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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^2), 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.

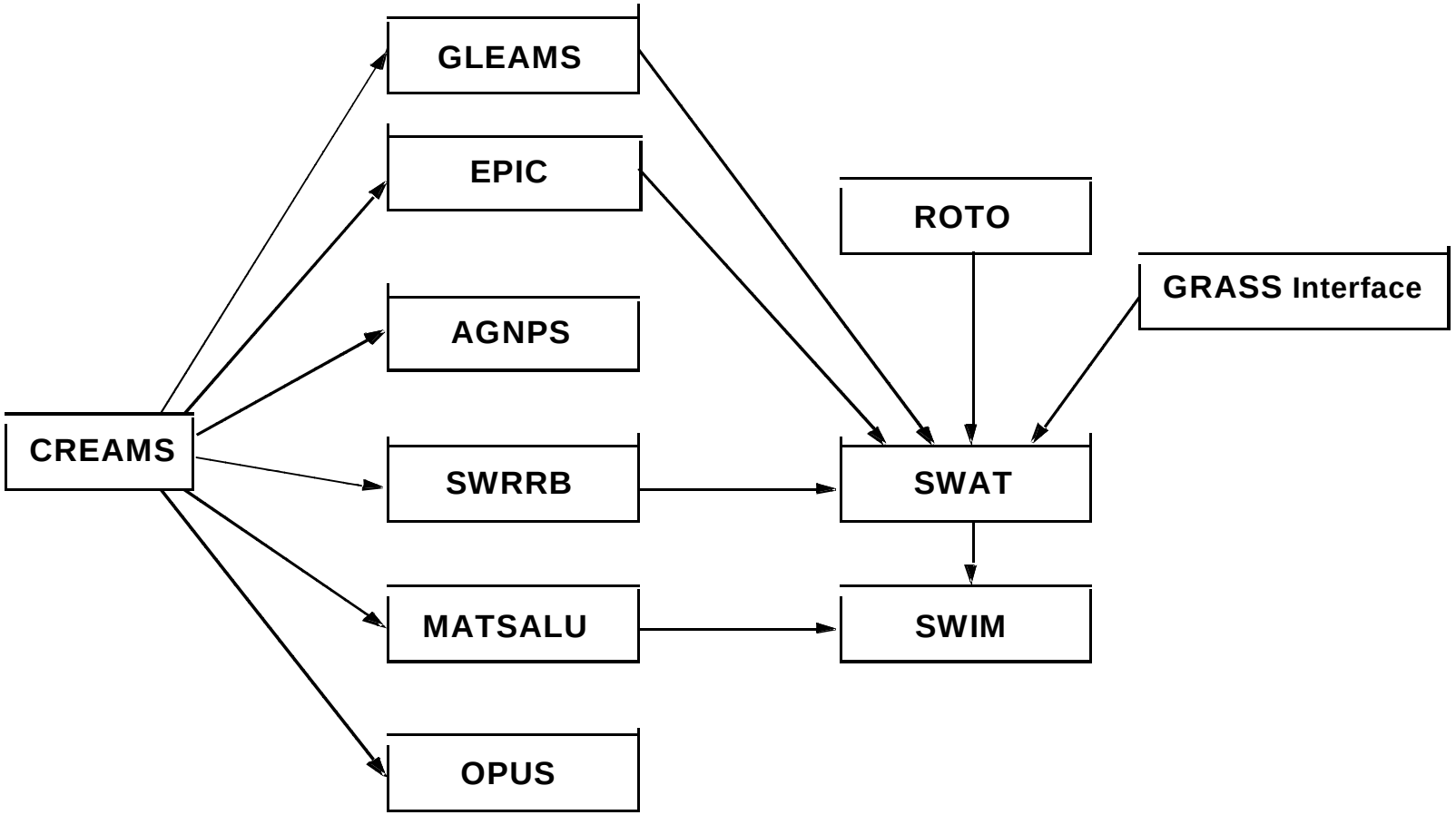

Fig. 1.1 Model development based on the CREAMS model

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 SWRBB, 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^2 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^2, 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

	Advantages	*Disadvantages*
SWAT	• Coupling with GIS • Hydrological module tested in several meso- and macroscale watersheds • Vegetation module (simplified EPIC) is adopted for different crops and natural vegetation	• Two-level disaggregation (basin and sub-basins) in SWAT-93 • Connection to specific American data sets (especially soil, climate) • SWAT as a long-term predictor was always tested and validated only with monthly time step
MATSALU	• Three-level disaggregation scheme • N-module was tested in mesoscale watershed in connection with hydrology and river transport	• Connection to specific Estonian data sets, not transferable to other basins • Four coupled models, not a coupled watershed model

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^2), 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_3-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.

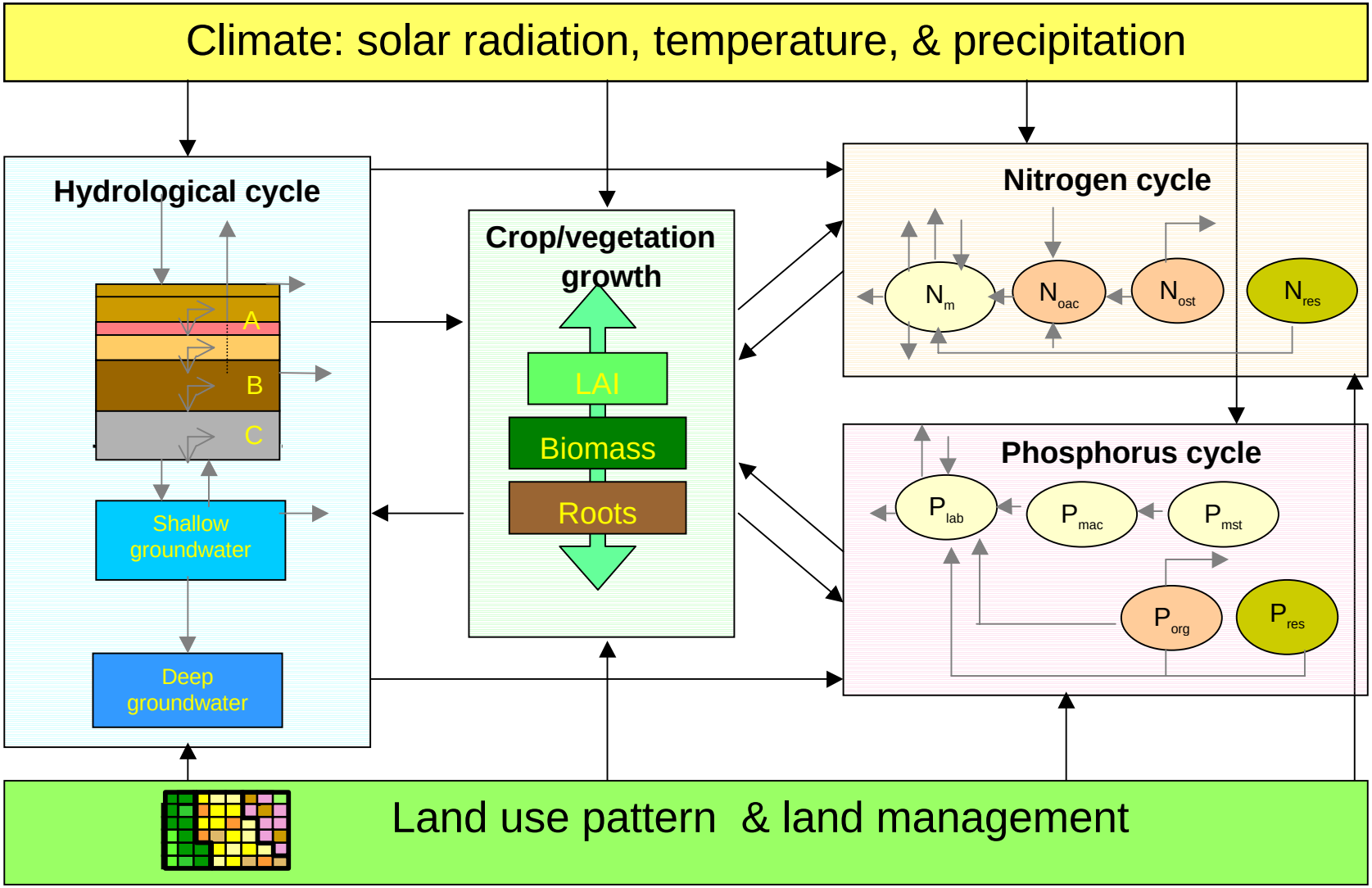

Fig. 1.2 Flow chart of the SWIM model, integrating hydrological processes, crop/vegetation growth, and nutrient dynamics

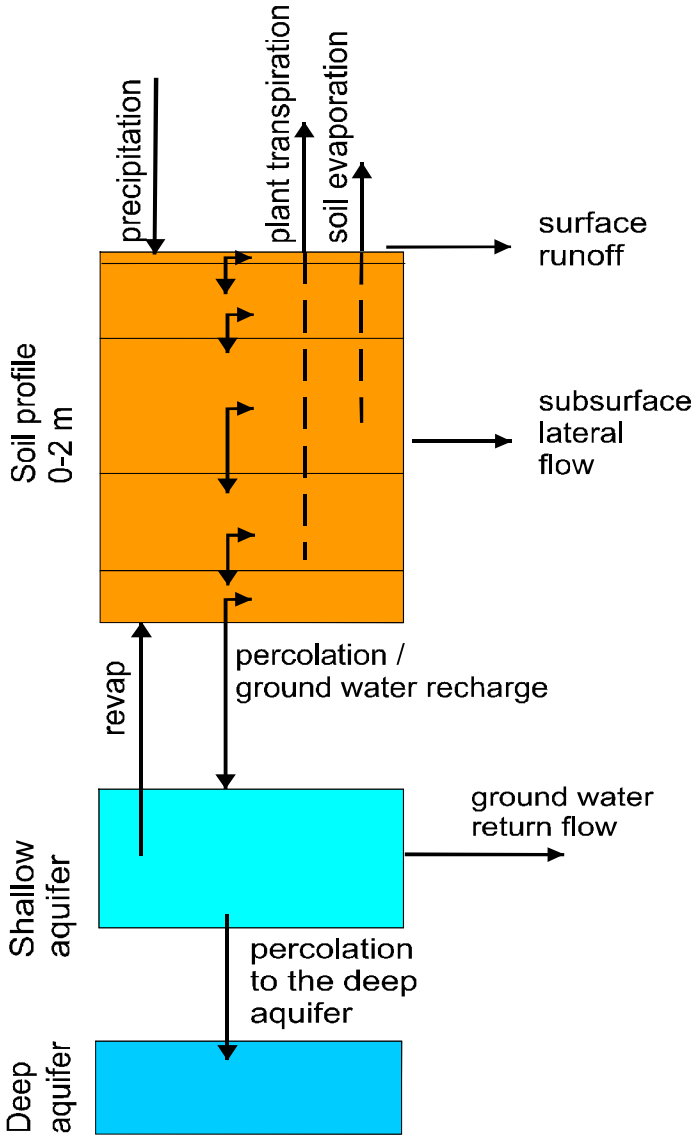

Fig. 1.3 Flow chart of hydrological processes in soil as implemented in SWIM

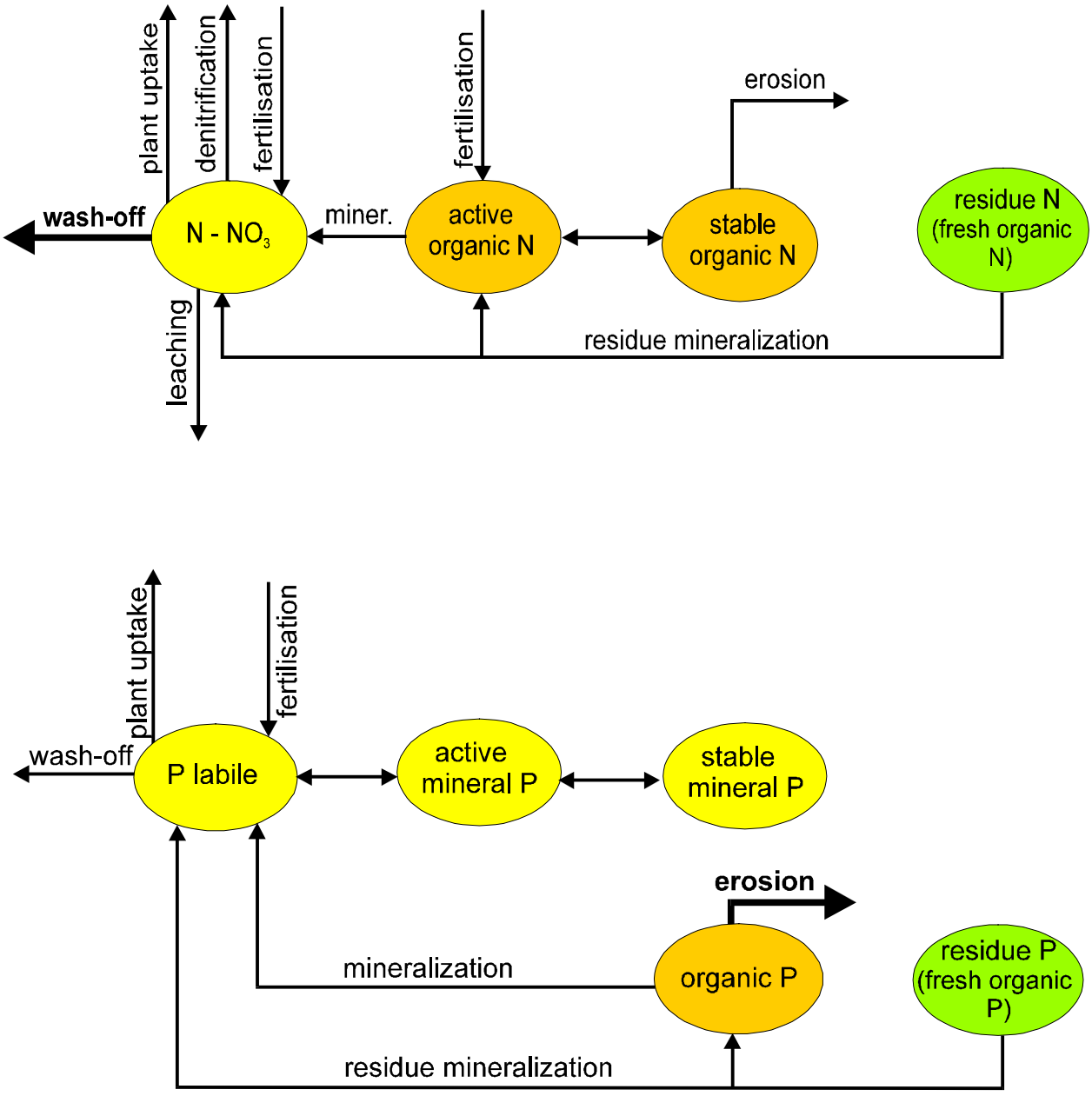

Fig. 1.4 Nitrogen and phosphorus flow charts as implemented in SWIM

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^2) 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.

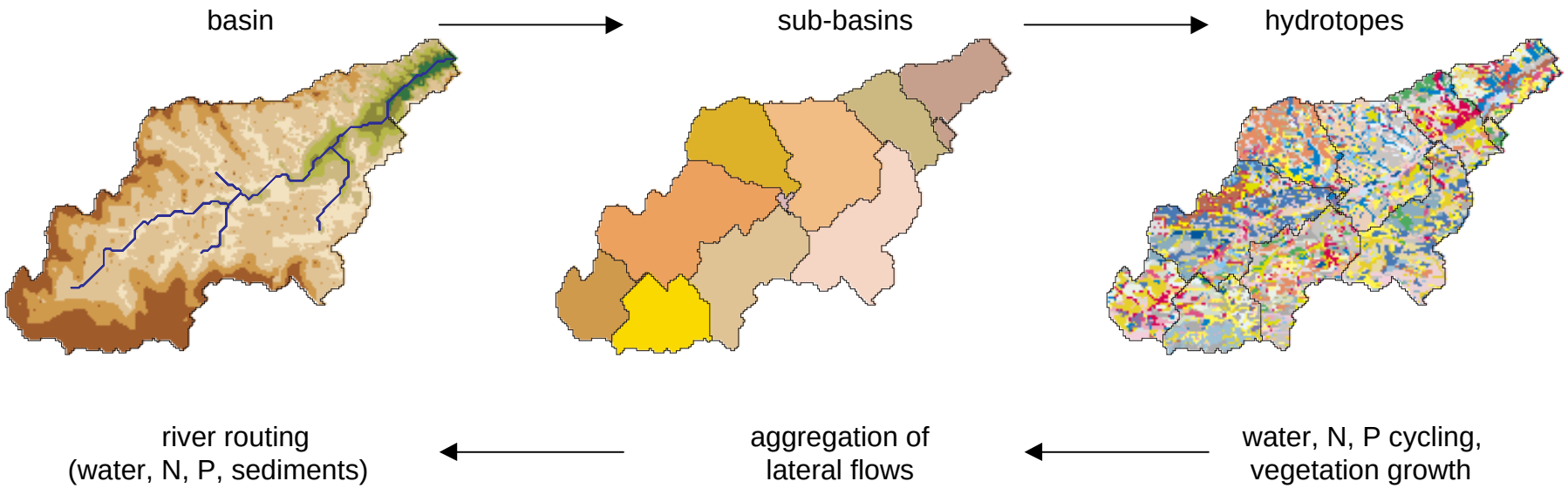

Fig 1.5 Three level disaggregation scheme ’basin - sub-basins – hydrotopes‘ implemented in SWIM

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 co-ordinate 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 non-linearly 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 empirism 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 stabile 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 requrrent 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.

2. Mathematical Description of the Model Components

In this chapter a mathematical description of all model components is given. First, hydrological processes are described in Section 2.1, followed by vegetation/crop growth processes (Section 2.2), nutrient dynamics processes (Section 2.3), and erosion (Section 2.4). After that a description of the channel routing processes is given in Section 2.5. This chapter is based mostly on the SWAT User Manual (Arnold et al., 1994) and the MATSALU model description (Krysanova et al., 1989a).

2.1 Hydrological Processes

The hydrological submodel in SWIM is based on the following water balance equation

$$SW(t+1) = SW(t) + PRECIP - Q - ET - PERC - SSF \quad (1)$$

where *SW(t)* is the soil water content in the day t, *PRECIP* – precipitation, *Q* – surface runoff, *ET* - evapotranspiration, *PERC* - percolation, and *SSF* – subsurface flow.

All values are the daily amounts in mm. Here the precipitation is an input, assuming that precipitation may differ between sub-basins, but it is uniformly distributed inside the sub-basin. The melted snow is added to precipitation.

The surface runoff, evapotranspiration, percolation below root zone and subsurface flow are described below. Some river basins, especially in the semiarid zone, have alluvial channels that abstract large quantities of stream flow. The transmission losses reduce runoff volumes when the flood wave travels downstream. This reduction is taken into account by a special module that accounts for transmission losses.

2.1.1 Snow Melt

If air temperature is below 0, precipitation occurs as snow, and snow is accumulated. If snow is present on soil, it may be melted when the temperature of the second soil layer exceeds 0°C (according to the model requirements, the depth of the first soil layer must be always set to 10 mm). The approach used is similar to that of CREAMS model (Knisel, 1980). Snow is melted as a function of the snow pack temperature in accordance with the equation

$$\begin{aligned} SML &= 4.57 \cdot TMX \\ 0. &\le SML \le SNO \end{aligned} \quad (2)$$

where *SML* is the snowmelt rate in mm d^{-1}, *SNO* is the snow in mm of water, *TMX* is the maximum daily air temperature in °C.

Melted snow is treated the same as rainfall for estimating runoff volume and percolation, but rainfall energy is set to 0.

2.1.2 Surface Runoff

The model takes the daily rainfall amounts as input and simulates surface runoff volumes and peak runoff rates. Runoff volume is estimated by using a modification of the Soil Conservation Service (SCS) curve number technique (USDA-SCS, 1972; Arnold *et al.*, 1990). The technique was selected for use in SWIM as well as in SWAT due to several reasons:

(a) it is reliable and has been used for many years in the United States and worldwide;
(b) the required inputs are usually available;
(c) it relates runoff to soil type, land use, and management practices; and
(d) it is computationally efficient.

The use of daily precipitation data is a particularly important feature of the technique because for many locations, and especially at the regional scale, more detailed precipitation data with time increments of less than one day are not available.

Surface runoff is estimated from daily precipitation taking into account a dynamic retention coefficient SMX by using the SCS curve number equation

$$Q = \frac{(PRECIP - 0.2 \cdot SMX)^2}{PRECIP + 0.8 \cdot SMX}, \qquad PRECIP > 0.2 \cdot SMX$$
$$Q = 0, \qquad PRECIP \leq 0.2 \cdot SMX \tag{3}$$

where *Q* is the daily runoff in mm, *PRECIP* is the daily precipitation in mm, and *SMX* is a retention coefficient.

The retention coefficient *SMX* varies a) spatially, because soils, land use, management, and slope vary, and b) temporally, because soil water content is changing. The retention coefficient *SMX* is related to the curve number *CN* by the SCS equation

$$SMX = 254 \cdot \left(\frac{100}{CN} - 1 \right) \tag{4}$$

To illustrate the approach, **Fig. 2.1** shows estimation of surface runoff Q from daily precipitation with equations (3) and (4) assuming different CN values.

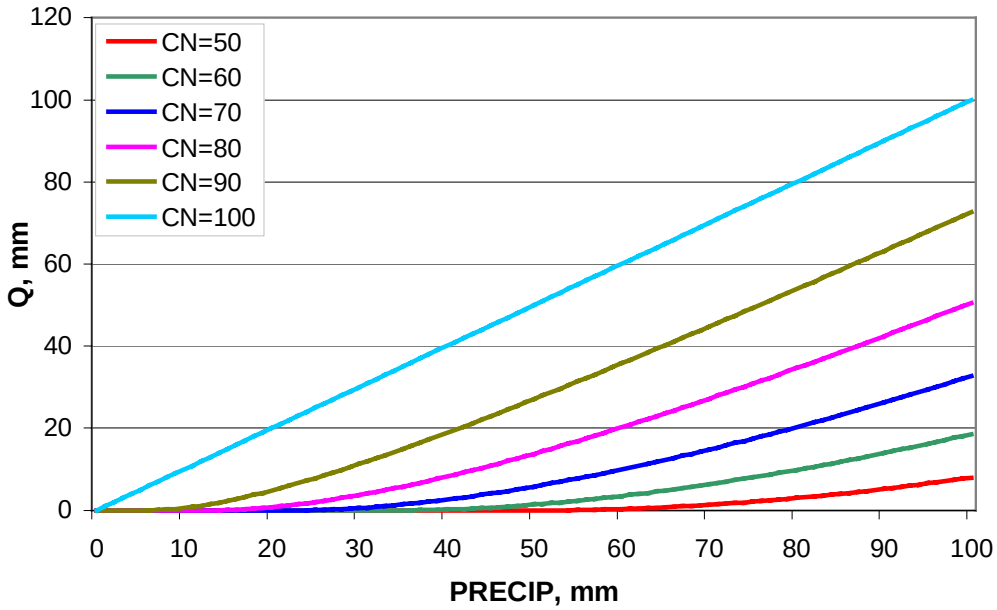

Fig. 2.1 Estimation of surface runoff, Q, from daily precipitation, PRECIP, for different values of CN (equations 3 and 4)

The parameter *CN* is defined in three variations:

- for moisture condition 1 (or dry conditions) as CN_1
- for moisture condition 2 (or average conditions) as CN_2 and
- for moisture condition 3 (or wet conditions) as CN_3.

CN_2 can be obtained from the SCS hydrology handbook (USDA-SCS, 1972) for a set of land use types, hydrologic soil groups and management practices (see also **Tab. 3.20** in Chapter 3 of the Manual). The corresponding values of CN_1 and CN_3 are also tabulated in the handbook. For computing purposes, CN_1 and CN_3 were related to CN_2 with the equations (see also **Fig. 2.2**)

$$CN_1 = CN_2 - \frac{20 \cdot (100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636 \cdot (100 - CN_2)]} \tag{5}$$

or an approximation of equation 5:

$$CN_1 = -16.911 + 1.3481 \cdot CN_2 - 0.013793 \cdot CN_2^2 + 0.00011772 \cdot CN_2^3 \tag{6}$$

and

$$CN_3 = CN_2 \cdot \exp[0.00673 \cdot (100 - CN_2)] \tag{7}$$

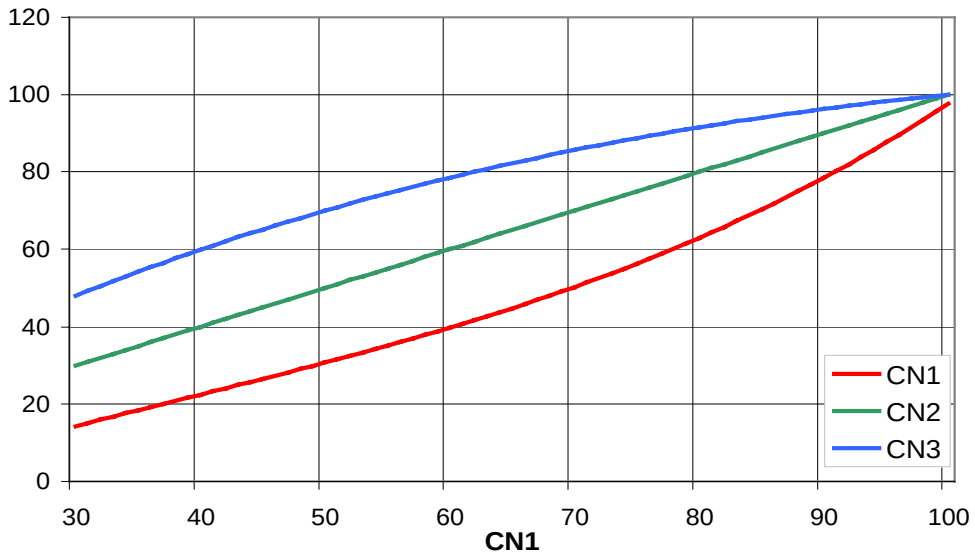

Fig. 2.2 Correspondence between CN_1, CN_2 and CN_3 (equations 6, 7)

The values of CN_1, CN_2 and CN_3 are related to land use types, hydrologic soil groups and management practices. An additional assumption was made to relate curve numbers to slope. Namely, it was assumed that the CN_2 value is appropriate for a 5% slope, the following equation was derived (Arnold et al., 1994) to adjust it for lower and higher slopes (see also **Fig. 2.3**):

$$CN_{2s} = CN_2 + \frac{CN_3 - CN_2}{3} \cdot \left(1 - 2 \cdot \exp\left(-13.86 \cdot SS\right)\right) \tag{8}$$

where CN_{2s} is the adjusted CN_2 value, and SS is the slope steepness in m m^{-1}.

The retention coefficient is changing dynamically due to fluctuations in soil water content according to the equation

$$SMX = SMX_1 \cdot \left(1 - \frac{SW}{SW + \exp\left(WF_1 - WF_2 \cdot SW\right)}\right) \tag{9}$$

where SMX_1 is the value of SMX associated with CN_1, SW is the soil water content in mm, and WF_1 and WF_2 are shape parameters. **Fig. 2.4** depicts the relationships between the retention coefficient SMX and the curve number CN, on one hand, and the relative soil water content, on the other hand.

