detention storage capacity on ground surface
Coefficients of discharges for weir formulae

Input data
Specified levels and flows at boundaries
Man-controlled discharges
Topography of overland flow plane and river cross sections
Riverbed lining thickness
Riverbed lining permeability

 Unsaturated zone
Model parameters (for each soil type)
Soil moisture tension/content relationship
Unsaturated hydraulic conductivity as a function of soil moisture content
Maximum bypass ratio of net rainfall

Input data
Distribution codes for soil profiles
Distribution codes for soil types in soil profiles
Vertical node discretization in UZ

Saturated zone
Model parameters
Storage coefficients
Saturated hydraulic conductivities
Drainage depth
Time constant for drainage routing

Input data
Specified flows, gradients and heads at boundaries
Location of abstraction or recharge wells
Pumping and recharge rates
Vertical node discretization in SZ

Snow melt
Model parameters
Degree-day factor
Snow zero plane displacement
Snow roughness height

Input data
Meteorological and precipitation data

Data Overlays

A number of input data and parametric data values are required for each grid square in the horizontal grid. This is done as a stack of overlays containing codes describing structural data as well as data types. For each data type (e.g., soil type codes) a number of attributes (soil physical/properties) are attached specifying the actual properties of the data type.

23.4. ADVECTION DISPERSION MODULE (MIKE SHE AD)

MIKE SHE AD simulates the detailed transport and spreading of dissolved conservative solutes from non-point and point sources. It may be coupled with chemical reaction modules to describe also the behaviour of non-conservative solutes.

The module describes the transport and spreading of solutes in the water flowing on the ground surface, in the soil water and in the groundwater by solving the advection-dispersion equation for the respective regimes.

In the following only the equations and the methodology is shown for the groundwater component. The methodology for the other components is very similar. Like for the WM module the largest problem encountered during the development of the AD module has been associated to the couplings between the various components.

EQUATIONS (shown for groundwater component only)

The transport of dissolved solutes in groundwater is described by solving the advection-dispersion equation numerically in a fully three-dimensional scheme.

The governing partial differential equation may be written as

\[
\frac{\partial c}{\partial t} = - \frac{\partial}{\partial x_i} \left( c v_i \right) + \frac{\partial}{\partial x_i} \left( D_{ij} \frac{\partial c}{\partial x_j} \right) + R_c \quad i, j = 1, 2, 3
\]  

(23.11)

Symbol list

\[c(x_i)\] - concentration of the solute [mg/l]

\[R_c\] - sources or sinks [mg/l/s]

\[D_{ij}\] - dispersion coefficients [m²/s]

\[v_i\] - velocity components [m/s]

Important Parameters

The dispersion coefficients are the key parameters. They are determined from a number of dispersivities and the velocity components. The dispersivities have to be provided as input parameters.

Traditionally, the dispersion coefficients are assumed to solely depend on the longitudinal dispersivity, \(\alpha_L\), and the transverse dispersivity, \(\alpha_T\), but this assumption is only valid for isotropic conditions. Instead we suggest that the dispersion coefficients are calculated from four dispersivities so that a more correct description is achieved under anisotropic conditions.
23.6. APPLICATION EXPERIENCE

The MIKE SHE is today being used operationally by a large number of organisations in different countries ranging from university and research organisations to consulting engineering companies. The original SHE version has been tested on a number of research catchments and applied to a few other projects, see e.g. Bathurst (1986), Refsgaard et al (1992) and Bathurst (this book) for further details.

MIKE SHE has as an extended version of SHE been applied to a large number of projects during the past few years. A list of applications in which DHI has been directly involved are shown in Tables (23.3) and (23.4) for research and consultancy projects, respectively. These applications illustrate the very wide range of water resources problems for which the MIKE SHE is a suitable tool.

TABLE 23.3.  
List of MIKE SHE applications on externally funded research projects

<table>
<thead>
<tr>
<th>Location</th>
<th>Project Title</th>
<th>Period</th>
<th>Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>Strategic environmental research programme</td>
<td>1993-96</td>
<td>Groundwater pollution</td>
</tr>
<tr>
<td>Sweden</td>
<td>Effects of forestry drainage and clear-cutting on flood conditions</td>
<td>1991-92</td>
<td>Impacts of human activity on floods</td>
</tr>
<tr>
<td>EU</td>
<td>Modelling of the nitrogen and pesticide transport and transformation on catchment scale</td>
<td>1991-94</td>
<td>Agricultural pollution</td>
</tr>
<tr>
<td>Denmark</td>
<td>Research programme on groundwater pollution from waste disposal site</td>
<td>1988-90</td>
<td>Groundwater pollution</td>
</tr>
<tr>
<td>Denmark</td>
<td>Research programme on nitrogen, phosphorous and organic matter</td>
<td>1986-90</td>
<td>Simulation of nitrogen on catchment scale. Coupling with Daisy crop growth and nitrogen model</td>
</tr>
<tr>
<td>Denmark</td>
<td>Validation of pesticide models</td>
<td>1994-96</td>
<td>Leaching of pesticides in clayey soils with preferential flow paths</td>
</tr>
</tbody>
</table>
TABLE 23.4.
List of MIKE SHE applications on consultancy projects with DHI involvement

<table>
<thead>
<tr>
<th>Location</th>
<th>Project Title</th>
<th>Period</th>
<th>Topics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estonia</td>
<td>Tapa Airbase - Groundwater Model</td>
<td>1993</td>
<td>Groundwater pollution</td>
</tr>
<tr>
<td>Slovakia</td>
<td>Danubian Lowland - Groundwater Model</td>
<td>1992-95</td>
<td>Surface water quality, river and reservoir erosion and sedimentation, groundwater quality and geochemistry (redox), wetland ecology Coupling with ARC/INFO and Informix</td>
</tr>
<tr>
<td>Denmark</td>
<td>Four projects og Optimisation of remedial measures for safeguarding groundwater resources from pollution from waste disposal sites</td>
<td>1992-93</td>
<td>Groundwater pollution</td>
</tr>
<tr>
<td>Denmark</td>
<td>Environmental impact assessment of a highway construction</td>
<td>1992-93</td>
<td>Effects of groundwater drawdown due to tunnel construction</td>
</tr>
<tr>
<td>Australia</td>
<td>Irrigation salinity</td>
<td>1991-93</td>
<td>Process simulation of an irrigation district with focus on flow and salinity transport</td>
</tr>
<tr>
<td>Denmark</td>
<td>Identification of new well field for water supply</td>
<td>1991-92</td>
<td>Groundwater, effects of abstraction on streamflows and wetlands</td>
</tr>
<tr>
<td>Hungary</td>
<td>Assessment of pollution hazards in groundwater supplies</td>
<td>1991</td>
<td>Groundwater pollution</td>
</tr>
<tr>
<td>Denmark</td>
<td>Water supply planning in Aarhus county</td>
<td>1988-90</td>
<td>Groundwater resources, effects of abstractions on hydraulic heads and streamflows</td>
</tr>
</tbody>
</table>

In addition to the applications listed in the two tables MIKE SHE is used by other organisations to a large number of projects which are not known to the authors.

The SHE was originally developed with a view to describe the entire land phase of the hydrological cycle in a given catchment with a level of detail sufficiently fine to be able to claim a physically-based concept (Abbott et al. 1986a,b). The equations used in the model are with few exceptions non-empirical and well-known to represent the physical processes at the appropriate scales in the different parts of the hydrological cycle. The parameters in these equations can be obtained from measurements as long as they are compatible with the representative volumes for which the equations are derived.

In most regional catchment studies carried out so far, it has not been possible to represent the spatial variations in catchment characteristic with such a detail that the model could be considered physically-based. In fact, this was realised at an early stage when the applications changed from testing against analytical solutions and small scale research areas to applications on medium sized catchment areas.

However, it is the experience that the spatial resolutions and variations in properties used, provide a very good representation of the conditions in the areas modelled. In practise the spatial variations are derived from maps describing topography, soil and land-use pattern and interpreted geological conditions, combined with information about the general properties of the different map units. The model parameters values are then modified during calibration to match observed conditions at discrete points.

There are a number of fundamental scale problems which needs to be carefully considered in the model applications. This is particular important when describing the interaction between the surface flow and the subsurface flows. A few areas where scale problems are encountered include:

- The interaction between groundwater and river. Since the flow is based on Darcy's law using the gradient between the river water level and the groundwater heads in the adjacent grid squares, the flow rates and the resultant head changes will depend on the spatial resolution used. This is an important aspect in for example simulating the hydrograph recessions correct.
- In catchments with a dense drainage network it is often not possible to represent entire drainage system (many streams are of ephemeral nature). For such situations subgrid variations in the topography need to be accounted for in order to simulate the hydrograph response in the main streams correctly.
- For modelling of infiltration and vertical unsaturated flow in the soil, the hydraulic parameters used in Richards' equation can be obtained from laboratory measurements on small undisturbed soil
samples. However, for grid squares covering large areas (eg. 25 ha) these are seldom representative unless completely homogeneous conditions exist in the horizontal directions. Therefore effective or representative parameters are used, which means that the simulated soil moisture conditions can not be verified directly.

In fact much of the criticism against MIKE SHE arise often from the way the unsaturated flow is simulated and very seldom on how the groundwater conditions are treated.

For most catchment simulations the use of Richards' equation becomes conceptual rather than physically based and simpler approaches could be chosen. Nevertheless, this equation provides a good routing description, and the capability to simulate capillary rise under shallow water table conditions is an important option for studies where eg. wetland areas are included. For situations where Darcy law does not apply a simple macropore option is included in the solution.

Because representative parameter values are used, the reliability of the results depends very much on the data available for comparison of the simulated spatial and temporal variations with observations. This is well-known from groundwater applications, where the aquifer properties (conductivities or transmissivities) are derived based on calibration against observed head variations in discrete points. For regional catchment studies the model performance is usually evaluated based on comparisons against river discharges and groundwater heads. Very seldom measured soil moisture data are available, and if they are such comparisons will require that the site specific properties are known.

It is often stated that distributed models requires a large number of data and therefore very time consuming and complicated to set up and calibrate. In fact, a number of short-term screening evaluation projects have been carried out with MIKE SHE for example in connection with studying the contamination risks from waste disposals. In these studies only sparse existing information about the hydrogeological conditions was available. The model was used to obtain an improved knowledge about the possible flow patterns around the waste disposal site based on the existing geological interpretations. These applications could also be used to identify where existing knowledge is lacking and assist in defining appropriate monitoring programme.

Another common argument against distributed models is the risk of overparameterization. This risk is of course always there. However, the general experience is that if the data are lacking to describe the spatial variations in the catchment it is too time-consuming and not worthwhile to modify a large number of parameter values in order to improve eg. hydrograph predictions. In such cases very few parameters are used in the calibration and the reliability of the results are evaluated with this in mind.

23.7. ONGOING RESEARCH

From the above application records it appears that MIKE SHE already has been used comprehensively both for research studies and for practical routine applications. These applications reflect that for certain types of studies there is no adequate alternative to an integrated, distributed, physically-based modelling approach like the MIKE SHE. Nevertheless, it is realized that MIKE SHE, in its present form, is far from being complete as a tool for advanced hydrological analyses. Many both practical and fundamental problems need to be solved through future research activities. A very significant part of the research carried out in these years in the international scientific community is in fact of direct relevance and most valuable in this context.

At DHI research and developments related to MIKE SHE is carried out in the following fields:

- Improvement of process descriptions. Research work on macropore flow and solute transport is presently undertaken. Other activities such as inclusion of density effects in the groundwater component and description of hysteresis phenomena in the unsaturated zone are planned in the coming years.

- Improvements of numerical efficiency is continuously taking place.

- Interface to geographic information systems (ARC/INFO) is being developed.

- Coupling with DHI's generalized river modelling system (MIKE 11, see Chapter 21 of this book) is going on. A coupled MIKE SHE/MIKE 11 enables description of sediment transport and water quality processes also in the river system as well as description of complex river and canal systems. Typical area of application is irrigation command areas, where networks of both irrigation and drainage canals exist together with a large number of different hydraulic regulating structures.

- Fundamental research on establishment of rigorous methodology on parameterization, calibration and validation is urgently needed. Some first, small steps have been taken as described in Refsgaard et al (1992), Jain et al (1992) and DHI (1993).

- Fundamental research on scale problems related to spatial variability of hydrological parameters is urgently needed. In particular problems related to different scales used for data sampling, process description and model discretization need to be addressed. Although comprehensive international research is carried out in these years no operational results and conclusions are evident.
23.8. CASE STUDY: MODELLING OF NITROGEN TRANSPORT AND TRANSFORMATION ON A CATCHMENT SCALE

23.8.1. Introduction

The present case study is one of the outputs from a comprehensive Danish research and development programme (1986-90), which was carried out with the aim of studying the pollution from nutrients and organic matters in agriculture. The research programme was multidisciplinary and involved a large number of research institutions. It included field investigations, process studies and modelling. The present case study briefly describes a distributed hydrological modelling of nitrate transport and transformation for the 440 km² Karup River catchment. The nitrogen modelling covers the entire land phase of the hydrological cycle - from the source on the soil surface, through the soil zone and the ground water to the streams. The modelling was based on the MIKE SHE CN, which is a combination of the MIKE SHE WM + AD modules and the DAISY model for simulation of the nitrogen dynamics in the root zone.

A more thorough description of the DAISY model is given by Hansen et al. (1991), whereas a detailed description of the present case study is presented by Styczynski and Storm (1993).

23.8.2. Model setup

The Karup catchment was represented in a three-dimensional network. The discretization is 500 m in the horizontal directions and varies in the vertical from 5 to 40 cm in the unsaturated zone, and 5 m in the permanently saturated zone. Information on soil and vegetation properties were collected, and from the information from a number of wells, a three-dimensional geological map was superimposed on the model grid to provide the hydrogeological parameter values. The topography and the river network have been digitized, and all relevant climatological data collected. The overall land use has been identified. Some of the data and parts of the MIKE SHE model setup are shown in Figs. 23.5 - 23.9.

23.8.3. Results

Discharge and groundwater table hydrographs

The streamflow is simulated for the period 1969 - 1988 at several sites. A comparison with measured discharge at the catchment outlet is shown for four years in Fig. 23.10. In addition the simulated groundwater table is compared with observations in selected wells (Fig. 23.11). The comparison shows that the modelling system simulates the hydrological regime with acceptable accuracy.

Fig. 23.10. Comparison between simulated and observed river runoff for the period 1971-74.

Fig. 23.11. Comparison between simulated and observed groundwater table time series in selected wells.
Leakage from the Root Zone

To simulate the trend in the nitrate concentrations in the groundwater and the streams, it is necessary to have information on the history of the fertilizer application in space and time. This information is difficult to obtain in details, for example it is not possible to estimate which type of crop was growing on one particular field in one particular year in the past. The most detailed information one can expect to obtain is an areal percentage of the various crops, and the types of farming practices that have been carried out in the area. Based on this information a series of 14 crop rotation schemes covering the period of interest was established, and at random distributed over the area.

Based on estimated application rates of organic and mineral fertilizer to the individual crops each year, the DAISY model simulates the crop growth, root uptake, mineralization and leakage of nitrate from the root zone. Figure 23.12 shows time series of application and leakage for selected crop rotation schemes. On farms which are based on mainly meat production a large amount of organic fertilizer will often be applied on the fields in the autumn. In this period there is a potential risk for significant losses to the groundwater system.

![Diagram](image)

**Fig. 23.12.** Nitrate leaching (NO₃⁻-N) from three of the crop rotations calculated by DAISY and summarized over four-months periods. The shown additions of N only include mineral fertilizer and the already mineralized part of manure.

Nitrate concentrations in groundwater

While the root zone model simulates one 'soil column' at a time the total model allows studies of the variations in space and time at regional scale. Fig. 23.13 illustrates the variation in simulated NO₃⁻-concentrations in the upper groundwater layer of the Karup catchment below three selected cropping schemes for two points with different depths of the unsaturated zone. A deep unsaturated zone is seen to dampen the influence of a single year.

