

# **SWIM**

**(Soil and Water Integrated Model)**

# **User Manual**

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## Abstract

Development of integrated tools for hydrological/vegetation/water quality modelling at the river basin scale is motivated by water resources management in densely populated agricultural areas (water pollution problem), arid and semi-arid regions (water scarcity), and mountainous and loess regions (erosion problem). The other motivation is an ongoing climate change and land use/land cover change. Development of water resources in the conditions of global change requires an understanding and adequate representation in models of basic hydrologic and related processes at mesoscale and large scale, i.e. in river basins of hundreds, thousands or tens of thousands of square kilometers.

The model SWIM (**S**oil and **W**ater **I**ntegrated **M**odel) was developed in order to provide a comprehensive GIS-based tool for hydrological and water quality modelling in mesoscale and large river basins (from 100 to 10,000 km<sup>2</sup>), which can be parameterised using regionally available information. The model was developed for the use mainly in Europe and temperate zone, though its application in other regions is possible as well. SWIM is based on two previously developed tools - SWAT and MATSALU (see more explanations in section 1.1).

The model integrates hydrology, vegetation, erosion, and nutrient dynamics at the watershed scale. SWIM has a three-level disaggregation scheme 'basin – sub-basins – hydrotopes' and is coupled to the Geographic Information System GRASS (GRASS, 1993). A robust approach is suggested for the nitrogen and phosphorus modelling in mesoscale watersheds. SWIM runs under the UNIX environment.

Model test and validation were performed sequentially for hydrology, crop growth, nitrogen and erosion in a number of mesoscale watersheds in the German part of the Elbe drainage basin. A comprehensive scheme of spatial disaggregation into sub-basins and hydrotopes combined with reasonable restriction on a sub-basin area allows performing the assessment of water resources and water quality with SWIM in mesoscale river basins. The modest data requirements represent an important advantage of the model. Direct connection to land use and climate data provides a possibility to use the model for analysis of climate change and land use change impacts on hydrology, agricultural production, and water quality.

However, the model is quite complicated, and it cannot be used as a black box. Understanding of the model code is a prerequisite for successful applications.



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# 1. Model Description

This chapter includes an overview about the model history (section 1.1), the general description of the model objectives, processes, and the spatial disaggregation (section 1.2), a short overview of the model components (section 1.3), and a detailed mathematical description of the model components (section 1.4).

## 1.1 Model History

The SWIM model is based on two previously developed tools – SWAT (Arnold *et al.*, 1993 & 1994), and MATSALU (Krysanova *et al.*, 1989a & b).

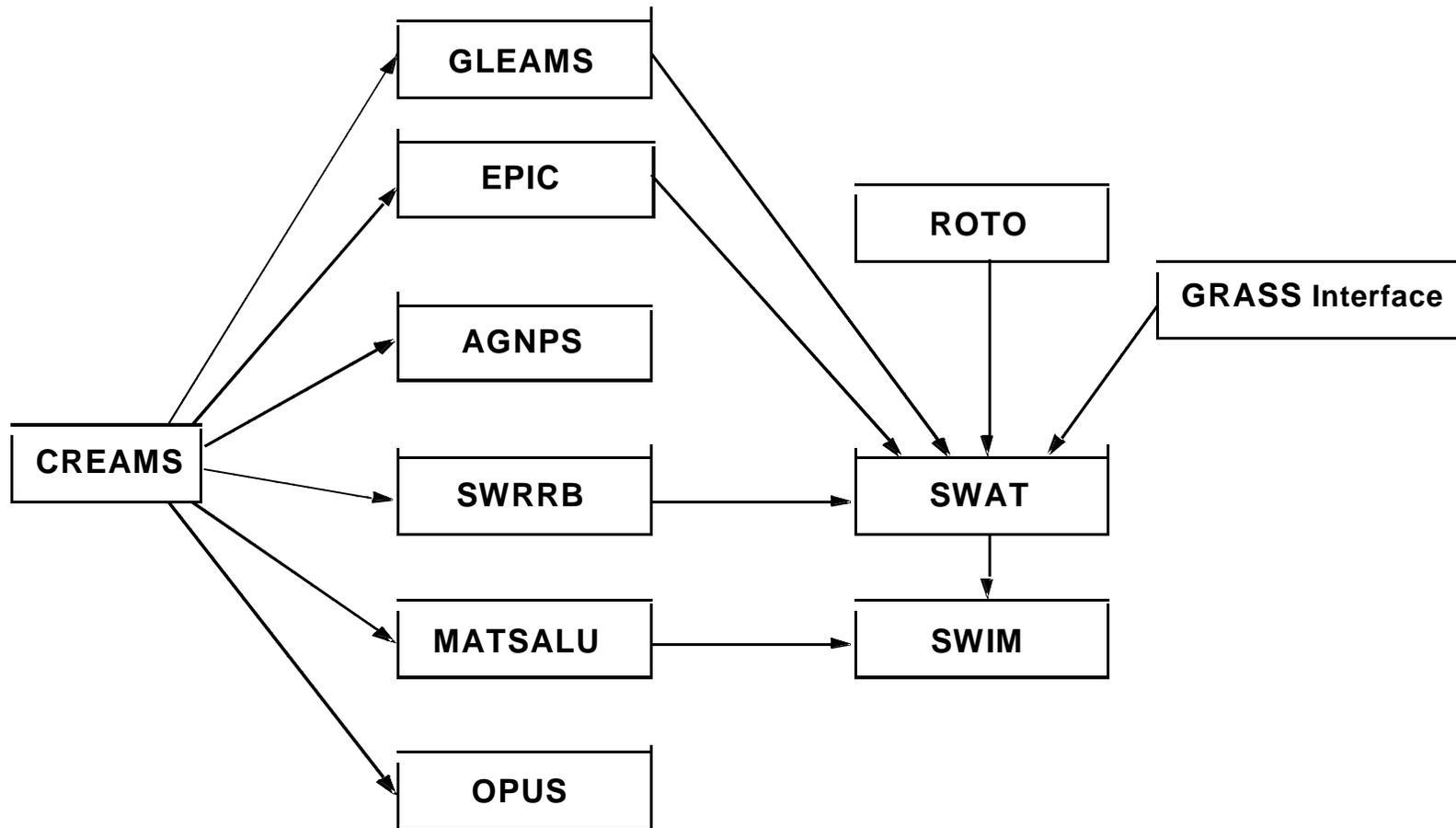
SWAT is a continuous-time distributed simulation watershed model. It was developed to predict the effects of alternative management decisions on water, sediment, and chemical yields with reasonable accuracy for ungauged rural basins. One of its attractive features is that there is a long period of modeling experience behind this model (see **Fig. 1.1**).

In the mid-1970's in response to the Clean Water Act, the USDA Agricultural Research Service (ARS) assembled a team of interdisciplinary scientists to develop a process-based, nonpoint source simulation model. From that effort, a field scale model called CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) was developed (Knisel, 1980) to simulate the impact of land management on water, sediment, and nutrients.