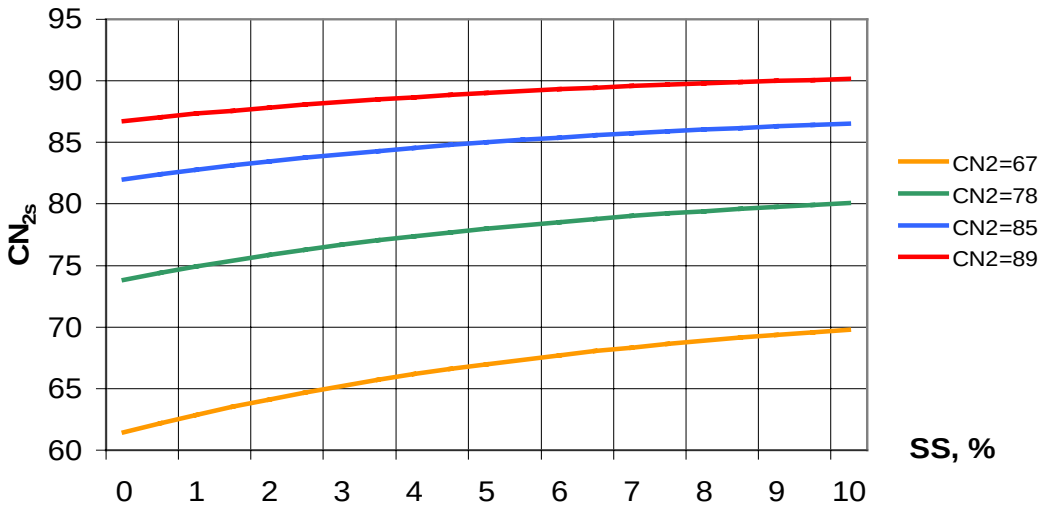

Fig. 2.3 Adjustment of curve number CN_2 to the slope (equation 8) for some typical values of CN_2 = 67, 78, 85, and 89, corresponding to straight row crop and four hydrologic groups A, B, C, and D, respectively

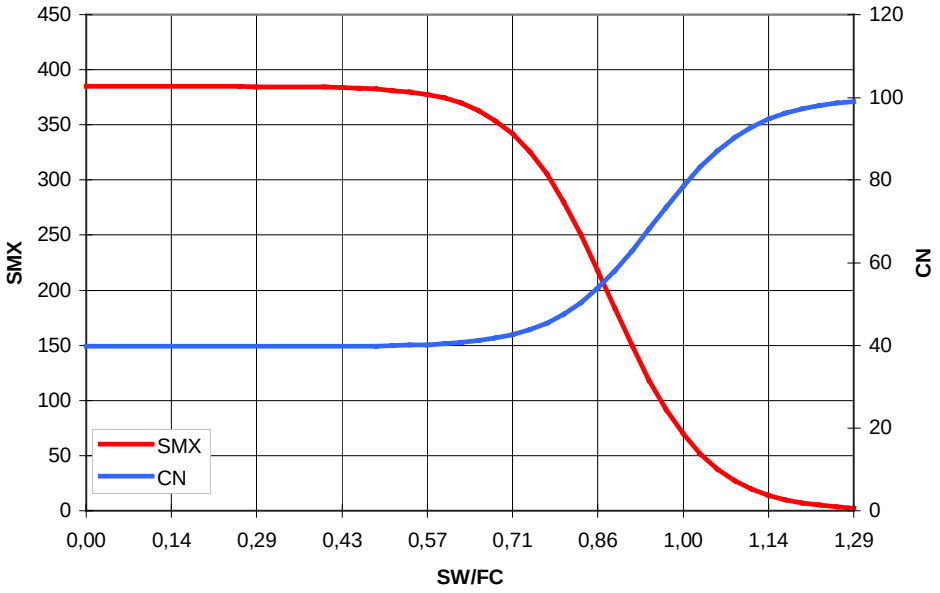

Fig. 2.4 Retention coefficient SMX and curve number CN as functions of soil water content SW (equation 9 and 4) assuming CN_2 = 60, WP = 5 mm mm^{-1}, FC = 35 mm mm^{-1}, PO = 45 mm mm^{-1}

The following assumptions are made for the retention coefficient SMX

$$\begin{aligned} SMX &= SMX_1 && if \;\; SW = WP, \\ SMX &= SMX_2 && if \;\; FCC = 0.7, \\ SMX &= SMX_3 && if \;\; SW = FC, \\ SMX &= 2.54 && if \;\; SW = PO \end{aligned} \qquad (10)$$

where SMX_2 is the retention parameter corresponding to CN_2, SMX_3 is the retention parameter corresponding to CN_3, *WP* is the wilting point water content in mm mm^{-1}, *FC* is the field capacity water content in mm mm^{-1}, *PO* is the soil porosity in mm mm^{-1}, and FFC is the fraction of field capacity defined with the equation

$$FFC = \frac{SW - WP}{FC - WP} \qquad (11)$$

The assumption that SMX = 2.54 in (10) means that at full saturation CN = 99 (approaches its maximum).

Values for WF_1 and WF_2 are obtained from a simultaneous solution of equation 8 according to the assumptions (10) as following

$$WF_1 = \ln\left(\frac{FC}{1 - SMX_3/SMX_1} - FC\right) + FC \cdot WF_2 \tag{12}$$

$$WF_2 = \frac{\ln\left(\frac{FC}{1 - SMX_3/SMX_1} - FC\right) - \ln\left(\frac{PO}{1 - 2.54/SMX_1} - PO\right)}{PO - FC} \tag{13}$$

The value of *FFC* defined in equation 11 represents soil water uniformly distributed through the root zone of soil or the upper 1m of soil. Runoff estimates can be improved if the depth distribution of water in soil is known. For example, water distributed near the soil surface results in more runoff than the same volume of water uniformly distributed throughout the soil profile. Since SWIM 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

$$FFC^* = \frac{\sum_{i=1}^{M}\left(FFC_i \cdot \frac{Z_i - Z_{i-1}}{Z_i}\right)}{\sum_{i=1}^{M}\left(\frac{Z_i - Z_{i-1}}{Z_i}\right)}, \qquad Z_i \le 1.0m \tag{14}$$

where FFC^* is the depth-weighted *FFC* value for use in (9), Z_i is the depth to the bottom of soil layer i in mm, and M is the number of soil layers.

Equation 14 performs two functions:

a) it reduces the influence of lower layers because FFC_i is divided by Z_i and
b) b) it gives proper weight to thick layers relative to thin layers because *FFC* is multiplied by the layer thickness.

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

$$SMX_{froz} = SMX \cdot (1. - \exp(-0.000862 \cdot SMX)) \tag{15}$$

where SMX_{froz} is the retention coefficient for frozen ground. Equation 15 increases runoff for frozen soils, but allows significant infiltration when soil is dry.

2.1.3 Peak Runoff Rate

The peak runoff rate is estimated in SWIM for sub-basins using the modified Rational formula (Maidment, 1993; Arnold et al. 1994). A stochastic element is included in the Rational formula to allow a more realistic simulation of peak runoff rates, given only daily rainfall and monthly rainfall intensity. The Rational formula can be written in the form

$$PEAKQ = \frac{RUNC \cdot RI \cdot A}{360} \tag{16}$$

where *PEAKQ* is the peak runoff rate in $m^3\ s^{-1}$, *RUNC* is a dimentionless runoff coefficient expressing the watershed infiltration characteristics, *RI* is the rainfall intensity in mm h^{-1} for the watershed's time of concentration, and *A* is the drainage area in ha.

The runoff coefficient can be calculated for each day from the amounts of precipitation and runoff as following

$$RUNC = \frac{Q}{PRECIP} \tag{17}$$

Since daily precipitation is input and *Q* is calculated with equation (3), *RUNC* can be estimated directly.

Rainfall intensity can be expressed as

$$RI = \frac{PRECIP_{tc}}{TC} \tag{18}$$

where *TC* is the watershed's time of concentration in h, and $PRECIP_{tc}$ is the amount of rainfall in mm during the time of concentration.

The value of $PRECIP_{tc}$ can be estimated by developing a relationship with total daily *PRECIP*. Generally, $PRECIP_{tc}$ and $PRECIP_{24}$ (24-h duration is appropriate for the daily time step model) are proportional for various frequencies.

Thus, a dimensionless parameter α that expresses the proportion of total daily rainfall that occurs during time of concentration can be introduced. Then

$$PRECIP_{tc} = \alpha \cdot PRECIP_{24} \tag{19}$$

The equation for the peak runoff rate is obtained by substituting equations 17, 18, and 19 into equation 16:

$$PEAKQ = \frac{\alpha \cdot Q \cdot A}{360 \cdot TC} \tag{20}$$

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

$$TC = TC_{ch} + TC_{ov} \tag{21}$$

where TC_{ch} is the time of concentration for channel flow in h, and TC_{ov} is the time of concentration for overland surface flow in h.

The time of concentration for channel flow can be calculated by the equation

$$TC_{ch} = \frac{CHFL}{3.6 \cdot CHV} \tag{22}$$

where *CHFL* is the average channel flow length for the basin in km and *CHV* is the average channel velocity in m s^{-1}.

The average channel flow length can be estimated by the equation

$$CHFL = \sqrt{CHL \cdot CHL_{cen}} \tag{23}$$

where *CHL* is the channel length from the most distant point to the watershed outlet in km and CHL_{cen} is the distance from the outlet along the channel to the watershed centroid in km. We can assume that $CHL_{cen}=0.5\ CHL$.

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 to depth ratio. Substitution of these estimated and assumed values, and conversion of units gives the following estimation of the time of concentration for channel

$$TC_{ch} = \frac{0.62 \cdot CHL \cdot CHN^{0.75}}{(QAV \cdot A)^{0.25} \cdot CHS^{0.375}} \tag{24}$$

where *CHN* is Manning's n, *QAV* is the average flow rate in mm h^{-1}, and *CHS* is the average channel slope in m m^{-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

$$QAV = QAV_0 \cdot A^{-0.5} \tag{25}$$

where QAV_0 is the average flow rate from a 1 ha area in mm h^{-1}.

Substitution of equation 25 into equation 24 gives the final equation for TC_{ch}:

$$TC_{ch} = \frac{0.62 \cdot CHL \cdot CHN^{0.75}}{QAV_0^{0.25} \cdot A^{0.125} \cdot CHS^{0.375}} \quad (26)$$

A similar approach is used to estimate the time of concentration for overland surface flow

$$TC_{ov} = \frac{SL}{3600 \cdot SV} \quad (27)$$

where *SL* is the surface slope length in m and *SV* is the surface flow velocity in m s^{-1}.

The surface flow velocity is estimated applying Manning's equation to a strip 1 m wide down the slope length, and assuming that flow is concentrated into a small trapezoidal channel with 1:1 side slopes and 5:1 bottom width to depth ratio as following

$$SV = \frac{0.00748 \cdot FD^{0.666} \cdot SS^{0.5}}{SN} \quad (28)$$

where *SV* is the surface flow velocity in m^3 s^{-1}, *FD* is flow depth in m, *SS* is the land surface slope in m m^{-1}, and *SN* is Manning's roughness coefficient 'n' for the surface.

The average flow depth FD is calculated from Manning's equation as a function of flow rate

$$FD = \left(\frac{QAV_0 \cdot SN}{5.025 \cdot SS^{0.5}} \right)^{0.375} \quad (29)$$

where AVQ_0 is the average flow rate in m^3 s^{-1}. Substitution of equations 28 and 29 into equation 27 gives

$$TC_{ov} = \frac{0.0556 \cdot SL \cdot SN^{0.75}}{QAV_0^{0.25} \cdot SS^{0.375}} \quad (30)$$

The average flow rate from a unit source area in the basin is estimated with the equation

$$QAV_0 = \frac{Q}{DUR} \quad (31)$$

where the rainfall duration *DUR* (in h) is calculated using the equation

$$DUR = \frac{2.303}{-\ln(1. - \alpha_{0.5})} \tag{32}$$

where $\alpha_{0.5}$ is the fraction of rainfall that occurs during 0.5 h. It is calculated with equation 19 using $PRECIP_{0.5}$ instead of $PRECIP_{tc}$.

Equation 32 is derived assuming that rainfall intensity is exponentially distributed. To evaluate α properly, variation in rainfall patterns must be considered. For some short duration storms, most or all the rain occurs during TC causing α to approach its upper limit of 1.0. Other storm events of uniform intensity cause α to approach a minimum value. By substituting the products of intensity and time into equation 19, an expression for the minimum value of α, α_{min}, is obtained

$$\alpha_{\min} = TC/24 \tag{33}$$

Thus, α ranges within the limits

$$TC/24 < \alpha < 1.0 \tag{34}$$

Although confined between limits, the value of α is assigned with considerable uncertainty when only daily rainfall and simulated runoff amounts are given. This can lead to considerable uncertainties in estimating daily runoff and has to be kept in mind. The value of α is estimated in the model from the gamma distribution, taking into account the average monthly rainfall intensity for the basin under study.

2.1.4 Percolation

A storage routing technique (Arnold et al., 1990) is used in SWIM to simulate percolation through each soil layer. The percolation from the bottom soil layer is treated as recharge to the shallow aquifer. The storage routing technique is based on the equation

$$SW(t+1) = SW(t) \cdot \exp\left(\frac{-\Delta t}{TT_i}\right) \tag{35}$$

where *SW(t+1)* and *SW(t)* are the soil water contents at the beginning and end of the day in mm, Δt is the time interval (24 h), and TT_i is the travel time through layer *i* in h. Thus, the percolation can be calculated by subtracting SW_t from SW_{t+1}:

$$PERC_i = SW_i \cdot \left[1. - \exp\left(\frac{-\Delta t}{TT_i}\right)\right] \tag{36}$$

where *PERC* is the percolation rate in mm d^{-1}. The travel time TT_i is calculated for each soil layer with the linear storage equation

$$TT_i = \frac{SW_i - FC_i}{HC_i} \tag{37}$$

where HC_i is the hydraulic conductivity in mm h^{-1} and *FC* is the field capacity water content for layer *i* in mm. The hydraulic conductivity is varying from the saturated conductivity value at saturation to near zero at field capacity (see also **Fig. 2.5**) as

$$HC_i = SC_i \cdot \left(\frac{SW_i}{UL_i} \right)^{\beta_i} \tag{38}$$

where SC_i is the saturated conductivity for layer i in mm h^{-1}, UL_i is soil water content at saturation in mm mm^{-1},and β_i is a shape parameter that causes HC_i to approach zero as SW_i approaches FC_i.

The equation for estimating β_i is

$$\beta_i = \frac{-2.655}{\log_{10}\left(\frac{FC_i}{UL_i} \right)} \tag{39}$$

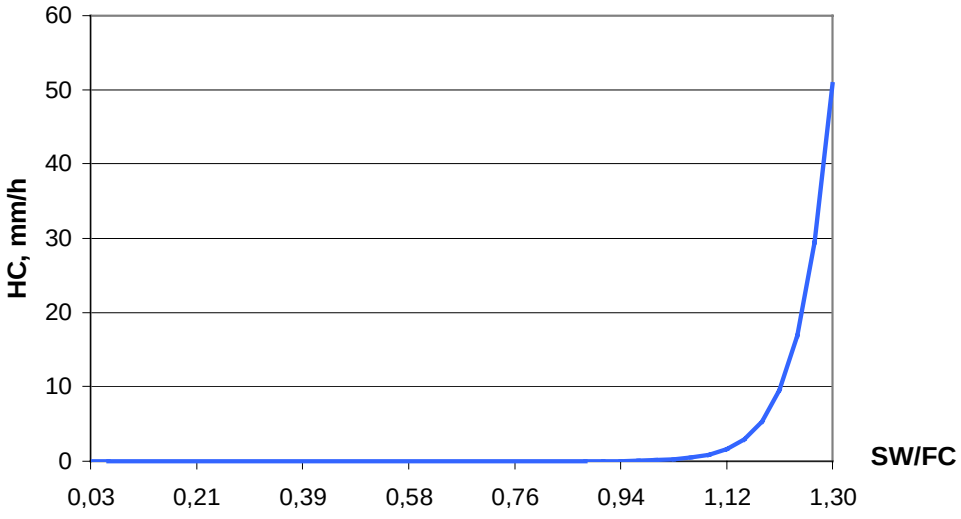

Fig. 2.5 Hydraulic conductivity as a function of soil water content (equation 39) assuming SC = 50.8 mm h^{-1}, FC = 33 mm mm^{-1}, UL = 43 mm mm^{-1}

The constant in equation 39 is set to –2.655 to assure that at field capacity

$$HC_i = 0.002 \cdot SC_i \tag{40}$$

Water flow through a soil layer may occur until the lower layer is not saturated. If the layer below the layer being considered is saturated, no flow can occur. The effect of lower layer water content is expressed by the equation

$$PERC_{ic} = PERC_i \cdot \sqrt{1 - \frac{SW_i + 1}{UL_i + 1}} \tag{41}$$

where $PERC_{ic}$ is the percolation rate for layer i in mm d^{-1} corrected for layer i+1 water content and $PERC_i$ is the percolation calculated with equation 36.

Percolation is also affected by soil temperature. If the temperature in a particular layer is O°C or below, no percolation is allowed from that layer.

Since the one-day time interval is relatively low for routing flow through the soil root zone, the water is divided into several portions for routing through soil. This is necessary because flow rates are dependent upon soil water content, which is continuously changing. For example, if the soil is extremely wet, equations 36, 37, and 38 may overestimate percolation, if only one routing is performed. To overcome this problem, each layer's inflow is divided into 4-mm slugs for routing.

Besides, when the inflow is divided into 4-mm slugs and each slug is routed individually through the layers, the relationship taking into account the lower layer water content (equation 41) works more realistically.

2.1.5 Lateral Subsurface Flow

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

$$\frac{SUP_2 - SUP_1}{t_2 - t_1} = WIR \cdot SL - \frac{SSF_1 + SSF_2}{2} \tag{42}$$

where *SUP* is the drainable volume of water stored in the saturated zone m m^{-1} (water above field capacity), t is time in h, *SSF* is the lateral subsurface flow in m^3 h^{-1}, *WIR* is the rate of water input to the saturated zone in m^2 h^{-1}, *SL* is the hillslope length in m, and subscripts 1 and 2 refer to the beginning and end of the time step, respectively. The drainable volume of water stored, *SUP*, is updated daily.

The lateral flow at the hillslope outlet is given by

$$SSF = \frac{2 \cdot SUP \cdot VEL \cdot SLW}{PORD \cdot SL} \tag{43}$$

where *VEL* is the velocity of flow at the outlet in mm h^{-1}, *SLW* is the hillslope width in m, and *PORD* is the drainable porosity of the soil in m m^{-1}. Velocity at the outlet is estimated as

$$VEL = SC \cdot \sin(\nu) \tag{44}$$

where *SC* is the saturated conductivity in mm h^{-1}, and ν is the hillslope steepness in m m^{-1} . Combination of equations 43 and 44 gives

$$SSF = 0.024 \cdot \frac{2 \cdot SUP \cdot SC \cdot \sin(\nu)}{PORD \cdot SL} \tag{45}$$

where *SSF* is in mm d^{-1}, *SUP* in m m^{-1}, γ in m m^{-1}, *PORD* in m m^{-1}, and *SL* in m.

If the saturated zone rises above the soil layer, water is allowed to flow to the layer above. The amount of flow upward is estimated as a function of saturated conductivity *SC* and the saturated slope length

$$QUP = \frac{24 \cdot SC \cdot SL_{sat}}{SL} \tag{46}$$

where *QUP* is the upward flow in mm d^{-1}, and Sl_{sat} is the saturated slope length in m.

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.

2.1.6 Potential Evapotranspiration

The method of Priestley-Taylor (1972) is used in the model for estimation of potential evapotranspiration, which requires only solar radiation, air temperature, and elevation as inputs. Instead, the method of Penman-Monteith (Monteith, 1965) can be used, if additional input data are available. The Penman-Monteith method requires solar radiation, air temperature, wind speed, and relative humidity as input.

The Priestley-Taylor method estimates potential evapotranspiration as a function of net radiation as following

$$EO = 1.28 \cdot \left(\frac{RAD}{HV} \right) \cdot \left(\frac{\delta}{\delta + \gamma} \right) \tag{47}$$

where *EO* is the potential evaporation in mm, *RAD* is the net radiation in MJ m^{-2}, *HV* is the latent heat of vaporization in MJ kg^{-1}, δ is the slope of the saturation vapor pressure curve in kPa C^{-1}, and γ is a psychrometer constant in kPa C^{-1}.

The latent heat of vaporization is estimated as a function of the mean daily air temperature T in °C

$$HV = 2.5 - 0.0022 \cdot T \tag{48}$$

The saturation vapor pressure *VP* is also estimated as a function of temperature

$$VP = 0.1 \cdot \exp\left[54.88 - 5.03 \cdot \ln(T + 273) - \frac{6791}{T + 273}\right] \tag{49}$$

Then the slope of the saturation vapor pressure curve is calculated with the equation

$$\delta = \left(\frac{VP}{T + 273}\right) \cdot \left(\frac{6791}{T + 273} - 5.03\right) \tag{50}$$

The psychrometer constant γ is calculated as a function of barometric pressure BP (in kPa)

$$\gamma = 6.6 \cdot 10^{-4} \cdot BP \tag{51}$$

The barometric pressure is estimated as a function of elevation ELEV (in m)

$$BP = 101 - 0.0115 \cdot ELEV + 5.44 \cdot 10^{-7} \cdot ELEV^2 \tag{52}$$

If actual net radiation is not available, in can be estimated from the maximum solar radiation as following. First, the maximum possible solar radiation *RAM* in Ly is calculated as

$$RAM = \\ = \frac{711}{D^2} \cdot \left(\phi \cdot \sin\left(\frac{2 \cdot \pi \cdot LAT}{360}\right) \cdot \sin(\theta) + \cos\left(\frac{2 \cdot \pi \cdot LAT}{360}\right) \cdot \cos(\theta) \cdot \sin(\phi)\right) \tag{53}$$

where *D* is the earth's radius vector in km, ϕ is the sun's half day length in radians, *LAT* is the latitude of the site in degrees, and θ is the sun's declination angle in radians.

The earth's radius vector *D* can be calculated for any day t as

$$D = \frac{1}{\sqrt{1. + 0.0335 \cdot \sin\left[\frac{2 \cdot \pi \cdot (t + 88.2)}{365}\right]}} \tag{54}$$

The sun's declination angle is calculated with the equation

$$\theta = 0.4102 \cdot \sin\left[\frac{2 \cdot \pi \cdot (t - 80.25)}{365}\right] \tag{55}$$

The sun's half day length is calculated as

$$\begin{aligned} &\phi = \cos^{-1}\left[\tan\left(\frac{2 \cdot \pi \cdot LAT}{360}\right) \cdot \tan(\theta)\right], && -1 \le \theta \le 1 \\ &\phi = 0\ , && \theta > 1 \\ &\phi = \pi\ , && \theta \le -1 \end{aligned} \tag{56}$$

Then the net radiation is estimated with the equation

$$RAD = RAM \cdot (1. - ALB) \tag{57}$$

where *RAD* is the solar radiation in MJ m^{-2} and *ALB* is albedo.

The albedo is estimated by considering the soil, crop/vegetation cover, and snow cover. When crops are growing, albedo is determined by using the equation

$$ALB = 0.23 \cdot (1. - SCOV) + ALB_{soil} \cdot SCOV \tag{58}$$

where 0.23 is the albedo for plants, ALB_{soil} is the soil albedo, and *SCOV* is a soil cover index.

The value of the soil cover index *SCOV* ranges from 0 to 1.0 according to the equation

$$SCOV = \exp(-0.05 \cdot BMR) \tag{59}$$

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

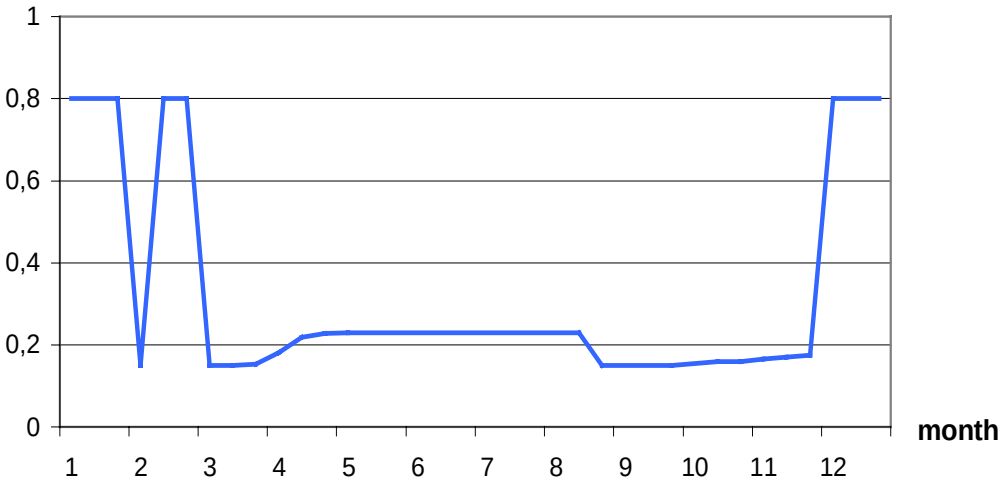

Fig. 2.6 An example of the annual dynamics of soil albedo (equations 58, 59)

If a snow cover exists with 5 mm or greater water content, the value of albedo is set to 0.8. If the snow cover is less than 5 mm and no crop is growing, the soil albedo is set to the input value (default value = 0.15). An example on **Fig. 2.6** shows possible seasonal dynamics of albedo in a temperate zone with a maximum 0.8 in winter (snow cover), minimum in march and september (equal to the bare soil albedo), and increasing up to 0.23 in summer (crop growth).

2.1.7 Soil Evaporation and Plant Transpiration.

The model calculates evaporation from soils and transpiration by plants separately using an approach similar to that of Ritchie (1972). The plant transpiration is calculated as

$$\begin{aligned} EP &= \frac{EO \cdot LAI}{3}\ , && 0 \le LAI \le 3.0 \\ EP &= EO\ , && LAI > 3.0 \end{aligned} \qquad (60)$$

where *EO* is the potential evapotranspiration in mm d^{-1} estimated by equation (47), *EP* is the plant water transpiration rate in mm d^{-1} and *LAI* is the leaf area index (area of plant leaves relative to the soil surface area).

If soil water is limited, plant water transpiration is reduced. The approach is described in section 2.2.2 about water stress.

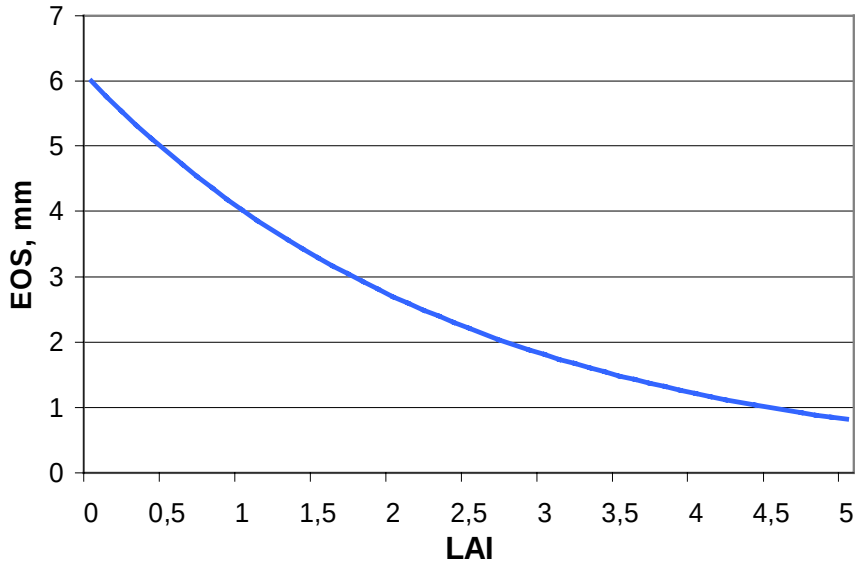

Fig. 2.7 Potential soil evaporation, ESO, as a function of leaf area index, LAI (equation 61) under assumption that EO = 6 mm d^{-1}

Potential soil evaporation *ESO* in mm d^{-1} is simulated by an exponential function of leaf area index *LAI* according to the equation of Richardson and Richie (1973) (see also **Fig. 2.7**):

$$ESO = EO \cdot \exp\left(-0.4 \cdot LAI\right) \tag{61}$$

Actual soil evaporation is calculated in two stages. In the first stage, soil evaporation is limited only by the energy available at the surface, and is equal to the potential soil evaporation. When the accumulated soil evaporation exceeds the first stage threshold (equal to 6 mm), the second stage begins. Then soil evaporation is estimated with the equation

$$ES = 3.5 \cdot \left(\sqrt{TST} - \sqrt{TST - 1}\right) \tag{62}$$

where *ES* is the soil evaporation for day t in mm d^{-1} and *TST* is the number of days since stage two evaporation began.

Actual soil water evaporation is estimated on the basis of the top 30 cm of soil and snow cover, if any. If the water content of the snow cover is greater or equal to ES, the soil evaporation comes from the snow cover. If ES exceeds the water content of the snow cover, water is removed from the upper soil layers if available.