Figure 23.14 shows the spatial variation in simulated NO₃⁻-concentrations in the upper groundwater layer at a specific time. The very large variation of concentration both in space and time is noticed.

![Diagram](image)

**Fig. 23.13.** Temporal variation in NO₃⁻-concentrations in the upper groundwater layer beneath three selected rotation schemes, with two different distances to the groundwater table. The data are extracted from selected grids (not averaged).
REFERENCES


DHI (1993): Validation of hydrological models, Phase II. Danish Hydraulic Institute, Hørsholm.


23 / References


Chapter 24

SWRRB--A WATERSHED SCALE MODEL FOR SOIL AND WATER RESOURCES MANAGEMENT

J.G. Arnold and J.R. Williams

24.1. INTRODUCTION

A model called SWRRB (Simulator for Water Resources in Rural Basins) was developed for simulating hydrologic and related processes in rural basins (Williams et al., 1985). The objective in model development was to predict the effect of management decisions on water and sediment yields with reasonable accuracy for ungaged rural basins throughout the U.S. To satisfy the objective, the model had to be (a) physically based, using readily available inputs (calibration is not possible on ungaged basins); (b) capable of computing the effects of management changes on outputs; (c) computationally efficient to allow simulation on a variety of management strategies without excessive cost; (d) capable of simulating long periods for use in frequency analysis; and (e) capable of operating on subdivided basins (soils, land use, management, etc. make subdivision necessary).

To create SWRRB, the CREAMS daily rainfall hydrology model was modified for application to large, complex, rural bains. The major changes involved were (a) the model was expanded to allow simultaneous computations on several subbasins to predict the basin water yield; (b) a return flow component was added; (c) a reservoir storage component was added for use in determining the effects of farm ponds and reservoirs on water and sediment yield; (d) a weather simulation model (rainfall, solar radiation, and temperature) was added to provide for longer term simulations and more representative weather inputs, both temporally and spatially; (e) a better method was developed for predicting the peak runoff rate; (f) a crop growth model was added to account for annual variation in growth; (g) a simple flood routing component was added; (h) components were added to simulate sediment movement through ponds, reservoirs, streams, and valleys; and (i) transmission losses were calculated.
Chapter 24

SWRRB--A WATERSHED SCALE MODEL FOR SOIL AND WATER RESOURCES MANAGEMENT

J.G. Arnold and J.R. Williams

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Recently, most of the SWRRB model development has been focused on problems involving water quality. Example additions include the GLEAMS (Leonard et al., 1987) pesticide fate component, optional SCS technology for estimating peak runoff rates and newly developed sediment yield equations. These and other less significant developments extend SWRRB's capabilities to deal with a wide variety of watershed management problems. The major processes included in the model are surface runoff, percolation, return flow, evapotranspiration, transmission losses, pond and reservoir storage, sedimentation, pesticide fate, nutrient cycling, and crop growth.

24.2. APPLICATIONS

The SWRRB model is currently being used throughout the world by consulting engineers, government agencies, universities, and chemical companies. Several applications follow to demonstrate the model's potential capabilities.

Hydrology Unit Model of the United States (HUMUS). The SCS is using the EPIC (Erosion-Productivity Impact Calculator), SWRRB, and ROTO models as part of the 1997 Resource Conservation Assessment. The models will be linked to national economic models and used for national planning of water supply and quality on the 18 major river basins in the U.S. This system of models allows water, sediment, and attached pollutants to be tracked from their point of origin to major rivers, reservoirs, and coastal zones. Geographic information systems are utilized to integrate the models with national soils, land use, and digital elevation databases. The GIS automatically extracts model input from the map layers and display model output.

Coastal Pollutant Discharge Inventory. As a part of the National Coastal Pollutant Discharge Inventory, the National Oceanic and Atmospheric Administration (NOAA) is using SWRRB to estimate non-point source loadings from non-urban lands in all coastal counties of the U.S. (Singer et al., 1988). Site-specific data are obtained from the SCS's National Resources Inventory and Soils-5 data bases, NOAA weather stations, U.S. Geological Survey digital land use data tapes, and other local sources. Simulations have been run for cropland, rangeland, and forest land in approximately 770 subwatersheds comprising the Gulf Coast, eastern, and western coastal zones of the U.S. Results are compiled by season and added to a comprehensive data base containing pollutant loadings from all significant discharge sources.

Pesticide Assessment. SWRRB was modified to include simulation of pesticide concentration in the runoff and sediment. The EPA has adopted this version of SWRRB as its pesticide assessment model. They have prepared their own user's manual, "Pesticide Runoff Simulator" (Holst and Kutney, 1987). Many chemical companies and consulting firms are using this version of the model for environmental assessment.

Effect of Urbanization on Reservoir Loadings. White Rock Lake in Dallas was built in 1910. The SCS completed sediment surveys on the lake in 1935, 1956, 1970, 1977, and 1984. Throughout this period, the percentage of urban area has increased from 0 to 77% in 1984. SWRRB was utilized to estimate the effects of urbanization on water and sediment delivery to White Rock Lake (Arnold et al., 1987).

Initially, simulated model results were compared with measured water yields, peak flow rates, and sediment yields. The comparisons showed that the model could do a reasonable job predicting the effect of urbanization on these variables. Also, the effect of urbanization on delivery ratios showed a positive linear correlation.

24.3. HYDROLOGY

The hydrology model is based on the water balance equation

$$SW_t = SW + \sum_{i=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i)$$  \hspace{1cm} (24.1)

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; 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, soils, etc. Thus, runoff, is predicted separately for each subarea and routed to obtain the total runoff for the basins. This increases accuracy and gives a much better physical description of the water balance.

24.3.1. Surface Runoff

The runoff model simulates surface runoff volumes and peak runoff rates, given daily rainfall amounts. Runoff volume is estimated by using a modification of the Soil Conservation Service (SCS) curve number technique (USDA-SCS, 1972). The technique was selected for use because (a) it is reliable and has been used for many years in the United States; (b) it
is computationally efficient; (c) the required inputs are generally available; and (d) it relates runoff to soil type, land use, and management practices. The use of readily available daily rainfall data is a particularly important attribute of the curve number technique because for many locations, rainfall data with time increments of less than 1 day are not available. Also, rainfall data manipulations and runoff computations are more efficient for data taken daily than at shorter intervals.

There are two options for estimating the peak runoff rate -- the modified Rational formula and the SCS TR-55 method (USDA-SCS, 1986). A stochastic element is included in the Rational equation to allow realistic simulation of peak runoff rates, given only daily rainfall and monthly rainfall intensity.

Runoff Volume

Surface runoff is predicted for daily rainfall by using the SCS curve number equation (USDA-SCS, 1972)

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

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

(24.2)

where \(Q\) is the daily runoff, \(R\) is the daily rainfall, and \(s\) is a retention parameter (see "Notations" section). The retention parameter, \(s\), varies (a) among watersheds because 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-SCS, 1972)

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

(24.3)

The constant, 254, in Eq. (24.3) gives \(s\) in mm. Thus, \(R\) and \(Q\) are also expressed in mm. \(CN_2\) -- the curve number for moisture condition 2, or average curve number -- can be obtained easily for any area by using the SCS hydrology handbook (USDA-SCS, 1972). The handbook tables consider soils, land use, and management. Assuming that the handbook \(CN_2\) value is appropriate for a 5% slope, we developed the following equation for adjusting that value for other slopes.

\[
CN_{2s} = \frac{1}{3}(CN_3 - CN_2) [1 - 2 \exp(-13.86S)] + CN_2
\]

(24.4)

where \(CN_{2s}\) is the handbook \(CN_2\) value adjusted for slope, \(CN_3\) is the curve number for moisture condition 3 (wet), and \(S\) is the average slope of the watershed. Values of \(CN_1\), the curve number for moisture condition 1 (dry), and \(CN_3\) corresponding to \(CN_2\) are also tabulated in the handbook. For computing purposes, \(CN_1\) and \(CN_3\) were related to \(CN_2\) with the equations

\[
CN_1 = CN_2 - \frac{20 (100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)]}
\]

(24.5)

\[
CN_3 = CN_2 \exp[0.00673 (100 - CN_2)]
\]

(24.6)

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

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

(24.7)

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. FCC is computed with the equation

\[
FFC = \frac{SW - WP}{FC - WP}
\]

(24.8)

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 Eq. (24.7) according to the assumptions that \(s=s_2\) when FCC=0.6 and \(s=s_3\), when \((SW-FC)/(PO-FC)=0.5\)

\[
w_1 = \ln\left( \frac{60}{1 - s_2/s_1} - 60 \right) + 60 \cdot w_2
\]

(24.9)

\[
w_2 = \ln\left( \frac{60}{1 - s_2/s_1} - 60 \right) - \ln\left( \frac{POFC}{1 - s_3/s_1} - POFC \right)
\]

(24.10)

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

\[
POFC = 100 \cdot \frac{\sum_{\ell=1}^{M} (POF_{\ell} - FC_{\ell})}{\sum_{\ell=1}^{M} (FC_{\ell} - WP_{\ell})}
\]

(24.11)
where \( \rho \) is the porosity of soil layer \( \ell \). Equations (24.9) and (24.10) assure that \( CN_1 \) corresponds with the wilting point and that the curve number cannot exceed 100.

The FFC value obtained in Eq. (24.8) 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. For example, water distributed near the soil surface results in more runoff than the same volume of water uniformly distributed throughout the top meter of soil. Also, a soil surface associated with a uniform distribution of soil water results in more runoff than a soil surface that is dry. Since SWRRB estimates water content of each soil layer daily, the depth distribution is available. The effect of depth distribution on runoff is expressed in the depth weighting function

\[
FFC^* = \frac{\sum_{\ell=1}^{M} FFC_{\ell} \frac{Z_{\ell} - Z_{\ell-1}}{Z_{\ell}}}{\sum_{\ell=1}^{M} \frac{Z_{\ell} - Z_{\ell-1}}{Z_{\ell}}}, \quad Z_{\ell} \leq 1.0m
\]  

(24.12)

where \( FFC^* \) is the depth weighted FFC value for use in Eq. (24.7), \( Z \) is the depth in m to the bottom of soil layer \( \ell \), and \( M \) is the number of soil layers. Equation (24.12) performs two functions: (1) it reduces the influence of lower layers because \( FFC_{\ell} \) is divided by \( Z_{\ell} \) and (2) it gives proper weight to thick layers relative to thin layers because FFC is multiplied by the layer thickness.

There is also a provision for estimating runoff from frozen soil. If the temperature in the second soil layer is less than 0°C, the retention parameter is reduced by using the equation

\[
s_f = 0.1s
\]  

(24.13)

where \( s_f \) is the retention parameter for frozen ground. Equation (24.13) increases runoff for frozen soils but allows significant infiltration when soils are dry.

**Peak Runoff Rate**

SWRRB contains two methods for estimating peak runoff rate—the modified Rational formula and the SCS TR-55 method (USDA-SCS, 1986).

**Rational Equation Method.** The rational equation can be written in the form

\[
q_p = (\rho) (r) (A) / 360
\]  

(24.14)

where \( q_p \) is the peak runoff rate in \( \text{m}^3 \cdot \text{s}^{-1} \), \( \rho \) is a runoff coefficient expressing the watershed infiltration characteristics, \( r \) is the rainfall intensity

\[
\text{in mm} \cdot \text{h}^{-1} \quad \text{for the watershed's time of concentration, and A is the drainage area in ha. The runoff coefficient can be calculated for each storm if the amount of rainfall and runoff are known}
\]

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

(24.15)

Since \( R \) is input and \( Q \) is computed with Eq. (24.1), \( \rho \) can be calculated directly. Rainfall intensity can be expressed with the relationship

\[
r = \frac{R_{tc}}{t_c}
\]  

(24.16)

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 \( R \). The Weather Service's TP-40 (Hershfield, 1961) provides accumulated rainfall amounts for various durations and frequencies. Generally, \( R_{tc} \) and \( R_{24} \) (24-h duration is appropriate for the daily time step model) are proportional for various frequencies. Thus,

\[
R_{tc} = \alpha R_{24}
\]  

(24.17)

where \( \alpha \) is a dimensionless parameter that expresses the proportion of total rainfall that occurs during \( t_c \).

The peak runoff equation is obtained by substituting Eqs. (24.15), (24.16), and (24.17) into Eq. (24.14).

\[
q_p = \frac{(\alpha) (Q) (A)}{360 \cdot (t_c)}
\]  

(24.18)

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

\[
t_c = t_{cc} + t_{cs}
\]  

(24.19)

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

\[
t_{cc} = \frac{L_c}{v_c}
\]  

(24.20)

where \( L_c \) is the average channel flow length for the watershed in km and \( v_c \) is the average channel velocity in \( \text{m} \cdot \text{s}^{-1} \). The average channel flow length can be estimated by using the equation

\[
L_c = \sqrt{LI(L_{ca})}
\]  

(24.21)
where L is the channel length from the most distant point to the watershed outlet in km and L_{cc} 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 gives

\[ t_{cc} = \frac{\sqrt{(L/L_{cc})^2}}{0.489q_{c}^{0.25}(\sigma)^{0.375}} \]  

(24.22)

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

\[ t_{cc} = \frac{1.75 (L^*) (n)^{0.75}}{(q_{c}^* \cdot \sigma)^{0.25}} \]  

(24.23)

where L^* is the channel length in km and q_{c}^* is the average flow rate in mm\cdot h^{-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

\[ q_{c}^* = q_{o}^* A^{-0.5} \]  

(24.24)

where q_{o}^* is the average flow rate from a 1 ha area in mm\cdot h^{-1}. The unit source flow rate is estimated with the equation

\[ q_{o}^* = \frac{Q}{DUR} \]  

(24.25)

where DUR, the rainfall duration in h is calculated using the equation

\[ DUR = \frac{4.605}{-2 \ln(1 - \alpha_s)} \]  

(24.26)

where \alpha_s is computed with Eq. (24.17) using R_s instead of R_{cc}. Equation (24.26) is derived assuming rainfall intensity is exponentially distributed. Details of the procedure for estimating \alpha_s and DUR are given in the water erosion section of this chapter.

Substituting Eq. (24.25) into Eq. (24.23) gives the final equation for t_{cc}

\[ t_{cc} = \frac{1.75 (L^*) (n)^{0.75}}{(q_{o}^*)^{0.25} (A)^{0.125} (\sigma)^{0.375}} \]  

(24.27)

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

\[ t_{cs} = \frac{\lambda}{v_s} \]  

(24.28)

where \lambda is the surface slope length in m and \nu_s is the surface flow velocity in m\cdot s^{-1}.

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

\[ v_s = \frac{0.8375 \cdot d^{0.666} s^{0.5}}{n} \]  

(24.29)

where v_s is the flow velocity in m^3s^{-1}, d is flow depth in m, s is the land surface slope in m\cdot m^{-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

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

(24.30)

where q_{o} is the average flow rate in m^3s^{-1}. Substituting Eqs. (24.29) and (24.30) into Eq. (24.28) gives

\[ t_{cs} = \frac{0.0216 (\lambda \cdot n)^{0.75}}{(q_{o}^*)^{0.25} (s)^{0.375}} \]  

(24.31)

To properly evaluate \alpha, variation in rainfall patterns must be considered. For some short duration storms, most or all the rain occurs during t_{cc} causing \alpha to approach its upper limit of 1.0. Other storms of uniform intensity cause \alpha to approach a minimum value. All other patterns cause higher \alpha values than the uniform pattern, because r_{cc} is greater than r_{24} for all patterns except the uniform. By substituting the products of intensity and time into Eq. (24.17), an expression for the minimum value of \alpha, \alpha_{min}, is obtained

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

(24.32)

Thus, a ranges within the limits

\[ t_{c}/24 \leq \alpha \leq 1.0 \]

Although confined between limits, the value of a 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 \( \frac{t_c}{24} \) to 1.0.