In the 1980's, several models have been developed with origins from the CREAMS model. One of them, the GLEAMS model (Groundwater Loading Effects on Agricultural Management Systems) (Leonard *et al.*, 1987) concentrated on pesticide and nutrient load to groundwater. Another model called EPIC (Erosion-Productivity Impact Calculator) (Williams *et al.*, 1984 & 1985) was originally developed to simulate the impact of erosion on crop productivity and has now evolved into a comprehensive agricultural field scale model aimed in the assessment of agricultural management and nonpoint source loads. One more model for estimating the effects of different management practices on nonpoint source pollution from field-sized areas and also based on CREAMS is the OPUS model (Smith, 1992). These three models can be applied for the field-scale areas or small homogeneous watersheds.

Other efforts involved modifying CREAMS to simulate complex watersheds with varying soils, land use, and management, which resulted in the development of several models, like AGNPS (Young *et al.*, 1989), SWRRB (Arnold *et al.*, 1990) and MATSALU (Krysanova *et al.*, 1989a & b).

AGNPS (AGricultural NonPoint Source) is a spatially detailed, single event (storm) model that subdivides complex watersheds into grid cells.



**Fig. 1.1** Model development based on the CREAMS model

SWRRB (Simulator for Water Resources in Rural Basins) was developed to simulate nonpoint source pollution from watersheds. It is a continuous time (daily time step) model that allows a basin to be subdivided into a maximum of ten sub-basins. To create SWRRB, the CREAMS model was modified for application to large, complex, rural basins.

The major changes involved were the following

- the model was expanded to allow simultaneous computations on several sub-basins;
- a better method was developed for predicting the peak runoff rate;
- a lateral subsurface flow component was added;
- a crop growth model was appended to account for annual variation in growth and its influence on hydrological processes;
- a pond/reservoir storage component was adjoined;
- a weather generator (rainfall, solar radiation, and temperature) was added for more representative weather inputs, both temporally and spatially;
- a module accounting for transmission losses was appended;
- a simple flood routing component was adjoined; and
- a sediment routing component was added to simulate sediment movement through ponds, reservoirs, streams, and valleys.

SWRRB was still limited to ten sub-basins and had a simplistic routing structure with outputs routed from the sub-basin outlets directly to the basin outlet. This problem led to the development of a model called ROTO (Routing Outputs to Outlet) (Arnold *et al.*, 1990), which took outputs from SWRRB run on multiple sub-basins and routed the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB sub-basin limitation by "linking" the sub-basin outputs.

Although the combination SWRRB + ROTO was quite effective, especially in comparison with CREAMS, the input and output of multiple files was cumbersome and required considerable computer storage. Limitations also occurred due to the fact that all SWRRB runs had to be made independently, and then the SWRRB outputs had to be input to ROTO for the channel and reservoir routing. Finally, the model called SWAT (Soil and Water Assessment Tool) was developed merging SWRRB and ROTO into one basin scale model. SWAT is a continuous time model working with daily time step, which allows a basin to be divided into hundreds or thousands of sub-watersheds or grid cells.

One more model, MATSALU, was developed in Estonia for the agricultural basin of the Matsalu Bay (which belongs to the Baltic Sea) with the area about 3,500 km<sup>2</sup> and the bay ecosystem in order to evaluate different management scenarios for the eutrophication control of the Bay. The model consists of four coupled submodels, which simulate 1) watershed hydrology, 2) watershed geochemistry, 3) river transport of water and nutrients, and 4) nutrient dynamics in the Bay ecosystem. Similar to SWRRB, its watershed components were essentially based on the CREAMS approach.

Spatial disaggregation in MATSALU is based on the overlay of three map layers: a map of elementary watersheds with an average area of 10 km<sup>2</sup>, a land use map, and a soil map, to obtain so-called Elementary Areas of Pollution (EAP). Conceptually the EAPs are similar to Hydrologic Response Units (HRU) or hydrotopes. The three-level disaggregation scheme of MATSALU includes 'the basin – elementary sub-basins – EAPs'. Since the model was developed for the MATSALU watershed and connected to specific data sets, it is not sufficiently transferable.

Merging the two tools: SWAT and MATSALU, we tried to keep their best features and maintain their advantages (see **Tab. 1.1**). The model code was mostly based on SWAT. The more comprehensive three-level spatial disaggregation scheme from MATSALU was introduced into SWAT as an initial step. The next step was to adjust the model for the use in European conditions, where data availability is different. This required some efforts in order to modify the data input. Besides, several modules were excluded from SWAT (pesticides, ponds/reservoirs, lake water quality) in order to avoid the overparametrization.

**Table 1.1** Comparison of advantages and disadvantages of SWAT and MATSALU

	<i>Advantages</i>	<i>Disadvantages</i>
<i>SWAT</i>	<ul style="list-style-type: none"> <li>• Coupling with GIS</li> <li>• Hydrological module tested in several meso- and macroscale watersheds</li> <li>• Vegetation module (simplified EPIC) is adopted for different crops and natural vegetation</li> </ul>	<ul style="list-style-type: none"> <li>• Two-level disaggregation (basin and sub-basins) in SWAT-93</li> <li>• Connection to specific American data sets (especially soil, climate)</li> <li>• SWAT as a long-term predictor was always tested and validated only with monthly time step</li> </ul>
<i>MATSALU</i>	<ul style="list-style-type: none"> <li>• Three-level disaggregation scheme</li> <li>• N-module was tested in mesoscale watershed in connection with hydrology and river transport</li> </ul>	<ul style="list-style-type: none"> <li>• Connection to specific Estonian data sets, not transferable to other basins</li> <li>• Four coupled models, not a coupled watershed model</li> </ul>

In parallel to the model development, its modules were sequentially tested in the Elbe basin, starting from hydrology. In contrast to SWAT, the hydrological module of SWIM has been validated with a daily time step. During the test, some subroutines were modified, some parameters were changed, and some components have been substituted.

Currently the model SWIM includes some common (or similar) modules of both predecessors and some new routines, like the flow routing, which is based on Muskingum method instead of ROTO in SWAT and Sant-Venant approach in MATSALU. The SWAT/GRASS interface was modified for SWIM.

Further development of the model is planned in the following directions:

- standardization of climate and crop management input data,
- addition of a module accounting for the carbon cycle in soil;
- addition of the lake and watershed modules;
- improving the description of lateral transport of nutrients; and
- modifying SWIM/GRASS interface to include automatic connection of climate/precipitation stations to sub-basins.

## 1.2 General Description

### 1.2.1 Model Objectives

The objectives of the model are two-fold:

- to provide a comprehensive GIS-based tool for the coupled hydrological/vegetation/water quality modelling in mesoscale watersheds (from 100 up to 10,000 km<sup>2</sup>), which can be parameterised using regionally available data, and
- to enable the use of the model for analysis of climate change and land use change impacts on hydrological processes, agricultural production and water quality at the regional scale.