2.1.8 Groundwater Flow

The groundwater submodel in the integrated river basin model like SWIM is intended for general use in regions where extensive field measurements are not available. Thus, the groundwater component has to be parameterized using readily available inputs. Also, it must have the level of sophistication similar to those of the other components. Therefore a detailed numerical model is not justified for this case, and a relatively simple yet realistic approach was chosen for use in SWAT and SWIM.

The simulated hydrological system consists of four control volumes that include:

- the soil surface,
- the soil profile or root zone,
- the shallow aquifer, and
- the deep aquifer.

The percolation from the soil profile is assumed to recharge the shallow aquifer. The surface runoff, the lateral subsurface flow from the soil profile, and return flow from the shallow aquifer contribute to the stream flow. The water balance equation for the shallow aquifer is

$$SAW(t+1) = SAW(t) + RCH - REVAP - GWQ - SEEP \tag{63}$$

where *SAW(t)* is the shallow aquifer storage in the day *t*, *RCH* is the recharge, *REVAP* is the water flow from the shallow aquifer back to the soil profile, *GWQ* is the return flow or groundwater contribution to streamflow, *SEEP* is the percolation or seepage to the deep aquifer (all – in mm d^{-1}), and *t* is the day.

REVAP is defined as water that raises from the shallow aquifer to the soil profile and is lost to the atmosphere by soil evaporation or plant root uptake.

The approach of Smedema and Rycroft (1983), who derived the non-steady-state response of groundwater flow to periodic recharge from Hooghoudt's (1940) steady-state formula, is used

$$GWQ = 8 \cdot \frac{KD \cdot GWH}{DS^2} \tag{64}$$

where *KD* is the hydraulic conductivity of groundwater in mm d^{-1}, *DS* is the drain spacing in m, and *GWH* is the water table height in m.

Assuming that the shallow aquifer is recharged by seepage from stream channels, reservoirs, or the soil profile (rainfall and irrigation), and is depleted by the return flow to the stream, fluctuations of water table can be estimated using the equation of Smedema and Rycroft (1983)

$$\frac{d(GWH)}{dt} = \frac{RCH - GWQ}{0.8 \cdot SY} \tag{65}$$

where *SY* is the specific yield.

The return flow can be estimated assuming that its variation with time is also linearly related to the rate of change of the water table height:

$$\frac{d(GWQ)}{dt} = 10 \cdot \frac{KD \cdot (RCH - GWQ)}{SY \cdot DS^2} = RF \cdot (RCH - GWQ) \tag{66}$$

where *RF* is the constant of proportionality or the reaction factor for groundwater.

Integration of equation 66 gives

$$GWQ(t+1) = GWQ(t) \cdot \exp(-RF \cdot \Delta t) + RCH \cdot [1 - \exp(-RF \cdot \Delta t)] \tag{67}$$

The relationship for the water table height is derived combining equations 64 and 67. It results in the following relationship

$$\begin{aligned} &GWH(t+1) = \\ &= GWH(t) \cdot \exp(-RF \cdot \Delta t) + \frac{RCH}{0.8 \cdot SY \cdot RF} \cdot (1. - \exp(-RF \cdot \Delta t)) \end{aligned} \tag{68}$$

The percolation from the soil profile is assumed to recharge the shallow aquifer. The delay time or drainage time of the aquifer is used to correct the recharge. Sangrey et al. (1984) used an exponential decay weighting function proposed by Venetis (1969) to estimate the delay time for return flow in their precipitation / groundwater response model

$$\begin{aligned} &RCH(t+1) = \\ &= \left(1. - \exp\left(-\frac{1}{DEL}\right)\right) \cdot RCH(t+1) + \exp\left(-\frac{1}{DEL}\right) \cdot RCH(t) \end{aligned} \tag{69}$$

where *DEL* is the delay time or drainage time of the aquifer in days (Sangrey et al., 1984). This equation will affect only the timing of the return flow and not the total volume. The equation (69) is used in SWIM to correct the recharge.

The volume of water flow from the shallow aquifer back to the soil profile, REVAP, is estimated with the equations

$$\begin{aligned} REVAP &= CR \cdot ET \ , & REVAP &> RST \\ REVAP &= 0 \ , & REVAP &\le RST \end{aligned} \tag{70}$$

where *ET* is the actual evapotranspiration occurring in the soil profile, CR is the *revap* coefficient, and *RST* is the *revap* storage in mm.

The amount of percolation or seepage from the shallow aquifer (recharge to the deep aquifer) is estimated as a linear function

$$SEEP = CS \cdot RCH \tag{71}$$

where *CS* is the seepage coefficient.

2.1.9 Transmission Losses

Many watersheds, especially in semiarid areas, have alluvial channels that abstract large quantities of stream flow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volumes because water is lost when the flood wave travels downstream.

A procedure for estimating transmission losses for ephemeral streams is described by Lane in the SCS Hydrology Handbook (USDA, 1983, chapter 19). The procedure is based on derived regression equations for estimation of transmission losses in the absence of observed inflow-outflow data. It enables the user to estimate transmission losses for similar channels of arbitrary length and width using channel geometry parameters (width and depth) and Manning's "n". This procedure is used in SWIM as well as in SWAT to estimate transmission losses.

The unit channel intercept and slope, and the decay factor are estimated with regression equations obtained from the analysis of observed data in different conditions:

$$AR = -0.001831 \cdot CHK \cdot DU \tag{72}$$

$$DEC = -1.09 \cdot \ln\left(1. - \frac{0.2649 \cdot CHK \cdot DU}{VOLQ_{in}}\right) \tag{73}$$

$$BR = \exp(-DEC) \tag{74}$$

where *AR* is the unit channel intercept in m^3, *CHK* is the effective hydraulic conductivity of the channel alluvium in mm h^{-1} (Lane, 1982; USDA, 1983 update), *DU* is the duration of streamflow in h, *DEC* is the decay factor in m km^{-1}, $VOLQ_{in}$ is inflow volume of m^3, and *BR* is the unit channel regression slope.

The inflow volume is assumed to be equal to the surface runoff from the sub-basin. The flow duration DU in h is estimated from

$$DU = \frac{Q \cdot A}{1.8 \cdot PEAKQ} \tag{75}$$

where *Q* is the surface runoff volume in mm, *A* is the drainage area in ha, and *PEAKQ* is the peak flow rate in $m^3\ s^{-1}$.

The regression parameters are estimated as

$$AX = [AR \cdot (1 - BR)] \cdot (1 - BR \cdot CHL) \tag{76}$$

$$BX = CHL \cdot CHW \cdot \exp(-2.04 \cdot DEC) \tag{77}$$

$$TH_0 = -\frac{AX}{BX} \tag{78}$$

where *AX* is the regression intercept in m km^{-1}, *BX* is the regression slope, *CHW* is average width of flow in m, *CHL* is length of channel in km, and TH_o is the threshold volume for a unit channel in m^3.

Then the final equation for runoff volume after losses, $VOLQ_{tr}$, is

$$\begin{aligned} VOLQ_{tr} &= -AX + BX \cdot VOLQ_{in} && VOLQ_{in} > TH_0 \\ VOLQ_{tr} &= 0 && VOLQ_{in} < TH_0 \end{aligned} \tag{79}$$

The final equation for peak discharge after losses $PEAKQ_{tr}$, is

$$PEAKQ_{tr} = \frac{12.1 \cdot AX}{DU - (1 - BX) \cdot VOLQ_{in} + BX \cdot PEAKQ_{in}}, \quad VOLQ_{in} > 0 \tag{80}$$

where $PEAKQ_{in}$ is the initial peak runoff rate.

2.2 Crop / Vegetation Growth

2.2.1 Crop 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 EPIC root growth and nutrient cycling modules are not included.

A single model is used for simulating all the crops and natural vegetation considered (see **Table 3.14** in Chapter 3). The model 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. Later the term 'crop' will be used instead of 'crop or natural vegetation'.

Phenological development of the crop is based on accumulation of daily heat units. The value of heat units accumulated in the day t, *HUNA*, is calculated as

$$HUNA(t) = \left(\frac{TMX + TMN}{2} \right) - TB \ , \qquad HUNA \geq 0 \tag{81}$$

where *TMX* and *TMN* are the maximum and minimum temperature in °C, and *TB* is the crop-specific base temperature in °C assuming that no growth occurs at or below TB.

Then the heat unit index *IHUN* ranging from 0 at planting to 1 at physiological maturity is calculated as

$$IHUN = \frac{\sum_{t} HUNA(t)}{PHUN} \tag{82}$$

where *PHUN* is the value of potential heat units required for the maturity of the crop. The values of *PHUN* for different crops are provided in the crop database supplemented with the model.

Interception of solar radiation is estimated with Beer's law equation (Monsi and Saeki, 1953) as a function of photosynthetic active radiation and leaf area index (see **Fig. 2.8**)

$$PAR = 0.02092 \cdot RAD \cdot \left[1 - \exp(-0.65 \cdot LAI) \right] \tag{83}$$

where *PAR* is the photosynthetic active radiation in MJ m^{-2}, *RAD* is solar radiation in Ly, and *LAI* is the leaf area index.

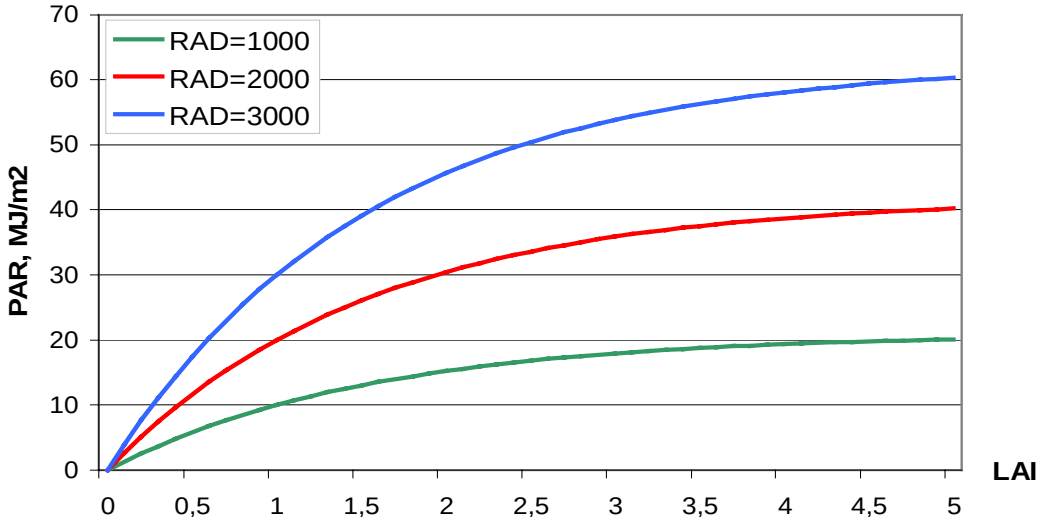

Fig. 2.8 Photosynthetic active radiation, PAR as a function of leaf area index, LAI for RAD= 1000, 2000 and 3000 Ly (equation 83)

Potential increase in biomass for a day is calculated using the approach of Monteith (1977) with the equation

$$\Delta BP = BE \cdot PAR \tag{84}$$

where ΔBP is the daily potential increase in total biomass in kg h^{-1} a^{-1}, and BE is the crop-specific parameter for converting energy to biomass in kg m^2 MJ^{-1} ha^{-1} d^{-1}. The latter one is taken from the crop database.

The potential increase in biomass estimated with equation 84 is adjusted daily if one of the plant stress factors is less than 1.0. The model considers stresses caused by water, nutrients, and temperature. The following equation is used to estimate the daily increase in biomass ΔB (in kg ha^{-1})

$$\Delta B = \Delta BP \cdot REGF \tag{85}$$

where *REGF* is the crop growth regulating factor estimated as the minimum stress factor:

$$REGF = \min(WS, TS, NS, PS) \tag{86}$$

where *WS, TS, NS, PS* are stress factors caused by water, temperature, nitrogen and phosphorus, all varying between 0 and 1.

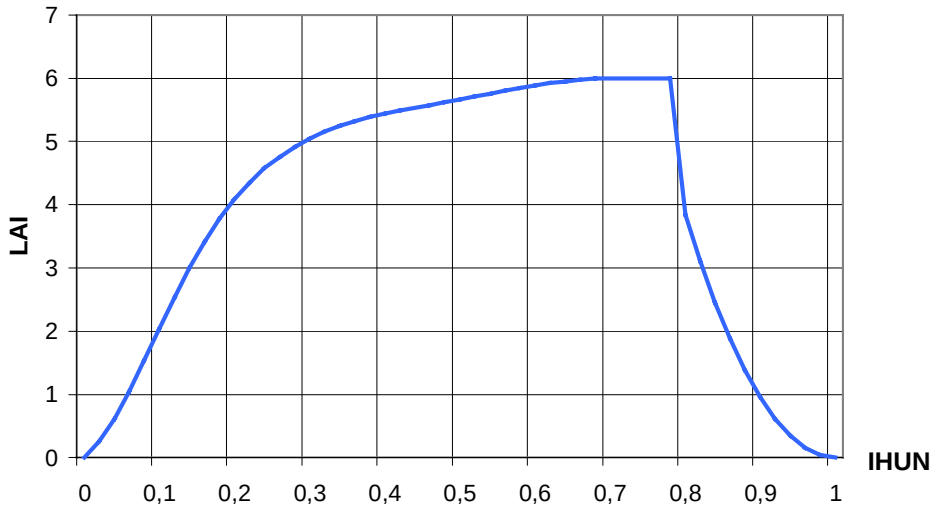

Fig. 2.9 Leaf area index as a function of the heat unit index (equation 87)

The leaf area index LAI is simulated as a function of heat units and biomass, differently for two phases of the growing season:

$$LAI = \frac{LAIMX \cdot BAG}{BAG + \exp\left(9.5 - 0.0006 \cdot BAG\right)}, \qquad IHUN \le DLAI$$
$$LAI = 16 \cdot LAIMX \cdot \left(1 - IHUN\right)^2, \qquad IHUN > DLAI \tag{87}$$

where *LAIMX* is the maximum potential LAI for the specific crop, *BAG* is aboveground biomass in kg ha^{-1}, and *DLAI* is the fraction of the growing season before *LAI* starts declining (crop-specific parameter). An example of LAI dynamics is shown in **Fig. 2.9**).

The aboveground biomass is estimated as

$$BAG = \left(1 - RWT\right) \cdot BT \tag{88}$$

where *RWT* is the fraction of total biomass partitioned to the root system, and *BT* is total biomass in kg ha^{-1}.

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 using the equation

$$RWT = \left(0.4 - 0.2 \cdot IHUN\right) \tag{89}$$

2.2.2 Growth Constraint: Water Stress

The water stress factor is calculated by considering water supply and water demand with the following equation

$$WS = \frac{\sum_{i=1}^{M} WU_i}{EP} \tag{90}$$

where WU_i is plant water use in layer i in mm. The value of potential plant transpiration *EP* is calculated in the evapotranspiration module.

The plant water use is estimated using the approach of Williams and Hann (1978) for simulating plant water uptake. First, the root depth is calculated with the equation

$$RD = 2.5 \cdot IHUN \cdot RDMX \tag{91}$$

where *RD* is the fraction of the root zone that contains roots and *RDMX* is the maximum root depth in m (crop-specific parameter).

Then the potential water use in each soil layer is estimated with the equation

$$WUP_i = \frac{EP}{1 - \exp(RDP)} \cdot \left(1 - \exp\left(-\frac{RDP \cdot RZD_i}{RD}\right)\right) \tag{92}$$

where WUP_i is the potential water use rate from layer i in mm d^{-1}, *RDP* is the rate-depth parameter, and RZD_i is the root zone depth parameter for the layer i in mm.

The latter one is defined as

$$RZD_i = \begin{cases} Z_i, & RD > Z_i \\ RD, & RD \le Z_i \end{cases} \tag{93}$$

The value of *RDP* used in the model (3.065) was determined assuming that about 30% of the total water use comes from the top 10% of the root zone. The details of evaluating *RDP* are given in Williams and Hann (1978). Equation 92 allows roots to compensate for water deficits in certain layers by using more water in layers with adequate supply.

Then the potential water use must be adjusted for water deficits to obtain the actual water use *WU* for each layer:

$$WU_i = WUP_i \cdot \frac{SW_i}{0.25 \cdot FC_i} \ , \qquad SW_i \le 0.25 \cdot FC_i \tag{94}$$

$$WU_i = WUP_i \ , \qquad SW_i > 0.25 \cdot FC_i \tag{95}$$

After the calculation of actual water use by plants, the plant transpiration EP is adjusted.

2.2.3 Growth Constraint: Temperature Stress.

The temperature stress factor is calculated as an asymmetrical function, differently for temperature below the optimal temperature TO, and above it. The equation for the temperature stress factor *TS* for temperatures below *TO* is

$$TS = \exp\left(\ln(0.9) \cdot \left(\frac{CTSL \cdot (TO - T)}{T + 1. \cdot 10^{-6}} \right)^2 \right) \qquad T \le TO \tag{96}$$

where *CTSL* is the temperature stress parameter for temperatures below TO, and T is the daily average air temperature in °C. The temperature stress parameter *CTSL* is evaluated as

$$CTSL = \frac{TO + TB}{TO - TB} \tag{97}$$

where *TB* is the base temperature for the crop in °C. Equation 96 assures that TS=0.9 when the air temperature is (TO+TB)/2.

For the temperatures higher than TO

$$TS = \exp\left(\ln(0.9) \cdot \left(\frac{TO - T}{CTSH + 1. \cdot 10^{-6}} \right)^2 \right) \qquad T > TO, \tag{98}$$

where the temperature stress parameter for temperatures higher than TO, *CTSH,* is evaluated as

$$CTSH = 2 \cdot TO - T - TB \tag{99}$$

An example of the temperature stress factor calculated with equations 96 and 98 is shown in **Fig. 2.10**.

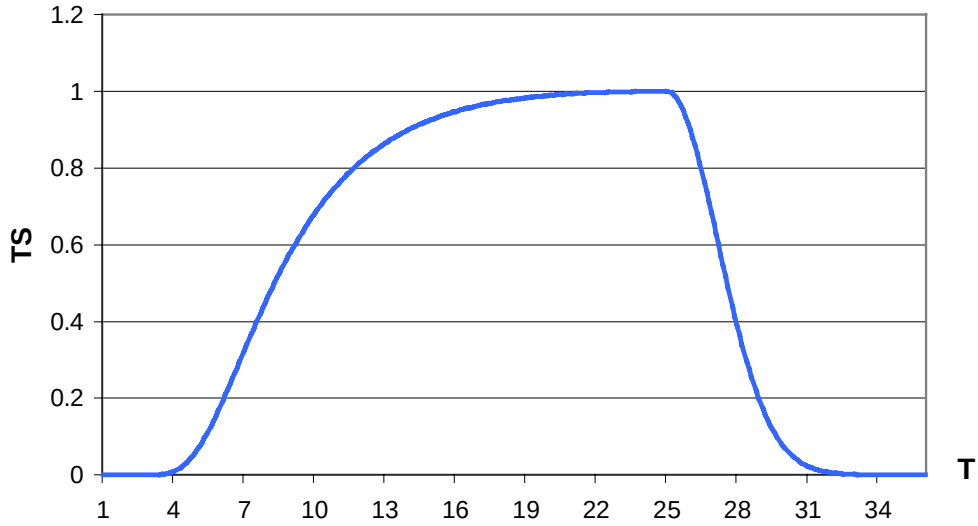

Fig. 2.10 Temperature stress factor as a function of average daily air temperature (equations 96 and 98), assuming TO = 25° C and TB = 3° C

2.2.4 Growth Constraints: Nutrient Stress

Estimation of nutrient stress factors is based on the ratio of simulated plant N and P contents to the optimal values of nutrient content. The stress factors vary non-linearly from 0 when N or P is half the optimal level to 1.0 at optimal N and P contents (Jones et al., 1984).

Let us consider the N stress factor first. As an initial step, the scaling factor SFN is calculated as

$$SFN = 200 \cdot \left(\frac{\sum UN(t)}{CNB \cdot BT} - 0.5 \right) \tag{100}$$

where *UN(t)* is the crop N uptake on day t in kg ha^{-1}, *CNB* is the optimal N concentration for the crop, *BT* is the accumulated total biomass in kg ha^{-1}.

Then the N stress factor is calculated with the equation (see also **Fig. 2.11**)

$$NS = \frac{SFN}{SFN + \exp(3.52 - 0.026 \cdot SFN)}, \qquad if \;\; SFN > 0 \tag{101}$$

The P stress factor, PS, is calculated analogously, using the optimal P concentration, COP, instead.

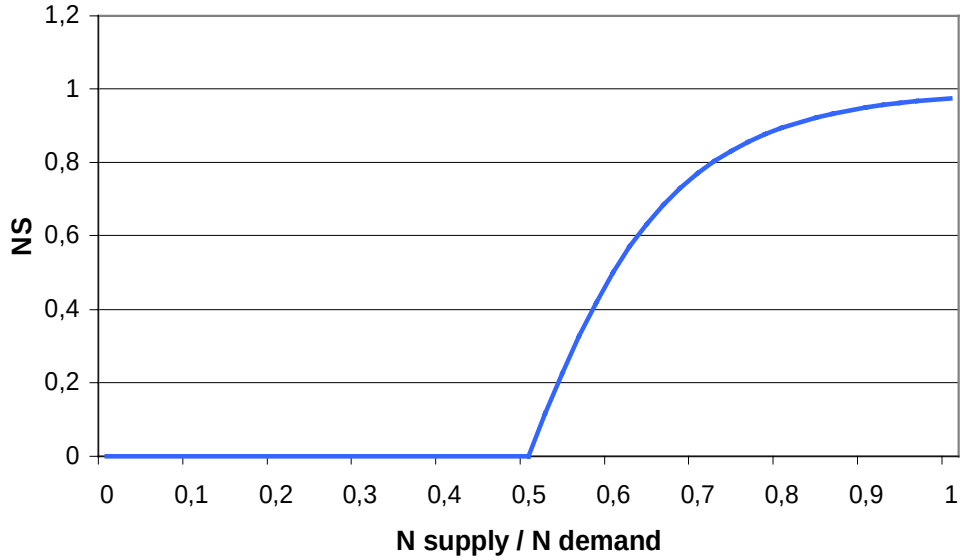

Fig. 2.11 Nitrogen stress factor as a function of N supply and N demand (equations 100 – 101)

2.2.5 Crop Yield and Residue

The economic yield of most crops is a reproductive organ. Harvest index (economic yield divided by aboveground biomass) is often a relatively stable value across a range of environmental conditions. Crop yield is estimated in the model using the harvest index concept

$$YLD = HI \cdot BAG \tag{102}$$

where *YLD* is the crop yield removed from the field in kg ha^{-1}, *HI* is the harvest index at harvest, and *BAG* is the above-ground biomass in kg ha^{-1}.

Harvest index *HIA* increases non-linearly during the growth season and can be estimated as the function of the accumulated heat units

$$HIA = HVSTI \cdot HIC_1 = \\ = HVSTI \cdot \frac{100 \cdot IHUN}{100 \cdot IHUN + \exp(11.1 - 10 \cdot IHUN)} \tag{103}$$

where *HVSTI* is the crop-specific harvest index under favourable growing conditions, and HIC_1 is a factor depending on *IHUN* (see **Fig. 2.12**).

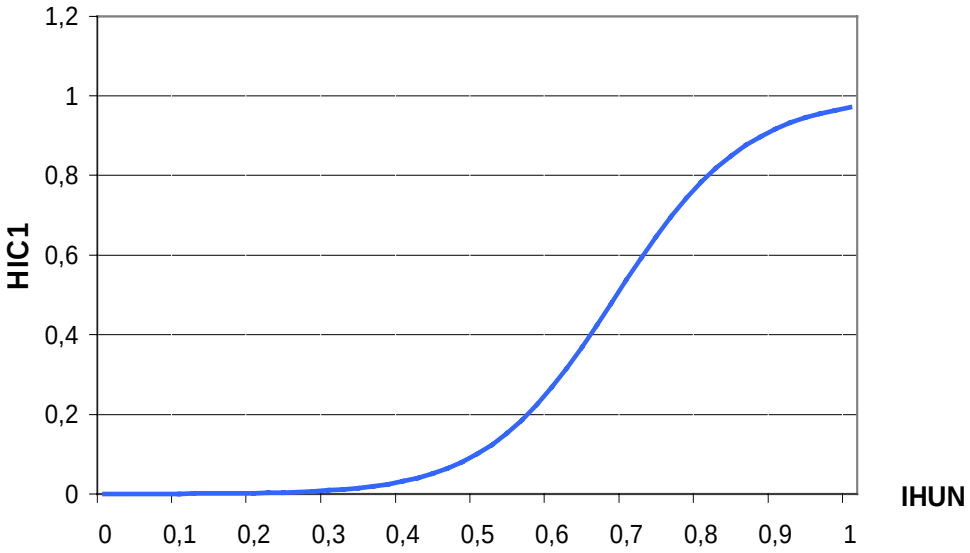

Fig. 2.12 Harvest index as a function of heat unit index (factor HIC_1, equation 103)

The constants in equation 103 are set to allow *HIA* to increase from 0.1 at *IHUN=0.5* to 0.92 at *IHUN=0.9*. This is consistent with economic yield development of crops, which produce most economic yield in the second half of the growing season.

Most crops are particularly sensitive to water stress, especially in the second half of the growing season, when major yield components are determined (Doorenbos and Kassam, 1979). The effect of water stress on the harvest index is described by the following two equations

$$HIAD = HIA \cdot HIC_2 = \\ = HIA \cdot \frac{WSF}{WSF + \exp(6.117 - 0.086 \cdot WSF)} \quad (104)$$

$$WSF = 100 \cdot \frac{SWU}{SWP + 1.e^{-6}} \quad (105)$$

where *HIAD* is the adjusted harvest index, *WSF* is a parameter expressing water supply conditions for crop, HIC_2 is a factor depending on *WSF* (see also factor HIC_2 at **Fig. 2.13**), *SWU* is accumulated actual plant transpiration in the second half of the growing season (*IHUN>0.5*), and SWP is accumulated potential plant transpiration in the second half of the growing season. The harvest index at harvest, *HI* is equal to *HIAD*.

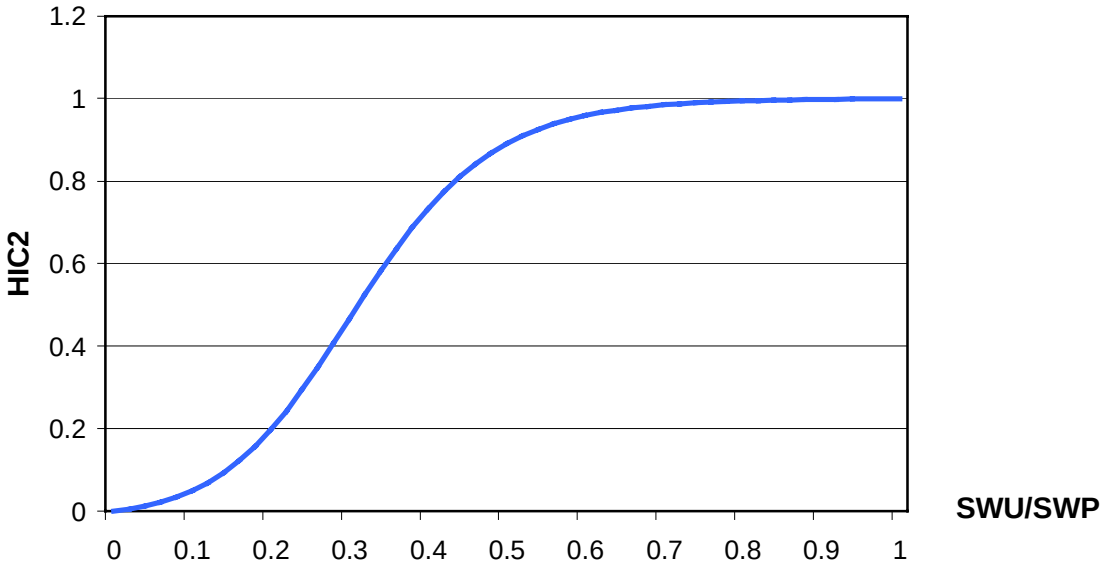

Fig. 2.13 Harvest index as a function of soil water content (factor HIC_2, equation 104)

The residue *RSD* is estimated at harvest as

$$RSD = (1 - RWT) \cdot BT \cdot HI \tag{106}$$

where *RWT* is the fraction of roots, and *BT* is the total biomass. This relationship can be modified for some crops if residue come from the roots.