The peak of the \( \alpha \) distribution changes monthly because of seasonal differences in rainfall intensities. The Weather Service (U.S. Department of Commerce, 1979) provides information on monthly maximum rainfall intensities that can be used to estimate the peak \( \alpha \) for each month.

**TR-55 Method.** The SCS TR-55 Method for estimating peak runoff rate has been described in detail (USDA-SCS, 1986). Only the essential equations are presented here. The peak runoff rate is dependent on the rainfall distribution and amount, the runoff curve number, and the time of concentration as expressed in the equation

\[
q_p = (q^*_p) (R)
\]  
(24.33)

where \( q_p \) is the peak rate in mm\( \cdot \)h\(^{-1}\), \( q^*_p \) is the peak rate per unit of rainfall in mm\( \cdot \)h\(^{-1}\)\( \cdot \)mm\(^{-1}\), and \( R \) is the storm rainfall amount in mm. A set of curves are available (USDA-SCS, 1986) for estimating \( q^*_p \) given rainfall distribution (SCS Type I, IA, II, or III), the runoff curve number, and the watershed time of concentration. A map of the United States is given (USDA-SCS, 1986) to determine appropriate storm type. The curves relating \( q^*_p \), \( t_c \), and CN have been fitted with a seventh degree polynomial for use in computer solutions.

Time of concentration is estimated with the equation

\[
t_c = t_{cc} + t_{cs} + t_{sf}
\]  
(24.34)

where \( t_c \) is the watershed time of concentration in h and \( t_{cc}, t_{cs}, \) and \( t_{sf} \) are the \( t_c \) components attributed to channel flow, surface flow, and shallow channel flow. The channel component is computed with the equation

\[
t_{cc} = \frac{(L - \lambda - L_{sf}) n}{3.6 d^{0.67} \sigma^{0.5}}
\]  
(24.35)

where \( t_{cc} \) is the channel time of concentration in h, \( L \) is the channel length from the most distant point to the watershed outlet in km, \( \lambda \) is the surface slope length in km, \( L_{sf} \) is the shallow flow length in km, \( \sigma \) is Manning’s roughness coefficient, \( d \) is the average channel flow depth in m, and \( n \) is the channel slope in m\( \cdot \)m\(^{-1}\). The shallow flow component of \( t_c \) is estimated with the equation

\[
t_{sf} = \frac{L_{sf}}{v_{sf}}
\]  
(24.36)

where \( v_{sf} \) is the average shallow flow velocity in km\( \cdot \)h\(^{-1}\) is estimated with the equation

\[
v_{sf} = 17.7 S^{0.5} \leq 2.19 km \cdot h^{-1}
\]  
(24.37)

where \( S \) is surface flow slope in m\( \cdot \)m\(^{-1}\). The length of shallow flow, \( L_{sf} \) is estimated with the equations

\[
\begin{align*}
L_{sf} &= 0.05 & L > 0.1 km \\
&= L - 0.05 & 0.05 < L \leq 0.1 km \\
&= 0.0 & L \leq 0.05 km
\end{align*}
\]  
(24.38)

Note that \( t_{sf} \) is constrained to less than 0.1 h even with \( S = 0.001 \). Thus, \( t_{sf} \) is generally insignificant. The surface flow component of \( t_c \) is estimated with the equation

\[
t_{cs} = \frac{0.0913 (\lambda \cdot n)^{0.8}}{S^{0.4} \cdot R^{0.5}}
\]  
(24.39)

**Percolation**

The percolation component of SWRRRB uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer. Once groundwater below the rootzone, 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

\[
SW_i = SW_{oi} \exp(-\Delta t/TT_i)
\]  
(24.40)

where \( SW_i \) and \( SW \) and 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 \( SW_i \) from \( SW_{oi} \):

\[
O_i = SW_{oi}[1 - \exp(-\Delta t/TT_i)]
\]  
(24.41)

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

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

\[
TT_i = (SW_i - FC_i)/H_i
\]  
(24.42)

where \( H_i \) is the hydraulic conductivity in mm\( \cdot \)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.

\[
H_i = SC_i \left( \frac{SW_i}{UL_i} \right)^{\beta_i}
\]  
(24.43)
where \( SC_i \) is the saturated conductivity for layer \( i \) in mm•h\(^{-1}\) and is a parameter that causes \( H_i \) to approach zero as \( SW_i \) approaches \( FC_i \).

The equation for estimating \( \beta \) is

\[
\beta_i = \frac{-2.655}{\log_{10}(FC_i/UL_i)}
\]

(24.44)

The constant (-2.655) in Eq. (24.44) was set to assure \( H_i = 0.002SC_i \) at field capacity.

Flow through a soil layer may be reached by a saturated lower soil layer. If the layer immediately below the layer being considered is saturated, no flow can occur. The effect of lower layer water content is expressed in the equation

\[
O_{ci} = O_i \sqrt{1 - \frac{SW_i + 1}{UL_i + 1}}
\]

(24.45)

where \( O_{ci} \) is the percolation rate for layer \( i \) in mm•d\(^{-1}\) corrected for layer \( i+1 \) water content and \( O_i \) is the percolation computed with Eq. (24.41).

The crack-flow model allows percolation of infiltrated rainfall even though the soil water content is less than field capacity. When the soil is dry and cracked, infiltrated rainfall can flow through the cracks of a layer without becoming part of the layer’s soil water. However, the portion that does become part of a layer’s stored water cannot percolate until the storage exceeds field capacity.

Crack-flow is simulated with the relationships similar to those used to estimate percolation above field capacity. The amount of percolate caused by crack flow is estimated with the equation

\[
O_i = O_{i-1} \left[ \exp(-\Delta t / TT_{ci}) \right]
\]

(24.46)

where \( O_{i-1} \) is the flow from the layer above in mm•d\(^{-1}\) (R-Q for the top layer) and \( TT_{ci} \) is the crack flow travel time in h. Crack flow travel time is estimated with the equation

\[
TT_{ci} = \frac{I_{i-1}}{(\zeta_i)}
\]

(24.47)

where \( \zeta_i \) is a dimensionless (0-1) soil parameter that expressed degree of cracking and is a function of soil water and clay content.

\[
\zeta_i = 0.01(CL_A)_i \left(1 - \frac{SW}{SW + \exp(7.0 - 0.11SW)}\right)
\]

(24.48)

where \( CL_A_i \) is the clay content of soil layer \( i \) (0-1).

Percolation is also affected by soil temperature. If the temperature in a particular layer is \( T^\circ C \) or below, no percolation is allowed from that layer.

Water can, however, percolate into the layer as dictated by Eqs. (24.41) and (24.46).

Since the one-day time interval is relatively low for routing flow through soils, it is desirable to divide the water into several parts for routing. This is necessary because flow rates are dependent upon soil water content which is continuously changing. For example, if the soil is extremely wet, Eqs. (24.41), (24.42), and (24.43) might greatly over estimate percolation if only one routing was performed using the entire amount (\( SW-FC_i \)). To overcome this problem, SWRRB divides each layer’s inflow into 4-mm slugs for routing. Also, by dividing the inflow into 4-mm slugs and routing each slug individually through all layers, the lower layer water content relationship (Eq. (24.43)) is allowed to function. The lower layer water content effect cannot be calculated realistically by routing all of the input through one layer before proceeding to the next layer.

### 24.3.2. Lateral Subsurface Flow

The kinematic storage model developed by Sloan et al. (1983) uses the mass continuity equation with the entire soil profile as the control volume. The mass continuity equation in finite difference form for the kinematic storage model is

\[
\frac{S_2 - S_1}{t_2 - t_1} = iL - q_{lat1} + q_{lat2} \frac{1}{2}
\]

(24.49)

where \( S \) is the drainable volume of water stored in the saturated zone m•m\(^{-1}\) (water above field capacity), \( t \) is time in h, \( q_{lat} \) is the lateral flow in m\(^3\)•h\(^{-1}\), \( i \) is the rate of water input to the saturated zone in m\(^2\)•h\(^{-1}\), \( L \) is the hillslope length in m, and subscripts 1 and 2 refer to the beginning and end of the time step, respectively. The saturated thickness normal to the hillslope, \( H_o \), is

\[
H_o = \frac{2S}{\Theta_d L}
\]

(24.50)

where \( \Theta_d \) is the drainable porosity of the soil. The drainable volume of water stored, \( S \), is updated daily in the watershed model. The lateral flow at the hillslope outlet is given by

\[
q_{lat} = H_o \nu w
\]

(24.51)

where \( \nu \) is the velocity of flow at the outlet and \( w \) is the hillslope width. Velocity at the outlet is estimated from

\[
\nu = K_s \sin(\alpha)
\]

(24.52)
where $K_s$ is the saturated conductivity. Combining Eqs. (24.50) and (24.52) into 51 yields

$$q_{sat} = 0.024 \frac{2 S K_s \sin(\alpha)}{\Theta_d L}$$  \hspace{1cm} (24.53)

where $q_{sat}$ is in mm·d⁻¹, $S$ in m·h⁻¹, $\alpha$ in m·m⁻¹, $\Theta_d$ in m·m⁻¹, and $L$ in m. If the saturated zone rises above the soil later, water is allowed to flow to the layer above (back to the surface for the upper soil layer). The amount of flow upward is estimated from $K_s$ and the saturated slope length.

$$q_{sat} = 24 K_s L_s / L$$  \hspace{1cm} (24.54)

where $q_{sat}$ is the upward flow in mm·d⁻¹, and $L_s$ is the saturated slope length in m.

Most comprehensive hydrologic models divide the soil profile into multiple layers, and allow for percolation from one soil layer to the next and percolation from the bottom soil layer past the soil profile (as recharge to the shallow aquifer). To account for multiple layers, the model is applied to each soil layer independently starting at the upper layer.

### 24.3.3. Evapotranspiration

The model offers two options for estimating potential evaporation-Hargreaves and Samani (1985), and Priestley-Taylor (1972). The Priestley-Taylor method requires solar radiation and air temperature as input. The Hargreaves method requires air temperature only.

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 evaporation and leaf area index (LAI, area of plant leaves relative to the soil surface area). 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.

#### Potential Evaporation

The Priestley-Taylor (1972) method provides estimated potential evaporation based only on temperature and radiation is

$$E_o = 1.28 \left( \frac{h_o}{HV} \right) \left( \frac{\delta}{\delta + y} \right)$$  \hspace{1cm} (24.55)

where $E_o$ is the potential evaporation in mm, $\delta$ is the slope of the saturation vapor pressure curve in kPa·C⁻¹, $\gamma$ is a psychrometer constant in kPa·C⁻¹·h, $h_o$ is the net radiation in MJ·m⁻², and $HV$ is the latent heat of vaporization in MJ·kg⁻¹. The latent heat of vaporization is estimated with the temperature function

$$HV = 2.50 - 0.0022 T$$  \hspace{1cm} (24.56)

where $T$ is the mean daily air temperature in °C. The saturation vapor pressure is also estimated as a function of temperature by using the equation

$$e_a = 0.1 \exp \left( 54.88 - 5.03 \ln \left( T + 273 \right) - \frac{6791}{T + 273} \right)$$  \hspace{1cm} (24.57)

The slope of the saturation vapor pressure curve is estimated with the equation

$$\delta = \left( \frac{e_a}{T + 273} \right) \left( \frac{6791}{T + 273} + 5.03 \right)$$  \hspace{1cm} (24.58)

The psychrometer constant is computed with the equation

$$\gamma = 6.6 \times 10^{-4} PB$$  \hspace{1cm} (24.59)

where $PB$ is the barometric pressure (kPa). The barometric pressure is estimated as a function of elevation by using the equation

$$PB = 101 - 0.0115 ELEV + 5.44 \times 10^{-7} ELEV^2$$  \hspace{1cm} (24.60)

where $ELEV$ is the elevation of the site in m.

The maximum possible solar radiation is computed with the equations

$$RAMX = 30 \left( 1.0 + 0.0335 \sin \left( \frac{2\pi}{365} (i + 88.2) \right) \right)$$  \hspace{1cm} (24.61)

$$XT \sin \left( \frac{2\pi}{360} LAT \right) \sin(SD) + \cos \left( \frac{2\pi}{360} LAT \right) \cos(SD) \sin(XT)$$

$$XT = \cos^{-1} \left( -\tan \left( \frac{2\pi}{360} LAT \right) \tan(SD) \right), \hspace{0.5cm} 0 \leq XT \leq \pi$$  \hspace{1cm} (24.62)

where $LAT$ is the latitude of the site in degrees, $SD$ is the sun's declination angle (radians), and $i$ is the day of the year. The sun's declination angle is calculated with the equation

$$SD_i = 0.4102 \sin \left[ \frac{2\pi}{365} (i - 80.25) \right]$$  \hspace{1cm} (24.63)
The net radiation is estimated with the equation

$$h_{oi} = RA_i (1 - AB_{si})$$  \hspace{1cm} (24.64)$$

where $RA_i$ is the solar radiation in MJ m$^{-2}$ and $AB_{si}$ is albedo.

The Hargreaves and Samani (1985) method estimates potential evaportranspiration as a function of extraterrestrial radiation and air temperature. Hargreaves' method was modified for use in SWRRB 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. The modified equation is

$$E_o = 0.0032 \left( \frac{RAMX}{HV} \right) (T + 17.8) (T_{mx} - T_{mm})^{0.6}$$  \hspace{1cm} (24.65)$$

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

Both methods estimate albedo by considering the soil, crop, and snow cover. If a snow cover exists with 5 mm or greater water content, the value of albedo is set to 0.6. If the snow cover is less than 5 mm and no crop is growing, the soil albedo is the appropriate value. When crops are growing, albedo is determined by using the equation

$$AB = 0.23 (1.0 - EA) + (AB_s)(EA)$$  \hspace{1cm} (24.66)$$

where 0.23 is the albedo for plants, $AB_s$ is the soil albedo, and $EA$ is a soil cover index. The value of $EA$ ranges from 0 to 1.0 according to the equation

$$EA = \exp(-0.05CV)$$  \hspace{1cm} (24.67)$$

where CV is the sum of the above ground biomass and crop residue in t*ha$^{-1}$.

**Soil and Plant Evaporation**

The model computes evaporation from soils and plants separately by an approach similar to that of Ritchie (1972).

$$E_p = \frac{(E_o)(LAI)}{3.0}, \quad 0 \leq LAI \leq 3.068$$ \hspace{1cm} (24.68)$$

$$E_p = E_o, \quad LAI > 3.0$$ \hspace{1cm} (24.69)$$

where $E_p$ is the predicted plant water evaporation rate in mm•d$^{-1}$. If soil water is limited, plant water evaporation will be reduced as described in the plant growth section of this chapter.

Potential soil water evaporation is simulated by considering soil cover according to the following equation

$$E_s = (E_o)(EA)$$  \hspace{1cm} (24.70)$$

where $E_s$ is the potential soil water evaporation rate in mm•d$^{-1}$. Potential soil water evaporation is reduced during periods of high plant water use with the equation

$$E_s^* = \min \left[ ES, \frac{(E_s)(EA)}{E_s + E_p} \right]$$  \hspace{1cm} (24.71)$$

When $E_p$ is low $E_s^* \rightarrow E_s$ but as $E_p$ approaches $E_o$, $E_s^* \rightarrow E_o/(1.+EA)$.

Actual soil water evaporation is estimated on the basis of the top 0.2 m of soil and snow cover, if any. If 5 mm or more (water content) of snow is present albedo is set to 0.6 and EA to 0.5 for estimating $E_o$ and snow is evaporated at that rate. When all snow is evaporated, soil water evaporation begins. Such evaporation is governed by soil depth and water content according to the equation

$$EV_Z = E_s^* \left[ \frac{Z}{Z + \exp (2.374 - 0.00713 \cdot Z)} \right]$$  \hspace{1cm} (24.72)$$

$EV$ is the total soil water evaporation in mm from soil of depth $Z$ in mm. The coefficients of Eq. (24.72) are set to give $EV=0.5 \ E_s^*$ when $Z=10$ mm and $EV=0.95 \ E_s^*$ when $Z=100$ mm.