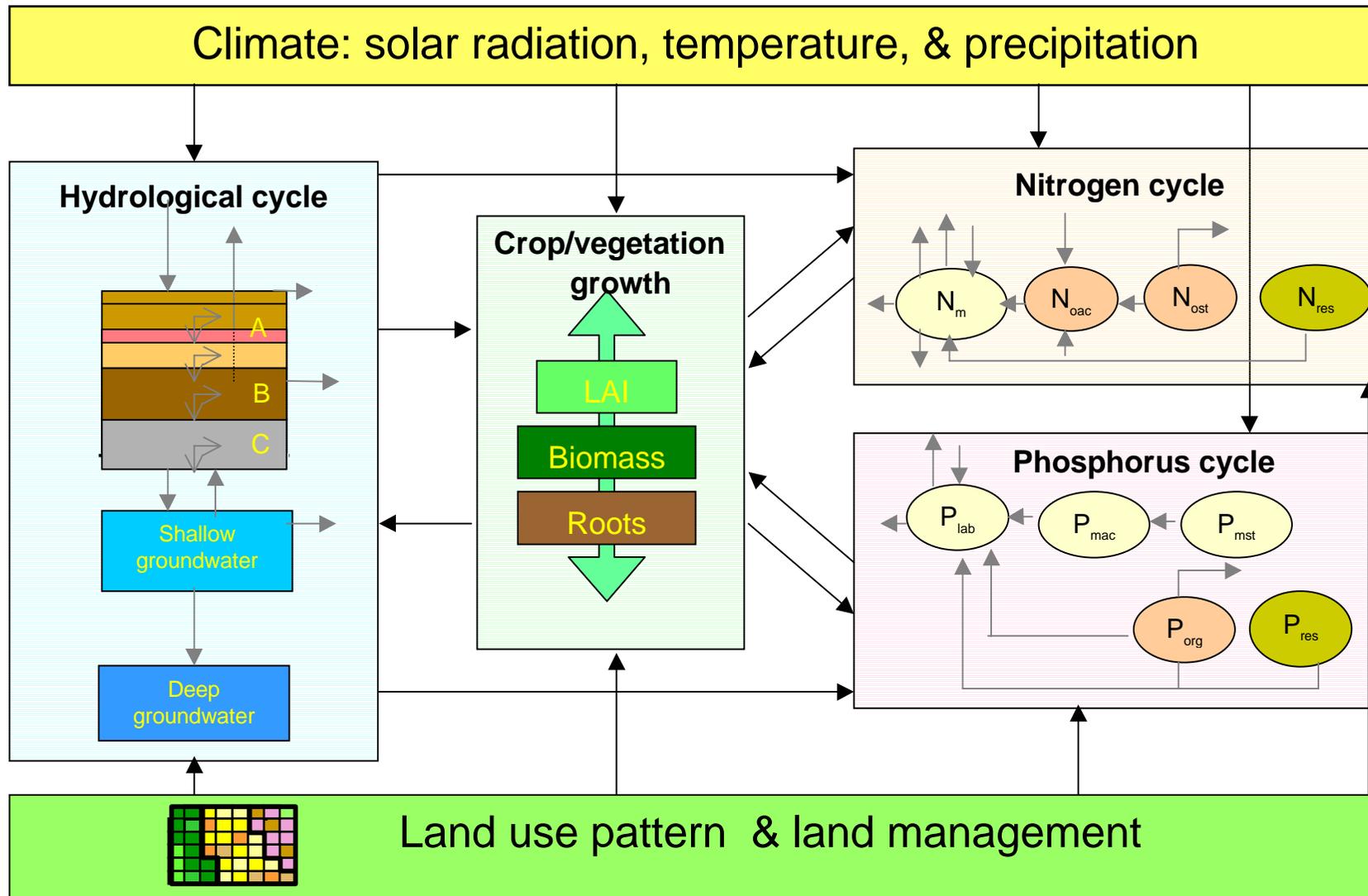
### 1.2.2 Processes Described in the Model

SWIM integrates hydrology, erosion, vegetation, and nitrogen/phosphorus dynamics at the river basin scale (**Fig. 1.2**) and uses climate input data and agricultural management data as external forcing. The hydrological module is based on the water balance equation, taking into account precipitation, evapotranspiration, percolation, surface runoff, and subsurface runoff for the soil column subdivided into several layers.

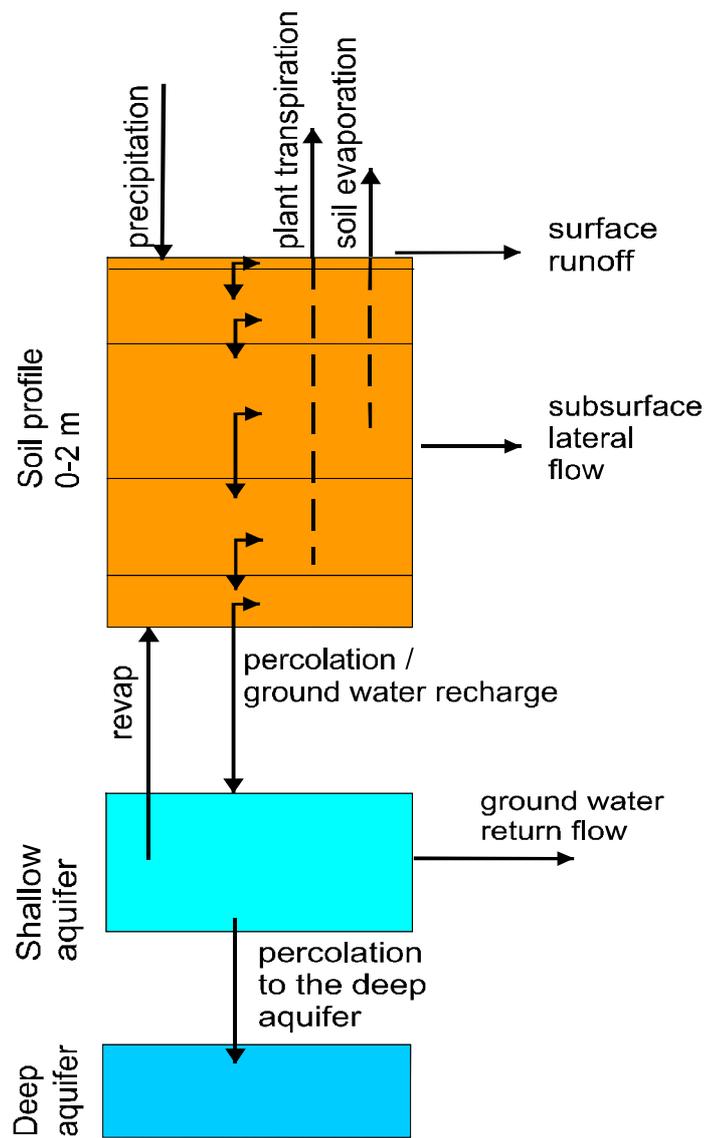
The simulated hydrological system consists of four control volumes: the soil surface, the root zone, the shallow aquifer, and the deep aquifer (**Fig. 1.3**). The percolation from the soil profile is assumed to recharge the shallow aquifer. Return flow from the shallow aquifer contributes to the streamflow. The soil column is subdivided into several layers in accordance with the soil data base. The water balance for the soil column includes precipitation, evapotranspiration, percolation, surface runoff, and subsurface runoff. The water balance for the shallow aquifer includes ground water recharge, capillary rise to the soil profile, lateral flow, and percolation to the deep aquifer.