All processes described in Sections 2.2.1 – 2.2.5 are presented graphically in **Fig. 2.14**. There are three basic blocks in the crop module (depicted by the grey coloured boxes) that are used to estimate the crop yield: accumulated heat units (top middle), stress factors (lower half), and harvest index (top left). The stress factors include temperature stress, nutrient stress (nitrogen and phosphorus), and water stress. The crop growth regulating factor is estimated as the minimum of these four factors. Nutrient stress is determined from the actual and potential nutrient uptake. Water stress is induced from water use and plant transpiration. The heat units accumulation is estimated from the crop specific minimum growth temperature, the daily minimum and maximum air temperatures and the assumed accumulated heat units. The adjusted harvest index is evaluated from the actual and potential transpiration and the crop specific harvest index. The small rectangles denote dependent variables, whereas the coloured ovals refer to model parameters independent from the others computed within the module. They describe the specifications of crop (green), climate (blue) and soil (brown).

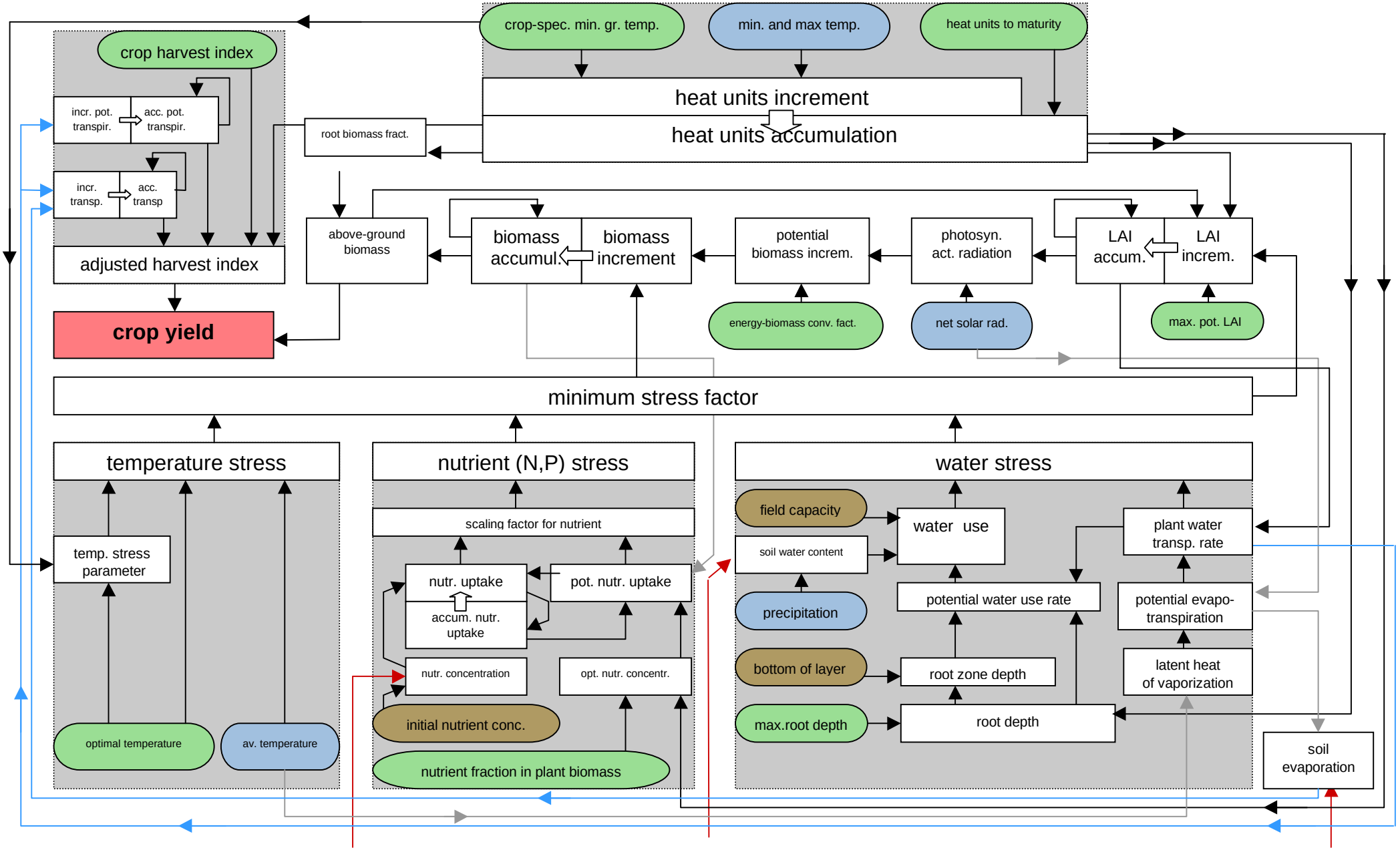

Fig. 2.14 Scheme of operations included in SWIM crop module

2.2.6 Adjustment of Net Photosynthesis to Altered CO_2

Different approaches for the adjustment of net photosynthesis and evapotranspiration to altered atmospheric CO_2 concentration have been used in modelling studies (Goudrian et al., 1984; Rotmans et al., 1993). Detailed results about the interaction of higher CO_2 and water use efficiency are described in (Easmus, 1991; Grossman et al., 1995; Kimball et al., in press).

Two different approaches can be used in SWIM for the adjustment of net photosynthesis (factor *ALFA*):

1) an empirical approach based on adjustment of the biomass-energy factor as suggested in EPIC and SWAT models (Arnold et al., 1994), and
2) a new semi-mechanistic approach derived by F. Wechsung from a mechanistic model for leaf net assimilation (Harley et al., 1992), which takes into account the interaction between CO_2 and temperature.

The second method and its application for climate change impact study with SWIM is described in Krysanova, Wechsung et al., 1999)

The factor ALFA is defined as

$$ALFA = \frac{AS_2}{AS_1} \tag{107}$$

where AS_1 and AS_2 are net leaf assimilation rates (μmol m^{-2} s^{-1}) in two periods, corresponding to two different CO_2 concentrations.

In the first method ALFA is estimated as

$$ALFA = \frac{100 \cdot CA}{BE \cdot \left(CA + \exp\left(SHP_1 - CA \cdot SHP_2\right)\right)} \tag{108}$$

where *BE* is the biomass-energy factor as in equation (83), *CA* is the current atmospheric CO_2 concentration (μmol mol^{-1}), and SHP_1 and SHP_2 are the coefficients of the S-shape curve, describing the assumed change in BE for two different CO_2 concentrations.

For the CO_2 doubling, 1.1 times increase in BE is assumed for maize, and 1.3 times increase for wheat and barley (see **Fig. 2.15**).

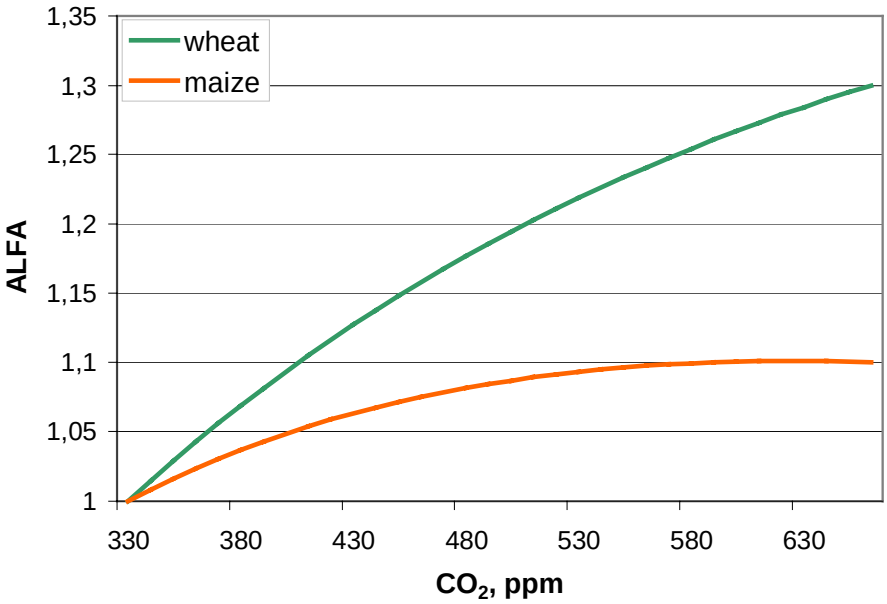

Fig. 2.15 Factor ALFA as a function of CO_2 concentration for wheat and maize estimated using the first method (equations 108, 109, 110) and assuming BE = 30 kg m^2 MJ^{-1} ha^{-1} d^{-1} for wheat and BE = 40 kg m^2 MJ^{-1} ha^{-1} d^{-1} for maize. The CO_2 concentration is changing from 330 to 660 ppm

If CO_2 concentration *CA* is changing from CA_1 to CA_2, and *BE* is changing from BE_1 to BE_2, the coefficients SHP_1 and SHP_2 can be estimated as following:

$$SHP_2 = \frac{\log(100 \cdot CA_1 / BE_1 - CA_1) - \log(100 \cdot CA_2 / BE_2 - CA_2)}{CA_2 - CA_1} \quad (109)$$

$$SHP_1 = \log(100 \cdot CA_1 / BE_1 - CA_1) + CA_1 \cdot SHP_2 \quad (110)$$

In the second method a temperature-dependent enhancement factor α was derived from Harley et al., 1992 for cotton

$$ALFA_{cot} = \exp\left[P_1 \cdot (CL_2 - CL_1) - P_2 \cdot \left((CL_2)^2 - (CL_1)^2\right) + P_3 \cdot TL \cdot (CL_2 - CL_1)\right] \quad (111)$$

where *TL* is the leaf temperature (°C), CL_1 and CL_2 are the current and future CO_2 concentration inside leaves (μmol mol^{-1}), and coefficients $P_1 = 0.3898 \cdot 10^{-2}$, $P_2 = 0.3769 \cdot 10^{-5}$, and $P_3 = 0.3697 \cdot 10^{-4}$.

It is assumed in the model that the leaf temperature *TL* coincides with the air temperature *TX,* and that the CO_2 concentration inside leaves is a linear function of the atmospheric CO_2 concentration:

$$CL = 0.7 \cdot CA \tag{112}$$

Then the cotton-specific factor ALFA was adjusted for wheat, barley and maize according to the latest crop-specific results reported in the literature (Peart et al., 1989; Kimball et al., in press)

$$ALFA_{wheat} = \left(ALFA_{\text{cot}}\right)^{0.6} \tag{113}$$

$$ALFA_{barley} = \left(ALFA_{\text{cot}}\right)^{0.6} \tag{114}$$

$$ALFA_{maize} = \left(ALFA_{\text{cot}}\right)^{0.36} \tag{115}$$

which imply an increase in leaf net photosynthesis of 31, 31 and 10% for wheat, barley and maize, respectively, if the atmospheric CO_2 increases from 360 to 720 ppm at 20°C and corresponds to the analogous assumption made in the first method. **Fig. 2.16** shows the temperature-dependent ALFA factor for cotton, wheat and maize in the case of CO_2 doubling (a) and in the case of 50% increase in CO_2 (b) assuming CA_1 = 330 ppm estimated with the second method (equations 111,112, 113, 115).

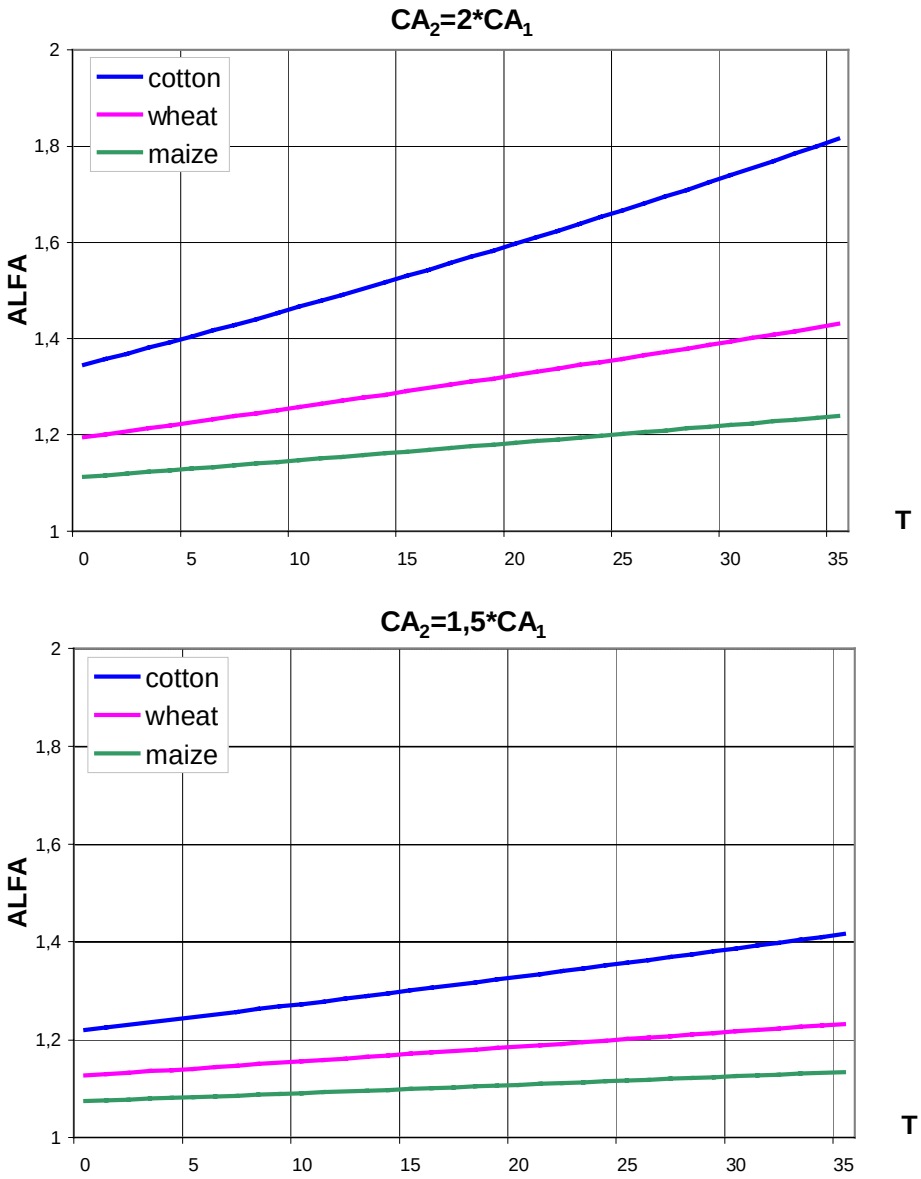

Fig. 2.16 ALFA factor for cotton, wheat and maize as dependent on temperature in the case of CO_2 doubling (a) and in the case of 50% increase in CO_2 (b) assuming initial CO_2 concentration 330 ppm (equations 111 - 115 and 121)

2.2.7 Adjustment of Evapotranspiration to Altered CO_2

Additionally, a possible reduction of potential leaf transpiration due to higher CO_2 (factor *BETA*) derived directly from the enhancement of photosynthesis (factor ALF) was taken into account in combination with both methods for the adjustment of net photosynthesis. The method was suggested by F. Wechsung.

The factor *BETA* is defined as

$$BETA = \frac{EPO_2}{EPO_1} \tag{116}$$

where EPO_1 and EPO_2 are potential plant transpiration rates (mol m^{-2} s^{-1}) in two periods, corresponding to two different CO_2 concentrations.

Assuming that

$$\frac{AS}{EPO} = \frac{CA - CL}{VPD} \cdot \frac{RESW}{RESC} \tag{117}$$

where VPD is the vapour pressure deficit (kPa), RESC is the total leaf resistance to CO_2 transfer (m^2 s mol^{-1}), RESW is the total leaf resistance to water vapour transfer (m^2 s mol^{-1}).

From definitions 107 and116 and equation 117 the ratio can be estimated

$$\frac{ALFA}{BETA} = \frac{CA_2 - CL_2}{CA_1 - CL_1} \cdot \frac{VPD_1}{VPD_2} \cdot \frac{RESW_2}{RESC_2} \cdot \frac{RESC_1}{RESW_1} \tag{118}$$

The following assumptions can be accepted for a given plant (see, e.g. Morrison, 1993)

$$\frac{RESW_2}{RESC_2} \approx \frac{RESW_1}{RESC_1} \tag{119}$$

and

$$VPD_2 \approx VPD_1 \tag{120}$$

Then the following estimation is derived for BETA from equations 112, 118, 119 and 120

$$BETA = ALFA \cdot \frac{CA_1}{CA_2} \tag{121}$$

Jarvis and McNaughton (1986) postulate that on the regional scale there is no control of stomatal resistance on evapotranspiration, because the humidity profiles are adjusted within the planetary boundary layer. This response would counter stomatal closure as a negative feedback. On the other hand, recent model studies suggest that stomata have far more control on regional and global evapotranspiration than postulated by Jarvis and McNaughton (Kimball et al., 1995).

Simulation runs with SWIM, which included the CO_2 fertilization effect on crops, have been carried out (Krysanova, Wechsung et al., 1999) applying both methods for ALFA factor in two variants: without and with factor BETA. In this way it is possible to account for current uncertainty regarding significance of stomatal effects on higher CO_2 for regional evapotranspiration. The comparison of two methods for estimation of ALFA factor is shown in **Fig. 2.17.**

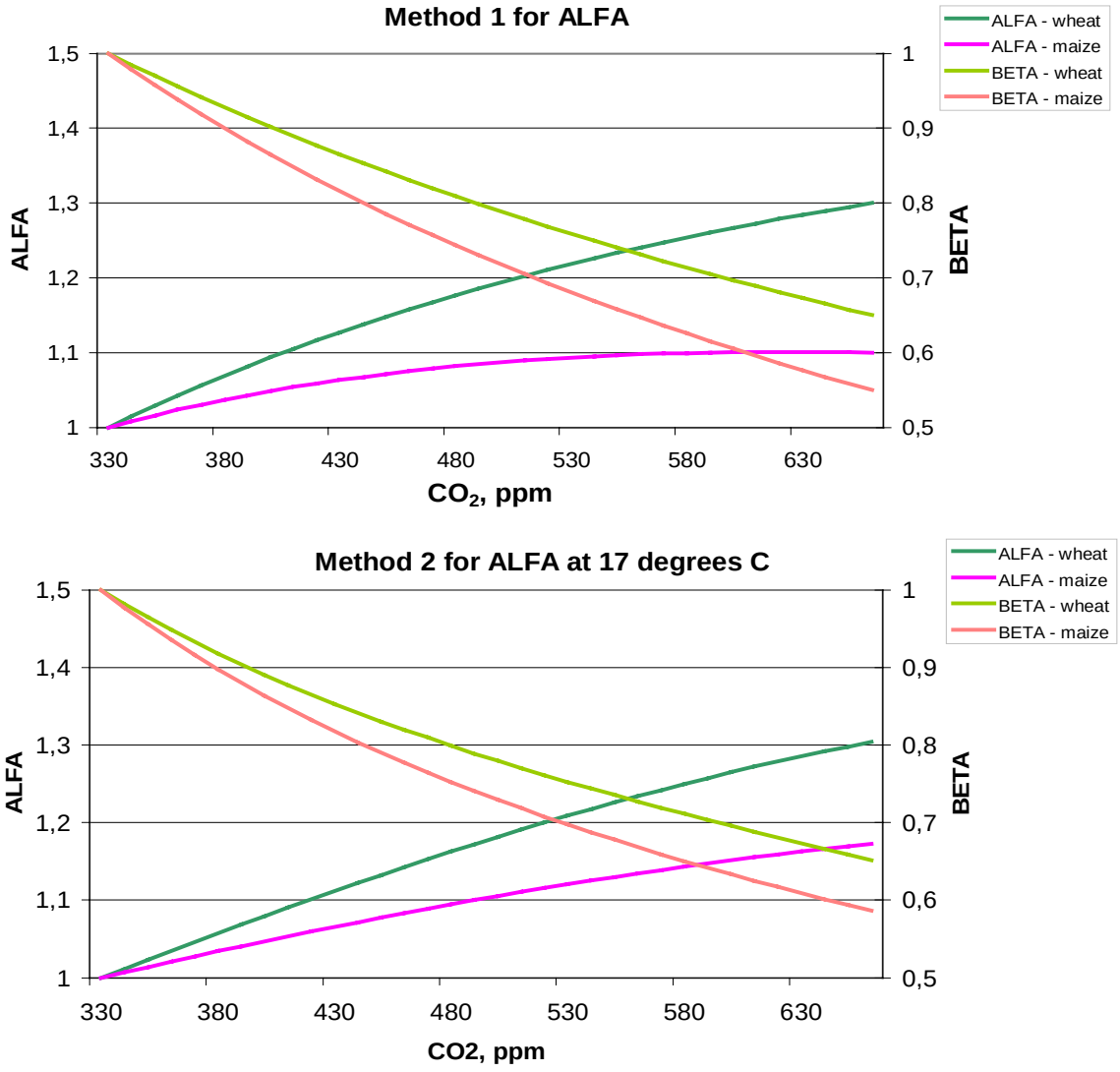

Fig. 2.17 Comparison of two methods for the estimation of ALFA and BETA factors: ALFA and BETA as functions of CO_2 concentration under assumption that temperature is 17° C for the second method

2.3 Nutrient Dynamics

Sub-basin nutrient cycling modules were taken from MATSALU and SWAT, and modified where necessary. The approach used in SWAT was modified from the EPIC model (Williams et al., 1984). The model simulates water, sediment and nutrients dynamics in every hydrotope, aggregates results for sub-basins, and then routes the water, sediment, and nutrients with lateral flow from the sub-basin outlet to the basin outlet.

2.3.1 Soil Temperature

Several processes of nutrient transformation, like mineralisation, are of microbial character, therefore estimation of soil temperature is necessary. Daily average soil temperature is defined at the center of each soil layer. The basic soil temperature equation is

$$TSO(Z,t) = TAV + \frac{AMP}{2} \cdot \cos\left(\frac{2 \cdot \pi}{365} \cdot (t - 200) - \frac{Z}{DD}\right) \cdot \exp\left(-\frac{Z}{DD}\right) \quad (122)$$

where *TSO(Z,t)* is the soil temperature at the depth *Z* in the day *t* in °C, *Z* is depth from the soil surface in mm, *t* is time d, *TAV* is the average annual air temperature in °C, *AMP* is the annual amplitude in daily average temperature in °C, and *DD* is the damping depth for the soil in mm.

The damping depth *DD* can be defined as a function of soil bulk density *BD* and water content *SW* as expressed in the following equations

$$DD = DP \cdot \exp\left[\ln\left(\frac{500}{DP}\right) \cdot \left(\frac{1 - SPD}{1 + SPD}\right)^2\right] \quad (123)$$

$$DP = 1000 + \frac{2500 \cdot BD}{BD + 686 \cdot \exp(-5.63 \cdot BD)} \quad (124)$$

$$SPD = \frac{SW}{(0.356 - 0.144 \cdot BD) \cdot ZM} \quad (125)$$

where *DP* is the maximum damping depth for the soil in 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 *SPD* is a scaling parameter.

Equation (122) reflects average conditions, if only TAV and AMP parameters are used. Since air temperature is provided as input, the soil temperature module can use the air temperature as driver to correct equation 122.

First, the bare soil surface temperature is estimated as

$$TGB(t) = WFT \cdot (TMX - T) + T \ , \qquad PRECIP = 0 \tag{126}$$

$$TGB(t) = WFT \cdot (T - TMN) + TMN \ , \qquad PRECIP > 0 \tag{127}$$

where *TGB(t)* is the bare soil surface temperature in °C in the day t, *TMX, T,* and *TMN* are the maximum, average and minimum daily air temperature in °C, and *WFT* is a proportion of rainy days in a month.

Equation 127 uses the minimum air temperature as a base to estimate surface temperature on rainy days. Higher temperatures are estimated on dry days using equation 126. The value of *WFT* is determined by considering the number of rainy days in this month:

$$WFT = \frac{NRD}{NDD} \tag{128}$$

where *NDD* is the number of days in a month, and *NRD* is the number of rainy days in a month.

The soil surface temperature is also affected by residue and snow cover. This effect is introduced by lagging the predicted base surface temperature with the equation

$$TG(t) = BCV \cdot TGB(t-1) + (1 - BCV) \cdot TGB(t) \tag{129}$$

where *BCV* is a lagging factor for simulating residue and snow cover effects on surface temperature. The value of BCV is 0 for bare soil and approaches 1.0 as cover increased as expressed in the equation

$$BCV = \max\left\{ \begin{array}{c} \dfrac{COV}{COV + \exp\left(7.563 - 1.297 \cdot 10^{-4} \cdot COV\right)}, \\ \dfrac{SNO}{SNO + \exp\left(6.055 - 0.3022 \cdot SNO\right)} \end{array} \right\} \tag{130}$$

where *COV* is the land cover, or the sum of above ground biomass and crop residue in kg ha^{-1} and *SNO* is the water content of the snow cover in mm.

Then the soil temperature at any depth is estimated with equation 122 by substituting *TG(t)* for *TS(0,t). TG(t)* is a better estimate of the surface temperature than *T(0,t),* because current weather and cover conditions are considered. At the soil surface (*Z*=0), the proper substitution can be accomplished by adding *TG(t)* and subtracting *TS(0,t)* from equation 122. Differences between *TG(t)* and *TS(0,t)* are damped as *Z* increases. So, the final equation for estimating soil temperature at any depth is

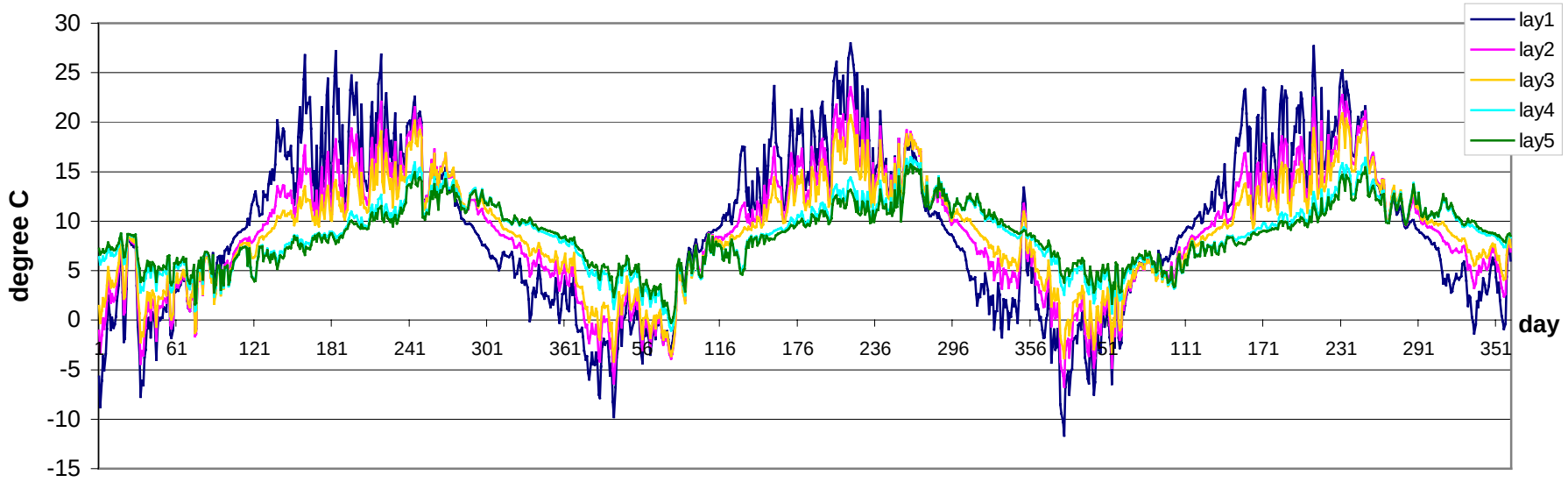

Fig. 2.18 An example of soil temperature dynamics in five soil layers simulated with SWIM using equation 131

$$TSO(Z,t) = TAV + \\ + \left(\frac{AMP}{2} \cdot \cos\left(\frac{2 \cdot \pi}{365} \cdot (t - 200) - \frac{Z}{DD} \right) + TG(t) - TS(0,t) \right) \cdot \exp\left(- \frac{Z}{DD} \right) \quad (131)$$

An example of soil temperature dynamics as simulated by SWIM using equation 131 is shown in **Fig. 2.18**.