Potential soil water evaporation for a layer is estimated by taking the difference between $EV$'s at the layer boundaries

$$SEV_{\ell} = EV_{\ell(t)} - EV_{\ell(t-1)}$$  \hspace{1cm} (24.73)$$

where $SEV$ is the potential soil evaporation for layer $\ell$ in mm.

The depth distributed estimate of soil water evaporation may be reduced according to the following equation if soil water is limited in a layer

$$SEV_{\ell}^* = SEV_{\ell} \ \exp \left( \frac{2.5(SW_{\ell} - FC_{\ell})}{FC_{\ell} - WP_{\ell}} \right), \quad SW_{\ell} < FC_{\ell}$$  \hspace{1cm} (24.74)$$

where $SEV_{\ell}^*$ is the adjusted soil water evaporation estimate in mm.

$$SEV_{\ell}^* = SEV_{\ell}, \quad SW_{\ell} \geq FC_{\ell}$$  \hspace{1cm} (24.75)$$

The final step in adjusting the evaporation estimate is to assure that the soil water supply is adequate to meet the demand

$$SEV_{\ell}^* = \min \left( SEV_{\ell}^*, SW_{\ell} - b_{\ell} WP_{\ell} \right)$$  \hspace{1cm} (24.76)$$
where $b_w$ may range from 0. to 1.0 in the top 0.5 m of soil and is set to 1.0 below 0.5 m. Thus, SWRRB can be adjusted to allow the top 0.5 m to dry down to any fraction of wilting point.

### 4.3.4. Snowmelt

If snow is present, it may be melted on days when the second soil layer temperature exceeds 0°C. Snow is melted as a function of the snowpack temperature using the equation

$$ SML = T (1.52 + 0.54 \cdot SPT) \quad (24.77) $$

where $SML$ is the snowmelt rate in mm*d^-1, $SNO$ is the snow present in mm of water, $T$ is the mean daily air temperature in °C, and $SPT$ is the snowpack temperature in °C. The snowpack temperature is estimated with the equation

$$ SPT = \min \left( T_s, T(2) \right) \quad (24.78) $$

where $T_s$ is the temperature at the top of the snowpack and $T(2)$ is the temperature at the center of soil layer 2. The equations for estimating $T_s$ and $T(2)$ are presented in the soil temperature section. Melted snow is treated the same as rainfall for estimating runoff volume and percolation, but infall energy is set to 0.0 and peak runoff rate is estimated by assuming uniformly distributed rainfall for a 24-h duration.

### 4.3.5. Transmission Losses

Any semi-arid watersheds have alluvial channels that abstract large quantities of streamflow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volumes as water is lost as the flood wave travels upstream. Chapter 19 of the SCS Hydrology Handbook (USDA, 1983 update) by Leonard J. Lane describes a procedure for estimating transmission losses for ephemeral streams. This procedure is used in SWRRB when channel data (width, depth, Manning's "n") are available. It is based on the method for estimating transmission losses in the absence of served inflow or outflow data assuming no lateral inflow or out-of-bank flow. The procedure is based on derived regression equations and enables a user to estimate transmission losses for similar channels of arbitrary length and width. Analysis of observed data resulted in regression equations for peak discharge after losses $q_p$ is

$$ a_r = -0.001831 \cdot (CHK) \cdot DUM \quad (24.79) $$

$$ k_r = -1.09 \ln(1.0 - 0.2649) \cdot (CHK) \cdot DU / P \quad (24.80) $$

where $a_r$ is the unit channel intercept in m³, CHK is the effective hydraulic conductivity of the channel alluvium in mm/hr (Lane, 1982; USDA, 1983 update), DU is the duration of streamflow in h, $k_r$ is the decay factor in m·km⁻¹·P_in is inflow volume of m³, and $b_r$ is the unit channel regression slope. The regression parameters are

$$ a_x = \left[ a_r \left( 1 - b_r \right) \right] (1.0 - b_r L_c) \quad (24.82) $$

$$ b_x = e^{-2.04k_r} \cdot L_c \cdot w \quad (24.83) $$

$$ P_o = -a_x / b_x \quad (24.84) $$

where $a_x$ is the regression intercept in m·km⁻¹, $b_x$ is the regression slope, $w$ is average width of flow in m, $L_c$ is length of reach in km, and $P_o$ is the threshold volume for a unit channel in m³. The prediction equation for volume after losses, $Q_l$, is

$$ Q_l = 0 \quad P_m < P_o \quad (24.85) $$

$$ Q_l = -a_x + b_x P_m \quad P_m > P_o $$

Transmission losses are calculated twice for each subbasin. First, losses occurring within the subbasin are estimated. The inflow volume, $P$, is assumed to be equal to the surface runoff from the subbasin. The flow duration, is estimated from

$$ DU = (Q_l (A)/(1.8 \cdot q_p)) \quad (24.86) $$

where $Q$ is the surface runoff volume in mm, $A$ is the drainage area in ha, and $q_p$ is the peak flow rate in m³·s⁻¹. Then losses occurring from the subbasin outlet to the basin outlet are estimated. The prediction equation for peak discharge after losses $q_p$, is

$$ q_{pl} = 0 \quad Q = 0 \quad (24.87) $$

$$ q_{pl} = 12.1 a_x / DU - (1.0 - b_x) P_m + b_x q_p \quad Q > 0 $$

Now duration of flow from subbasin to basin outlet is estimated with Eq. (24.86) using $Q_l$ and $q_{pl}$, and the procedure is repeated to estimate losses from the subbasin outlet to the basin outlet. The volume and peak rate after losses are

$$ Q_l = Q - TL \quad (24.88) $$

where TL is the transmission loss in mm.
24.4. WEATHER

The weather variables necessary for driving SWRRB are precipitation, air temperature, and solar radiation. If daily precipitation data are available, they can be input directly to SWRRB. If not, the weather component of the model can simulate daily rainfall and temperature. Solar radiation is always simulated. One set of weather variables may be simulated for the entire basin, or they can be simulated for each subbasin. Descriptions of the models used for simulating precipitation, temperature, and solar radiation follow.

24.4.1. Precipitation

The SWRRB precipitation model developed by Nicks (1974) is a first-order Markov chain model. Thus, input for the model must include monthly probabilities of receiving precipitation. On any given day, the input must include information as to whether the previous day was dry or wet. A random number 0--1 is generated and compared with the appropriate wet-day probability. If the random number is less than or equal to the wet-day probability, precipitation occurs on that day. Random numbers greater than the wet-day probability give no precipitation. Since the wet-day 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-day probabilities are not available, the average monthly number of rainy days may be substituted. The probability of a wet day is calculated directly from the number of wet days:

\[ PW = \frac{NWD}{ND} \quad (24.89) \]

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:

\[ P(W/D) = \beta PW \quad (24.90) \]

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. The probability of a wet day following a wet day can be calculated directly by using the equation

\[ P(W/W) = 1.0 - \beta + P(W/D) \quad (24.91) \]

where P(W/W) is the probability of a wet day after a wet day. When \( \beta \rightarrow 1.0 \), wet days do not affect probability of rainfall--\( P(W/D) = P(W/W) = PW \). Conversely, low \( \beta \) values give strong wet day effects--\( \beta \rightarrow 0.0 \), \( P(W/D) \rightarrow 1.0 \). Thus, \( \beta \) controls the interval between rainfall events but has no effect on the number of wet days. For many locations, \( \beta = 0.75 \) gives satisfactory estimates of \( P(W/D) \). Although Eqs. (24.90) and (24.91) may give slightly different probabilities than those estimated from rainfall records, they do guarantee correct simulation of the number of rainfall events.

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

\[ R_i = \left( \frac{(SND_i - SCF_k)}{6.0} \left( \frac{SCF_k}{6.0} + 1 \right)^3 \right)^{-1} RSDV_k + \bar{R}_k \quad (24.92) \]

where \( R \) is the amount of rainfall for 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 \( \bar{R} \) is the mean daily rainfall in month \( k \).

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

\[ R_i = \frac{(-\ln(\mu))^{\frac{1}{\zeta}}}{\int_{0}^{1} (-\ln(\chi))^{\frac{1}{\zeta}} d\chi} \quad (24.93) \]

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 larger the \( \zeta \) value, the more extreme the rainfall events. A value of 1.3 gives satisfactory results at many locations in the United States. The denominator of Eq. (24.93) assures that the mean long-term simulated rainfall is correct. The modified exponential is usually a satisfactory substitute and requires only the monthly mean daily rainfall as input.

If precipitation is to be simulated for each subbasin, the amount computed using Eqs. (24.92) or (24.93) is assumed to be the mean for all gages for the day. The center of the storm is located in a rectangle with boundaries set at a distance of 100 km from the basins' maximum and minimum \( x \) and \( y \) rain gage coordinates. Thus, the storm center could be located in the basin or as much as 100 km in any direction from the basin. Each storm center is defined by drawing two random numbers-one for the \( x \) scale and one for the \( y \) scale. Rainfall at each gage is computed using an area reduction function (Nicks and Igo, 1980).

\[ RF = \frac{1 - (AO)(DUR)^{-0.148}}{337.5 + 1.09 AO} \quad (24.94) \]

where RF is a reduction ratio (0-1), DUR is the rainfall duration in h, and AO is area represented by the rain gage in km². The circular area, AO, is calculated using the distance between the gage and the storm center to compute the diameter.

\[ AO = 0.7854 \left( x_c - x_i \right)^2 + (y_c - y_i)^2 \quad (24.95) \]
where \( x \) and \( y \) are coordinates of the rain gages in km and subscripts \( c \) and \( i \) refer to the storm center and the gage for which \( RF \) is being computed.

Finally, rainfall is generated for each gage using the equation

\[
R_i = \frac{\left( RF_i \right) \left( R \right) \left( N \right)}{\sum_{i=1}^{N} RF_i} \tag{24.96}
\]

where \( R_i \) is the daily rainfall for rain gage \( i \), \( RF_i \) is the reduction factor, \( R \) is the mean daily rainfall, and \( N \) is the number of subbasins.

Daily precipitation is partitioned between rainfall and snowfall using a combination of maximum daily air temperature (\( T_{mx} \)) and surface layer soil temperature (\( T(1) \)). If the average of \( T_{mx} \) and \( T(1) \) is \( 0 \)°C or below, the precipitation is snowfall, otherwise, it is rainfall.

### 24.4.2. Air Temperature and Solar Radiation

The model developed by Richardson (1981) was selected for use in SWRRB because it simulates temperature and radiation, which are mutually correlated with rainfall. The residuals of daily maximum and minimum air temperature and solar radiation are generated from a multivariate normal distribution.

The multivariate generation model used implies that the residuals of maximum temperature, minimum temperature, and solar radiation are normally distributed and that the serial correlation of each variable may be described by a first-order linear autoregressive model. Details of the multivariate generation model were described by Richardson (1981). The dependence structure of daily maximum temperature, minimum temperature, and solar radiation was described by Richardson (1982).

The temperature model requires monthly means of maximum and minimum temperatures and their standard deviations as inputs. If the standard deviations are not available, the long-term observed extreme monthly minimums and maximums may be substituted. The model estimates standard deviation as 0.25 of the difference between the extreme and the mean for each month. For example:

\[
SDTMX_k = 0.25 \left( TE_{mx,k} - T_{mx,k} \right) \tag{24.97}
\]

where \( SDTMX \) is the standard deviation of the daily maximum temperature, \( TE \) is the extreme daily maximum temperature, and \( T \) is the average daily maximum temperature for month \( k \).

The solar radiation model uses the extreme approach extensively. Thus, only the monthly means of daily solar radiation are required as inputs. The equation for estimating standard deviation is

\[
SDRA_k = 0.25 \left( RAMX_k - RA_k \right) \tag{24.98}
\]

where \( SDRA \) is the standard deviation of daily solar radiation in \( \text{MJ} \cdot \text{m}^{-2} \), \( RAMX \) is the maximum daily solar radiation at midmonth, and \( RA \) is the mean daily solar radiation for month \( k \).

Maximum temperature and solar radiation tend to be lower on rainy days. Thus, it is necessary to adjust the mean maximum temperature and solar radiation downward for simulating rainy day conditions. For \( T_{mx} \) this is accomplished by assuming that wet day values are less than dry day values by some fraction of \( T_{mx} - T_{mn} \):

\[
TW_{mx,k} = TD_{mx,k} - \Omega_T \left( T_{mx,k} - T_{mn,k} \right) \tag{24.99}
\]

where \( TW \) is the daily mean maximum temperature for wet days in °C in month \( k \), \( TD \) is the daily mean maximum temperature for dry days, \( \Omega_T \) is a scaling factor ranging from 0.0 to 1.0, \( T_{mx} \) is the daily mean maximum temperature, and \( T_{mn} \) is the daily mean minimum temperature. Choosing \( \Omega_T=1.0 \) provides highest deviations on wet days and \( \Omega_T=0.0 \) ignores the wet day effect. Observed data indicate that \( \Omega_T \) usually lies between 0.5 and 1.0.

Since Eq. (24.99) gives lower mean maximum temperature values for wet days, a companion equation is necessary to slightly increase mean maximum temperature for dry days. The development is taken directly from the continuity equation

\[
(T_{mx,k}) \left( ND_k \right) = (TW_{mx,k}) \left( NWD_k \right) + (TD_{mx,k}) \left( NDD_k \right) \tag{24.100}
\]

where \( ND \) is the number of days in a month, \( NWD \) is the number of wet days, and \( NDD \) is the number of dry days. The desired equation is obtained by substituting Eq. (24.99) into Eq. (24.100) and solving for \( TD \)

\[
TD_{mx,k} = T_{mx,k} + \left( \frac{NWD_k}{ND_k} \right) \Omega_T \left( T_{mx,k} - T_{mn,k} \right) \tag{24.101}
\]

Use of the continuity equation guarantees that the long-term simulated value for mean maximum temperature agrees with the input value of \( T_{mx} \).

The method of adjusting solar radiation for wet and dry days is similar to that of adjusting maximum temperature. The radiation on wet days is a fraction of the dry day radiation

\[
RAW_k = \Omega_R RAD_k \tag{24.102}
\]

where \( RAW \) is the daily mean solar radiation on wet days in \( \text{MJ} \cdot \text{m}^{-2} \), \( \Omega_R \) is a scaling factor ranging from 0.0 to 1.0, and \( RAD \) is the daily mean solar radiation on dry days. An \( \Omega_R \) value of 0.5 gives satisfactory results for many locations. The dry day equation is developed by replacing temperature with radiation in Eq. (24.101) and substituting Eq. (24.102) for RAW. Then,

\[
RAD_k = \frac{(RA_k) \left( ND_k \right) \Omega_R \left( NWD_k \right) + NDD_k}{\Omega_R \left( NWD_k \right) + NDD_k} \tag{24.103}
\]

where \( RA \) is the daily mean solar radiation for month \( k \) in \( \text{MJ} \cdot \text{m}^{-2} \).
24.5. SEDIMENT YIELD

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

\[ Y = 11.8 \left( V q_p \right)^{0.56} \left( K \right) \left( C \right) \left( PE \right) \left( LS \right) \]  

(24.104)

where Y is the sediment yield from the subbasin in t, V is the surface runoff column for the subbasin in m³, \( q_p \) is the peak flow rate for the subbasin in m³s⁻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)

\[ LS = \left( \lambda / 22.1 \right)^{\xi} \left( 65.41 S^2 + 4.565 S + 0.65 \right) \]  

(24.105)

The exponent \( \xi \) varies with slope and is computed in SWRRB with the equation

\[ \xi = 0.6 \left[ 1 - \exp\left( -35.835 S \right) \right] \]  

(24.106)

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

\[ C = \exp\left[ (-0.2231 - CVM) \exp(-0.00115 CV) + CVM \right] \]  

(24.107)

where CM is the soil cover (above ground biomass+residue in 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

\[ CVM = 1.463 \ln \left( CVA \right) + 0.1034 \]  

(24.108)

The value of CVA for each crop is determined from tables prepared by Wischmeier and Smith (1978). Values of K are contained in the SCS Soil survey, and PE factors can be estimated for each subbasin using information contained in Wischmeier and Smith (1978).