The nitrogen module includes the following pools (**Fig. 1.4**): nitrate nitrogen (NO<sub>3</sub>-N), active and stable organic nitrogen, organic nitrogen in the plant residue, and the flows: fertilisation, input with precipitation, mineralisation, denitrification, plant uptake, wash-off with surface and subsurface flows, leaching to ground water, and loss with erosion. The phosphorus module includes the pools: labile phosphorus, active and stable mineral phosphorus, organic phosphorus, and phosphorus in the plant residue, and the flows: fertilisation, sorption/desorption, mineralisation, plant uptake, loss with erosion, wash-off with lateral flow. The wash-off to surface water and leaching to groundwater are more important for nitrogen, while phosphorus is mainly transported with erosion.

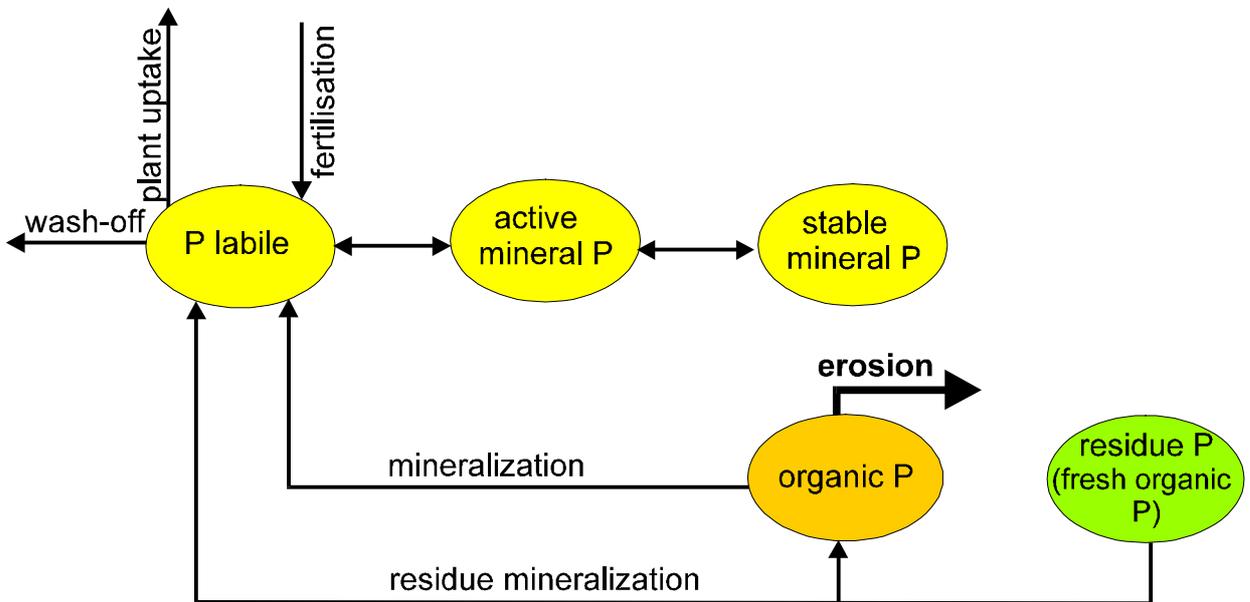
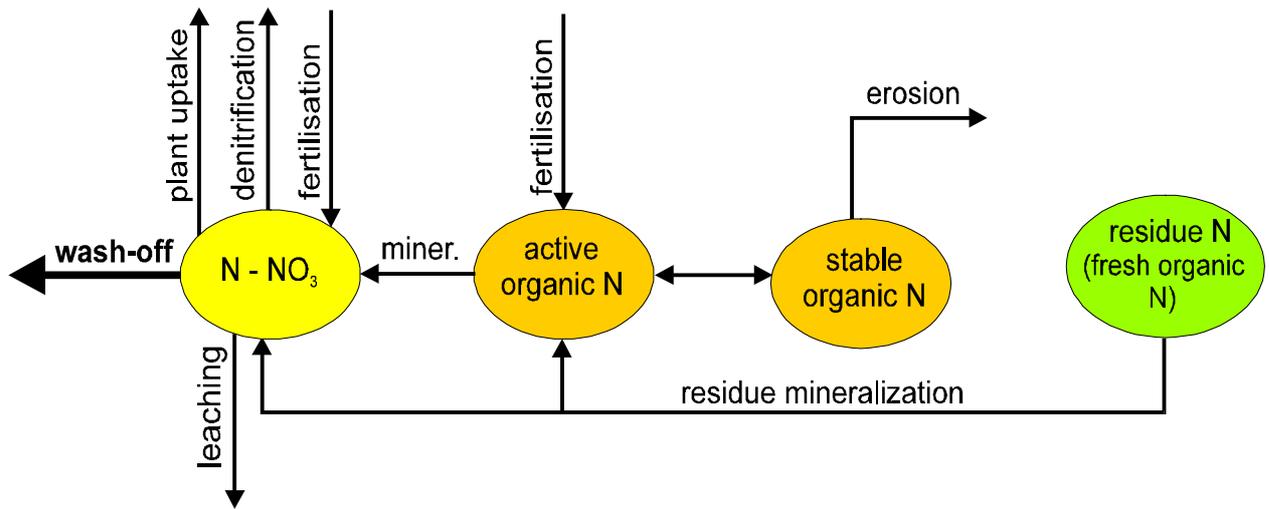
The module representing crop and natural vegetation is an important interface between hydrology and nutrients. The same as in SWAT, a simplified EPIC approach (Williams *et al.*, 1984) is included in SWIM for simulating all arable crops considered (wheat, barley, corn, potatoes, alfalfa, and others), using unique parameter values for each crop, which were obtained in different field studies. Simplification relates mainly to less detailed description of phenological processes and lower requirements on the input information. This enables to simulate crop growth in a distributed modelling framework for quite large basins and regions. Non-arable and natural vegetation is included in the database through some 'aggregated' vegetation types like 'grass', 'pasture', 'forest', etc. and can be simulated as well.



**Fig. 1.2** Flow chart of the SWIM model, integrating hydrological processes, crop/vegetation growth, and nutrient dynamics



**Fig. 1.3** Flow chart of hydrological processes in soil as implemented in SWIM



**Fig. 1.4** Nitrogen and phosphorus flow charts as implemented in SWIM

### 1.2.3 Spatial Disaggregation

A three-level disaggregation scheme similar to that used in MATSALU is implemented in SWIM for mesoscale basins (Fig. 1.5). The three-level disaggregation scheme in SWIM implies 1) basin, 2) sub-basins, and 3) hydrotopes inside sub-basins. The idea is that a mesoscale basin (from 100 to 10,000 km<sup>2</sup>) is first subdivided into sub-basins of reasonable average area (see explanation in section 3.1.3). This can be done using the *r.watershed* program of GRASS (or any other GIS with similar capabilities), which is applied to a Digital Elevation Model of the area with a certain threshold for the average size of the sub-basin.