2.3.2 Fertilization and Input with Precipitation

Fertilization in form of mineral and active organic N and P is treated as input information in SWIM. The amounts and dates should be specified in advance. The amounts of fertilizers applied can be either strict or calculated values, depending on whether the strict or flexible fertilization scheme is applied. In the latter case the amounts of applied N and P depend on the actual concentration of mineral N and P in soil.

To estimate the N contribution from rainfall, SWIM uses an average rainfall N and P concentration, specific for the region. The amount of N and P in precipitation is estimated as the product of rainfall amount and concentration.

2.3.3 Nitrogen Mineralisation

The nitrogen mineralisation model is a modification of the PAPRAN mineralisation model (Seligman and van Keulen, 1981). The model considers two sources of mineralisation:
(a) fresh organic N pool, associated with crop residue, and
(b) the active organic N pool, associated with the soil humus.

Step 1. When the model is initialized, organic N associated with humus is divided into two pools: active or readily mineralisable organic nitrogen *ANOR* and stable organic nitrogen *SNOR* (in kg ha^{-1}) by using the equation

$$ANOR = ANFR \cdot NOR \quad (132)$$

where *ANFR* is the active pool fraction (set to 0.15), *NOR* is the total organic N in kg ha^{-1} estimated from the initial soil data.

Organic N flow between the active and stable pools is described with the equilibrium equation

$$ASNFL = CASN \cdot \left[\frac{ANOR}{ANFR} - SNOR \right] \quad (133)$$

where *ASNFL* is the flow in kg ha^{-1} d^{-1} between the active and stable organic N pools, *CASN* is the rate constant (10^{-4} d^{-1}). The daily flow of humus-related organic N, *ASNFL*, is added to the stable organic N pool and subtracted from the active organic N pool.

Step 2. The residue is decomposed daily in accordance with the equation

$$RSD = RSD \cdot (1 - DECR) \tag{134}$$

where *DECR* is the decomposition rate. Fresh organic N pool *FON* is associated with residue. It is recalculated with the same equation daily:

$$FON = FON \cdot (1 - DECR) \tag{135}$$

and N mineralisation flow from fresh organic N in kg ha^{-1} d^{-1}, *FOMN*, is estimated as

$$FOMN = DECR \cdot FON \tag{136}$$

The decomposition rate *DECR* is a function of C:N ratio, C:P ratio, temperature, and water content in soil

$$DECR = 0.05 \cdot \min(CNRF, CPRF) \cdot \sqrt{TFM_2 \cdot WFM} \tag{137}$$

where *CNRF* and *CPRF* are the C:N and C:P ratio factors of mineralisation, respectively, and TFM_2 and *WFM* are the temperature and soil water factors of mineralisation, respectively. The values of CNRF and CPRF are calculated with the equations

$$CNRF = \exp\left[-\frac{0.693 \cdot (CNR - 25)}{25}\right] \tag{138}$$

$$CPRF = \exp\left[-\frac{0.693 \cdot (CPR - 200)}{200}\right] \tag{139}$$

where *CNR* is the C:N ratio and *CPR* is the C:P ratio.
The CNR and CPR are calculated with the equations

$$CNR = \frac{0.58 \cdot RSD}{FON + NMIN} \tag{140}$$

$$CPR = \frac{0.58 \cdot RSD}{FOP + PLAB} \tag{141}$$

where *FON* is the amount of fresh organic N in kg ha^{-1} , *FOP* is the amount of fresh organic P in kg ha^{-1}, *NMIN* is the amount of mineral nitrogen (or nitrate nitrogen plus ammonium nitrogen) in kg ha^{-1}, and *PLAB* is the amount of labile P in kg ha^{-1}.

The temperature factor in 137 is expressed by the equation (see also **Fig. 2.19**)

$$TFM_2 = \frac{TSO(2,t)}{TSO(2,t) + \exp[6.82 - 0.232 \cdot TSO(2,t)]} \tag{142}$$

where *TSO(2,t)* is soil temperature in the second soil layer in °C (the depth of first layer is 10 mm). The soil water factor considers the relation of total soil water to field capacity

$$WFM = \frac{SW}{FC} \tag{143}$$

The N mineralisation flow from residue, *FOMN*, calculated by equation 136 is distributed between mineral nitrogen and active organic nitrogen pools in the proportion 4:1.

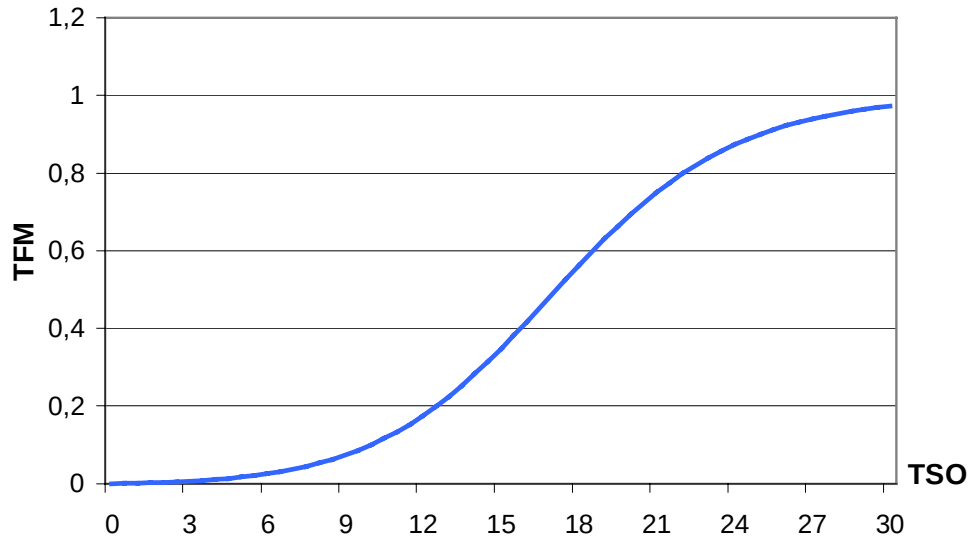

Fig. 2.19 Temperature factor of mineralisation, TFM (equation 142)

Step 3. The stable organic N pool is not subjected to mineralisation. Only the active pool of organic N in soil is exposed to mineralisation. The mineralisation from the active organic N is expressed by the equation

$$HUMN_i = COMN \cdot \sqrt{TFM_i \cdot WFM_i} \cdot ANOR_i \quad (144)$$

where $HUMN_i$ is the mineralisation rate in kg ha^{-1} d^{-1} for the active organic N pool in layer i, *COMN* is the humus rate constant for N (0.0003 d^{-1}), and TFM_i and WFM_i are the temperature and water factors of mineralisation for the layer i.

The temperature and water factors are calculated for any soil layer the same as for residue decomposition using equations 142 and 143. At the end of the day, the humus mineralisation is subtracted from the active organic N pool and added to the mineral N pool.

2.3.4 Phosphorus Mineralisation

The phosphorus mineralisation model is structurally similar to the nitrogen mineralisation model, with some differences as explained below.

Step 1. Fresh organic P pool *FOP* is associated with residue. It is recalculated daily as

$$FOP = FOP \cdot (1 - DECR) \quad (145)$$

Then the P mineralisation flow from fresh organic P in kg ha^{-1} d^{-1}, *FOMP*, is estimated as

$$FOMP = DECR \cdot FOP \quad (146)$$

where the rate DECR is calculated the same as for nitrogen using equation 137.

Step 2. Mineralisation of organic P associated with humus is estimated for each soil layer with the following equation

$$HUMP_i = COMP \cdot \sqrt{TFM_i \cdot WFM_i} \cdot POR_i \quad (147)$$

where $HUMP_i$ is the mineralisation rate in kg ha^{-1} d^{-1} i, *COMP* is the humus mineralisation rate constant for P, and POR is the P organic pool in soil layer i.

To maintain the P balance at the end of a day, the mineralized humus is subtracted from the organic P pool and added to the mineral P pool, and the mineralized residue is subtracted from the FOP pool. Then 1/5 of *FOMP* is added to the *POR* pool, and 4/5 of *FOMP* is added to labile P pool, *PLAB*.

2.3.5 Phosphorus Sorption / Adsorption

Mineral phosphorus is distributed between three pools: labile phosphorus, PLAB, active mineral phosphorus, PMA and stabile mineral phosphorus, PMS. Mineral P flow between the active and stable mineral pools is governed by the equilibrium equation

$$ASPFL = CASP \cdot \left(4 \cdot PMA - PMS\right) \tag{148}$$

where *ASPFL* is the flow in kg ha^{-1} d^{-1} between the active and stable mineral P pools, *CASP* is the rate constant (0.0006 d^{-1}). The daily flow *ASPFL* is added to the stable mineral pool and subtracted from the active mineral pool.

Mineral P flow between the active and labile mineral pools is governed by the equilibrium equation

$$ALPFL = PLAB - CALP \cdot PMA \tag{149}$$

where *ALPFL* is the flow in kg ha^{-1} d^{-1} between the active and labile mineral P pools, *CALP* is the equilibrium constant (default: 1.). The daily flow *ALPFL* is added to the active mineral pool and subtracted from the labile mineral pool.

2.3.6 Denitrification

Denitrification causes NO_3 to be volatilized from soil. The denitrification occurs only in the conditions of oxygen deficit, which usually is associated with high water content. Besides, as one of the microbial processes, denitrification is a function of temperature and carbon content. The equation used to estimate the denitrification rate is

$$\begin{aligned} DENIT_i &= WFD_i \cdot TCFD_i \cdot NIT_i, && SW_i / FC_i \geq 0.9 \\ DENIT &= 0. && SW_i / FC_i < 0.9 \end{aligned} \tag{150}$$

where *DENIT* is the denitrification flow in layer *i* in kg ha^{-1} d^{-1}, *WFD* is the soil water factor of denitrification, and *TCFD* is the combined temperature-carbon factor.

The soil water factor considers total soil water and is represented by the exponential equation (see **Fig. 2.20**)

$$WFD_i = 0.06 \cdot \exp\left(\frac{3 \cdot SW_i}{FC}\right) \tag{151}$$

where SW_i is the soil water content in layer i in mm and FC_i is the field capacity in mm mm^{-1}.

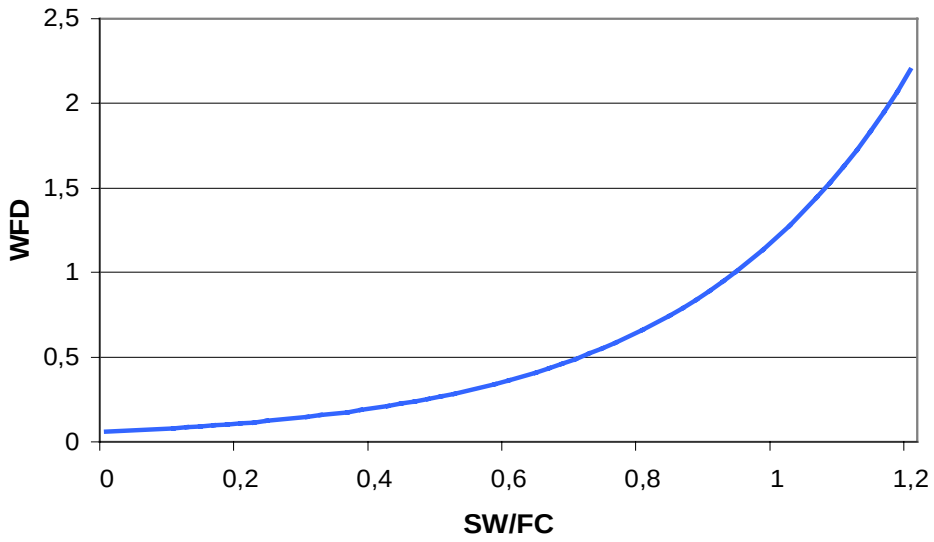

Fig. 2.20 Soil water factor of denitrification (equation 151)

The combined temperature and carbon factor is expressed by the equation

$$TCFD_i = 1 - \exp\left(CDN \cdot TFM_i \cdot CBN_i\right) \tag{152}$$

where *CDN* is a shape coefficient, TFM_i coincides with the temperature factor of mineralisation, and CBN_i is the carbon content, and subscript i refers to the layers.

2.3.7 Nutrient Uptake by Crops

Nitrogen uptake by crop is estimated using a supply and demand approach. The daily (day t) crop N demand can be computed using the equation

$$NDEM(t) = CNB(t) \cdot BT(t) - CNB(t-1) \cdot BT(t-1) \tag{153}$$

where *NDEM(t)* is the N demand of the crop in kg ha^{-1}, *CNB(t)* is the optimal N concentration in the crop biomass, and BT(t) is the accumulated biomass in kg ha^{-1}. Three parameters BN_1, BN_2, and BN_3 are specified for every crop in the crop database, which describe: BN_1 - normal fraction of nitrogen in plant biomass excluding seed at emergence, BN_2 – at 0.5 maturity, and BN_3 - at maturity.

Then the optimal crop N concentration is calculated as a function of growth stage using the equation (see also **Fig. 2.21**)

$$CNB = (BN_1 - BN_3) \cdot \left[1 - \frac{IHUN}{IHUN + \exp(SP_1 - SP_2 \cdot IHUN)} \right] + BN_3 \qquad (154)$$

where SP1 and SP2 are shape parameters assuring the definition above, and IHUN(t) is the heat unit index expressing the fraction of the growing season as calculated in equation 81. The crop is allowed to take nitrogen 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.

The same approach is used to estimate P uptake, differing only by the parameter values.

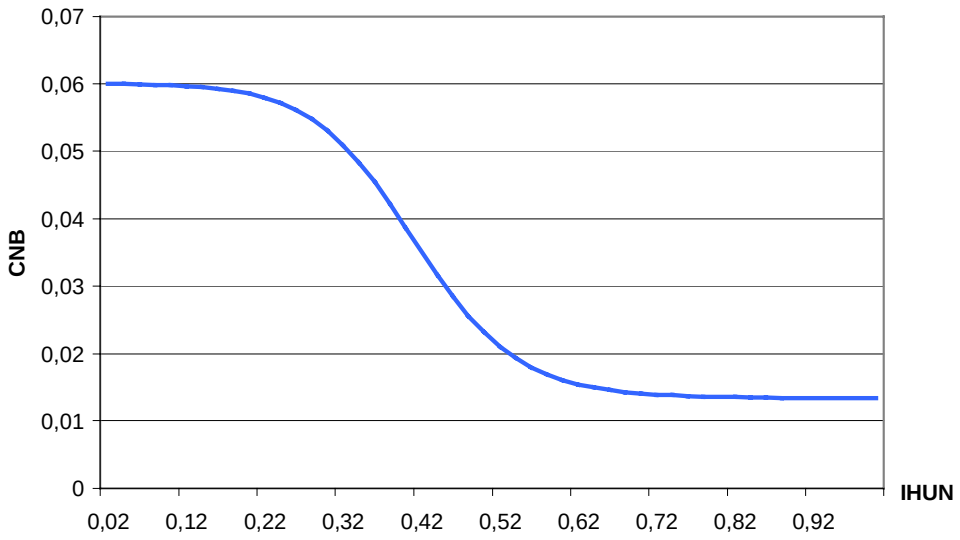

Fig. 2.21 The optimal crop N concentration, CNB, as a function of growth stage IHUN (equation 154) assuming BN1 = 0.06 g g^{-1}, BN2 = 0.0231 g g^{-1} and BN3 = 0.0134 g g^{-1}

2.3.8 Nitrate Loss in Surface Runoff and Leaching to Groundwater

The total amount of water lost from the soil layer i is the sum of surface runoff, lateral subsurface flow (or interflow), and percolation from this layer:

$$WTOT_i = Q_i + SSF_i + PERC_i \tag{155}$$

where *WTOT* is the total water lost from the soil layer in mm, Q is the surface runoff in mm, *SSF* is the lateral subsurface flow in mm, and *PERC* is the percolation in mm, and i is the layer.

The amount of nitrate nitrogen lost with $WTOT_i$ is the product of NO_3-N concentration and water loss as expressed by the equation

$$NFL_i = WTOT_i \cdot CON_i \tag{156}$$

where NFL_i is the amount NO_3-N lost from the layer *i* in kg ha^{-1} and CON_i is the concentration of NO_3-N in the layer *i* in kg ha^{-1}.

The amount of NO_3-N left in the layer is adjusted daily as

$$NMIN(t) = NMIN(t-1) - WTOT_i \cdot CON_i \tag{157}$$

where *NMIN(t-1)* and *NMIN(t)* are the amounts of NO_3-N contained in the layer at the beginning and end of the day (in kg ha^{-1}).

Then the NO_3-N concentration can be estimated by dividing the weight of NO_3-N by the water storage in the layer:

$$CON_i(t) = CON_i(t-1) - CON_i(t-1) \cdot \left(- \frac{WTOT_i}{PO_i - WP_i} \right) \tag{158}$$

where $CON_i(t)$ is the concentration of NO_3-N at the end of the day in kg ha^{-1}, *PO* is the soil porosity in mm mm^{-1}, and *WP* is the wilting point water content for soil layer in mm mm^{-1}.

Equation 158 is a finite different approximation of the exponential equation

$$CON_i(t) = CON_i(t-1) - \exp\left(- \frac{WTOT_i}{PO_i - WP_i} \right) \tag{159}$$

Then the integration of equation 159 allows to calculate *NFL* for any WTOT value

$$NFL_i = NMIN_i \cdot CW_i = NMIN_i \cdot \left(1 - \exp\left(-\frac{WTOT}{PO_i - WP_i}\right)\right) \tag{160}$$

The coefficient CW as the function of relative water content is depicted in **Fig. 2.22**. The average concentration for the day is

$$CON_i = \frac{NFL_i}{WTOT_i} \tag{161}$$

Amounts of NO_3-N contained in surface runoff, lateral subsurface flow, and percolation are estimated as the products of the volume of water and the concentration with equation 161.

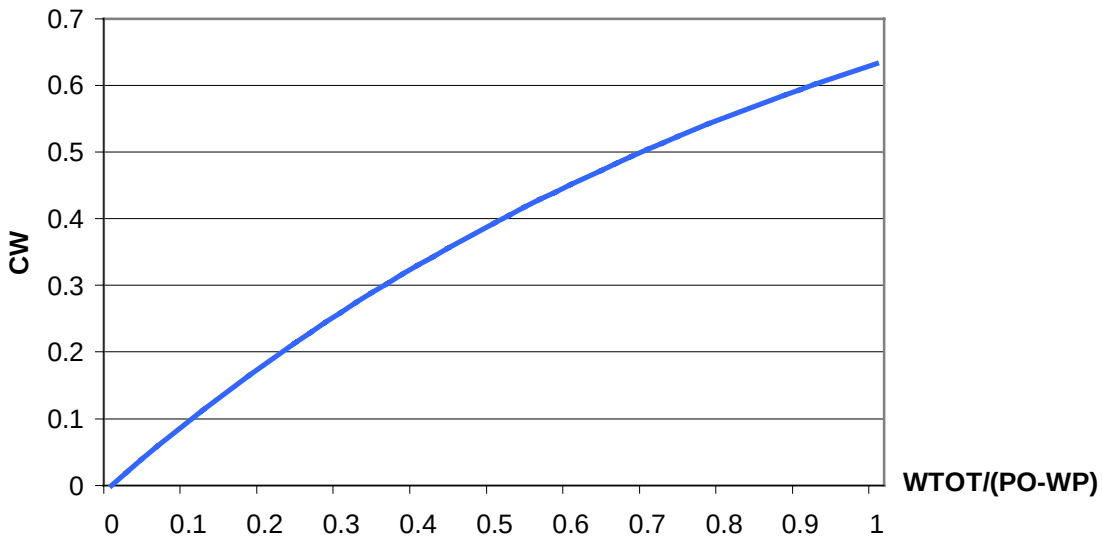

Fig. 2.22 Coefficient CW to calculate the amount NO_3-N lost from the layer as a function of water content (equation 160)

2.3.9 Soluble Phosphorus Loss in Surface Runoff

Phosphorus in soil is mostly associated with the sediment phase. Therefore the soluble P runoff equation can be expressed in the simple form

$$PFL = \frac{0.01 \cdot COP \cdot Q}{CSW} \tag{162}$$

where *PFL* is the soluble P in kg ha^{-1} d^{-1} lost with surface runoff, *Q* is the surface runoff in mm, *COP* is the concentration of labile phosphorus in soil layer in g t^{-1}, and *CSW* is the P concentration in the sediment divided by that of the water in m^3 t^{-1}. The value of COP is input to the model and remains constant. The default value of CSW used in the model is 175.

All processes described in Sections 2.3.1 – 2.3.9 are presented graphically in **Figs. 2.23** (for nitrogen cycle) and **2.24** (for phosphorus).

The nitrogen module operates with four main pools depicted by the blue rectangles in **Fig. 2.23**: nitrate, stable organic N, mineralisable organic N and fresh organic N (crop residue). The nitrate pool is influenced by the following flows (depicted as flags): N fertilizer application, N precipitation input, N leaching, potential N uptake by plants and denitrification. The latter one is subject to the impact of the following variables and parameters: soil water content, field capacity, shape coefficient, temperature factor of mineralisation and carbon content. The exchange between stable and mineralisable organic nitrogen pools, whose intensity depends on the size of these pools and the rate constant, is shown on the right-hand side. The mineralisation is a function of soil temperature, soil water content, field capacity and the humus rate constant.

The phosphorus module (**Fig. 2.24**) consists of five pools, namely fresh organic P (crop residue), organic P, labile P, active and stable mineral P. Labile P is influenced by the following five flows: decomposition, mineralisation, potential nutrient uptake, P loss by leaching and P exchange with the active mineral phosphorus pool. The size of the latter two flows is modulated by the amount of P in the concerned pools. The two-directional influence we meet in the case of the exchange flow between active and stable mineral P, and the mineralisation and decomposition flows (also pictured as flags). Mineralisation, decomposition, and soil erosion control the amount of organic P. The same as for the nitrogen cycle, mineralisation is influenced by soil temperature, soil water content, field capacity and the humus rate constant, whereas the decomposition rate essentially depends on the C-N-ratio, C-P-ratio and soil temperature.

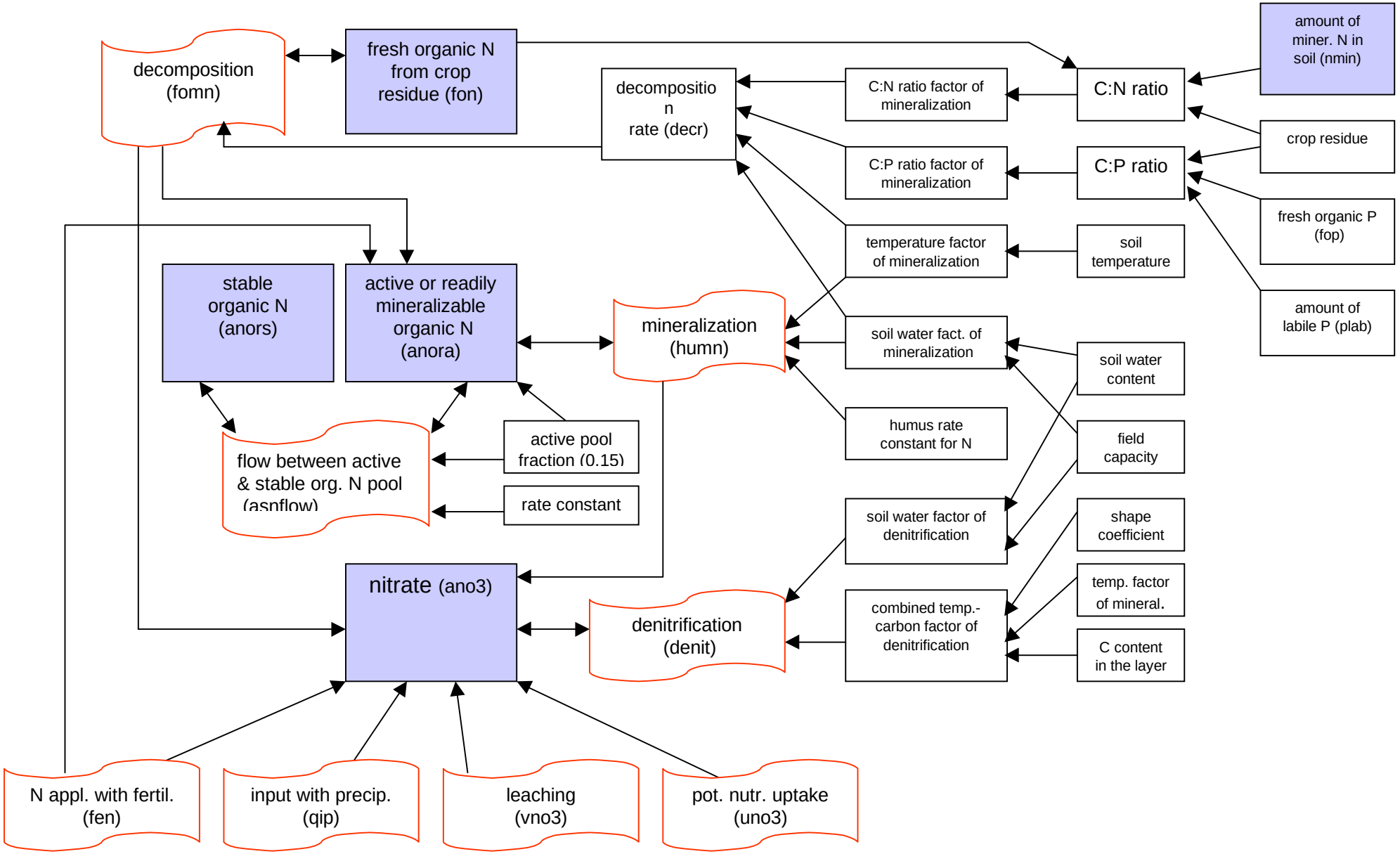

Fig. 2.23 Scheme of operations included in SWIM nitrogen module

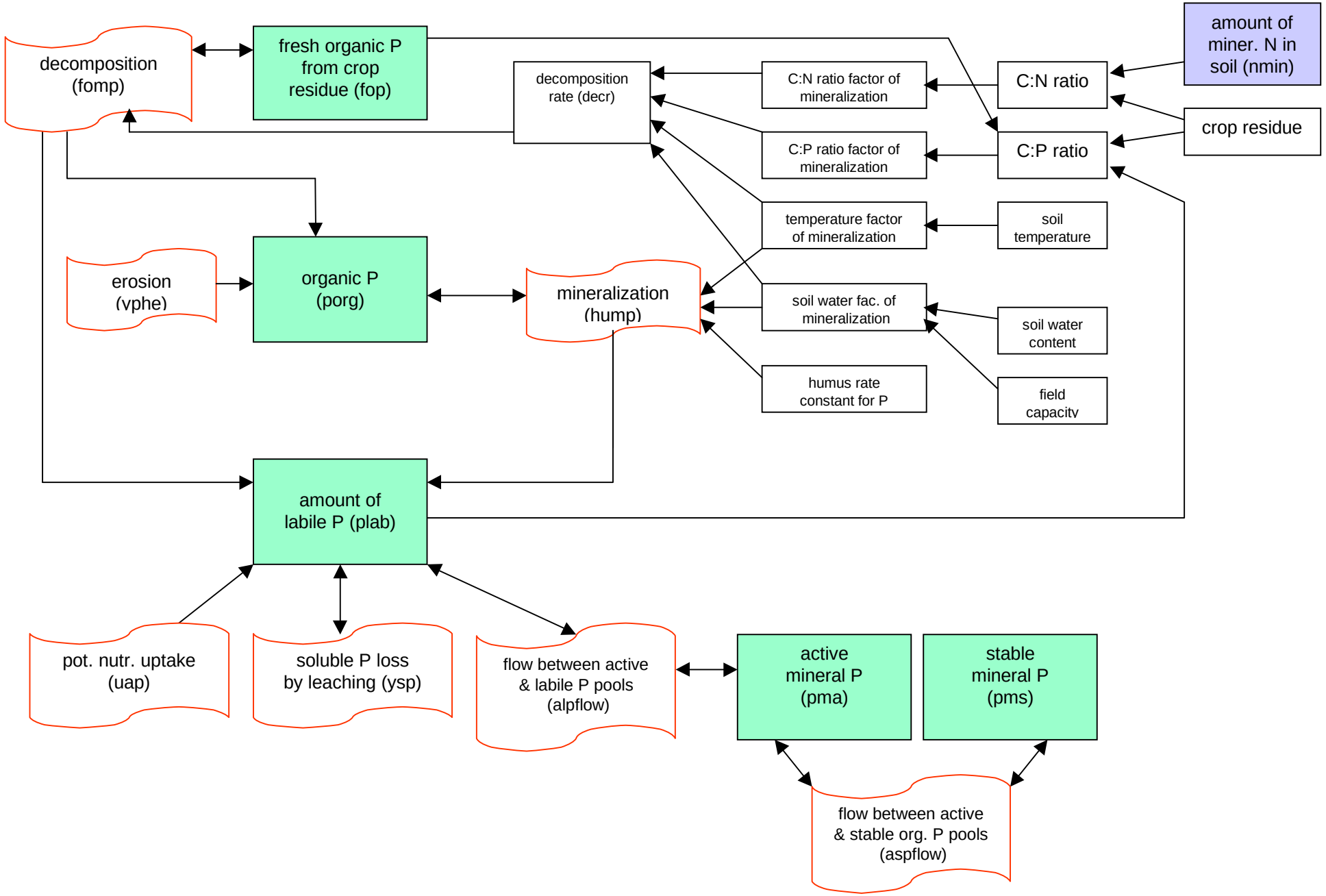

Fig. 2.24 Scheme of operations included in SWIM phosphorus module

2.4 Erosion

2.4.1 Sediment Yield

Sediment yield is calculated for each sub-basin with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977), practically the same as in SWAT:

$$YSED = 11.8 \cdot (VOLQ \cdot PEAKQ)^{0.56} \cdot K \cdot C \cdot ECP \cdot LS \quad (163)$$

where *YSED* is the sediment yield from the sub-basin in t, *VOLQ* is the surface runoff column for the sub-basin in m^3, *PEAKQ* is the peak flow rate for the sub-basin in $m^3 s^{-1}$, K is the soil erodibility factor, *C* is the crop management factor, *ECP* is the erosion control practice factor, and *LS* is the slope length and steepness factor.