24.6. 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 SWRRB model. SWRRB allows for simultaneous computations on each subbasin and routes the water, sediment, and nutrients from the subbasin outlets to the basin outlet.

24.6.1. Nitrogen

Nitrate Loss in Surface Runoff

The amount of NO₃-N in runoff is estimated for each subbasin for considering the top soil layer (10 mm thickness) only. The total amount of water leaving the layer is the sum of runoff, lateral subsurface flow, and percolation.

\[ QT = Q + O_1 + QR_1 \]  

(24.109)

where QT is the total water lost from the first layer in mm, Q is the runoff volume in mm, O₁ is the percolation from the first layer in mm, and QR₁ is the lateral flow from the first layer in mm. The amount of NO₃-N lost with QT is

\[ VNO3 = \left( QT \right) \left( C_{NO3} \right) \]  

(24.110)

where VNO3 is the amount NO₃-N lost from the first layer and \( C_{NO3} \) is the concentration of NO₃-N in the first layer. At the end of the day, the amount of NO₃-N left in the layer is

\[ WNO3 = WNO3_0 - \left( QT \right) \left( C_{NO3} \right) \]  

(24.111)

where WNO₃₀ and WNO₃ are the weights of NO₃-N contained in the layer at the beginning and ending of the day. The NO₃-N concentration can be estimated by dividing the weight of NO₃-N by the water storage volume:

\[ C'_{NO3} = C_{NO3} - C_{NO3} \left( \frac{-QT}{PO_1 - WP_1} \right) \]  

(24.112)

where \( C'_{NO3} \) is the concentration of NO₃-N at the end of the day, PO is the soil porosity, and WP is the wilting point water content for soil layer one in mm. Equation (24.112) is a finite difference approximation for the exponential equation

\[ C'_{NO3} = C_{NO3} - \exp \left( \frac{-QT}{PO_1 - WP_1} \right) \]  

(24.113)

thus, VNO3 can be computed for any QT value by integrating Eq. (24.113).

\[ VNO3 = WNO3 \left( 1 - \exp \left( \frac{-QT}{PO_1 - WP_1} \right) \right) \]  

(24.114)

The average concentration of QT for the day is

\[ C_{NO3} = \frac{VNO3}{QT} \]  

(24.115)
Amounts of NO₃-N contained in runoff, lateral flow, and percolation are estimated as the products of the volume of water and the concentration from Eq. (24.115).

**Nitrate Leaching**

Leaching and lateral subsurface flow in lower layers are treated with the same approach used in the upper layer except surface runoff is not considered.

**Organic N Transport by Sediment**

A loading function developed by McElroy et al. (1976) are modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic N loss for each subbasin. The loading function

\[ YON = 0.001 \cdot (Y \cdot CON \cdot ER) \] (24.116)

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 top soil layer in g*m⁻³, 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. The enrichment ratio is the concentration of organic N in the sediment divided by that of the soil. Enrichment ratios are logarithmically related to sediment concentration as described by Menzel (1980). An individual event enrichment sediment concentration relationship was developed for SWRRB considering upper and lower bounds. The upper bound of enrichment ratio is the inverse of the sediment delivery ratio. Exceeding the inverse of the delivery ratio implied that more organic N leaves the watershed than is dislodged from the soil. The delivery ratio is estimated for each runoff event using the equation

\[ DR = \left( \frac{q_p}{r_{ep}} \right)^{0.56} \] (24.117)

where DR is the sediment delivery ratio (subbasin sediment yield divided by gross sheet erosion), \( q_p \) is the peak runoff rate in mm*h⁻¹, and \( r_{ep} \) is the peak rainfall excess rate in mm*h⁻¹. Equation (24.117) is based on sediment yield estimated using MUSLE (Williams, 1975). The rainfall excess rate cannot be evaluated directly because the hydrology model only predicts the total daily runoff volume. An estimate of the rate can be obtained, however, using the equation

\[ r_{ep} = r_p - f \] (24.118)

where \( r_p \) is the peak rainfall rate in mm*h⁻¹ and \( f \) is the average infiltration rate in mm*h⁻¹. The average infiltration rate can be computed from the equation

\[ f = R - Q / DUR \] (24.119)

where DUR is the rainfall duration in h and R is rainfall in mm. The procedure for estimating the rainfall duration is given in Williams et al. (1984).

\[ DUR = 4.605R / r_p \] (24.120)

The lower limit of enrichment ratio is 0.75 and particle size distribution is the same as that of the soil. Thus, \( 1 \leq ER \leq 1 / DR \). The logarithmic equation estimating enrichment ratio is

\[ ER = x_1 \cdot e^{-x_2} \] (24.121)

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. To approach an enrichment ratio is 1.0, the sediment concentration would be extremely high. Conversely, a very low sediment concentration would cause the enrichment ratio to approach 1/DR. The simultaneous solution of Eq. (24.121) at the boundaries assuming sediment concentrations range from 500 to 250,000 g*m⁻³ gives

\[ x_2 = \log(1 / DR) / 2.699 \] (24.122)

\[ x_1 = 1 / (0.25)^2 \] (24.123)

**Crop Uptake**

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

\[ UND_i = (C_{NB})_i \cdot B_i - (C_{NB})_{i-1} \cdot B_{i-1} \] (24.124)

where \( UND_i \) 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 in kg*ha⁻¹. The optimal crop N concentration is computed as a function of growth stage using the equation

\[ C_{NB} = 4.0 \cdot (bn) + 1.54 \cdot (bn) \cdot \exp(-bn \cdot B_i) \] (24.125)

where \( bn \) is a crop parameter expressing N concentration and \( B_i \) is the fraction of the growing season. The value of \( B_i \) is estimated as a function of heat units

\[ B_{i,t} = \sum_{k=1}^{i} \frac{HUI}{PHU} \] (24.126)

where HU is the daily heat units in °C above the crop's base temperature and PHU is the potential heat units to mature the crop in °C.
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.

### 24.6.2. Phosphorus

#### Soluble P Loss in Surface Runoff

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

\[
YSP = 0.01(C_{LPP}) \cdot (Q) / k_d
\]  
(24.127)

where YSP is the soluble P in kg·ha⁻¹ lost in runoff volume Q in mm, C_{LPP} is the concentration of AP in soil layer P in g·m⁻³, and k_d is the P concentration in the sediment divided by that of the water in m³·t⁻¹. The value of CLP is input to the model and remains constant. The value of k_d used in SWRRB is 175.

#### P Transport by Sediment

Sediment transport of P is simulated with a loading function as described in organic N transport. The P loading function is

\[
YP = 0.01 \cdot (Y) \cdot (C_p) \cdot (ER)
\]  
(24.128)

where YP is the sediment phase of P loss in runoff in kg·ha⁻¹ and c_p is the concentration of P in the top soil layer in g·t⁻¹.

### 24.6.3. Fertilizer Application

The date and rate of N and P application is input to the model. The entire amount of N and P is added to the first soil layer and is available for water and sediment transport, leaching, and crop uptake.

### 24.7. PESTICIDES

GLEAMS (Leonard et al., 1987) technology for simulating pesticide transport by runoff, percolate, soil evaporation, and sediment was added to SWRRB. Pesticides may be applied at any time and rate to plant foliage or below the soil surface at any depth. When pesticide is applied, there is a loss to the atmosphere. Thus, the amount that reaches the ground or plants is expressed by the equation

\[
PAPE = (PAPR) \cdot (PAEF)
\]  
(24.129)

where PAPE is the effective amount of pesticide applied in kg·ha⁻¹·PAPR is the actual amount applied in kg·ha⁻¹, and PAEF is an application efficiency factor.

To determine how much pesticide reaches the ground, the amount of ground cover provided by plants is estimated with the equation

\[
GC = (1.0 - ERFC \cdot (1.33LAI_{t,m} - 2.0)) / 2.
\]  
(24.130)

where GC is the fraction of the ground that is covered by plants, and LAI is the leaf area index on day, t. Therefore, the amount of pesticide that reaches the plants is computed with the equation

\[
FP = (GC) \cdot (PAPE)
\]  
(24.131)

where FP is the amount of pesticide that is intercepted by plants. The remaining pesticide falls to the ground and is simply the difference between the effective amount applied and the amount intercepted by plants.

\[
GP = PAPE - FP
\]  
(24.132)

where GP is the amount of pesticide that reaches the ground.

Pesticide that remains on the plant foliage can be washed off by rain storms. It is assumed that the fraction of pesticide that is potentially dislodgable is washed off the plants once a threshold rainfall amount is exceeded. The model uses a threshold value of 2.5 mm and potential washoff fractions for various pesticides have been estimated (Leonard et al., 1987). The appropriate equations for computing washoff and adding to the ground amount are:

\[
WO = \begin{cases} 
(WOF) \cdot (FP), & R \geq 2.5 \text{ mm} \\
0, & R < 2.5 \text{ mm}
\end{cases}
\]  
(24.133)

where WO is the amount of pesticide washed off the plants by a rainstorm of R in mm and WOF is the washoff fraction for the particular pesticide.

Pesticide on the plants and in the soil is lost from the system based on the decay equations

\[
GP = (GP_0) \cdot \exp(-0.693 / HLS)
\]  
(24.134)
where \( GP_0 \) and \( GP \) are the initial and final amounts of pesticide on the ground, \( FP_0 \) and \( FP \) are the initial and final amounts of pesticide on the plants, HLS is the half life for pesticide in the soil in d, and HLP is the half life of the foliar residue in d. Values of HLP and HLS have been established for various pesticides (Leonard et al., 1987).

Another way that pesticide can be lost from the zone considered in computing runoff (top 10 mm of soil) is through leaching. The GLEAMS leaching component is used here with slight modification. The change in the amount of pesticide contained in the top 10 mm zone is expressed as a function of time, concentration, and amount of infiltration using the equation

\[
\frac{dGP}{dt} = (PSTC_w) \cdot (f)
\]  

(24.138)

where \( GP \) is the amount of pesticide in the top 10 mm zone at time \( t \), \( PSTC_w \) is the pesticide concentration in the water in g\( \cdot t^{-1} \), and \( f \) is the water flow rate through the zone in \( mm \cdot h^{-1} \). The total amount of pesticide contained in the top 10 mm zone is the sum of the adsorbed and mobile phases.

\[
GP = 0.01 \cdot (PSTC_w) \cdot (SW) + 0.1 \cdot (PSTC_s) \cdot (BD)
\]  

(24.139)

where \( SW \) is the amount of water stored in the top 10 mm of soil in mm, \( PSTC \) is the concentration of adsorbed pesticide in g\( \cdot t^{-1} \), and \( BD \) is the soil bulk density in \( t \cdot m^{-3} \). The ratio of the concentration of pesticide adsorbed to the concentration of pesticide in the water has been estimated for various pesticides (Leonard et al., 1987) and is expressed by the equation

\[
K_d = \frac{C_s}{C_w}
\]  

(24.140)

where \( K_d \) is the partitioning constant. Substituting Eq. (24.140) into Eq. (24.139) gives

\[
GP = 0.01 \cdot (PSTC_w) \cdot (SW) + 0.1 \cdot (PSTC_w) \cdot (K_d) \cdot (BD)
\]  

(24.141)

Solving Eq. (24.141) for \( PSTC_w \) gives

\[
PSTC_w = \frac{GP}{0.01 \cdot SW + 0.1 \cdot (K_d) \cdot (BD)}
\]  

(24.142)

Substituting \( PSTC_w \) from Eq. (24.142) into Eq. (24.138) yields

\[
\frac{dGP}{dt} = \frac{(GP)(f)}{0.01 \cdot SW + 0.1 \cdot (K_d) \cdot (BD)}
\]  

(24.143)

Rearranging Eq. (24.143) and integrating gives the equation expressing the amount of pesticide as a function of the amount of water flowing through the zone.

\[
GP = GP_0 \cdot \exp \left( \frac{-f}{0.01 \cdot SW + 0.1 \cdot (K_d) \cdot (BD)} \right)
\]  

(24.144)

where \( GP_0 \) is the initial amount of pesticide in the top 10 mm zone in kg\( \cdot ha^{-1} \), \( GP \) is the amount that remains after the amount of flow \( f \) in \( mm \) passes through the zone, \( SW \) is the initial water storage in \( mm \), \( K_d \) is the partitioning coefficient in \( m^3 \cdot t^{-1} \), and \( BD \) is the soil bulk density in \( t \cdot m^{-3} \).

To obtain the amount of pesticide leached by the amount of water \( f \), \( GP \) is subtracted from \( GP_0 \) using the equation

\[
PSTL = GP_0 \left( 1 - \exp \left( \frac{-f}{0.01 \cdot SW + 0.1 \cdot (K_d) \cdot (BD)} \right) \right)
\]  

(24.145)

where \( PSTL \) is the amount of pesticide leached by \( f \).

Pesticide concentration in percolate is computed with the equation

\[
PSTC_L = \min \left\{ \frac{PSTL}{f}, PSTC_{SOI} \right\}
\]  

(24.146)

where \( PSTC_{SOI} \) is the pesticide solubility and \( PSTC_L \) is the pesticide concentration in the percolate in g\( \cdot m^{-3} \). Finally, \( PSTL \) is the product of \( O \) and \( PSTC_L \).

Pesticide loss in surface runoff is estimated with a modification of Eq. (24.145) that includes an abstraction coefficient

\[
PSTQ = GP_0 \cdot \left( 1 - \exp \left( \frac{-(Q)(ab)}{0.01 \cdot SW + 0.1 \cdot (ab) \cdot (K_d) \cdot (BD)} \right) \right)
\]  

(24.147)

where \( PSTQ \) is the pesticide loss in surface runoff in kg\( \cdot ha^{-1} \), \( Q \) is the surface runoff volume in \( mm \), and \( ab \) is the abstraction coefficient.

The calculation sequence is: (1) Soil layer 1--Leaching is estimated first by substituting \( 0 \) for \( f \) in Eqs. (24.145) and (24.146). Then \( PSTL \) is removed from layer 1 and placed into layer 2. Next runoff and lateral flow losses are estimated simultaneously by substituting \( O \cdot Q \cdot R \) for \( Q \) in Eq. (24.147). The average concentration is obtained by dividing the resulting \( PSTQ \) by \( Q+QR \). Individual losses are estimated for runoff \( Q \cdot PSTC_{Q+QR} \) and lateral flow \( Q \cdot PSTC_{Q+QR} \). Finally, these losses are removed from layer 1. (2) Soil layers 2--Leaching and lateral flow losses are estimated simultaneously by substituting \( O \cdot Q \cdot R \) for \( Q \) in Eqs. (24.145) and (24.146). Individual losses are calculated as in (1) \( Q \cdot PSTC_L \) and \( O \cdot PSTC_L \).
subtracted from layer \( \ell \) and \( O_t \cdot \text{PSTC}_t \) is added to layer \( \ell + 1 \). The process is repeated layer by layer to the bottom of the soil profile.

The total amount of pesticide lost in the runoff is estimated by adding the soluble fraction computed with Eq. (24.147) to the amount that is adsorbed to the sediment. Pesticide yield from the adsorbed phase is computed with an enrichment ratio approach. The enrichment ratio equation is

\[
PSTY = (Y) \cdot \text{PSTC}_s \cdot (ER) \cdot (0.001)
\]

where PSTY is the pesticide yield adsorbed to the sediment in kg\( \cdot \text{ha}^{-1} \cdot \text{y}^{-1} \), \( Y \) is the sediment yield in t\( \text{ha}^{-1} \cdot \text{y}^{-1} \), and ER is the enrichment ratio (concentration of pesticide in the sediment divided by the pesticide concentration in the top 10 mm of soil) computed with Eq. (24.121). The pesticide concentration in the soil is calculated by substituting Eq. (24.140) into Eq. (24.142) and solving for PSTC_s.

\[
PSTC_s = \frac{(K_d) \cdot (GP) \cdot (0.01)}{SW + 0.1 \cdot (K_d) \cdot (BD)}
\]

Soil layers with low storage volumes have high leaching potentials not only because percolation is greater, but also because storage volume displacement is greater (higher concentration). Pesticides with low \( K_d \) values and high solubility are transported rapidly with water. Conversely, high \( K_d \) value pesticides are adsorbed to soil particles and travel largely with sediment.