After that the hydrotopes (or HRUs) are delineated within every sub-basin, based on land use and soil types. Normally, a hydrotope is a set of disconnected units in the sub-basin, which have a unique land use and soil type. A hydrotope can be assumed to behave in a hydrologically uniform way within the sub-basin.

### 1.2.4 GIS Interface

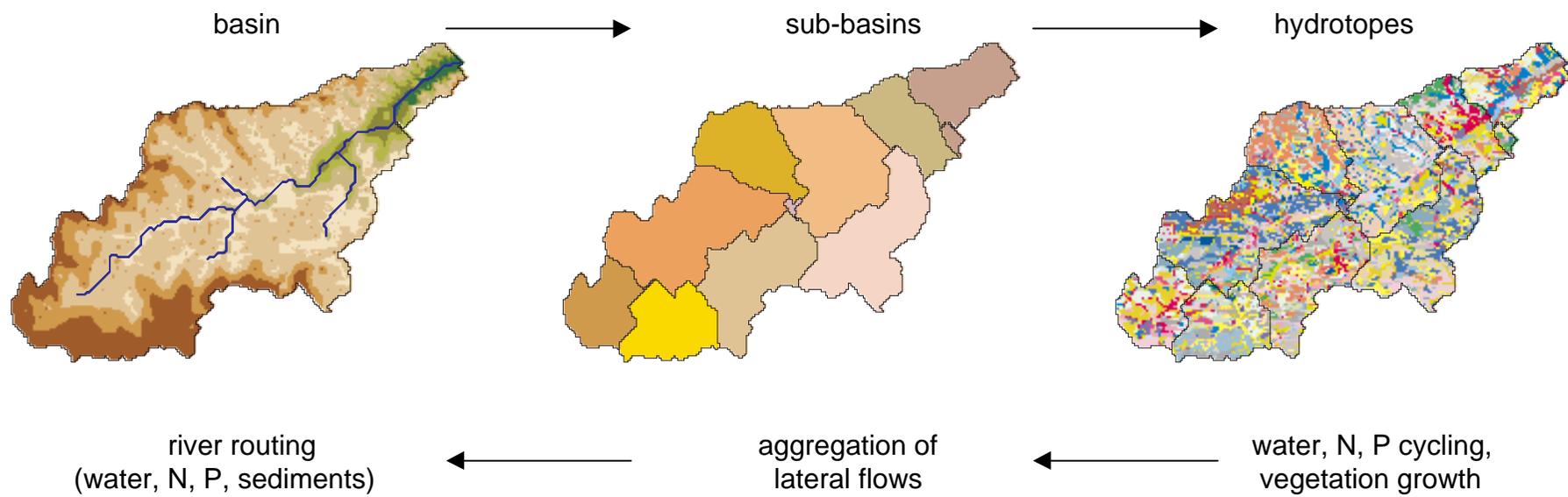
The SWAT/GRASS interface (Srinivasan, Arnold, 1993; Srinivasan *et al.*, 1993) was adopted and modified for SWIM to extract spatially distributed parameters of elevation, land use, soil types, and groundwater table. The interface creates a number of input files for the basin and sub-basins, including the hydrotope structure file (indicating sub-basin number, land use and soil type for every hydrotope) and the routing structure file (indicating how the sub-basins are connected via river network). To start the interface, the user must have at least four map layers of a basin. Three of them are the elevation map, the land use map, and the soil map. The fourth, sub-basin map, should be created in advance either using the *r.watershed* program of GRASS or by subdividing the basin in any other way.

**Step 1. Sub-basin attributes** This is the first step to be fulfilled. The program calculates area, resolution, and co-ordinate boundaries for the basin and each sub-basin, using a given sub-basin map. Further, the fraction of each sub-basin area to the basin area is calculated.

**Step 2. Topographic attributes** The program estimates the stream length, stream slope and geometrical dimensions using the *r.stream.att* tool (Srinivasan, Arnold, 1994). The cross sectional dimensions (width and depth) of a stream are estimated using a neural network that is embedded in the interface, based on the drainage area and average elevation of a sub-basin (which should be "trained" on the regional data before use). The accumulation area and aspect are computed using the standard methods in GRASS. The weighted average method is used to estimate the overland slope and slope length. Finally, the channel USLE (Universal Soil Loss Equation) factors K and C are estimated using a standard table.

**Step 3. Hydrotope structure** The program defines the basin hydrotope structure by overlaying the sub-basin map with land use and soil layers. The structure file is created to run the model. Each line in the file describes the characteristics of one hydrotope - its sub-basin number, land use, and soil.

**Step 4. Weather attributes** The program selects the closest weather/precipitation station to every sub-basin. Then either actual weather information can be used, or the weather generator (in this case the long-term monthly statistical parameters must be available for precipitation and temperature for the station). This part of the interface has to be modified to provide more flexible input of climate information.



**Fig 1.5** Three level disaggregation scheme 'basin - sub-basins – hydrotopes' implemented in SWIM

**Step 5. Ground water attributes** The ground water parameters are estimated for each sub-basin using the alpha layer (the reaction factor described in 2.2). This parameter defines the time lag needed to the groundwater flow as it leaves the shallow aquifer to reach the stream.

**Step 6. Routing structure** The interface creates the routing structure for the basin based on the elevation map. The routing structure is put in a special file, which provides the information about when to add flows and route through sub-basins and when to add inflow (or subtract withdrawals) from any sub-basins.

Steps 1, 2, 5, 6 described above are the same as in the SWAT/GRASS interface, steps 3 and 4 are new, and some other steps from SWAT/GRASS (such as irrigation and nutrient attributes) were excluded.

### ***1.2.5 Modelling Procedure***

First, the SWIM/GRASS interface runs to produce necessary input files. After that the model itself can be run. The model operates on a daily time step. After the input parameters are read from files, the three-step modelling procedure is applied. First, water and nitrogen dynamics and crop/vegetation growth are calculated for every hydrotope. Then the outputs from the hydrotopes, especially the lateral water and nutrient flows, are averaged (area-weighted average) to estimate the sub-basin output. Finally, the routing procedure is applied to the sub-basin outputs, taking transmission losses into account.

## 1.3 Overview of the SWIM/GRASS Interface

### 1.3.1 Main Menu

A menu-driven interface from GRASS to SWIM integrates SWIM with GRASS by preparing a set of input files required to run a SWIM simulation. The interface provides a menu of steps to prepare the input files. Each simulation is treated as "a project" by SWIM/INPUT, which has a name (analogously to the GRASS project name). The inputs collected for the steps are recorded under the project name, so that they may be copied or recalled for further completion or modification.

The first menu displayed when running SWIM/INPUT includes functions:

- to create a new project,
- to work on existing projects,
- to copy an existing project, and
- to remove existing projects.