The only difference between SWAT and SWIM in the erosion module is that the surface runoff, the soil erodibility factor K and the crop management factor C are estimated in SWIM for every hydrotope, and then averaged for the sub-basin (weighted areal average). In SWAT there are two options: option 1 based on two-level disaggregation "basin – sub-basins", when the above mentioned factors are first estimated for the sub-basins, and option 2 similar to that of SWIM, when the factors are estimated first for HRUs (Hydrologic Response Units).

The soil erodibility factor K is estimated from the texture of the upper soil layer or is taken from a database.

The crop management factor, C, is evaluated with the equation,

$$C = \exp[CMN + (-0.2231 - CMN) \cdot \exp(-0.00115 \cdot COV)] \quad (164)$$

where *COV* is the soil cover (above ground biomass + residue) in kg ha^{-1} and *CMN* is the minimum value of C.

The value of *CMN* is estimated from the average annual value of C factor, *CAV*, using the equation

$$CMN = 1.463 \cdot \ln(CAV) + 0.1034 \quad (165)$$

The value of *CAV* for each crop is determined from tables prepared by Wischmeier and Smith (1978).

The erosion control practice is estimated as default value of 0.5, if no other data are available (which is usually the case for mesoscale basins and regional case studies).

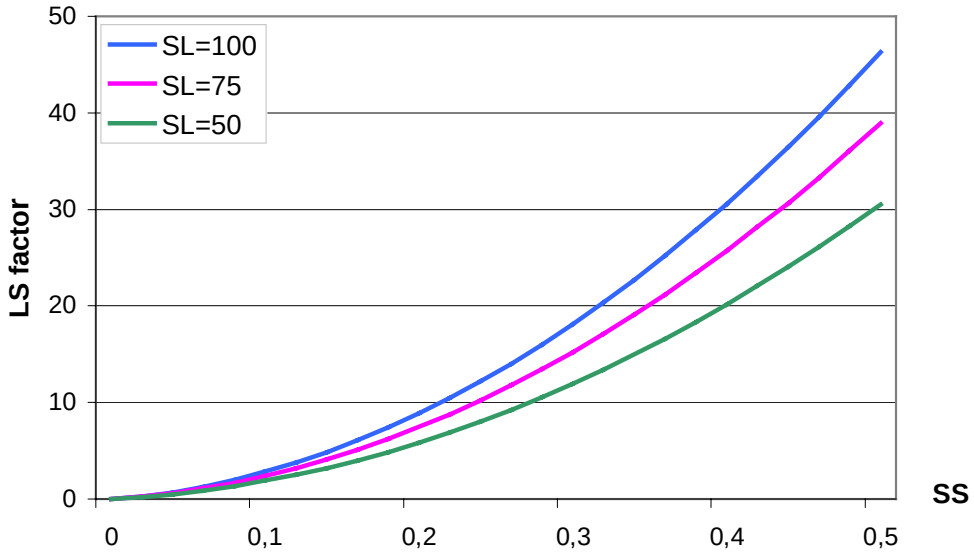

Fig. 2.25 The LS factor calculated as a function of slope steepness SS for different slope lengths SL (equations 166-167)

The LS factor is estimated with the equation (Wischmeier and Smith, 1978) (see **Fig. 2.25**)

$$LS = \left(\frac{SL}{22.1} \right)^{\xi} \cdot \left(65.41 \cdot SS^2 + 4.565 \cdot SS + 0.065 \right) \quad (166)$$

where *SL* is the slope length, *SS* is the slope steepness, and the exponent ξ varies with slope and is computed with the equation

$$\xi = 0.6 \cdot \left[1 - \exp\left(-35.835 \cdot SS \right) \right] \quad (167)$$

The slope length and slope steepness are calculated in SWIM/GRASS interface for every sub-basin.

2.4.2 Organic Nitrogen Transport by Sediment

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

$$YON = 0.001 \cdot YSED \cdot CNOR \cdot ER \tag{168}$$

where *YON* is the organic N runoff loss at the sub-basin outlet in kg ha^{-1}, *CNOR* is the concentration of organic N in the top soil layer in g t^{-1}, and *ER* is the enrichment ratio. The value of CNOR is input to the model and is constant throughout the simulation.

The enrichment ratio is the concentration of organic N in 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 considering upper and lower bounds. The upper bound of the enrichment ratio is the inverse of the sediment delivery ratio *DR* (sub-basin sediment yield divided by gross sheet erosion): *ER<1/DR*. 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

$$DR = \left(\frac{PEAKQ}{PRER} \right)^{0.56} \tag{169}$$

where *DR* is the sediment delivery ratio, *PEAKQ* is the peak runoff rate in mm h^{-1}, and *PRER* is the peak rainfall excess rate in mm h^{-1}.

Equation 169 is based on sediment yield estimated using MUSLE (Williams, 1975). The rainfall excess rate cannot be evaluated directly because the model uses only the total daily runoff volume, and not the event rainfall. An estimation of PRER can be obtained, however, using the equation

$$PRER = PRR - AIR \tag{170}$$

where *PRR* is the peak rainfall rate in mm h^{-1} and *AIR* is the average infiltration rate in mm h^{-1}.

The peak rainfall rate can be calculated with the equation

$$PRR = 2 \cdot PRECIP \cdot \log\left(\frac{1}{1 - \alpha_{0.5}} \right) \tag{171}$$

The average infiltration rate can be calculated with the equation

$$AIR = \frac{PRECIP - Q}{DUR} \tag{172}$$

where *DUR* is the rainfall duration in h, and *PRECIP* is rainfall in mm.

The rainfall duration is estimated the same as in equation 32 according to Williams et al. (1984).

$$DUR = \frac{4.605 \cdot PRECIP}{PRR} = -\frac{2.3025}{\log((1 - \alpha_{0.5})} \tag{173}$$

The enrichment ratio is estimated with the logarithmic equation

$$ER = PCON \cdot SEDC^{PEXP} \tag{174}$$

where *SEDC* is the sediment concentration in g m^{-3}, and *PCON* and *PEXP* are parameters set by the upper and lower limits.

To approach the lower limit for the enrichment ratio, 1.0, the sediment concentration should be extremely high. Conversely, a very low sediment concentration would cause the enrichment ratio to approach 1/DR. The simultaneous solution of equation 174 at the boundaries assuming that sediment concentrations range from 500 to 250000 g m^{-3} gives the following estimations for *PEXP* and *PCON*

$$PEXP = \frac{\log\left(\frac{1}{DR}\right)}{2.699} \tag{175}$$

$$PCON = \frac{1}{0.25^{PEXP}} \tag{176}$$

2.4.3 Phosphorus Transport by Sediment

Phosphorus transport with sediments is simulated with a loading function similar to that described in 2.4.2 for the organic N transport. The loading function for phosphorus is

$$YP = 0.01 \cdot YSED \cdot POR_1 \cdot ER \tag{177}$$

where *YP* is the sediment phase of P loss in runoff in kg ha^{-1}, and POR_1 is the concentration of organic P in the top soil layer in g t^{-1}.

2.5 River Routing

2.5.1 Flow Routing

The model uses the Muskingum flow routing method (see Maidment, 1993 and Schulze, 1995). For a given reach, the continuity equation may be expressed as:

$$\frac{d(STOR)}{dt} = QIN(t) - QOUT(t) \tag{178}$$

where *d(STOR)/dt* is the rate of change of storage within the reach (m^3 s^{-1}), *QIN(t)* is the inflow rate (m^3 s^{-1}) at time t, and *QOUT(t)* is the outflow rate (m^3 s^{-1}) at time t.

The Muskingum method assumes a variable discharge storage equation:

$$STOR(t) = KST \cdot [X \cdot QIN(t) + (1 - X) \cdot QOUT(t)] \tag{179}$$

where *STOR(t)* is the storage (m^3) in river reach at time t, *KST* is the storage time constant for the reach (s), and X is the dimentionless weighting factor in river reach routing.

Here *KST* is the ratio of storage to discharge and has the dimention of time. In physical terms, *KST* is considered to be an average reach travel time for a flood wave, and X indicates the relative importance of the input *QIN* and outflow *QOUT* in determining the storage in a reach. The lower and upper limits for *X* are 0 and 0.5, respectively. Typical values of *X* for a river reach range between 0.0 and 0.3, with a mean value near 0.2.

Thus, from 179 the change in storage over time Δt is given as

$$\begin{aligned} &STOR(t+1) - STOR(t) = \\ &= KST \cdot [X \cdot QIN(t+1) + (1 - X) \cdot QOUT(t+1)] - \\ &- KST \cdot [X \cdot QIN(t) + (1 - X) \cdot QOUT(t)] \end{aligned} \tag{180}$$

The Muskingum equation is derived from the finite difference form of the continuity equation 178 and equation 180 as the following:

$$QOUT(t+1) = C_1 \cdot QIN(t+1) + C_2 \cdot QIN(t) + C_3 \cdot QOUT(t) \tag{181}$$

where the parameters C1, C2 and C3 are determined as (see also **Fig. 2.26**)

$$C_1 = \frac{-KST \cdot X + 0.5 \cdot \Delta t}{KST - KST \cdot X + 0.5 \cdot \Delta t} \tag{182}$$

$$C_2 = \frac{KST \cdot X + 0.5 \cdot \Delta t}{KST - KST \cdot X + 0.5 \cdot \Delta t} \tag{183}$$

$$C_3 = \frac{KST - KST \cdot X - 0.5 \cdot \Delta t}{KST - KST \cdot X + 0.5 \cdot \Delta t} \tag{184}$$

Here *KST* and Δt must have the same time units and the three coefficients C_1, C_2 and C_3 sum to 1.0. Numerical stability is attained and the computation of negative outflows is avoided if the following condition is fulfilled

$$2 \cdot KST \cdot X < \Delta t < 2 \cdot KST \cdot (1 - X) \tag{185}$$

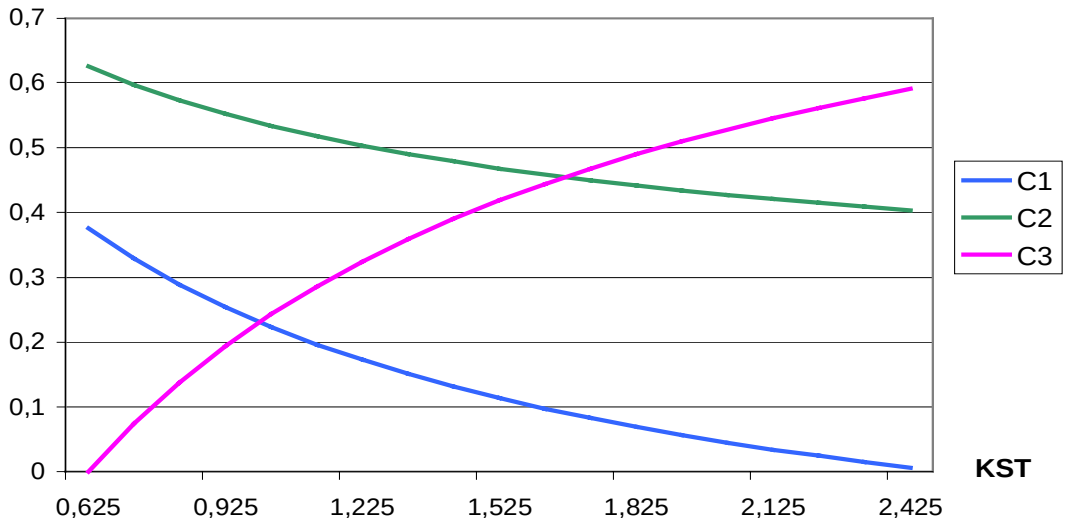

Fig. 2.26 Coefficients C_1, C_2 and C_3 as functions of parameter KST as used to calculate flow routing with the Muskingum equations 182-184 assuming that X = 0.2 and $\Delta t = 1$

Estimation of *KST* is based on the reach geometry

$$KST = \frac{CHL}{CLR} \tag{186}$$

where *CHL* is the reach length, and *CLR* is the wave celerity.

The celerity may be estimated by using the Manning formula with an adjusting coefficient for a certain reach shape. For the wide rectangular reach the celerity may be estimated (Schulze, p. AT13-9) as

$$CLR = \frac{5 \cdot CHV}{3} \tag{187}$$

where *CHV* is the average stream velocity in m s^{-1}. The average velocity is estimated from the Manning formula as

$$CHV = \frac{HR^{2/3} \cdot \sqrt{CHS}}{CHN} \tag{188}$$

where *HR* is hydraulic radius, *CHS* is channel bottom slope, *CHN* is the Manning's roughness N. The value of X is set in the model to 0.2.

2.5.2 Sediment Routing

The sediment routing model consists of two components operating simultaneously – deposition and degradation in the streams. Deposition in the stream channel is based on the stream velocity in the channel, which is estimated as a function of the peak flow rate, the flow depth, and the average channel width with the equation

$$CHV = \frac{PEAKQ}{FD \cdot CHW} \tag{189}$$

where *CHV* is the stream velocity in the channel in m s^{-1}, *PEAKQ* is the peak flow rate in m^3 s^{-1}, *FD* is the flow depth in m, and *CHW* is the average channel width in m.

The flow depth is calculated using the Manning's formula as

$$FD = \left(\frac{PEAKQ \cdot CHN}{CHW \cdot \sqrt{CHS}} \right)^{0.6} \tag{190}$$

where *CHN* is the channel roughness, N, and *CHS* is the channel slope in m m^{-1}.

The sediment delivery ratio *DELR* through the reach is described by the logarithmic equation suggested by J. Williams (similar to equation 174)

$$DELR = \frac{Q}{YSED_{in}} \cdot SPCON \cdot CHV^{\,sp\exp} \tag{191}$$

where $YSED_{in}$ is the sediment amount entering the reach, and the parameters SPCON (between 0.0001 and 0.01) and SPEXP (between 1.0 and 1.5) can be used for calibration. The power function in 191 is shown in **Fig. 2.27** for different combinations of SPCON and CHV.

If *DELR < 1.0*, the degradation is zero, and deposition is estimated from the sediment input as

$$\begin{aligned} DEP &= YSED_{in} \cdot (1 - DELR), \\ DEGR &= 0. \end{aligned} \tag{192}$$

Otherwise, if *DELR≥1*. the deposition is zero, and the degradation is calculated from the sediment input as

$$\begin{aligned} DEP &= 0. \\ DEGR &= YSED_{in} \cdot (DELR - 1) \cdot CHK \cdot CHC \end{aligned} \tag{193}$$

where *CHK* is the channel K factor or the effective hydraulic conductivity of the channel alluvium (see also equation 71), and *CHC* is the channel C factor.

Finally, the amount of sediment reaching the sub-basin outlet, $YSED_{out}$, is

$$YSED_{out} = YSED_{in} - DEP + DEGR \tag{194}$$

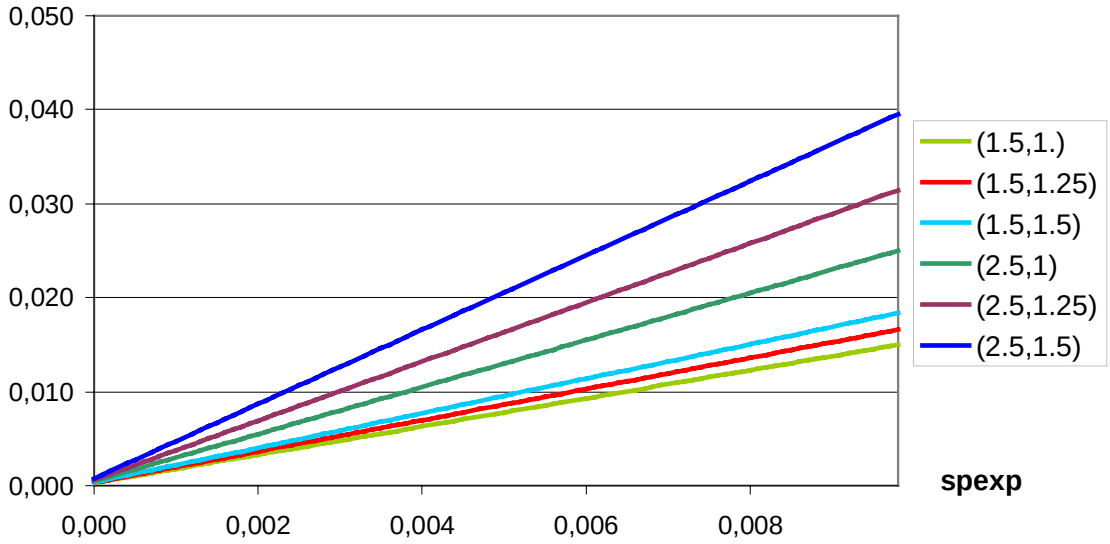

Fig. 2.27 Function SPCON·CHV^{spexp} to estimate the sediment delivery ratio DELR (equation 191) for different combinations of (CHV, SPCON)

2.5.3 Nutrient Routing

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.

Table 2.1 Abbreviations to Equations 1 – 194

α	the dimensionless parameter that expresses the proportion of total rainfall that occurs during time of concentration	-	19, 20, 32, 33, 34
$\alpha_{0.5}$	the fraction of rainfall that occurs during 0.5 h	-	32
α_{min}	minimum value of $\alpha_{.0.5}$, the fraction of rainfall that occurs during 0.5 h	-	33
β_i	a shape parameter to estimate the hydraulic conductivity for the layer i	-	38, 39
ν	the hillslope steepness	radian, or m m^{-1}	44, 45
δ	the slope of the saturation vapor pressure curve	kPa C^{-1}	47, 50
γ	a psychrometer constant	kPa C^{-1}	47
ϕ	the sun's half day length	radians	53
θ	the sun's declination angle	radians	53
ξ	the exponent to calculate the slope length and steepness factor of erosion, LS	-	166
ΔB	the daily increase in biomass	kg ha^{-1}	85
ΔBP	the daily potential increase in total biomass	kg ha^{-1} d^{-1}	84
Δt	the time interval (24 h)	h	35
A	the drainage area	ha	16, 20, 24, 25, 26
AIR	the average infiltration rate	mm h^{-1}	170
ALB	the albedo	-	57
ALB_{soil}	the bare soil albedo	-	58
ALFA	a factor to adjust net photosynthesis to altered CO2 concentration	-	107
$ALFA_{barley}$ $ALFA_{cot}$ $ALFA_{maize}$ $ALFA_{wheat}$	a factor to adjust net photosynthesis to altered CO_2 concentration for barley, cotton, maize and wheat (temperature dependent)	-	114
ALPFL	the flow from the active to the labile mineral P pool	kg ha^{-1} d^{-1}	149
AMP	the annual amplitude in daily average temperature	°C	122
ANFR	the active pool fraction (default: set to 0.15)	-	132
ANOR	active or readily mineralisable organic nitrogen	kg ha^{-1}	132
AR	the unit channel intercept	m^3	72
AS	the net leaf assimilation rate	μmol m^{-2} s^{-1}	107

ASNFL	the flow from the active to the stable organic N pool	kg ha^{-1} d^{-1}	133
ASPFL	the flow from the active to the stable mineral P pool	kg ha^{-1} d^{-1}	148
AX	the regression intercept to estimate the threshold volume for a unit channel	m km^{-1}	76
BAG	the aboveground biomass	kg ha^{-1}	87
BCV	a lagging factor for simulating residue and snow cover effects on surface temperature	-	129
BD	the soil bulk density	t m^{-3}	124
BE	the crop-specific parameter for converting energy to biomass	kg m^2 MJ^{-1} ha^{-1} d^{-1}	84
BETA	a factor to adjust potential leaf transpiration to CO_2 concentration		116
BMR	the sum of the above ground biomass and crop residue	t ha^{-1}	59
BN_1	the normal fraction of nitrogen in plant biomass at emergence (excluding seeds)	g g^{-1}	154
BN_2	the normal fraction of nitrogen in plant biomass at 0.5 maturity.	g g^{-1}	154
BN_3	the normal fraction of nitrogen in plant biomass at maturity	g g^{-1}	154
BP	the barometric pressure	kPa	51, 52
BR	the unit channel regression slope	-	74
BT	the accumulated total biomass	kg ha^{-1}	88
BX	the regression slope	-	77
C	the crop management factor,	-	163
C_1	a parameter to calculate river routing	-	181
C_2	a parameter to calculate river routing	-	181
C_3	a parameter to calculate river routing	-	181
CA	the current atmospheric CO_2 concentration	µmol mol^{-1}	108
CALP	the equilibrium constant between the active and labile mineral P pools (default: 1.)	-	149
CASN	the rate constant for the flow from the active to stable organic N pool	d^{-1}	133
CASP	the rate constant for the flow between the stable and active mineral P pools (default: 0.006)	d^{-1}	148
CAV	the average annual value of C factor	-	165
CBN_i	the carbon content in the layer i	kg ha^{-1}	152
CDN	a shape coefficient to estimate the combined temperature-carbon factor of denitrification, TCFD	-	152

CHC	the channel C factor	-	193
CHFL	the average channel flow length for the basin	km	22, 23
CHK	the effective hydraulic conductivity of the channel alluvium in	mm h^{-1}	72
CHL	the channel length from the most distant point to the watershed outlet	km	23, 24, 26
CHL_{cen}	the distance from the outlet along the channel to the watershed centroid	km	23
CHN	Manning's roughness coefficient n for the channel	-	24, 26
CHS	the average channel slope	m m^{-1}	24, 26
CHV	the average stream velocity in the channel	m s^{-1}	22
CHW	the average channel width	m	77
CL_1	the current CO_2 concentration inside leaves	µmol mol^{-1}	111
CL_2	the future CO_2 concentration inside leaves	µmol mol^{-1}	111
CLR	the stream wave celerity	m s^{-1}	186
CMN	the minimum value of C	-	164
CN	the curve number	-	4
CN_1	the curve number for soil moisture condition 1 (dry)	-	5, 6
CN_2	the curve number for soil moisture condition 2 (average)	-	5, 7, 8
CN_{2s}	the curve number for soil moisture condition 2 adjusted for slope	-	8
CN_3	the curve number for soil moisture condition 3 (wet)	-	7, 8
CNB	the optimal N concentration for the crop	g g^{-1}	100
CNOR	the concentration of organic N in the top soil layer	g t^{-1}	168
CNR	the C:N ratio	-	138, 140
CNRF	the C:N ratio factor of mineralisation	-	137
COMN	the humus rate constant for N (default: 0.0003)	d^{-1}	144
COMP	the humus mineralisation rate constant for P	kg ha^{-1} d^{-1}	147
$CON_i(t)$	the concentration of NO_3-N in the layer i on the day t	kg ha^{-1} mm^{-1}	156
COP	the concentration of labile phosphorus in soil layer	g t^{-1}	162
COV	the land cover, or the sum of above ground biomass and crop residue	kg ha^{-1}	130
CPR	the C:P ratio	-	139, 141
CPRF	the C:P ratio factor of mineralisation	-	137
CR	the revap coefficient	-	70
CS	the seepage coefficient	-	71

CSW	the P concentration in the sediment divided by that of the water	$m^3\ t^{-1}$	162
CTSH	the temperature stress parameter for the crop for temperatures above TO	-	98, 99
CTSL	the temperature stress parameter for the crop for temperatures below TO	-	96, 97
D	the earth's radius vector	km	53
DD	the damping depth for the soil	mm	122
DEC	the decay factor	$m\ km^{-1}$	73
DECR	the residue decomposition rate	-	134
DEGR	the degradation in stream	t	192, 193
DEL	the delay time or drainage time of the aquifer	day	69
DELR	the sediment delivery ratio through the reach	-	191
DENIT	the denitrification flow in layer i	$kg\ ha^{-1}\ d^{-1}$	150
DEP	the deposition in stream	t	192, 193
DLAI	the fraction of the growing season before LAI starts declining	-	87
DP	the maximum damping depth for the soil	mm	123
DR	the sediment delivery ratio	-	169
DS	the drain spacing	m	64
DU	the duration of streamflow	h	72
DUR	the rainfall duration	h	31, 32
ECP	the erosion control practice factor,	-	163
ELEV	the elevation of the site	m	52
EO	the potential evaporation	mm	47
EP	the plant water transpiration rate	$mm\ d^{-1}$	60
EPO	the potential plant transpiration rates	$mol\ m^{-2}\ s^{-1}$	116
ER	the enrichment ratio	-	168
ES	the soil evaporation for day t	$mm\ d^{-1}$	62
ESO	the potential soil evaporation	$mm\ d^{-1}$	61
ET	the evapotranspiration	$mm\ d^{-1}$	1
FC	the field capacity water content	vol % or $mm\ mm^{-1}$	10, 11, 12, 13, 37, 39
FD	the flow depth	m	28, 29
FFC	the fraction of field capacity	-	10, 11, 14
FFC*	the depth-weighted FFC value	-	14
FOMN	N mineralisation flow from fresh organic N	$kg\ ha^{-1}\ d^{-1}$	136

FOMP	P mineralisation flow from fresh organic P	kg ha^{-1} d^{-1}	146
FON	the fresh organic N pool	kg ha^{-1}	135
FOP	the amount of fresh organic P	kg ha^{-1}	141
GWH	the water table height	m	64
GWQ	the return flow	mm d^{-1}	63
HC_i	the hydraulic conductivity	mm h^{-1}	37, 38, 40
HI	the harvest index at harvest	-	102
HIAD	the adjusted harvest index	-	104
HIC_1	the factor to estimate harvest index as depending on IHUN		103
HIC_2	the factor to estimate harvest index as depending on WSF		104
HR	the hydraulic radius	m	188
$HUMN_i$	the mineralisation rate for the active organic N pool in layer i,	kg ha^{-1} d^{-1}	144
$HUMP_i$	the mineralisation rate in the layer i	kg ha^{-1} d^{-1}	147
HUNA	the value of heat units accumulated in the day t	°C	81
HV	the latent heat of vaporization	MJ kg^{-1}	47, 48
HVSTI	the crop-specific harvest index	-	103
i	the soil layer	-	14
IHUN	the heat unit index	-	82
K	the soil erodibility factor	-	163
KD	the hydraulic conductivity in shallow aquifer	mm d^{-1}	64
KST	the storage time constant for the reach	s	179
LAI	the leaf area index	-	60
LAIMX	the maximum potential LAI for the specific crop	-	87
LAT	the latitude of the site	degrees	53
LS	the slope length and steepness factor	-	163
M	the number of soil layers	-	14
NDD	the number of days in a month	d	128
NDEM(t)	the N demand of the crop	kg ha^{-1}	153
NFL_i	the amount NO_3-N lost from the layer i	kg ha^{-1}	156
NMIN	the amount of mineral nitrogen (or nitrate nitrogen plus ammonium nitrogen) in soil	kg ha^{-1}	140
NOR	the total organic N pool	kg ha^{-1}	132
NRD	the number of rainy days in a month	d	128