\section*{24.8. SOIL TEMPERATURE}

Daily average soil temperature is simulated at the center of each soil layer. The basic soil temperature equation is

\[
T(Z, t) = \bar{T} + \frac{AM}{2} \exp(-Z/DD) \cos \left[ \frac{2\pi}{365} (t - 200) - Z/DD \right]
\]

where \( Z \) is depth from the soil surface in mm, \( t \) is time in days, \( T \) is the average annual air temperature in °C, \( AM \) is the annual amplitude in daily average temperature in °C, and \( DD \) is the damping depth for the soil in mm. Equation (24.150) provides estimates of air temperature \((Z=0)\) as well as soil temperature. Since air temperature is provided by the weather component of SWRRB, the soil temperature model should be capable of using these air temperatures as drivers. Otherwise, Eq. (24.150) would predict the same temperatures for a given day each year. To allow simulated air temperature to be used as the soil temperature driver, equations were developed to estimate soil surface temperature.

\[
TGB_{IDA} = (z_j) \cdot (T_{mx}) + (1 - z_j)(T_{mn}), \quad R = 0
\]

where \( TGB_{IDA} \) is the bare soil surface temperature in °C, \( T_{mx} \) and \( T_{mn} \) are the maximum and minimum daily air temperature in °C, \( z \) is a weighting factor for estimating soil surface temperature on dry days, and \( j \) specifies the month. Obviously, Eq. (24.152) uses the minimum air temperature to estimate surface temperature on rainy days. Higher temperatures are estimated on dry days using Eq. (24.151). The value of \( z \) is determined by considering the average \( T_{mx} \), \( T_{mn} \), and number of rainy days in this month.

\[
z_j = \frac{NDD_j}{T_{mx} - T_{mn}} \cdot (NDD_j - T_{mn}) - T_{mn}
\]

where \( N \) is the number of days in a month, \( R \) is the number of rainy days, and \( NDD \) is the number of dry days. Equation (24.153) assures that the long-term average soil surface temperature and air temperature are equal.

The soil surface temperature is also affected by residue and snow cover. This effect can be simulated by lagging the predicted base surface temperature using the equation

\[
TGB_{IDA} = (bcv) \cdot (TGB_{IDA-1}) + (1 - bcv) \cdot (TGB_{IDA})
\]

where \( bcv \) is a lagging factor for simulating residue and snow cover effects on surface temperature. The value of \( bcv \) is 0 for base soil and approaches 1.0 as cover increases as expressed in the equation

\[
bcv = \max \left( \frac{CV}{SNO + \exp(6.055 - 0.3022 \cdot SNO)} \right)
\]

where \( CV \) is the sum of above ground biomass and crop residue in kg\( \cdot \text{ha}^{-1} \) and \( SNO \) is the water content of the snow cover in mm.

The soil temperature at any depth is estimated with Eq. (24.150) by substituting \( TGB \) for \( T(0,t) \). \( TGB \) is a better estimate of the surface temperature then \( T(0,t) \) because current weather and cover conditions are considered. At soil surface \((Z=0)\), the proper substitution can be accomplished by adding \( TGB \) and subtracting \( T(0,t) \) from Eq. (24.150). Differences between \( TGB \) and \( T(0,t) \) are damped as \( Z \) increases. Thus, the final equation for estimating soil temperature at any depth is

\[
T(Z, t) = T + \left( \frac{AM}{2} + TGB - T(0,t) \right) \cos \left[ \frac{2\pi}{365} (t - 200) - \frac{Z}{DD} \right] \cdot \exp \left( -\frac{Z}{DD} \right)
\]
The damping depth (DP) is a function of soil bulk density and water content as expressed in the equations

\[
DP = 100 + \left( \frac{2500 \, BD}{BD + 686 \, \exp(-5.63 \, BD)} \right) \tag{24.157}
\]

\[
S_p = \frac{SW}{(0.356 - 0.144 \, BD) \, ZM} \tag{24.158}
\]

\[
DD = DP \, \exp \left( \ln \left( \frac{500}{DP} \right) \left( \frac{1 - S_p}{1 + S_p} \right)^2 \right) \tag{24.159}
\]

where DP is the maximum damping depth for the soil mm, BD is the soil bulk density in t•m^{-3}, ZM is the distance from the bottom of the lowest soil layer to the surface in mm, and \( S_p \) is a scaling parameter.

### 24.9. CROP GROWTH

The crop model in SWRRB is a simplification of the EPIC crop model (Williams et al., 1984). SWRRB 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 in SWRRB 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. Perennial crops maintain their root systems throughout the year, although the plant may become dormant after frost.

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

\[
HU_i = (T_{mx,i} + T_{mn,i} / 2) - T_b, \quad HU_k \geq 0 \tag{24.160}
\]

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.

\[
HUI = \frac{\sum_{k=1}^{i} HU_k}{PHU_j} \tag{24.161}
\]

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.

### 24.9.1. Potential Growth

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

\[
PAR_i = 0.02092 \, (RA_i) [1 - \exp(-0.65 \, LAI_i)] \tag{24.162}
\]

where PAR is photosynthetic active radiation in MJ•m^{-2}, RA is solar radiation in Ly, 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

\[
DB_{p,i} = (BE_j) \, (PAR_i) \tag{24.163}
\]

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^{-1}.

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

\[
LAI_i = \frac{(LAI_{max}) \, (B_{AG})}{B_{AG} + \exp(9.5 - 0.0006 \, B_{AG})}, \quad HUI_i \leq DLAI \tag{24.164}
\]

\[
LAI_i = (16)(LAI_{max})(1 - HUI_i)^2, \quad HUI_i > DLAI \tag{24.165}
\]

where LAI_{max} is the maximum LAI potential for the crop, \( B_{AG} \) is above ground biomass in kg•ha^{-1}, and DLAI is the fraction of the growing season when LAI starts declining (\( = .75 \)).

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

\[
RWT_i = (0.4 - 0.2 \, HUI_i) \tag{24.166}
\]

where RWT is the fraction of total biomass partitioned to the root system on day i. Thus, \( B_{AG} \) is calculated from the equation

\[
B_{AG} = (1 - RWT_i) \, (B_{TOT}) \tag{24.167}
\]

where \( B_{TOT} \) is total biomass in kg•ha^{-1} on day i.
24.9.2. Crop Yield

The economic yield of most grain, pulse, and tuber crops is a reproductive organ. 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.

\[ YLD_j = (HI_j) \cdot (BA_{AG}) \quad (24.168) \]

where \( YLD \) is the amount of the crop removed from the field in kg·ha⁻¹, \( HI \) is the harvest index at harvest, and \( BA_{AG} \) is the above-ground biomass in kg·ha⁻¹ for crop \( j \). Harvest index increases non-linearly from zero at planting using the equation

\[ HIA_i = HI_{0j}(HUF_i - HUF_{i-1}) \quad (24.169) \]

where \( HIA \) is the harvest index on day \( i \), \( HI_0 \) is the harvest index under favorable growing conditions, and \( HUF \) is the heat unit factor that affects harvest index on day \( i \) and the previous day \( i-1 \).

The harvest index heat unit is computed with the equation

\[ HUF_i = \frac{HUI_i}{HUI_i + \exp(6.50 - 10.0 \cdot HUI_i)} \quad (24.170) \]

The constants in Eq. (24.170) are set to allow \( HUF \) to increase from 0.1 at \( HUI = 0.5 \) to 0.92 at \( HUI = 0.9 \). This is consistent with economic yield development of grain crops which produce most economic yield in the second half of the growing season.

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). Optimum conditions 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

\[ HIA_i = \frac{HIA_i}{1 + (WSYF_i) \cdot (FHU_i) \cdot (0.9 - WS)} \quad (24.171) \]

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

\[ FHU_i = \sin \left( \frac{\pi}{2} \left( \frac{HUI_i - 0.3}{0.3} \right) \right), \quad 0.3 \leq HUI_i \leq 0.9 \quad (24.172) \]

\[ FHU_i = 0., \quad HUI < 0.3HUI > 0.9 \quad (24.173) \]

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

24.9.3. Growth Constraints

The potential biomass predicted with Eq. (24.163) is adjusted daily if one of the plant stress factors is less than 1.0 using the equation

\[ \Delta B = (\Delta B_p) \cdot (REG) \quad (24.174) \]

where \( REG \) is the one crop growth regulating factor (the minimum stress factor).

Water Stress

The water stress factor is computed by considering supply and demand in the equation

\[ WS = \frac{\sum_{i=1}^{N_s} U_i}{E_p} \quad (24.175) \]

where \( WS \) is the water stress factor (0-1) and \( U_i \) is plant water used in layer \( i \) in mm. The value of \( E_p \) is predicted in the evapotranspiration model.

A model (Williams and Hann, 1978) for simulating plant water uptake is used to estimate the \( E_p \) distribution. Root depth is calculated with the equation

\[ RD_n = \frac{2.5 \cdot \sum_{i=1}^{N_s} E_{pi}}{\sum_{i=1}^{N_s} E_{pi}} \quad (24.176) \]

where \( RD_n \) is the fraction of the root zone that contains roots on day \( n \) and \( N_s \) is the number of days in the growing season.
24.10. TILLAGE AND RESIDUE

The SWRRB tillage component was designed to partition the above ground biomass at harvest. A portion of the biomass is incorporated into the soil while the remainder is left on the soil surface as residue. Once the residue is incorporated, it has no impact on the model. Also no change is made in bulk density due to tillage.

The residue is set at harvest according to one of the four tillage practices chosen.

Fall plow: \[ RSD = 0.5 \text{ WLV} \] (24.182)

Spring plow: \[ RSD = 0.25 \text{ WLV} \] (24.183)

Conservation tillage: \[ RSD = 0.50 \text{ WLV} \] (24.184)

Zero tillage: \[ RSD = 0.95 \text{ WLV} \] (24.185)

where RSD is the residue left after harvest in kg ha⁻¹ and WLV is the above ground biomass minus crop yield at harvest in kg ha⁻¹.

The residue decays throughout the remainder of the year (harvest to next harvest) as a function of soil water content and soil temperature.

\[ DECR = 0.05 \text{min(CDG, SUT)} \] (24.186)

where DECR is the daily decrease in residue, and

\[ RSD = RSD (1 - DECR) \] (24.87)

where CDG and SUT are soil water and soil temperature residue decay factors.

\[ CDG = \frac{0.9 \text{ ST}_2}{\text{ST}_2 + \exp(9.93 - 0.312 \text{ ST}_2)} \] (24.188)

and

\[ SUT = \frac{SW_2}{FC_2} \] (24.189)

where ST₂, SW₂, and FC₂ are the soil temperature, soil water content, and field capacity of the second soil layer.
24.11. IRRIGATION

The SWRRB user has the option to simulate dryland or irrigated agricultural areas. If irrigation is indicated, he must also specify the runoff ratio (volume of water leaving the field/volume applied) and a plant water stress level to start irrigation. The plant water stress factor ranges from 0 to 1.0 (1 means no stress and 0 means no growth). These stress factors are described in the Crop Growth section. When the user-specified stress level is reached, water is applied according to the equation

\[ AIR = \frac{FC - SW}{1 - EF} \]  

(24.190)

where FC is the root zone field capacity in mm, SW is the root zone water content before irrigation in mm, EF is the runoff ratio, and AIR is the volume of irrigation water applied in mm.

24.12. FLOOD ROUTING

Since SWRRB is primarily a long-term water and sediment yield simulator, a high degree of accuracy in predicting hydrographs is not as necessary as for other applications like flood control planning and flood forecasting. Also, SWRRB must operate as efficiently as possible to be useful in water resources planning that requires long-term simulations of numerous management strategies. Therefore, flood routing is not performed in SWRRB and daily bains outflow is estimated by summing subbasin outflows. All surface runoff reaches the basin outlets on the day of the event. Subsurface flow is lagged as a function of basin lag time. Accurate prediction of subbasin peak rates is important since they are used in estimating subbasin sediment yields.

24.13. PONDS AND RESERVOIRS

24.13.1. Ponds

This component of SWRRB was designed to account for the effects of farm ponds on water yield. The water balance equation is

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

(24.191)

where VM is the volume of the water stored in all ponds 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 m³. The inflow, QI is composed of surface runoff from the total pond drainage area and rainfall on the water surface area.

\[ QO = VM - VM_{mx}, \quad VM > VM_{mx} \]  

\[ QO = 0, \quad VM \leq VM_{mx} \]  

(24.192)

where VM_{mx} is the maximum permanent pool storage of all ponds in the subbasin in m³.

The evaporation is computed with the equation

\[ EV = 10 \ (\eta) \ (E_{ap}) \ (SA) \]  

(24.193)

where \( \eta \) is an evaporation coefficient (0.6) and SA is the surface area of all ponds in the subbasin in ha.

Seepage from the ponds is computed with the equation

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

(24.194)

where SC is the saturated conductivity of the pond bed in mm·h⁻¹.

Since pond surface area is required for computing evaporation and seepage, a relationship between surface area and volume is necessary. Data from a large number of stock ponds and small reservoirs in Texas and Oklahoma (USDA-SCS, 1957) indicate that surface area can be calculated with the equation

\[ SA = \omega_1 \ (VM)^{\omega_2} \]  

(24.195)

where \( \omega_1 \) is a parameter (1.3×10⁻⁴) and \( \omega_2 \) is a fairly constant parameter (0.9). The SWRRB model assumes \( \omega_2=0.9 \) and determines \( \omega_1 \) for each subbasin using \( SA_{mx} \) and \( VM_{mx} \).

24.13.1. Reservoirs

Although this component was mainly designed to simulate flow through small reservoirs like those constructed on SCS PL566 projects, 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

\[ QOR = VR - VR_F, \quad VR > VR_F \]  

\[ QOR = (RR)/(Dt), \quad VR_S < VR \leq VR_F \]  

\[ QOR = 0, \quad VR < VR_S \]  

(24.196)

where QOR is the daily outflow in m³, VR is the volume of water in the reservoir in m³, VR_F is the reservoir capacity at the emergency spillway crest in m³, RR is the principal spillway release rate in m³·s⁻¹, and VR_S is the reservoir capacity at the principal spillway crest in m³.
The relationships (Eqs. (24.193), (24.194), and (24.195)) used to estimate evaporation and seepage from ponds are also applicable to reservoirs. However, 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 Eq. (24.195). The resulting equations are

\[
\omega_1 = \frac{\log SA_F - \log SA_S}{\log VR_F - \log VR_S} \tag{24.197}
\]

\[
\omega_2 = \frac{SA_F}{VR^{\omega_2}} \tag{24.198}
\]

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

### 24.14. 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 \( \text{t} \cdot \text{m}^{-3} \), Stokes' Law for fall velocity becomes:

\[
V_f = 411 \ (d^2) \tag{24.199}
\]

where \( V_f \) is the fall velocity in m\( \cdot \)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

\[
y_f = (V_f) \ (TT) \tag{24.200}
\]

The sediment delivery ratio (DR) through the reach is estimated with the equations:

\[
DR = \begin{cases} 
\frac{1 - 0.5 \ (y_f)}{d_q} & \text{if } y_f < d_q \\
0.5 \ (d_q) & \text{if } y_f > d_q 
\end{cases} \tag{24.201}
\]

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

Finally, deposition is calculated with the equation:

\[
DEP = SED_{IN} \ (1 - DR) \tag{24.203}
\]

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:

\[
SP = \gamma \ q \ S_w \tag{24.204}
\]

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 reentrainment, \( DEG_R \), is

\[
R = \alpha_{sp} \ \gamma^{1.5} \ (dur) \ (w) \ (d_g \ S_w \ V_c)^{1.5} \tag{24.205}
\]

where \( \alpha_{sp} \) is a parameter dependent on maximum stream power for the reach and \( V_c \) is the velocity in the channel.