The user has to set the current GRASS mapset where the SWIM/GRASS project will be created, otherwise an error message or erroneous results will occur. The main menu includes steps to be completed to prepare input files for SWIM, plus some other miscellaneous functions as following:

```
SWIM / GRASS Project Data Extraction Menu
Project Name:  Dahme <example>

          Choose desired option:

0  Quit
1  Extract data from layers
2  Display Raster, Vector and/or Site Maps
run 3  Extract Basin Attributes
run 4  Extract Hydrotope Structure
run 5  Extract Topographic Attributes
run 6  Extract Groundwater Attributes
run 7  Compute Routing Structure and Create .fig file
run 8  Extract Climate Station
run 9  Extract Precipitation Station

Option: 0__

AFTER COMPLETING ALL ANSWERS, HIT <ESC> TO CONTINUE
(OR <Ctrl-C> TO EXIT)
```

Steps 3-9 record and display their status to the left of the step number. If a step has not been run, "run" status is displayed (as seen above). If the step has been successfully completed, the status will be listed as "done". In some cases, a change in one step will cause the need to run another step again, in which case the status will read "rerun". If a step having the status of "done" or "rerun" is run again, it will attempt to offer previous inputs as defaults.

### **1.3.2 Options of the Main Menu**

This section describes the options of the main menu. All steps are verbose to provide as much immediate information as needed, however it is necessary that the user is also familiar with the operations of SWIM itself.

The sub-basin map must be delineated in advance based on the topography. The GRASS *r.watershed* command can be used to create the sub-basin map from an elevation map layer (see e.g. Section 3.1.6).

Step 2 helps to display either a raster, vector or site maps over the sub-basin map and also to display the sub-basin number on the graphical screen. Step 2 can be used only in conjunction with the GRASS graphic monitor.

Steps 3 through 9 collect inputs (either maps from the currently available mapsets or other text/numerical inputs) in order to create or extract the necessary portions of SWIM inputs for that step. Step 3 should be the first step; step 7 should be completed before moving into step 0 to leave the interface.

**Menu Option 3:** Extract Basin Attributes

**Map Input:** Sub-basin Map

**Technical Description:** This is the first step before attempting to extract any other input. Using a given sub-basin map the program calculates area, resolution, and geographic coordinate boundaries for the basin and for each sub-basin. The fraction of each sub-basin within the basin is also estimated.

**Description:** All raster values in the input sub-basin map greater than zero will be used to create reclass rules to set the project MASK to the basin and sub-basin areas. Each time the project is called, the MASK will be automatically set. The project resolution is extracted from the sub-basin map in meters and used to set the cell size of the all other extraction of data from other GIS layers. When the user runs the step 5 to extract topographic attributes, and an 'memory error' message appears, then either the program has to be run with larger memory or the resolution of the sub-basin map has to be increased by running the *r.resample* to set bigger resolution of the sub-basin map.

A part of this step attempts to find the minimal region needed to contain the basin mask at the given resolution. A region will be calculated to allow at least a one-cell border around the basin area. After the project mask, region and resolution are set, the information is recorded and will be reset automatically each time the project is called. If any of the inputs in this step are subsequently reset, all other steps that may have been completed will be marked with a status of "rerun" or "run", since changing basin, resolution or region will require that inputs will have to be resampled and extracted once again.

**Menu Option 4:** Extract Hydrotope Structure

**Map Input:** Basin Map, Land Use Map, Soil Map

**Description:** This step prompts for the name of an elevation map, land use map and soil map for the project basin. The program starts the GRASS command *r.stats* for these three maps and stores the output in the file *project\_name.str* except these data where one of the first three numbers is zero.

### **Menu Option 5: Extract Topographic Attributes**

**Map Input:** Elevation Map

**Technical Description:** The topographic features required for entire basin and for each sub-basin are gathered using an elevation map. By masking the entire basin and each sub-basin, the stream length, stream slope and stream dimensions are estimated using the concept of *r.stream.att* tool (Srinivasan and Arnold, 1994) along with proper aggregation methods. The accumulation (drainage) area is computed for each sub-basin along with the drainage aspect of which sub-basin flows into which sub-basin.

This information is later used to automate the routing structures for the SWIM model. The starting and ending nodes of the stream for the basin and each sub-basin are estimated. Using the *r.topo.att* tool (Srinivasan and Arnold, 1994) overland slope and slope length are estimated and aggregated by the weighted average or mode (dominant) method. The channel USLE K, USLE C, Manning's "n" and USLE P factors are estimated using a standard table and the knowledge obtained in the topographic attributes extraction processes.

**Description:** This step prompts for the name of an elevation map for the project basin. The elevation map should be true elevations in meters. If not, the user must apply *r.mapcalc* to convert to meters. Programs have been developed to process an elevation surface map and create SWIM slope and aspect map for the basin and for each sub-basin. The channel length, channel slope, channel dimensions, average overland slope and slope length are the parameters that are required for SWIM are extracted in this step.

This is one of the time consuming process. If this process is not completed due to memory allocation problems the user is advised to either run the interface with a higher memory machine or increase the resolution of the basin map and resample the data and run through all the steps. The elevation map can be "filtered" to remove "pits" and other potential problems to SWIM modelling with the *r.fill.dir* (Srinivasan and Arnold, 1994) program. The extracted topographic attributes are stored in files with *.sub* and *.rte* extensions for each sub-basin.

### **Menu Option 6: Extract Groundwater Attributes**

**Input Map:** Alpha Map for Groundwater

**Technical Description:** The groundwater parameters are created for each sub-basin using the so-called alpha layer map. This parameter is required to lag the groundwater flow as it leaves the shallow aquifer to return to the stream (Arnold et. al., 1993).

**Description:** The interface prompts for the availability of the alpha parameter map. If the answer is 'no', the interface assumes a default values for all the groundwater parameters. If there is a groundwater parameter alpha map, the category values should be in hundreds. The other groundwater parameters such as initial groundwater height etc. are assumed to be default values. A detailed description of the procedure to create the alpha map can be found in Arnold *et al.*, 1993.

### **Menu Option 7: Compute Routing Structure and Create .fig file**

**Input Data:** Automatic

**Technical Description:** In this step the interface creates a <project name.fig> file, which is the main engine for running the SWIM model. This file has the information about when to add flows and route through sub-basins and when to route through reservoirs and add inflow or subtract withdrawals from any sub-basins and/or reaches. This step is automated using the elevation map. Altering either step numbers 3 or 5 will require running this step again.

Also this step determines the channel width and depth of flow for routing. This is done using neural network that is embedded in the interface, which has been trained on the USGS (United States Geologic Survey) defined 2-digit Hydrologic Unit Areas (HUA). Several hundreds of width and depth information were collected and used in training the neural network by the 2-digit HUA. A detailed description about the neural network method and the datasets used here can be obtained by sending an e-mail request to

*srin@brcsun0.tamu.edu* or  
*muttiah@brcsun0.tamu.edu*.

The neural network needs the drainage area and the average elevation of a sub-basin to find its width and depth of channel.