NS	the stress factors caused by nitrogen	-	86
PAR	photosynthetic active radiation	MJ m^{-2}	83
PCON	a shape parameter to calculate the enrichment ratio ER	-	174
PEAKQ	the peak runoff rate	m^3 s^{-1}	16, 20
$PEAKQ_{in}$	the initial peak discharge rate	m^3 s^{-1}	80
$PEAKQ_{tr}$	the peak discharge rate after losses	m^3 s^{-1}	80
PERC	the percolation, the percolation in layer i	mm d^{-1}	1
$PERC_{ic}$	the percolation rate for layer i corrected for layer i+l water content	mm d^{-1}	41
PEXP	a shape parameter to calculate the enrichment ratio ER	-	174
PFL	the soluble P lost with surface runoff	kg ha^{-1}	162
PHUN	the value of potential heat units required for the maturity of crop	°C	82
PLAB	the amount of labile P	kg ha^{-1}	141
PMA	the active mineral P pool	kg ha^{-1}	148
PMS	the stabile mineral P pool	kg ha^{-1}	148
PO	the soil porosity, the soil porosity for the layer i	vol % or mm mm^{-1}	10, 13
POR	the P organic pool in soil layer i	kg ha^{-1} or g t^{-1}	147
PORD	the drainable porosity of the soil	m m^{-1}	43, 45
PRECIP	the precipitation	mm d^{-1}	1, 3, 17
$PRECIP_{24}$	the amount of rainfall during 24 hours	mm	19
$PRECIP_{tc}$	the amount of rainfall during the watershed's time of concentration	mm	18, 19
PRER	the peak rainfall excess rate	mm h^{-1}	169
PRR	the peak rainfall rate	mm h^{-1}	170
PS	the stress factors caused phosphorus	-	86
Q	the surface runoff	mm d^{-1}	1, 3, 17, 20, 31
QAV	the average flow rate	mm h^{-1}	24, 25
QAV_0	the average flow rate from a 1 ha area	mm h^{-1}	25, 26, 29, 30, 31
QIN(t)	the inflow rate at time t,	m^3 s^{-1}	178
QOUT(t)	the outflow rate at time t	m^3 s^{-1}	178
QUP	the upward flow	mm d^{-1}	46
RAD	the net solar radiation	MJ m^{-2}, or Ly	47
RAM	the maximum possible solar radiation	MJ m^{-2}, or Ly	53

RCH	the recharge	mm d^{-1}	63
RD	the fraction of the root zone that contains roots	-	91
RDMX	the maximum root depth (crop-specific parameter)	m	91
RDP	the rate-depth parameter	mm	92
REGF	the crop growth regulating factor estimated as the minimum stress factor	-	85, 86
RESC	the total leaf resistance to CO_2 transfer	m^2 s mol^{-1}	117
RESW	is the total leaf resistance to water vapour transfer	m^2 s mol^{-1}	117
REVAP	the water flow from the shallow aquifer back to the soil profile	mm d^{-1}	63
RF	the constant of proportionality or the reaction factor for groundwater	-	67
RI	the rainfall intensity for the watershed's time of concentration	mm h^{-1}	16, 18
RSD	the crop residue	kg ha^{-1}	106
RST	the revap storage	mm	70
RUNC	a runoff coefficient expressing the watershed infiltration characteristics	-	16, 17
RWT	the fraction of total biomass partitioned to the root system	-	88
RZD_i	the root zone depth parameter for the layer i	mm	92, 93
SAW_t	the shallow aquifer storage	mm	63
SC	the saturated conductivity	mm h^{-1}	38, 40, 44, 45, 46
SCOV	the soil cover index	-	58
SEDC	the sediment concentration	g m^{-3}	174
SEEP	the percolation or seepage to the deep aquifer	mm d^{-1}	63
SFN	the scaling factor to estimate the N stress factor	-	100
SHP_1	the coefficient of the S-shape curve, describing the assumed change in BE for two different CO_2 concentrations	-	108
SHP_2	the coefficient of the S-shape curve, describing the assumed change in BE for two different CO_2 concentrations	-	108
SL	the surface slope length (or hillslope length)	m	27, 30, 42, 43, 45, 46
SL_{sat}	the saturated slope length	m	46
SLW	the hillslope width	m	43
SML	the snowmelt rate	mm d^{-1}	2

SMX	the retention parameter for estimation of daily runoff	-	3, 4, 9, 10, 15
SMX_1	the value of SMX associated with CN_1, corresponding to moisture conditions 1	-	9, 10, 12, 13
SMX_2	SMX = SMX_2 when FCC = 0.7	-	10
SMX_3	SMX = SMX_3, when SW = FC	-	10, 12, 13
SMX_{froz}	the retention parameter for frozen ground	-	15
SN	Manning's roughness coefficient for the surface	-	28, 29, 30
SNO	the water content of snow cover	mm	2
SP_1	a shape parameter to estimate the optimal N concentration in the crop biomass	-	154
SP_2	a shape parameter the optimal N concentration in the crop biomass	-	154
SPCON	a shape parameter to estimate the sediment delivery ratio through the reach, DELR (between 0.0001 and 0.01)	-	191
SPD	a scaling parameter to estimate damping depth	-	123
SPEXP	a shape parameter to estimate the sediment delivery ratio through the reach, DELR (between 1.0 and 1.5)	-	191
SS	the land surface slope	$m\ m^{-1}$	8, 28, 29, 30
SSF	the subsurface flow	$mm\ d^{-1}$	1, 43, 45
STOR	the storage within the reach	$m^3\ s^{-1}$	178
SUP	the drainable volume of water stored in the saturated zone (water above field capacity)	$m\ m^{-1}$	42, 43, 45
SV	the surface flow velocity	$m\ s^{-1}$ or $m^3\ s^{-1}$	27, 28
SW(t)	the soil water content in day t	mm	1, 9, 10, 11, 35, 37, 38, 41
SWP	the accumulated potential plant transpiration in the second half of the growing season	mm	105
SWU	the accumulated actual plant transpiration in the second half of the growing season (IHUN>0.5)	mm	105
SY	the specific yield	-	65
t	the time	day	1
T	the mean daily air temperature	°C	48, 49, 50
TAV	the average annual air temperature	°C	122
TB	the crop-specific base temperature	°C	81
TC	the time of concentration	h	18, 20, 21, 33, 34
TC_{ch}	the time of concentration for channel flow	h	21, 22, 24, 26

TCFD	the combined temperature-carbon factor of denitrification	-	150
TC_{ov}	the time of concentration for surface flow	h	21, 27, 30
TFM_i	the temperature factor of mineralisation for the layer i	-	137
TGB(t)	the bare soil surface temperature in the day t,	°C	126, 127
TH_o	the threshold volume for a unit channel	m^3	78
TL	the leaf temperature	°C	111
TMN	the minimum temperature	°C	81
TMX	the maximum daily air temperature	°C	2
TO	the optimal temperature for the crop	°C	96
TS	the stress factors caused by temperature	-	86
TSO(Z,t)	the soil temperature at the depth Z in the day t	°C	122
TST	the number of days since stage two evaporation began	day	62
TT_i	the travel time through layer i	h	35
UL_i	the soil water content at saturation	mm mm^{-1}	38, 39, 41
UN(t)	the crop N uptake on day t	kg ha^{-1}	100
VEL	the velocity of flow at the outlet	mm h^{-1}	43, 44
VOLQ	the surface runoff column for the sub-basin	m^3	163
$VOLQ_{in}$	inflow volume	m^3	73
$VOLQ_{tr}$	the runoff volume after losses	m^3	79
VP	the saturation vapor pressure	kPa	49, 50
VPD	the vapour pressure deficit	kPa	117
WF_1	the shape parameter for estimation of the retention parameter SMX	-	9, 12
WF_2	the shape parameter for estimation of the retention parameter SMX	-	9, 12, 13
WFD	the water factor of denitrification	-	150
WFM	the water factor of mineralisation	-	137
WFT	a proportion of rainy days in a month	-	126, 127
WIR	the rate of water input to the saturated zone	m^2 h^{-1}	42
WP	the wilting point water content	vol % or mm mm^{-1}	10, 11
WS	the stress factors caused by water	-	86
WSF	a parameter expressing water supply conditions for crop	-	104, 105
WTOT	the total water lost from the soil layer	mm	155
WU_i	the plant water use in layer	mm	90

WUP_i	the potential water use rate from layer i	mm d^{-1}	92
X	a dimentionless weighting factor in river reach routing	-	179
YLD	the crop yield removed from the field	kg ha^{-1}	102
YON	the organic N runoff loss at the sub-basin outlet	kg ha^{-1}	168
YP	the sediment phase of P loss in runoff	kg ha^{-1}	177
YSED	the sediment yield from the sub-basin	t	163
$YSED_{in}$	the sediment amount entering the reach	t	191
$YSED_{out}$	the amount of sediment reaching the sub-basin outlet	t	194
Z_i	the depth to the bottom of soil layer i	mm	14
ZM	the distance from the bottom of the lowest soil layer to the surface	mm	125

3. SWIM Code Structure and Input Parameters

In this chapter the code structure of the both parts of the modelling system:

- the SWIM/GRASS interface, and
- the simulation part of SWIM

are described. The SWIM/GRASS interface is applied to prepare necessary (but not all) input files to run the simulation part of SWIM. The simulation part of SWIM performs simulation of ecohydrological processes in river basins or regions.

In section 3.1 the code structure of the SWIM/GRASS interface is given, and in section 3.2 the code of the SWIM simulation part is described. The latter is described in more detail. The code development is continuing, and it is assumed that SWIM users should be able to understand and, if necessary, to modify some modules/subroutines of the simulation part or add new modules. Therefore the latter is described in more detail.

In Section 3.3 input and output files are described, and in Section 3.4 all input parameters are listed and defined.

3.1 Structure of the SWIM/GRASS Interface

It is recommended to read the overview of SWIM/GRASS interface (Section 1.3) before reading this section.

The code includes menus and all menu-driven operations as described in Section 1.3. The subroutine *main* displays the first menu, which allows either to create a new project, or to copy, remove, or work on an existing project. The subroutine *main_menu()* provides the main menu, which lists steps to be completed by the interface.

When the step is chosen, the *sub_menu()* switches between the following important subroutines (see **Fig. 3.1**):

- *get_basin_info* - to request and extract a basin information from the user supplied map layer,
- *hydro_struct_swim* – to create structure file for a basin based on basin map, land use map and soil map,
- *get_topo_info* – to request an elevation map and extract the topographic properties using programs *ram.sub-basin* and *compute_slp_len*,
- *rw_gw_swim* – to read the extracted groundwater properties and write them in SWIM format,
- *com_rout_info_swim* – to compute routing structure, including basin number, starting elevation, ending elevation, starting and ending accumulation cells, stream length and the next draining sub-basin number
- *get_climate_station_s* – to extract the numbers of nearest 3 climate stations for a basin or each sub-basin,
- *get_precipit_station_s* – to extract the number of nearest 3 precipitation stations for a basin or each sub-basin,
- *write_cio_1* - to write the extracted control properties in SWIM format,
- *save_swim_project* – to save the project status information in proj_file which is the project_name with .proj extension. This program will be used at the end of each project, in order to keep track of the project status.

All files included in SWIM/GRASS interface are listed and described in **Tab. 3.1.** One file contains one subroutine with a similar or the same name. **Tab. 3.2** presents the file *swimmake,* which is used to compile SWIM/GRASS interface.

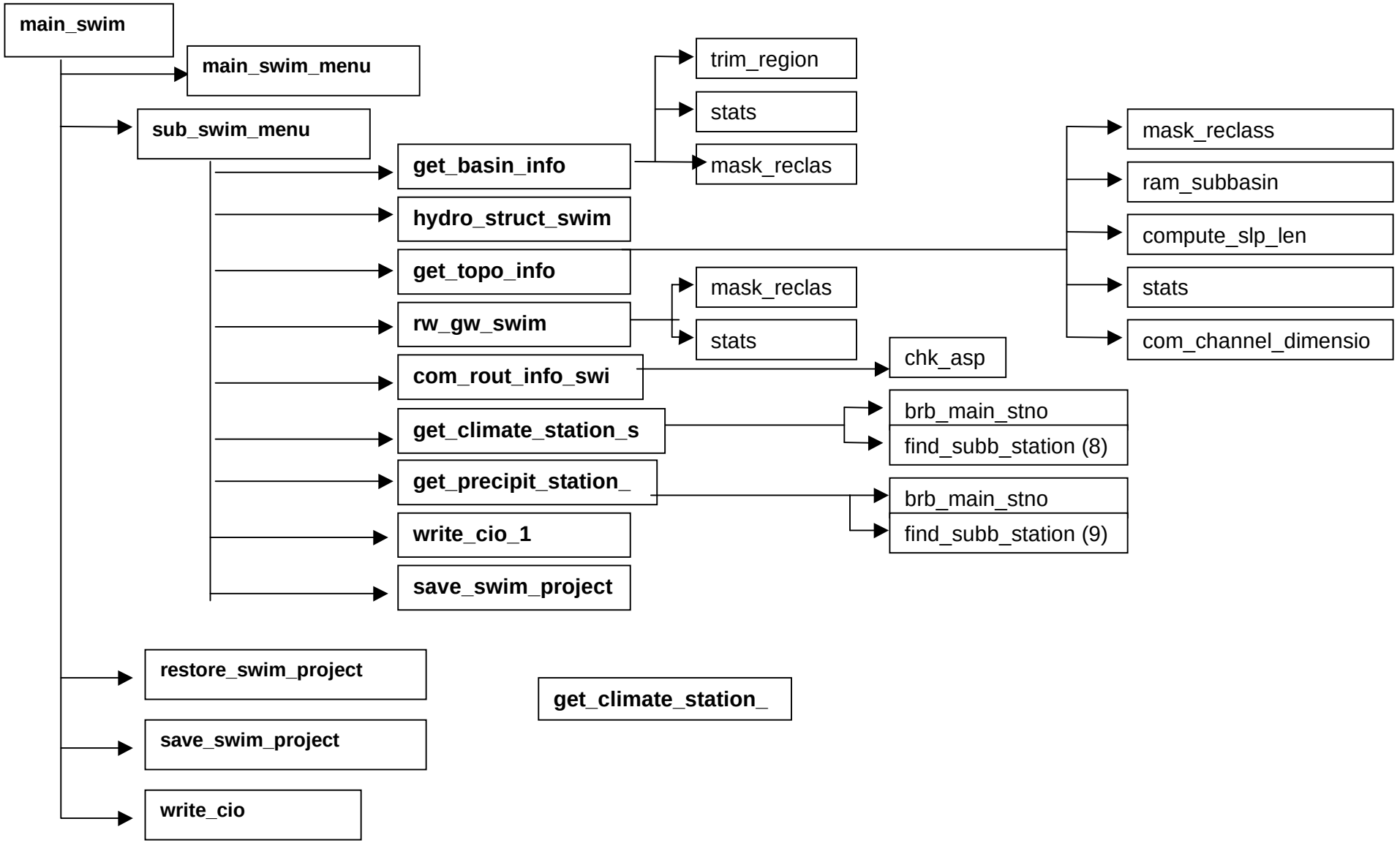

Fig. 3.1 Function tree of SWIM/GRASS interface

Table 3.1 Description of files included in SWIM/GRASS interface

No	*I line: file name* *II line: subroutine name*	*file/subroutine function*
1	cell_open.c int cell_open(name,mapset)	To open an old map with *name* in the *mapset* and return the file id.
2	cell_open_new.c int cell_open_new(name)	To open a new map with *name* in the current mapset and return the file id.
3	check_name.c int check_name(name,array,n)	To check if *name* corresponds to *array*.
4	chk_asp.c chk_asp()	To check the routing (aspect) data that was created in *com_rout_info().* This will interactively allow the user to change the aspect of the basins and to store that information in *proj_name.asp* file under *proj_name* directory. It will be read by restore_project while starting the project if the status [8] is done.
5	com_rout_info_swim.c com_rout_info()	To extract routing info from *basin->p*, *t.aspect*, and *temp_basin_acc* maps; The information gathered will be stored in a structure which will have basin number, starting elevation, ending elevation, starting and ending accumulation cells, stream length and the next draining sub-basin number.
6	compute_slp_len.c compute_slp_len(elev_map)	To generate a slope and aspect maps from the given elevation map using the neighbourhood technique for slope prediction. It creates a new temporary map called *temp_slope* which has the values of slope in tenths of percent and also creates a slope length map according to the unit stream power theory.
7	display_info.c display_info()	An option to display a raster map, a site map, a vector map, to display basin number, and to restore the screen
8	dummy_lcra.c dummy_data()	dummy data for .cod file (not used in SWIM)
9	find_subb_stations.c find_subb_stations()	This subroutine establishes correspondence between sub-basins and climate/precipitation stations
10	forms.c form1()	Forms to fill in (variant SWRRB, not used in SWIM)
11	get_basin_info.c get_basin_info()	This subroutine requests/extracts a basin information from user or from user supplied layer
12	get_climate_station_s.c get_climate_station()	This subroutine extracts the numbers of nearest 3 climate stations for a basin or each sub-basin using program brb_main_stationno.c. The climate station number list has to be stored in a file under the active directory. The station number(s) is (are) stored in climstat_3.dat under full_path. A label file called proj_name.climstat_3 is defined which can be used to mark the stations in a map.
13	get_crop_info.c get_crop_info()	This subroutine requests/extracts the crop properties from user supplied land use map. Each sub-basin is masked and the dominant land use name is selected then the *findcrop* routine is called to write out the land use properties in the needed format (SWAT version, not used in SWIM).
14	get_irr_nutrient_info.c get_irr_nutrient_info()	This automatically creates .mco file for each sub-basin depending on the user's choice for auto fertilizer and auto irrigation (SWAT variant, not used in SWIM).

15	get_mapset.c char *get_mapset(name)	To return the mapset of the map layer with the name. *name*: Name of the map whose mapset is needed. The mapset location is returned.
16	get_new_name.c char *get_new_name(promt,name)	To get the new map *name* in the current mapset using the specified *prompt*. It checks for the existence for the map layer with the same name and returns name, if succeeds, else quits. *promt*: any string to give info to the user what the program expects. *name*: name of the new map layer.
17	get_old_name.c char *get_old_name(prompt)	To get the old map name in any mapset using the specified *prompt*. It checks for the existence for the map layer and returns name, if succeeds else quits. *prompt*: To identify the layer one needs.
18	get_precipit_station_s.c get_pecipitation_station()	This subroutine extracts the number of nearest 3 precipitation stations for a basin or each sub-basin using program brb_main_stationno.c. The precipitation station number list has to be stored in a file in the active path. The station number(s) is (are) stored in prstat_3.dat under full_path. A label file called proj_name.prstat_3 is defined which can be used to mark the stations in a map.
19	get_rain_temp_info.c get_rain_temp_info()	This subroutine requests/extracts the rain gauge and temperature gauge station properties from user supplied map. From each sub-basin get the file name that is correspond to that sub-basin. The file has to be in SWAT format (not used in SWIM).
20	get_res_inflow.c get_res_inflow()	This requests/extracts reservoir, inflow and (re)compute the routing structures to create .fig file through a menu system (not used in SWIM).
21	get_soil_info.c get_soil_info()	This requests/extracts the soil properties from user supplied soils map. Each sub-basin is masked and the dominant soil name is picked and the *findsoil* routine is called to write out the soil properties in SWAT format (not used in SWIM).
22	get_topo_info.c get_topo_info()	This subroutine requests/extracts an elevation map from user and extracts the topological properties such as stream length and stream slope using *ram.sub-basin* program and average overland slope and slope length using *compute_slp_len* subroutine. It creates several intermediate layers like *temp_LS, temp_slen, temp_sslp, and temp_slope.*
23	hydro_struct_swim.c hydro_struct()	This function requests a basin map, land use map and soil map for one area, starts r.stats for these three maps, stores the output in "*proj_name.str*" under full_path except these where one of the first numbers is zero.
24	main_swim.c main()	Main program
25	main_swim_menu.c main_menu()	This subroutine provides the first menu to start with the SWIM/GRASS project.
26	mask_reclass.c mask_reclass(layer_name,cellnum,flag)	To create a temporary file for reclassification the *cellnum* into MASK layer
27	read_basin.c read_basin()	This subroutine reads the extracted basin properties in SWIM format. The basin file are stored in "data_dir" and are read in to the SWIM variables.

28	read_cod.c read_cod()	This subroutine reads the extracted control properties in SWIM format. The basin file are stored in "data_dir" and are read in to the SWIM variables.
29	read_crop.c read_crop(num)	This subroutine reads the extracted crop properties that are stored in SWIM format by the *findcrop* program from user supplied crop map. The crop files are stored in "data_dir" and are read in to the SWIM variables for each sub-basin "num"
30	read_res.c read_res(num)	This subroutine reads the user specified reservoir data that are stored in SWIM format. The reservoir files are stored in "data_dir" as res_num.res and are read in to the SWIM variables for each sub-basin "num" (not used in SWIM)
31	read_rout.c read_rout(num)	This subroutine reads the extracted sub-basin routing properties in SWIM format. The basin file are stored in "data_dir" and are read in to the SWIM variables for sub-basin "num".
32	read_soil.c read_soil(num)	This subroutine reads the extracted soil properties that are stored in SWIM format by the *findsoil* program from user supplied soils map. The soil files are stored in "data_dir" and are read in to the SWIM variables for each sub-basin "num"
33	read_sub-basin.c read_sub-basin(num)	This subroutine reads the extracted sub-basin properties in SWIM format. The basin file are stored in "data_dir" and are read in to the SWIM variables for sub-basin "num".
34	read_weather.c read_weather()	This subroutine reads the generated weather parameters from the weath_gen program which is stored in SWAT format. The weather station was selected is the most closest station from the approximate centre of the Basin. The weather file is stored in "data_dir" and are read in to the SWAT variables for the whole basin (not used)
35	restore_swim_project.c restore_project()	This subroutine program retrieves the project status information from proj_file which is the project_name with .proj extension into appropriate variables.
36	rm_rast_map.c rm_rast_map(map)	This subroutine removes current raster map
37	rw_gw_swim.c read_gw()	This subroutine reads the extracted groundwater properties in SWIM format. The groundwater parameter file are stored in "data_dir" and are read in to the SWIM variables.
38	save_swim_project.c save_project()	This program saves the project status information in proj_file which is the project_name with .proj extension. This program will be used at the end of each project, in order to keep track of the project status
39	stats.c stats(layer_name, flag, stat)	This routine gets the categories, area/# of cells of layer. this routine uses r.stats program flag: 1 - stores the output in a variables 2 - returns the cell number that has maximum occurrence 3 - returns the average value of the cell number 4 - returns the weighted average value of the cell number
40	sub_swim_menu.c sub_menu()	This subroutine is the major menu in a loop to update the various data from either layers or user inputs This program will be used while working on a ongoing project.
41	what.c	This subroutine checks current GRASS window

42	write_basin.c write_basin()	This subroutine writes the extracted basin properties in SWIM format. The basin file are stored in "data_dir" and are read as the SWIM variables.
43	write_cio_1.c write_cio()	This subroutines writes the extracted control properties in SWIM format. The basin file are stored in "data_dir" and are read as the SWIM variables.
44	write_cod.c write_cod()	This subroutine writes the extracted control properties in SWIM format. The basin file are stored in "data_dir" and are read as the SWIM variables.
45	write_crop.c write_crop(num,crp_fl)	This subroutine writes the extracted crop properties from crp_fl database in SWIM format. The crop files are stored in "data_dir" and are read as the SWIM variables for each sub-basin "num"
46	write_res.c write_res(num)	This subroutine writes the reservoir data provided by user in SWIM format The reservoir files are stored in "data_dir" as res_num.res and are read as the SWIM variables for each sub-basin "num"
47	write_rout.c write_rout()	This subroutine writes the extracted sub-basin routing properties in SWIM format. The basin file are stored in "data_dir" and are read as the SWIM variables for sub-basin "num".
48	write_soil.c write_soil(num)	This subroutine writes the extracted soil properties in SWIM format. The soil files are stored in "data_dir" and are read as the SWIM variables for each sub-basin "num"
49	write_sub-basin.c write_sub-basin()	This subroutine writes the extracted sub-basin properties in SWIM format. The basin file are stored in "data_dir" and are read as the SWIM variables for sub-basin "num".
50	write_weather.c	This subroutine writes the generated weather parameters from the weath_gen program and stores in SWIM format. The weather file is stored in "data_dir" and are read as the SWIM variables for the whole basin

Table 3.2 File *swimmake* used to compile SWIM/GRASS interface

```
Bin = ../bin
LIBDIR = /usr/local/grass/source/src/libes/LIB
RASTERLIB = $(LIBDIR)/libraster.a
DISPLAYLIB = $(LIBDIR)/libdisplay.a
D_LIB = $(LIBDIR)/libD.a
GISLIB = $(LIBDIR)/libgis.a
VASK = $(LIBDIR)/libvask.a
LIBES  = $(D_LIB) $(DISPLAYLIB) $(RASTERLIB) $(GISLIB) $(VASK)
EXTRACFLAGS = -L/usr/local/grass/source/src/libes

PGM = swim_input
LIST = \
                cell_open.o\
                cell_open_new.o\
                check_name.o\
                chk_asp.o\
                com_rout_info_swim.o\
                compute_slp_len.o\
                display_info.o\
                dummy_lcra.o\
                find_subb_stations.o\
                forms.o\
                get_basin_info.o\
                get_climate_station_s.o\
                get_crop_info.o\
                get_irr_nutrient_info.o\
                get_mapset.o\
                get_new_name.o\
                get_old_name.o\
                get_precipit_station_s.o\
                get_rain_temp_info.o\
                get_res_inflow.o\
                get_soil_info.o\
                get_topo_info.o\
                hydro_struct_swim.o\
                main_swim.o
                main_swim_menu.o\
                mask_reclass.o\
                read_basin.o\
                read_cod.o\
                read_crop.o\
                read_res.o\
                read_rout.o\
                read_soil.o\
                read_sub-basin.o\
                read_weather.o\
                restore_swim_project.o\
                rm_rast_map.o\
                rw_gw_swim.o\
                save_swim_project.o\
                stats.o\
                sub_swim_menu.o\
                what.o\
                write_basin.o\
                write_cio_1.o\
                write_cod.o\
                write_crop.o\
                write_res.o\
                write_rout.o\
                write_soil.o\
                write_sub-basin.o\
                write_weather.o\

$(PGM): $(LIST) $(LIBES)
                        $(CC) $(LDFLAGS) -o  $@ $(LIST) $(LIBES) -lm -lcurses
```

3.2 Structure of the SWIM Simulation Part

3.2.1 Files and their Functions

The simulation part of the model code consists of 33 files listed in **Tab. 3.3**. They can be subdivided regarding their main functions into the following parts:

1) main administrative files, representing three-level disaggregation procedure: basin - sub-basin - hydrotope,
2) climate data input or generation,
3) hydrological processes,
4) erosion, crop/vegetation growth and nutrient processes,
5) routing of water, sediments and nutrients,
6) administrative subroutines (common blocks, read input files, initialisation of variables, writing of results, and statistical evaluation of results).

Every file contains one or several subroutines with similar functions. Altogether there are 85 subroutines in the simulation part. General functions performed in the files are also shortly described in **Tab. 3.3**.

The block-scheme of the model operations is presented in **Fig. 3.2**. It shows the sequence of computing different processes.

The file *Makefile* used to compile SWIM code is given in **Tab. 3.4**.