The parameter \( \alpha_{sp} \) can be estimated with the equation:

\[
\alpha_{sp} = (69.44 \ \gamma \ DA \ S_c)^{-0.5} \tag{24.206}
\]

where \( S_c \) is the slope of the channel and the subscript \( mx \) 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 \( \alpha_{sp} \) becomes:

\[
\alpha_{sp} = (69.44 \ \gamma \ DA \ S_c)^{-0.5} \tag{24.207}
\]

where \( DA \) is the drainage area into the reach in \( \text{km}^2 \).

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:

\[
DEG_B = K \ C \ DEG_R \tag{24.208}
\]

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 redeposited before reaching the basin outlet.

\[
DEG = (DEG_R + DEG_B) \ (1 - DR) \tag{24.209}
\]
Finally, the amount of sediment reaching the basin outlet, $SED_{out}$, is:

$$SED_{out} = SED_{in} - DEP + DEG$$

(24.210)

where $SED_{in}$ is the sediment entering the reach.

24.14.2. Reservoir Sediment Routing

The sediment balance equation for reservoirs is:

$$SR_i = SR_{i-1} + SR_{in} - SR_{out} - SR_{DEP}$$

(24.211)

where $SR_i$ is the total sediment in the reservoir, $SR_{i-1}$ is the total sediment in the reservoir on the previous day, $SR_{in}$ is the incoming sediment, $SR_{out}$ is the sediment transported in the sediment outflow, and $SR_{DEP}$ is the amount of sediment deposited in the reservoir. Sediment outflow from reservoirs is calculated with the equation

$$SR_{out} = c_o q_o$$

(24.212)

where $c_o$ is the outflow sediment concentration. The outflow concentration is a function of the reservoir concentration at the beginning and end of the day

$$c_o = \frac{(c_s + c_s)}{2}$$

(24.214)

where $c_s$ and $c_s$ are the reservoir sediment concentrations at the beginning and end of the day, respectively.

The initial reservoir concentration is input to the model. The inflow concentration can be calculated since $q_i$ and $SR_{in}$ are simulated, but the final reservoir concentration is unknown. It can be computed using the continuity equation

$$V_2 c_s = V_1 c_s + q_i c_i - q_o c_o$$

(24.215)

where $V_1$ and $V_2$ are the storage volumes at the beginning and end of the day, and $c_i$ is the inflow sediment concentration. Substituting Eq. (24.214) into Eq. (24.215) and rearranging yields an expression for the final concentration

$$c_s = \frac{V_1 c_i + q_i c_i - (q_o c_o)}{V_2 + (q_o c_i)}$$

(24.216)

Between storms the final reservoir concentration decreases to an equilibrium concentration according to the equation

$$c_s = (c_s - c_s) \exp(-k_s t d_{SO}) + c_s$$

(24.217)

where $c_s$ is the reservoir concentration $t$ days after the value of $c_s$ is obtained, $k_s$ is the decay constant, $d_{SO}$ is the median particle size of the inflow sediment, and $c_s$ is the equilibrium sediment concentration (input to the model). A value of $k_s$ is evaluated by assuming that 99% of the 1 μm particles are settled within 25 days ($k_s = 0.184$).

24.15. NUTRIENT AND PESTICIDE ROUTING

24.15.1. Nitrate Routing

Once NO₃-N enters a stream it is considered a conservative material for the duration of an individual runoff event (Williams, 1980). Thus, NO₃-N routing is simply a matter of adding the yields from all subbasins to determine the basin yield.

24.15.2. Organic N Routing

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

$$YON_{Bi} = 0.01 (Y_B)_j (CONSB)_j (ER_R)_j$$

(24.218)

where $YON_{Bi}$ 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 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 estimate of $ER_R$ is calculated by Eqs. (24.121), (24.122), and (24.123) with the delivery ratio for the channel routing calculated from

$$DR = \frac{(Y_{SB})_j}{(Y_B)_j}$$

(24.219)

where $Y_{SB}$ is the sediment yield at the subbasin outlet in t·ha⁻¹, and $Y_B$ is the sediment yield from subbasin $j$ after it has been routing to the basin.
24.15.3. P Routing

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

\[ Y_{P_{ij}} = 0.01 \left( Y_P \right)_j \left( C_{PSB} \right)_j \left( ER_R \right)_j \]  \hspace{1cm} (24.220)

where \( Y_{P_j} \) 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\(^{-1}\).

24.15.4. Pesticide Routing

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

24.16. LAKE WATER QUALITY

Few models predict the effect of land management on off-site concerns such as lake water quality often environmental engineers assume a non-point source loading to lake water quality models and cannot directly predict the effects of land management decisions. At the same time, agricultural engineers and scientists model the non-point source loading and do not consider the off-site effects.

Here an integrated model was developed by linking SWRRB with a lake toxic model developed by Chapra (1989). The integrated model operates on a daily time step and is efficient enough to run for multiple years on a microcomputer. The model tracks the fate of pesticides from their initial application on the land to their final fate in the lake. This allows decision makers to directly predict the influence of upland agricultural management decisions on lake water quality.

24.16.1. Toxic Balance

The lake toxic balance is taken from Chapra (1989) and assumes well-mixed conditions. The system is partitioned into a well-mixed surface water layer underlain by a well-mixed sediment layer. The toxic is partitioned into dissolved and particulate in both the surface-water and sediment layers. The major processes simulated by the model are loading, outflow, reactions, volatilization, settling, diffusion, resuspension, and burial. Loading to the lake is estimated by non-point source model components, and toxic outflow is simply the water outflow from the lake water balance multiplied by the concentration. Volatilization is the exchange of toxic across the air-water interface and acts only one the dissolved fraction while settling acts only on the particulate-associated fraction. Toxic movement due to random water motion of mixing is referred to as diffusion, which is the mechanism by which contaminated sediment pore water can seep back into the lake. Resuspension occurs when flow suspends particles that have been previously deposited. In the burial process, the toxic is covered to a depth where it can no longer react with the lake and is considered lost from the system. The mass balance can be described mathematically as

\[ \frac{\Delta C_1}{\Delta t} = \]

\[ Q_1 C_i - Q_o C_i - K_1 V_i C_i - V_i \]  \hspace{1cm} (24.221)

\[ \frac{\Delta C_2}{\Delta t} = \]

\[ K_2 V_s C_s + V_g A F_{dr} (C_i - V_i) A C_2 - V_d A (C_i - V_i) C_2 \]  \hspace{1cm} (24.222)

where subscripts 1 and 2 indicate the water layer and sediment layer, respectively, \( V \) is volume in m\(^3\), \( C \) is total (dissolved and particulate) toxic concentration in mg m\(^{-3}\), \( \Delta \) is the time step (one day), \( Q \) is water volume in m\(^3\) (subscripts 1 and 0 indicate inflow and outflow, respectively), \( K \) is a first order reaction coefficient in day\(^{-1}\), \( V_V \) is the volatilization mass transfer coefficient in m\(^3\) day\(^{-1}\), \( A \) is area in m\(^2\), \( V_s \) is settling velocity in m day\(^{-1}\), \( V_r \) is resuspension velocity in m day\(^{-1}\), \( V_d \) is diffusion mixing velocity in m day\(^{-1}\), \( V_b \) is burial velocity in m day\(^{-1}\), and \( F_d \) and \( F_p \) are the fraction of total contaminant in dissolved and particulate form, respectively.

**Soil-Liquid Partitioning**

The total toxic concentration is separated into two components

\[ C = C_d + C_p \]  \hspace{1cm} (24.223)
where \( C_d \) is the dissolved component and \( C_p \) is the particulate component. These components represent fraction of the total concentration as in

\[
C_d = F_d \cdot C
\]  
(24.224)

\[
C_p = F_p \cdot C
\]  
(24.225)

The fractions \( F_d \) and \( F_p \) are a function of the contaminant's partition coefficient and the suspended solids concentration in the lake.

\[
F_d = \frac{1}{1 + K_d \cdot S}
\]  
(24.226)

\[
F_p = \frac{K_d \cdot S}{1 + K_d \cdot S}
\]  
(24.227)

where \( K_d \) is a partition coefficient in m\(^3\)g and \( S \) is the suspended solids concentration in the lake in g* m\(^3\). The partition coefficient quantifies the tendency of the toxic to associate the solid matter.

### 24.16.2. Phosphorus Mass Balance

A simple model for phosphorus mass balance was taken from Thomann and Mueller (1987). The model assumes: 1) completely mixed lake, 2) phosphorus limited, and 3) total phosphorus can be used as a measure of trophic status. The first assumption ignores lake stratification and intensification of phytoplankton in the epilimnion. The second assumption is generally valid when non-point sources dominated and the third assumption implies that a relationship exists between total phosphorus and biomass.

Despite the severity of the assumptions, the following model has been shown to produce very useful results (Thomann and Mueller, 1987). The mass balance equation for total phosphorus is

\[
V \frac{\Delta P}{\Delta t} = W - K_s \cdot p \cdot V - Q_p
\]  
(24.228)

where \( V \) is volume of the lake m\(^3\), \( p \) is total phosphorus concentration in the lake in mg\(^1\), \( Q \) is outflow volume in l, \( K_s \) is overall loss rate of total phosphorus in day\(^{-1}\), \( W \) is total phosphorus inflow in mg, and \( \Delta t \) is the time increment (one day). Vollenwelder (1975) and Chapa and Tarpachak (1976) discuss estimates of \( K_s \) and methods of estimating \( K_s \) from readily available parameters.

### 24.16.3. Relationship Between Total Phosphorus and Trophic Status

Empirical relationships from measured data have been postulated by several researchers including Bartsch and Gakstatter (1978), Rast and Lee (1978), Dillon and Rigler (1975), and Smith and Shapiro (1981). The relationships are similar and the Rast and Lee (1978) relationship was selected for use in the model.

\[
\log_{10}(chl \cdot a) = -0.76 \log_{10}(p) - 0.259
\]  
(24.229)

where chl is a chlorophyll a concentration in mg\(^1\).

Another measure of lake trophic status is secchi depth. Since water clarity is easily perceived by the general public, secchi depth is an important measure of water quality. Table 24.1 shows that relationship between secchi depth and public perception of water quality. The relationship between secchi depth and chlorophyll concentration is (Rast and Lee, 1978).

\[
\log_{10}(S_d) = 0.473 \log_{10}(chl \cdot a) + 0.803
\]  
(24.230)

where \( S_d \) is the secchi depth in m.

### TABLE 24.1

**Relationship between secchi depth and public perception of water quality of Anhebessacook Lake, Maine (from USEPA, 1980).**

<table>
<thead>
<tr>
<th>Secchi depth (mm)</th>
<th>Public Perception of Water Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 0.9</td>
<td>Gross pollution; lake is totally unusable for recreation</td>
</tr>
<tr>
<td>1 - 1.9</td>
<td>Algae blooms still evident; quality unacceptable for most uses</td>
</tr>
<tr>
<td>2 - 2.9</td>
<td>Some complaints of declining water quality; some impairment of water use</td>
</tr>
<tr>
<td>3 - 3.9</td>
<td>Satisfactory quality; no impairment of water use</td>
</tr>
<tr>
<td>4 - 4.9</td>
<td>Excellent water quality; a positive factor encouraging lake use</td>
</tr>
<tr>
<td>5 +</td>
<td>Exceptional quality for this lake</td>
</tr>
</tbody>
</table>
NOTATIONS

\[ \alpha \quad = \quad \text{dimensionless parameter that expresses the proportion of total rainfall that occurs during } t_c \]
\[ \alpha_{sp} \quad = \quad \text{parameter dependent on maximum stream power for the reach} \]
\[ \rho \quad = \quad \text{runoff coefficient expressing the watershed infiltration characteristics} \]
\[ \sigma \quad = \quad \text{average channel slope (m/m)} \]
\[ \lambda \quad = \quad \text{surface slope length in (m)} \]
\[ \lambda_s \quad = \quad \text{surface slope length (km)} \]
\[ \Delta t \quad = \quad \text{time interval (24 h)} \]
\[ \xi_i \quad = \quad \text{dimensionless soil parameter (0-1)} \]
\[ \theta_d \quad = \quad \text{drainable porosity of the soil} \]
\[ \delta \quad = \quad \text{slope of the saturation vapor pressure curve (kPa'C-1)} \]
\[ \gamma \quad = \quad \text{psychrometer constant (kPa'C-1)} \]
\[ \beta \quad = \quad \text{fraction usually in the range of 0.6 to 0.9} \]
\[ \mu \quad = \quad \text{uniform random number (0.0-1.0)} \]
\[ \zeta \quad = \quad \text{parameter usually in the range of 1.0 to 2.0} \]
\[ \Omega_R \quad = \quad \text{scaling factor (0.0 to 1.0)} \]
\[ \Omega_T \quad = \quad \text{scaling factor (0.0 to 1.0)} \]
\[ f \quad = \quad \text{water flow rate through the zone (mm/h)} \]
\[ A \quad = \quad \text{use rate-depth parameter} \]
\[ \delta \quad = \quad \text{optimal temperature for the crop (°C)} \]
\[ \eta \quad = \quad \text{evaporation coefficient} \]
\[ \omega_1 \quad = \quad \text{parameter (1.3X10^-4)} \]
\[ \omega_2 \quad = \quad \text{fairly constant parameter (0.9)} \]
\[ \gamma \quad = \quad \text{density of water} \]
\[ \Delta t \quad = \quad \text{time step (one day)} \]
\[ \Delta t \quad = \quad \text{time increment (one day)} \]
\[ A \quad = \quad \text{drainage area (ha)} \]
\[ A \quad = \quad \text{area (m^2)} \]
\[ ab \quad = \quad \text{abstraction coefficient} \]
\[ AB \quad = \quad \text{albedo} \]
\[ AB_s \quad = \quad \text{soil albedo} \]