**Description:** This is one of the tedious operation, by automating this operation through the GIS interface the user potentially saves several man hours and days of creating the ".fig" file. In addition updating this file is also easy while considering several hypothetical scenarios such as impact of reservoirs or inflow or withdrawal of flows or change in cropping and management information. The interface checks the outlet sub-basin of the watershed, which has to be confirmed by the user. Since this is determined by the elevation map, there could be errors due to the spatial accuracy and/or the resolution of the elevation map.

On completion of this step the interface creates a file <project name.flow>, which has routing information of each sub-basin to the outlet of the basin showing the path of the flow through other sub-basins. The model allows having multiple outlets for a basin, hence if the user accepts more than one outlet, then the interface will create several outlets for that basin. In the event of an error in the routing structure, the interface enters into another menu where in the user can either enter through keyboard or using graphical monitor determines how the flow has to occur. Once the user is satisfied with the routing structure, the interface prompts for the 2-digit HUA where the basin belongs. Hence, the user needs to know this info before running this step.

**Menu Option 8:** Extract Climate Station

**Input Data:** Climate Station File (number and coordinates (UTM) of each station)  
Climate Station Raster Map

**Technical Description:** This will extract the number of the three nearest climate stations for the basin or each sub-basin using the program *brb\_main\_stationno.c*. The step requires a climate station number file "name". The station numbers are stored in the file *name.cstn* under *full\_path*. It also creates a label file to mark the searched stations in the map on the Grass graphics monitor and in map hardcopies. The label file *name.clabel* is stored in the necessary path

.../grass/databases/project\_name/mapset/paint/labels.

To mark one station with its number the input in a label file has to look as follows:

```
east:          4610296.500000
north:         5806264.000000
xoffset:
yoffset:
ref:           lower center
font:          standard
color:         black
size:          500
background:    white
opaque:        yes

text:46663
```

After that the function *find\_subb\_stations()* is called. This function prompts for an existing raster map of climate stations. It extracts all climate stations in each sub-basin using the grass program *r.mapcalc* (see description of *find\_subb\_stations()*).

**Menu Option 9:** Extract Precipitation Station

**Input Data:** Precipitation Station File (number and coordinates of each station)

Precipitation Station Raster Map

**Technical Description:** This will extract the number of the three nearest precipitation stations for the basin or each sub-basin using program *brb\_main\_stationno.c*. The step requires a precipitation station number file "name". The station numbers are stored in the file *name.pstn* under *full\_path*. It also creates a label file to mark the searched stations in the map on Grass graphics monitor and in map hardcopies. The label file *name.plabel* is stored in the necessary path

.../grass/databases/project\_name/mapset/paint/labels.

After that function *find\_subb\_stations()* is called. This function prompts for an existing raster map of precipitation stations. It extracts all precipitation stations in each sub-basin using the grass program *r.mapcalc* (see description of *find\_subb\_stations()* ).

Once the steps are completed from 3 to 9, by choosing the option 0, the user leaves the interface. At this time the interface also creates the *file.cio* file, which has the entire input file names prepared by interface. At this junction, the user can run the SWIM model.

The steps 8 and 9 need further modification. Currently, they can be also omitted.

## 1.4 Overview of the Model Components

### 1.4.1 Hydrological Processes

**Snow melt** The snow melt component is similar to that of the CREAMS model (Knisel, 1980), according to a simple degree-day equation. Melted snow is then treated in the same way as rainfall for further estimation of runoff and percolation.

**Surface runoff** The runoff volume is estimated using a modification of the SCS curve number method (Arnold et al, 1990). Surface runoff is predicted as a nonlinear function of precipitation and a retention coefficient. The latter depends on soil water content, land use, soil type, and management. The curve number and the retention coefficient vary nonlinearly from dry conditions at wilting point to wet conditions at field capacity and approach 100 and 0 respectively at saturation. The modification essentially reduced the empiricism of the original curve number method. The reliability of the method has been proven by multiple validation of SWAT and SWIM in mesoscale basins. Nevertheless, there is a possibility to exclude the dependence of the retention coefficient on land use and soil, leaving the dependence on soil water content only, and assuming the same interval for all types of land use and soils.

**Percolation** The same storage routing technique as in SWAT is used to simulate water flow through soil layers in the root zone. Downward flow occurs when field capacity of the soil layer is exceeded, and as long as the layer below is not saturated. The flow rate is governed by the saturated hydraulic conductivity of the soil layer. Once water percolates below the root zone, it becomes groundwater. Since the one day time interval is relatively large for soil water routing, the inflow is divided into 4 mm slugs in order to take into account the flow rate's dependence on soil water content. If the soil temperature in a layer is below 0°C, no percolation occurs from that layer. The soil temperature is estimated for each soil layer using the air temperature as a driver (Arnold *et al.*, 1990).

**Lateral subsurface flow** Lateral subsurface flow is calculated simultaneously with percolation. The kinematic storage model developed by Sloan *et al.* (1983) is used to estimate the subsurface flow. The approach is based on the mass continuity equation in the finite difference form with the entire soil profile as the control volume. To account for multiple layers, the model is applied to each soil layer independently starting at the upper layer to 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).

**Evapotranspiration** Potential evapotranspiration is estimated using the Priestley-Taylor method (1972) that requires solar radiation and air temperature as input. It is possible to use the Penman-Monteith method (Monteith, 1965) instead if wind speed and relative air humidity data can be provided in addition. The actual evapotranspiration is estimated following the Ritchie (1972) concept, separately for soil and plants. Actual soil evaporation is computed in two stages. It is equal to the potential soil evaporation predicted by means of an exponential function of leaf area index (Richardson and Ritchie, 1973) until the accumulated soil evaporation exceeds the upper limit of 6 mm. After that stage two begins. The actual soil evaporation is reduced and estimated as a function of the number of days since stage two began. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index. When soil water is limited, plant transpiration is reduced, taking into account the root depth.

**Groundwater flow** The groundwater model component is the same as in SWAT (see Arnold *et al.*, 1993). The percolation from the soil profile is assumed to recharge the shallow aquifer. Return flow from the shallow aquifer contributes directly to the streamflow. The equation for return flow was derived from Smedema and Rycroft (1983), assuming that the variation in return flow is linearly related to the rate of change of the water table height. In a finite difference form, the return flow is a nonlinear function of ground water recharge and the reaction factor RF, the latter being a direct index of the intensity with which the groundwater outflow responds to changes in recharge. The reaction factor can be estimated for gaged sub-basins using the base flow recession curve.

#### **1.4.2 Crop / Vegetation Growth**

The crop model in SWIM and SWAT is a simplification of the EPIC crop model (Williams *et al.*, 1984). The SWIM model uses a concept of phenological crop development based on

- daily accumulated heat units;
- Monteith's approach (1977) for potential biomass;
- water, temperature, and nutrients stress factors; and
- harvest index for partitioning grain yield.

However, the more detailed approach implemented in EPIC for the root growth and nutrient cycling is not included in order to maintain a similar level of complexity of all submodels and to keep control on the model performance.