AIR \quad = \quad \text{volume of irrigation water applied (mm)}
AM \quad = \quad \text{annual amplitude in daily average temperature (°C)}
AO \quad = \quad \text{area represented by the rain gage (km^2)}
\[ a_r \quad = \quad \text{unit channel intercept (m^3)} \]
\[ a_x \quad = \quad \text{regression intercept (m*km)} \]
\[ B_1 \quad = \quad \text{fraction of the growing season} \]
\[ B_{AG} \quad = \quad \text{above ground biomass (kg*ha^-1)} \]
\[ bcv \quad = \quad \text{lagging factor for simulating residue and snow cover effects on surface} \]
\[ BD \quad = \quad \text{soil bulk density (ton*m^-3)} \]
\[ BE \quad = \quad \text{crop parameter for converting energy to biomass (kg*m^-2*ha^-1*MJ)} \]
\[ bn \quad = \quad \text{crop parameter expressing N concentration} \]
\[ B_p \quad = \quad \text{daily potential increase in total biomass (kg*ha^-1)} \]
\[ b_r \quad = \quad \text{unit channel regression slope} \]
\[ B_{TOT} \quad = \quad \text{total biomass on day i (kg*ha^-1)} \]
\[ b_x \quad = \quad \text{regression slope} \]
\[ C \quad = \quad \text{crop management factor} \]
\[ C \quad = \quad \text{total (dissolved and particulate) toxic concentration (mg*m)} \]
\[ C \quad = \quad \text{MUSLE factor for stream channel} \]
\[ c_a \quad = \quad \text{sediment concentration (g*m^-3)} \]
\[ C_d \quad = \quad \text{dissolved component} \]
\[ CDG \quad = \quad \text{soil water residue decay factors} \]
\[ CHK \quad = \quad \text{effective hydraulic conductivity of the channel alluvium (mm/hr)} \]
\[ chl \quad = \quad \text{chlorophyll a concentration (mg^-1)} \]
\[ c_i \quad = \quad \text{inflow sediment concentration} \]
\[ CLA_i \quad = \quad \text{clay content of soil layer i (0-1)} \]
\[ C_{LFP} \quad = \quad \text{concentration of AP in soil layer P (g*1^-1)} \]
\[ CM \quad = \quad \text{soil cover (above ground biomass+residue) (kg*ha^-1)} \]
\[ CN_1 \quad = \quad \text{curve number for moisture condition 1 (dry)} \]
\[ CN_2 \quad = \quad \text{curve number for moisture condition 2 (average)} \]
\[ CN_{2s} \quad = \quad \text{handbook CN2 value adjusted for slope} \]
\[ CN_3 \quad = \quad \text{curve number for moisture condition 3 (wet)} \]
\[ C_{NB} \quad = \quad \text{optimal N concentration of the crop} \]
\[ C_{\text{NO}} = \text{concentration of NO}_3^- \text{-N in the first layer} \]
\[ c_{\text{o}} = \text{outflow sediment concentration} \]
\[ \text{CON} = \text{concentration of organic N in the top soil layer (g*t}^{-1}) \]
\[ \text{CONSB} = \text{concentration of organic N in the sediment reaching the subbasin j outlet} \]
\[ C_p = \text{concentration of P in the top soil layer (g*t}^{-1}) \]
\[ C_p = \text{particulate component} \]
\[ C_{\text{PSB}} = \text{P concentration in the sediment reaching the subbasin j outlet (g*t}^{-1}) \]
\[ c_s = \text{reservoir concentration t days after the value of } c_s \text{ is obtained} \]
\[ c_{s1}, c_{s2} = \text{reservoir sediment concentrations at the beginning and end of the day} \]
\[ c_{v} = \text{equilibrium sediment concentration (input to the model)} \]
\[ CV = \text{sum of above ground biomass and crop residue (kg*ha}^{-1}) \]
\[ CVM = \text{minimum value of C} \]
\[ C_{\text{NO}} = \text{concentration of NO}_3^- \text{-N at the end of the day} \]
\[ d = \text{flow depth (m)} \]
\[ d = \text{sediment particle diameter} \]
\[ d_{50} = \text{median particle size of the inflow sediment} \]
\[ DA = \text{drainage area into the reach (km}^2) \]
\[ DD = \text{damping depth for the soil (mm)} \]
\[ DECR = \text{daily decrease in residue} \]
\[ DEG = \text{total degradation} \]
\[ DLAI = \text{fraction of the growing season when LAI starts declining} \]
\[ DP = \text{maximum damping depth for the soil (mm)} \]
\[ d_0 = \text{depth of flow} \]
\[ DR = \text{sediment delivery ratio (subbasin sediment yield divided by gross sheet erosion)} \]
\[ DU = \text{duration of streamflow (h)} \]
\[ DUR = \text{rainfall duration (h)} \]
\[ EA = \text{soil cover index} \]
\[ EFI = \text{runoff ratio} \]
\[ ELE = \text{elevation of the site (m)} \]
\[ E_{o} = \text{potential evaporation (mm)} \]
\[ E_p = \text{predicted plant water evaporation rate (mm*d}^{-1}) \]
\[ ER = \text{enrichment ratio} \]

\[ ER = \text{enrichment ratio for the channel routing from subbasin j to the channel outlet} \]
\[ F_5 = \text{potential soil water evaporation rate (mm*d}^{-1}) \]
\[ ET = \text{evapotranspiration (mm)} \]
\[ EV = \text{evaporation (m}^3) \]
\[ FC = \text{field capacity water content (mm)} \]
\[ FC_2 = \text{field capacity of the second soil layer} \]
\[ F_d = \text{fraction of total contaminant in dissolved form} \]
\[ FFC = \text{fraction of field capacity} \]
\[ FFC^* = \text{depth weighted FFC value} \]
\[ FHU = \text{function of crop stage} \]
\[ F_P = \text{fraction of total contaminant in particulate form} \]
\[ F_P = \text{final amount of pesticide on the plant} \]
\[ FP_0 = \text{initial amount of pesticide on the plant} \]
\[ G_C = \text{fraction of the ground that is covered by plants} \]
\[ G_P = \text{final amount of pesticide on the ground} \]
\[ GP_0 = \text{initial amount of pesticide on the ground} \]
\[ H_i = \text{hydraulic conductivity (mm*h}^{-1}) \]
\[ H_I = \text{harvest index at harvest} \]
\[ H_{iA} = \text{adjusted harvest index} \]
\[ H_{iO} = \text{harvest index under favorable growing conditions} \]
\[ H_LA = \text{harvest index on day i} \]
\[ HLP = \text{half life of the foliar residue (d)} \]
\[ HLS = \text{half life for pesticide in the soil (d)} \]
\[ h_o = \text{net radiation (MJ*}m^{-2}) \]
\[ H = \text{saturated thickness normal to the hillslope} \]
\[ HU = \text{heat units (C)} \]
\[ HUFH = \text{heat unit factor that affects harvest index on day i and on the previous day i-1} \]
\[ HUI = \text{heat unit index for day i} \]
\[ HV = \text{latent heat of vaporization (MJ*kg}^{-1}) \]
\[ i = \text{rate of water input to the saturated zone (m}^2*h}^{-1}) \]
\[ i = \text{day of the year} \]
K = MUSLE factor for stream channel
K = soil erodibility factor
K = first order reaction coefficient (day⁻¹)
k_d = P concentration in the sediment divided by that of the water (m³·s⁻¹)
k_p = partitioning coefficient (m³·s⁻¹)
k_r = decay factor (m·km⁻¹)
k_s = decay constant
K_s = saturated conductivity
K_s = overall loss rate of total phosphorus (day⁻¹)
L = channel length from the most distant point to the watershed outlet (km)
L = hillslope length (m)
L' = channel length (km)
LAI = leaf area index
LAI_max = maximum LAI potential for the crop
LAT = latitude of the site (degrees)
l_c = average channel flow length for the watershed (km)
l_c = distance from the outlet along the channel to the watershed centroid (km)
l_s = saturated slope length (m)
LS = slope length and steepness factor
M = number of soil layers
n = Manning’s roughness coefficient
N = number of subbasins
ND = number of days in a month
NDD = number of dry days
N_g = number of days in the growing season
NRD = number of rainy days
NWD = number of wet days
O = percolation rate (mm·d⁻¹)
O_l = percolation from the first layer (mm)
O_l = percolation rate for layer i (mm·d⁻¹)
O_l = flow from the layer above (mm·d⁻¹)
p = total phosphorus concentration in the lake (mg·l⁻¹)

P = percolation (mm)
P(W/D) = probability of a wet day following a dry day
P(W/W) = probability of a wet day after a wet day
PAEF = application efficiency factor
PAPE = effective amount of pesticide applied (kg·ha⁻¹)
PAPR = actual amount of pesticide applied (kg·ha⁻¹)
PAR = photosynthetic active radiation (MJ·m⁻²)
PB = barometric pressure (kPa)
PE = erosion control practice factor
PHU = potential heat units to mature the crop (°C)
P_i = inflow volume (m³)
P_o = threshold volume for a unit channel (m³)
PO = soil porosity
POFC = porosity-field capacity ratio
PSO1 = pesticide solubility (g·m⁻³)
PSTC = concentration of adsorbed pesticide (g·t⁻¹)
PSTC_L = pesticide concentration in the percolate (g·m⁻³)
PSTC_W = pesticide concentration in the water (g·t⁻¹)
PSTL = amount of pesticide leached by f
PSTQ = pesticide loss in surface runoff (kg·ha⁻¹)
PSTY = pesticide yield adsorbed to the sediment (kg·ha⁻¹)
PW = probability of a wet day
q = flow rate
Q = surface runoff volume (mm)
q_c = average flow rate (mm·h⁻¹)
q_p = peak rate per unit of rainfall (mm·h⁻¹·mm⁻¹)
q_p = peak runoff rate (m³·s⁻¹)
q_c = average flow rate (m³·s⁻¹)
QI = inflow during the day
Q = lateral flow (m³·h⁻¹)
q_o = average flow rate (m³·s⁻¹)
QO = outflow (m³)
$q_0$ = average flow rate from a 1 ha area (mm/h)
QOR = daily outflow (m³)
$q_p$ = peak flow rate (m³/s)
QR = return flow (mm)
$q_{1l}$ = lateral flow from the first layer (mm)
$q_{sat}$ = upward flow (mm/day)
QT = total water lost from the first layer (mm)
$r$ = rainfall intensity for the watershed’s time of concentration (mm/h)
R = daily rainfall in month k
RA = solar radiation (MJ/m²)
RAD = daily mean solar radiation on dry days
RAMX = maximum daily solar radiation at midmonth
RAW = daily mean solar radiation on wet days (MJ/m²)
RDn = fraction of the root zone that contains roots on day n
REG = crop growth regulating factor
$r_{ep}$ = peak rainfall excess rate (mm/h)
RF = reduction ratio (0-1)
RFn = reduction factor
Ri = daily rainfall for rain gage i
$r_p$ = peak rainfall rate (mm/h)
RR = principal spillway release rate (m³/s)
RSD = residue left after harvest (kg/ha)
RSDV = standard deviation of daily rainfall (mm)
Re = amount of rainfall during the watershed's time of concentration (mm)
RWT = fraction of total biomass partitioned to the root system on day i
RZ = root zone depth (mm)
s = land surface slope (m/m)
S = suspended solids concentration in the lake (g/m³)
S = drainable volume of water stored in the saturated zone (m³/m³)
S = average volume of water stored in the watershed
s1 = value of s associated with CN1
s3 = CN3 retention parameter

SA = reservoir surface area
S_c = slope of the channel
SCF = skew coefficient
SCi = saturated conductivity for layer i (mm/h)
Sd = secchi depth (m)
SD = sun’s declination angle (radians)
SDRA = standard deviation of daily solar radiation (MJ/m²)
SDTMX = standard deviation of the daily maximum temperature
SED_in = sediment entering the reach
SEP = seepage (m³)
SEV = potential soil evaporation for layer i (mm)
SEV * = adjusted soil water evaporation estimate (mm)
Sf = retention parameter for frozen ground
SML = snowmelt rate (mm/day)
SN = standard normal deviate for day i
SNO = water content of snow cover (mm)
Sp = scaling parameter
SPT = snow pack temperature (°C)
SRDEP = amount of sediment deposited in the reservoir
SR = total sediment in the reservoir
SRn-1 = total sediment in the reservoir on the previous day
SRin = incoming sediment
SRout = sediment transported in the sediment outflow
ST2 = soil temperature of the second soil layer
SUT = soil temperature residue decay factors
SW = amount of water stored in the top 10 mm of soil (mm)
SWW = water surface slope
SW = soil water content in the root zone (mm)
SW2 = soil water content of the second soil layer
SWO = soil water contents at the beginning of the day (mm)
t = time (d)
T = mean daily air temperature (°C)
T(2) = temperature at the center of soil layer 2
T_b = crop-specific base temperature (°C)
t_c = watershed's time of concentration (h)
t_w = time of concentration for channel flow (h)
t_s = time of concentration for surface flow (h)
TD = daily mean maximum temperature for dry days
TE = extreme daily maximum temperature
TGBIDA = bare soil surface temperature (°C)
TL = transmission loss (mm)
Tma, Tmn = daily maximum and minimum air temperatures (°C)
T_s = temperature at the top of the snow pack
t_rf = t_r components attributed to shallow channel flow
TT = travel time (h)
TT_c = crack flow travel time (h)
TW = daily mean maximum temperature for wet days (°C)
U_i = plant water use in layer i (mm)
UND = N demand of the crop (kg*ha⁻¹)
u_pi = potential water use rate from layer i (mm*day⁻¹)
v = velocity of flow at the outlet
V = volume (m³)
V_f = fall velocity (m*day⁻¹)
V1, V2 = storage volumes at the beginning and end of the day
V_b = burial velocity (m*day⁻¹)
V_c = average channel velocity (m*s⁻¹)
V_c = velocity in the channel
V_d = diffusion mixing velocity (m*day⁻¹)
VM = volume of the water stored in all ponds within a subbasin at the end of the day
VM_max = maximum permanent pool storage of all ponds in the subbasin (m³)
VM_O = volume of the water stored in all ponds within a subbasin at the beginning of the day
VNO3 = amount NO₃-N lost from the first layer
VR = resuspension velocity (m*day⁻¹)
VRF = reservoir capacity at the emergency spillway crest (m³)
VRG = reservoir capacity at the principal spillway crest (m³)
V_s = surface flow velocity (m*sec⁻¹)
V_s = settling velocity (m*day⁻¹)
V_s = average shallow flow velocity (m*sec⁻¹)
V_v = volatilization mass transfer coefficient (m*day⁻¹)
w = average width of flow (m)
W = total phosphorus inflow (mg)
w1, w2 = shape parameters
WLV = above ground biomass minus crop yield at harvest (kg*ha⁻¹)
WNO3 = weight of NO₃-N contained in the layer at the end of the day
WNO3_O = weight of NO₃-N contained in the layer at the beginning of the day
WO = amount of pesticide washed off the plants by a rainstorm (mm)
WOF = washoff fraction for the particular pesticide
WP = wilting point water content for soil layer one (mm)
WS = water stress factor for day i
WSYF = crop parameter expressing drought sensitivity
x, y = coordinates of the rain gages (km)
x1, x2 = parameters set by the upper and lower limits
Y = sediment yield (t*ha⁻¹)
Y_B = sediment yield reaching the basin outlet from subbasin j (t*ha⁻¹)
YLD = amount of the crop removed from the field (kg*ha⁻¹)
YON = organic N runoff loss at the subbasin outlet (kg*ha⁻¹)
YONB = organic N runoff loss at the basin outlet (kg*ha⁻¹)
YP = sediment phase of P loss in runoff (kg*ha⁻¹)
YPB = P yield at the basin outlet (kg*ha⁻¹)
YSB = sediment yield at the subbasin outlet (t*ha⁻¹)
YS = soluble P lost in runoff (kg*ha⁻¹)
z = weighting factor for estimating soil surface temperature on dry days
Z = depth to the bottom of soil layer (m)
ZM = distance from the bottom of the lowest soil layer to the surface (mm)
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Chapter 25

THE EPIC MODEL

J.R. Williams

25.1. INTRODUCTION

The Erosion-Productivity Impact Calculator (EPIC) (Williams et al., 1984) model was developed to assess the effect of soil erosion on soil productivity. It was used for that purpose as part of the 1985 RCA (1977 Soil and Water Resources Conservation Act) analysis. Since the RCA application, the model has been expanded and refined to allow simulation of many processes important in agricultural management (Sharpless and Williams, 1990).

EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally a field-sized area, up to 100 ha (weather, soils, and management systems are assumed to be homogeneous). The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control.

Recently, most of the EPIC model development has been focused on problems involving water quality and global climate/CO₂ change. Example additions include the GLEAMS (Leonard et al., 1987) pesticide fate component, nitrification and volatilization submodels, a new more physically based wind erosion component, optional SCS technology for estimating peak runoff rates, newly developed sediment yield equations, and mechanisms for simulating CO₂ effects on crop growth and water use. These and other less significant developments extend EPIC’s capabilities to deal with a wide variety of agricultural management problems.

Example applications include: (1) 1985 RCA analysis; (2) 1988 drought assessment; (3) soil loss tolerance tool; (4) Australian sugarcane model (AUSCAN); (5) pine tree growth simulator; (6) global climate change analysis (effect of CO₂, temperature, and precipitation change on runoff and crop yield); (7) farm level planning; (8) five-nation EEC assessment of environmental/agricultural policy alternatives; (9) Argentine assessment of erosion/productivity; (10) USDA-Water Quality Demonstration Project Evaluation; (11) N leaching index national analysis.

The purpose here is to fully describe the new more comprehensive EPIC model and present example applications. Descriptions of the EPIC components and the mathematic relationships used to simulate the processes involved follow.