A single model is used for simulating all the crops and natural vegetation included in the crop database attached to the model. Annual crops grow from planting date to harvest date or until the accumulated heat units reach the potential heat units for the crop. Perennial crops maintain their root systems throughout the year, although the plants may become dormant after frost.

Phenological development of the crop is based on daily heat unit accumulation. Interception of photosynthetic active radiation is estimated with Beer's law equation (Monsi and Saeki, 1953) as a function of solar radiation and leaf area index. The potential increase in biomass is the product of absorbed PAR and a specific plant parameter for converting energy into biomass.

The potential biomass is adjusted daily if one of the four plant stress factors (water, temperature, nitrogen, and phosphorus) is less than 1.0 using the product of a minimum stress factor and the potential biomass. The water stress factor is defined as the ratio of actual to potential plant transpiration. The temperature stress factor is computed as a function of daily average temperature, optimal and base temperatures for plant growth. The N and P stress factors are based on the ratio of accumulated N and P to the optimal values.

The fraction of daily biomass growth partitioned to roots is estimated to range linearly between two fractions specified for each vegetation type - 0.4 at emergence to 0.2 at maturity. Root depth increases as a linear function of heat units and potential root depth. Leaf area index is simulated as a nonlinear function of accumulated heat units and crop development stages. Crop yield is estimated using the harvest index, which increases as a nonlinear function of heat units from zero at planting to the optimal value at maturity. The harvest index is affected by water stress in the second half of the growing period.

### 1.4.3 Nutrient Dynamics

**Nitrogen mineralisation** The nitrogen mineralisation model is a modification of the PAPRAN mineralisation model (Seligman and van Keulen, 1981). Organic nitrogen associated with humus is divided into two pools: active or readily mineralisable organic nitrogen and stable organic nitrogen. The model considers two sources of mineralisation: a) fresh organic nitrogen pool, associated with crop residue, and b) the active organic nitrogen pool, associated with the soil humus. Organic N flow between the active and stable organic nitrogen pools is governed by the equilibrium equation. Mineralisation of fresh organic nitrogen is a function of the C:N ratio, C:P ratio, soil temperature, and soil water content. The N mineralisation flow from residue is distributed between the mineral nitrogen (80%) and active organic nitrogen (20%) pools. Mineralisation of the active organic nitrogen pool depends on soil temperature and water content.

**Phosphorus mineralization** The phosphorus mineralisation model is structurally similar to the nitrogen mineralisation model. To maintain phosphorus balance at the end of a day, humus mineralisation is subtracted from the organic phosphorus pool and added to the mineral phosphorus pool, and residue mineralisation is distributed between the organic phosphorus pool (20%) and the labile phosphorus (80%).

**Sorption / adsorption of phosphorus** Mineral phosphorus is distributed between three pools: labile phosphorus, active mineral phosphorus, and stable mineral phosphorus. Mineral phosphorus flow between the active and stable mineral pools is governed by the equilibrium equation, assuming that the stable mineral pool is four times larger. Mineral phosphorus flow between the active and labile mineral pools is governed by the equilibrium equation as well, assuming equal distribution.

**Denitrification** Denitrification, as one of the microbial processes, is a function of temperature and water content. The denitrification occurs only in the conditions of oxygen deficit, which usually takes place when soil is wet. The denitrification rate is estimated as a function of soil water content, soil temperature, organic matter, a coefficient of soil wetness, and mineral nitrogen content. The soil water factor is an exponential function of soil moisture with an increasing trend when soil becomes wet.

**Crop uptake of nutrients** Crop uptake of nitrogen and phosphorus is estimated using a supply and demand approach. Six parameters are specified for every crop in the crop database, which describe:  $BN_1$  and  $BP_1$  - normal fraction of nitrogen and phosphorus in plant biomass excluding seed at emergence,  $BN_2$  and  $BP_2$  - at 0.5 maturity, and  $BN_3$  and  $BP_3$  - at maturity. Then the optimal crop N and P concentrations are calculated as functions of growth stage. The daily crop demand of nutrients is estimated as the product of biomass growth and optimal concentration in the plants. Actual nitrogen and phosphorus uptake is the minimum of supply and demand. The crop is allowed to take nutrients 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 nutrient content has been depleted.

**Soluble nutrient loss in surface water and groundwater** The amount of  $NO_3$ -N and soluble P in surface runoff is estimated considering the top soil layer only. Amounts of  $NO_3$ -N and soluble P in surface runoff, lateral subsurface flow and percolation are estimated as the products of the volume of water and the average concentration. Retention factor is taken into account through transmission losses. Because phosphorus is mostly associated with the sediment phase, the soluble phosphorus loss is estimated as a function of surface runoff and the concentration of labile phosphorus in the top soil layer.

#### **1.4.4 Erosion**

Sediment yield is calculated for each sub-basin with the Modified Universal Soil Loss Equation (MUSLE, Williams and Berndt, 1977), almost the same as in SWAT. The equation for sediment yield includes the runoff factor, the soil erodibility factor, the crop management factor, the erosion control practice factor, and the slope length and steepness factor. The only difference from SWAT is that the surface runoff, the soil erodibility factor and the crop management factor are estimated for every hydrotope, and then averaged for the sub-basin (weighted areal average).

Estimation of the runoff factor requires the characteristics of rainfall intensity as described in Arnold *et al.*, 1990. To estimate the daily rainfall energy in the absence of time-distributed rainfall, the assumption about exponential distribution of the rainfall rate is made. This stochastic element is included to allow more realistic representation of peak runoff rates, given only daily rainfall and monthly rainfall intensity. This allows a simple substitution of rainfall rates into the equation. The fraction of rainfall that occurs during 0.5 hours is simulated stochastically, taking into account average monthly rainfall intensity for the area. Soil erodibility factor can be estimated from the texture of the upper soil layer. The slope length and steepness factor is estimated based on the Digital Elevation Model of a watershed by SWIM/GRASS interface for every sub-basin.

#### **1.4.5 River Routing**

The Muskingum flow routing method (Maidment, 1993) is used in SWIM. The Muskingum equation is derived from the finite difference form of the continuity equation and the variable discharge storage equation. The outflow rate for the reach is estimated using a recurrent equation with two parameters. They are the storage time constant for the reach, KST, and a dimensionless weighting factor, X. In physical terms, the parameter KST corresponds to an average reach travel time, and X indicates the relative importance of the inflow and outflow in determining the storage in the reach.

The sediment routing model consists of two components operating simultaneously – deposition and degradation in the streams. The approach is based on the estimation of the stream velocity in the channel as a function of the peak flow rate, the flow depth, and the average channel width. The sediment delivery ratio is estimated using a power function (power 1 to 1.5) of the stream velocity. If the sediment delivery ratio is less than 1, the deposition occurs in the stream, and degradation is zero. Otherwise, degradation is estimated as a function of the sediment delivery ratio, the channel K factor (or the effective hydraulic conductivity of the channel alluvium), and the channel C factor.

Nitrate nitrogen and soluble phosphorus are considered in the model as conservative materials for the duration of an individual runoff event (Williams, 1980). Thus they are routed by adding contributions from all sub-basins to determine the basin load.