Table 3.3 Files and subroutines included in SWIM code

No	*File name*	*Subroutines*	*Main function*
I. Main administrative files, representing three-level disaggregation procedure: Basin – Sub-basin - Hydrotope			
1.	main.f	main	Initialisation (calls subroutines reading input data), annual and daily loops, routing structure, and aggregation of results for the basin
2.	sub-basin.f	sub-basin()	Sub-basin operations: initial conditions in hydrotopes in the first day, calls hydrotop, aggregates hydrotop outputs, and provides outputs from sub-basin for routing
3.	hydrotop.f	hydrotop()	Simulation of all hydrological, vegetation and nutrient cycling processes in hydrotopes
II. Climate parameters read or generate			
4.	cliread.f	cliread + sub2prst	Reading observed climate and hydrological data
5.	clicon.f	clicon + clgen()	Generation of daily climate data from monthly statistical data
III. Hydrological processes			
6.	solt.f	solt() + snom()	Calculation of soil temperature and snow melt
7.	curn.f	curno() + volq() + peakq() + tran()	Simulation of daily runoff, peak runoff rate and transmission losses for hydrotopes
8.	evap.f	evap()	Calculation of soil evaporation and potential plant transpiration
9.	perc.f	purk() + perc() + percrack()	Calculation of percolation and lateral subsurface flow from soil
10.	gwat.f	gwmod()	Calculation of groundwater contribution to streamflow
IV Erosion, crop and nutrients			
11.	eros.f	ecklsp() + ysed()+ enrsb() + orgnsed()+ psed()	Simulation of erosion processes
12.	crop.f	crpmd() + operat() + growth()	Simulation of crop planting, growth and harvesting
13.	veget.f	vegmd()	Simulation of non-crop vegetation
14.	vegfun.f	wstress() + tstress() + npstress() + scurve() + ascrv() + adjustbe()	Special functions for crop and vegetation: water, temperature and N&P stress, CO2 adjustment of the biomass-energy ratio (alpha factor)
15.	cropyld.f	cryld_brb	Calculation of crop yield for districts in Brandenburg
16.	ncycle.f	ncycle() + nlch() + nuptake() + fert()	Simulation of N cycle in soil

17.	pcycle.f	pcycle() + psollch() + puptake()	Simulation of P cycle in soil
V Routing of water, sediments and nutrients			
18.	route.f	route()+ add()+ transfer()	Calculation of water, sediment and nutrient routing
19.	routfun.f	rthyd()+ rtsed()+ enrrt()+ rtorgn+ rtpsed+ ttcoefi()+ coefs()+qman	Routing functions
VI Administrative subroutines			
20.	compar.f		Common parameters: dimensions
21.	common.f		Common blocks: parameters and variables
22.	open.f	open + opensub + opensoil + openstruct + closef + caps()	Opening and closing input/output files
23.	readcod.f	readcod	Reading xxx.cod* and xxx.fig input files: codes for print and routing
24.	readbas.f	readbas	Reading xxx.bsn and xxx.str input files: basin and calibration parameters, and hydrotope structure
25.	readcrp.f	readcrp	Reading crop.dat input file
26.	readsub.f	readsub	Call of readwet, reading sub-basin input files: xxxNN.sub**, xxxNN.gw, and xxxNN.rte
27.	readsol.f	readsol + rflowtt()	Reading soil parameters from soilNN.dat files
28.	readwet.f	readwet	Reading monthly weather statistical parameters for the basin
29.	init.f	blockdata + init + initsums + initsub	Block data and initialisation of variables
30.	initcrop.f	initcrop()	Initialisation of crop management parameters
31.	genres.f	wr_daily, wr_month(), wr_annual	Writing daily, monthly and annual general results
32.	flohyd.f	flomon() + floann + floave + crop_gis + hydro_gis	Writing monthly, annual and average annual water and N flows for selected hydrotopes; Writing crop yield and annual water flows (for hydrotopes) in the GRASS input format
33.	stat.f	alpha() + gammad() + distn() + gcycl() + randn() + xmonth + xnash()	Statistical functions and criteria of fit

* xxx substitutes here a basin name specified when using SWIM/GRASS interface

** xxxNN substitutes here a sub-basin number NN name established automatically by SWIM/GRASS interface

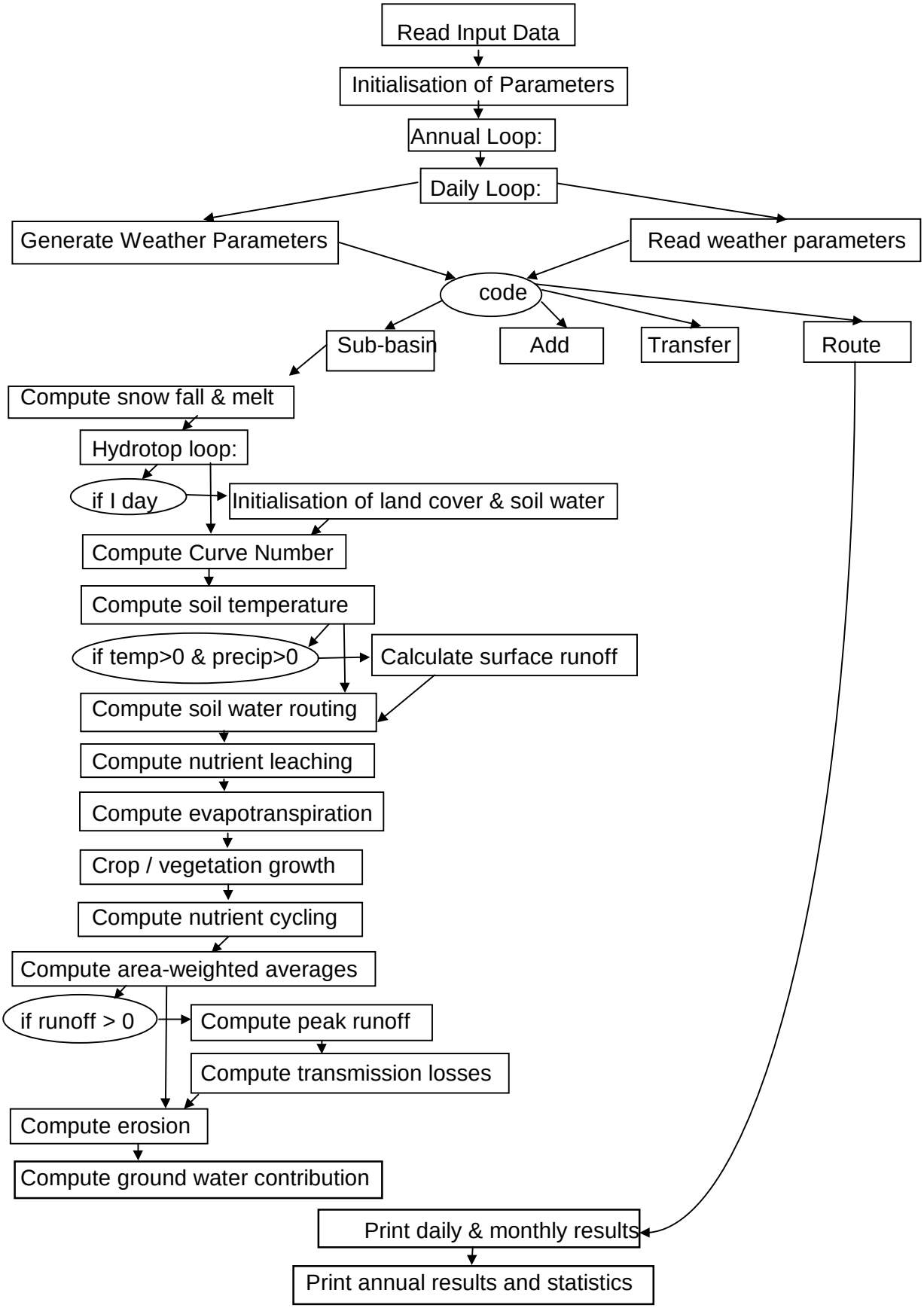

Fig. 3.2 Scheme of operations in the simulation part of SWIM

Table 3.4 File *Makefile* used to compile SWIM code

```
OBJ =      clicon.o\
           cliread.o\
           crop.o\
           cropyld.o\
           curn.o\
           eros.o\
           evap.o\
           flohyd.o\
           genres.o\
           gwat.o\
          hydrotop.o\
          init.o\
          initcrop.o\
          main.o\
          ncycle.o\
          open.o\
          pcycle.o\
          perc.o\
          readcod.o\
          readcrp.o\
          readbas.o\
          readsub.o\
          readsol.o\
          readwet.o\
          route.o\
          routfun.o\
           solt.o\
          sub-basin.o\
          stat.o\
          veget.o\
          vegfun.o
FFLAGS = -g -qflttrap=invalid:zerodivide:overflow:enable

swim: $(OBJ)
          f77 $(FFLAGS)   $(OBJ) -lm -bloadmap:map.out  -o swim
$(OBJ): common.f
.f.o:
          f77 $(FFLAGS) -c $*.f
clean:
          rm -f $(OBJ) swim
```

3.2.2 Subroutines and their Functions

All the subroutines included in SWIM code are shortly described in **Tab. 3.5**. In addition, the Table indicates, where every subroutine is called.

Table 3.5 Description of subroutines included in SWIM simulation part

File	*Subroutine*	*Subroutine description*	*Called in*
main.f	main	Main program. Calls subroutines reading input data and initialisation subroutines. Establishes annual and daily loops, and the routing structure. Aggregates results for the basin.	
sub-basin.f	sub-basin	Sub-basin operations: initialisation in hydrotopes, call hydrotop, aggregation of hydrotope outputs, setting lateral flows for routing	main
hydrotop.f	hydrotop	Simulation of all hydrological, vegetation and nutrient cycling processes in hydrotopes	sub-basin
cliread.f	cliread	this subroutine read climate data	main
	sub2prst	this subroutine establishes the correspondence between sub-basins and precipitation stations	main
clicon.f	clicon	this subroutine controls weather inputs	main
	clgen()	this subroutine simulates daily solar radiation, daily precipitation, and max. and min. air temperature at the user option	clicon
solt.f	solt	this subroutine estimates daily average temperature at the bottom of each soil layer	hydrotop
	snom	this subroutine calculates daily snow melt when the average air temperature exceeds 0 degrees	sub-basin
curn.f	curno()	this subroutine sets curve number parameters	hydrotop
	volq()	this subroutine predicts daily runoff given daily precipitation and snowmelt using a modified curve number approach	hydrotop
	peakq()	this subroutine computes the peak runoff rate using a modification of the Rational Formula	sub-basin
	tran()	this subroutine computes channel transmission losses	sub-basin
evap.f	evap()	this subroutine computes the amount of soil evaporation and potential plant evaporation using Ritchie's model	hydrotop

perc.f	purk()	this is the master percolation component It divides each layer's flow into 4 mm slugs and manages the routing process	hydrotop
	perc()	this subroutine computes percolation and lateral subsurface flow from a soil layer when field capacity is exceeded - hillflow method	purk
	percrack	this subroutine computes percolation by crack flow	purk
gwat.f	gwmod()	this subroutine estimates groundwater contribution to streamflow	sub-basin
eros.f	ecklsp()	this subroutine calculates K, P, and LS factors for hydrotope	hydrotop
	ysed()	this subroutine predicts daily soil loss caused by water erosion using the Modified Universal Soil Loss Equation	sub-basin
	enrsb()	this subroutine computes enrichment ratio for sub-basin	sub-basin
	orgnsed()	this subroutine computes organic N loss with erosion	sub-basin
	psed()	this subroutine computes P loss with erosion	sub-basin
crop.f	crpmd()	Main crop routine: calls operat() and growth() subroutines	hydrotop
	operat	this subroutine sets crop operations: planting, harvesting, and kill	crpmd
	growth	this subroutine predicts daily potential growth of total crop biomass and roots and calculates the leaf area index. It incorporates residue and decays residue on ground surface. It calls subroutines *wstress* and *tstress* and adjusts daily dry matter to stress.	crpmd
veget.f	vegmd()	this subroutine predicts daily potential growth of total plant biomass and roots and calculates the leaf area index.	hydrotop
vegfun.f	wstress()	this subroutine distributes potential plant transpiration through the root zone and calculates actual plant water use based on soil water availability. It estimates water stress factor for crops.	crpmd, vegmd
	tstress()	this subroutine computes temperature stress for crop growth	growth, vegmd
	npstress()	this subroutine computes N & P stress factor	nuptake, puptake
	scurve()	S-curve function	growth, adjustbe
	ascrv()	S-curve function	readcrp
	adjustbe()	this subroutine adjusts biomass-energy ration to CO_2 concentration	growth

cropyld.f	cryld_brb	this subroutine calculates crop yield for districts in BRB, closed if not Brandenburg	main
ncycle.f	ncycle()	this subroutine calculates N cycle: daily N mineralisation and immobilisation considering fresh organic material (crop residue) and active and stable humus	hydrotop
	nlch()	this subroutine computes nitrate leaching from soil	hydrotop
	nuptake()	this subroutine computes N-uptake by crops and natural plants	growth, vegmd
	fert()	this subroutine applies N and P specified by date and amount	hydrotop
pcycle.f	pcycle	this subroutine computes P cycle: P flux between labile, active mineral and stable mineral P pools	hydrotop
	psollch	this subroutine computes soluble P leaching	hydrotop
	puptake	this subroutine computes P-uptake by crops and natural vegetation	growth, vegmd
route.f	route()	this subroutine controls the channel routing	main
	add()	this subroutine adds outputs for	main
	transfer()	this subroutine controls the channel routing	main
routfun.f	rthyd()	this subroutine routes a daily flow through a reach using a constant storage coefficient	route
	rtsed()	this subroutine routes sediment from sub-basin to basin outlets, accounting for deposition (based on fall velocity) and degradation in stream	route
	enrrt()	this subroutine computes enrichment coefficient for N routing	route
	rtorgn	this subroutine computes organic N routing	route
	rtpsed	this subroutine computes P routing	route
	ttcoefi()	this subroutine computes travel time coeffs phi() for the simplified routing	main
	coefs()	this subroutine calculates routing coefficients	ttcoefi
	qman()	this subroutine computes flow using Manning equation	ttcoefi
open.f	open	this subroutine opens main input files	main
	opensub	this subroutine opens sub-basin input files	readsub
	opensoil	this subroutine opens soil data files 15	readsol
	openstruct	this subroutine opens 16 - structure file	readbas
	closef	this subroutine closes files 11,12,13,14	main
	caps()	this subroutine removes extra blanks	open, opensub, opensoil, openstruct

readcod.f	readcod	this subroutine reads codes for printing, routing	main
readbas.f	readbas	this subroutine reads basin parameters and calibration parameters	main
readcrp.f	readcrp	this subroutine reads crop parameters	main
readsub.f	readsub	this subroutine reads sub-basin input parameters	main
readsol.f	readsol	this subroutine reads soil input parameters	main
	rflowtt()	this subroutine computes return flow travel time	readsol
readwet.f	readwet()	this subroutine reads monthly statistical weather parameters, provided by user	readsub
init.f	block data	block data	
	init	this subroutine initialises variables in main	main
	initsums	this subroutine initialises variables for GIS output	main
	initsub	this subroutine initialises sub-basin variables	sub-basin
initcrop.f	initcrop()	this subroutine initialises crop management	main
genres.f	wr_daily	this subroutine writes daily general results	main
	wr_month()	this subroutine writes monthly general results	main
	wr_annual	this subroutine writes annual general results	main
flohyd.f	flomon()	this subroutine writes monthly water and N flows for selected hydrotopes	main
	floann	this subroutine writes annual water and N flows for selected hydrotopes	main
	floave	this subroutine writes average annual water and N flows for selected hydrotopes	main
	crop_gis	this subroutine writes crop yield for GRASS	sub-basin
	hydro_gis	this subroutine writes annual sums of water flows for hydrotopes (for GRASS)	sub-basin
stat.f	alpha()	this subroutine computes alpha, the fraction of total rainfall that occurs during 0.5h	sub-basin, clicon
	gammad()	this function provides numbers from gamma distribution	alpha
	distn()	this function computes the distance from the mean of a normal distribution	clgen
	gcycl()	this function cycles the random number generator	main
	randn()	this function provides random numbers ranging from 0. to 1.	init, readsub, gcycl, clicon, clgen, gammad
	xmonth	this subroutine calculates the month, given the day of the year	main
	xnash()	this subroutins computes criteria of fit	main

3.2.3 Main Administrative Subroutines and the Parameter Read Part

The subroutine *main* performs initialisation of the simulation run by reading input data and initialising variables and parameters. It establishes annual and daily loops, and inside the daily loop it calls sequentially the *sub-basin* subroutine for every sub-basin to calculate all processes in sub-basin, and then routes lateral flows to the basin outlet following the routing structure file *xxx.fig*. The main subroutine also writes daily, monthly and annual results for the basin.

The subroutine *sub-basin* performs sub-basin operations: initialisation of variables for hydrotopes, calling of *hydrotope* subroutine, aggregation of hydrotope outputs, and setting lateral flows for routing.

The subroutine *hydrotop* controls simulation of all hydrological, vegetation and nutrient cycling processes in hydrotopes, by calling different related subroutines.

The structure of *main, sub-basin* and *hydrotop* subroutines is shown in the following **Tables 3.6, 3.7** and **3.8**. The user has to keep in mind that some of the calls are conditional, though it is not indicated in the Tables.

Table 3.6 Structure of the subroutine MAIN

```
MAIN PROGRAM BEGIN:
call open
call readcod
call gcycl(ign,xx)
call readbas
call sub2prst
call readsub
call readsol
call init
call ttcoefi(j), j=1,lu
call closef
ANNUAL LOOP: CYCLE 540:iy = 1, nbyr
        call initcrop(iy)
        DAILY LOOP: CYCLE 530: i = id1, nd
                call initsums
                call cliread
                SWITCH:  icode: (1,2,5)
                        call sub-basin(icode,ihout,inum1,inum2,inum3,rnum1)
                        call route(icode,ihout,inum1,inum2,inum3,rnum1,nrch)
                        call transfer (icode,ihout,inum1,inum2,inum3)
                        call add (icode,ihout,inum1,inum2,inum3)
                call wr_daily
                call xmonth
                call flomon(mo1)
                call wr_month(mo1)
                call floann
                call wr_annual
        END OF CYCLE 530
        call xnash(runo,runs,365)
        call cryld_brb
END OF CYCLE 540
call floave
MAIN PROGRAM END
```

Table 3.7 Structure of the subroutine SUB-BASIN

SUB-BASIN BEGIN*:*

call initsub

call snom(j)

call alpha(j

EAP LOOP: CYCLE 100: jea = 1, neap(j)

call hydrotop(j,jea,k,n)

call crop_gis(j,jea,k)

call hydro_gis(j,jea)

END OF EAP LOOP 100

call peakq(j)

call tran(j)

call ysed(j)

call enrsb(j)

call orgnsed(j)

call psed(j)

call gwmod(j)

SUB-BASIN END

Table 3.8 Structure of the subroutine HYDROTOP

```
HYDROTOP BEGIN:
call curno(cn2(k,n),j,jea,k,n)
call solt(zz,j,jea,k,n)
call volq(j,jea,k,n)
call ecklsp(j,jea,k,n)
call purk(j,jea,k,n)
        call perc(j,je,k,n,j1,j2)
call evap((j,jea,k,n)
call fert(j,jea,k,n,ii)
SWITCH n:
        call crpmd(j,jea,k,n)
                call operat(j,je,k,n)
                call wstress(j,je,k,n)
                call growth(j,je,k,n)
                        call tstress(tgx,j,n)
                        call adjustbe()
                        call nuptake(j,je,k,n)
                                call npstress(uno3,uno3pot,uu)
                        call puptake(j,je,k,n)
                                call npstress(uap,uapot,uu)
                        call scurve()
        call vegmd(j,jea,k,n)
                call wstress(j,je,k,n)
                call tstress(tgx,j,n)
                call nuptake(j,je,k,n)
                        call npstress(uno3,uno3pot,uu)
                call puptake(j,je,k,n)
                        call npstress(uap,uapot,uu)
call nlch(j,jea,k,n)
call psollch(j,jea,k,n)
call ncycle(j,jea,k,n)
call pcycle(j,jea,k,n)
HYDROTOP END
```

Table 3.9 Structure of the subroutines OPEN, READCOD, READBAS, READCRP, READSUB, READSOL, READWET

Subroutine	*Objective*	*Internal structure**
open	open files	read 1 - file = file.cio **call caps**
readcod	read codes	read 2 - file = codedat read 3 - file = routin
readbas	read basin parameters, crop parameters and basin structure file	read 4 - file = basndat read 7 - file = struct.dat **call openstruct**::: read 8 - file = str.cio call caps open 9 - file = strdat write 9 **call openstruct**::: read 8 - file = str.cio call caps open 9 - file = strdat read 9 - file = strdat
readcrp	reads crop parameters	read 5 - file = crop.dat **call ascrv**() **call ascrv**() **call ascrv**()
readsub	reads sub-basin parameters	**call opensub** call caps **call readwet** read 12 - file = subdat read 13 - file = gwdat read 14 - file = routdat
readwet	reads weather parameters	read 11 - file = wgendat
readsol	reads soil parameters	**call opensoil** call caps **call rflowtt()**

* for some files an internal name is indicated (e.g. routin), see Table 3.10 for clarification

3.3 Input and Output Files

For application of the model the user has to prepare a number of input files. Regarding the way of data preparation, all the files can be subdivided into following categories:

- files created by SWIM/GRASS interface,
- climate and hydrological data prepared by user,
- soil data – standard (BÜK-1000) or created by user in the same format
- standard crop database (file **crop.dat** is ready),
- four additional files prepared by user from example files.

The following input files are prepared by SWIM/GRASS interface (see **Tab. 3.10**):

- **file.cio** – 1 file,
- **str.cio** – 1 file,
- **xxx.fig** – 1 file,
- **xxx.str** – 1 file,
- **xxxNN.sub** – M files, where M is the number of sub-basins,
- **xxxNN.gw** – M files, where M is the number of sub-basins,
- **xxxNN.rte** – M files, where M is the number of sub-basins.

The user has to prepare either one climate/hydrological file **clim.dat**, which includes all climate and hydrological data (see Sections 4.2.2 and 4.2.5), or four files

- **prec.dat**
- **temp.dat**,
- **radi.dat**
- **runoff.dat**,

which include separately all precipitation, temperature, radiation, and runoff data for the basin. In addition, a file sub2prst.dat may be prepared, which indicates the correspondence between sub-basins and precipitation stations. This is especially useful in case of a large number of sub-basins.

The user has either to prepare all soil data, or to use available soil database for the Elbe, BÜK-1000, if this map is used. In addition, a file soil.cio has to be prepared or copied, which includes a list of all soil data file names.

The rest four files are the following:

- **xxx.cod**, which includes program codes for printing;
- **xxx.bsn**, which includes a set of basin parameters and a set of calibration parameters,
- **wstor.dat**, which includes initial water storages for the reaches (may be all put to 0, or taken from the test model run at the end of the year), and
- **wgen.dat**, which includes monthly climate statistics.

The monthly statistical data are used to run the weather generator. In case if real climate data are used, SWIM requires only average monthly maximum and minimum temperatures for the basin (needed for soil temperature routine). They can be calculated using an additional program *wgenpar* from the available climate data, taking as long series as possible. Then the calculated average monthly maximum and minimum temperatures have to be substituted into wgen.dat file.

Table 3.10 Input files

Unit No.	*Internal name*	*External name*	*read in*	*Description*	*Type*
1	file.cio	file.cio	open, opensub	**C**ontrol **I**nput **O**utput file. It contains all the input file names that are used by the model.	created by SWIM/GRASS
2	codedat	xxx.cod	readcod	This is the input control code file. In contains the number of sub-basins, the number of years of simulation, beginning year of simulation and print codes.	created by user from an example file
3	routin	xxx.fig	readcod	This is the basin configuration input file. It contains the routing commands to route and add flows through a basin.	created by SWIM/GRASS
4	basndat	xxx.bsn	readbas	This is the general basin input file. It contains a set of general basin parameters (including drainage area) and a set of parameters that can be used for calibration.	created by user from an example file
7	struct	xxx.str	readbas	This is the basin structure file. It describes sub-basins and hydrotopes by land use categories and soil types.	created by SWIM/GRASS
8	strlist	str.cio	openstruct	This is the control file for the basin structure. It contains file names to write sub-basin structure.	created by SWIM/GRASS
9	direc//strdat	Struc/subbNN.str	readbas	These are sub-basin structure files created by SWIM	created by SWIM
10	sub-prst.dat	sub-prst.dat	sub2prst	This file establishes correspondence between sub-basins and precipitation stations.	created by user
5	cropdb	crop.dat	readcrp	This is the crop data base input file. It contains crop specific parameters that are input to the model.	standard file
11	wgen.dat	wgen.dat	readwet	This is the weather generator input file. It contains monthly statistical parameters required for generating daily weather. Some of the parameters are needed by the model, even if observed weather data are used.	created by user from an example file
12	direc//subdat	Sub/xxxNN.sub	readsub	This is the general sub-basin input file. It contains general inputs specific for each sub-basin (area, land and channel slopes and lengths, etc.	created by SWIM/GRASS

13	direc//gwdat	Sub/xxxNN.gw	readsub	This is the groundwater input file. It contains shallow aquifer data, including a recession parameter, specific yield, a revap coefficient, and a deep aquifer percolation coefficient.	created by SWIM/GRASS
14	direc//routdat	Sub/xxxNN.rte	readsub	This is the sub-basin routing input file. This file contains data on channel dimensions (length, slope, width, depth, etc.) for the min channel in the sub-basin.	created by SWIM/GRASS
20	wstor.dat	wstor.dat	readsub	This file includes data on initial water storage in m^3 in the reaches corresponding to the sub-basins.	created by user from an example file
15	soillist	soil.cio	opensoil	This is the control file for the soil database. It contains soil file names.	created by user or standard (BÜK-1000)
16	direct//soildat	Soil/soilNN.dat	readsol	These are soil parameter input files. They contain soil physical and chemical parameters.	created by user or standard (BÜK-1000)
21	clim.dat	clim.dat	cliread	This is climate (and) hydrological input data file. It may include all necessary climate and hydrological data, or only climate data for the basin.	created by user
22	prec.dat	prec.dat	cliread	This is precipitation input data file. It includes precipitation data from all used precipitation stations in/close to the basin.	created by user
23	temp.dat	temp.dat	cliread	This is temperature input data file. It includes temperature data from all used climate stations in/close to the basin.	created by user
24	radi.dat	radi.dat	cliread	This is radiation input data file. It includes radiation data from all used climate stations in/close to the basin.	created by user
25	runoff.dat	runoff.dat	cliread	This is hydrological input data file. It includes water discharge in the basin outlet (used for the hydrological validation).	created by user

Table 3.11 Output files

Unit No.	*File name*	*Where used*	*Description*
GENERAL OUTPUT			
31	Res/wgen.out	readwet	Weather generator output
32	Res/rin.out	readbas, readsub, readsol	Write input parameters
SUBROUTINES OUTPUT			
41	Res/curn.out	curno, volq	specific subroutine output
42	Res/solt.out	solt	specific subroutine output
43	Res/tran.out	tran	specific subroutine output
44	Res/perc.out	purk, perc	specific subroutine output
45	Res/evap.out	evap	specific subroutine output
46	Res/crop.out	crop, cropyld	specific subroutine output
47	Res/eros.out	ecklsp, ysed, sub-basin	specific subroutine output
48	Res/nutr.prn	ncycle, sub-basin	specific subroutine output
49	Res/rout.out	ttcoefi, rtsed	specific subroutine output
50	Res/wstr.out	wstress	specific subroutine output
HYDROTOPE OUTPUT			
51	Res/htp-1.prn	subbasin	Daily water outputs for a hydrotop (chosen by user)
52	Res/htp-2.prn	subbasin	Daily water outputs for a hydrotop (chosen by user)
53	Res/htp-3.prn	subbasin	Daily water outputs for a hydrotop (chosen by user)
54	Res/htp-4.prn	subbasin	Daily water outputs for a hydrotop (chosen by user)
55	Res/htp-5.prn	vegmd	Daily water outputs for a hydrotop (chosen by user)
56	Res/htp-6.prn	vegmd	Daily water outputs for a hydrotop (chosen by user)
57	Res/htp-7.prn	vegmd	Daily water outputs for a hydrotop (chosen by user)
SUB-BASIN OUTPUTS			
61	Res/subd.prn	subbasin	Daily water flow outputs for all sub-basins
62	Res/subm.prn	wr_month, wr_annual	Monthly sub-basin outputs for all sub-basins
63	Res/sub-1.prn	subbasin	Daily water outputs for a chosen sub-basin
64	Res/sub-2.prn	subbasin	Daily water outputs for a chosen sub-basin
65	Res/sub-3.prn	subbasin	Daily water outputs for a chosen sub-basin
BASIN & RIVER OUTPUTS			
71	Res/bad.prn	wr_daily	Daily water outputs for basin
72	Res/bam.prn	wr_month	Monthly water outputs for basin

73	Res/bay.prn	wr_annual	Annual water outputs for basin
74	Res/rch.prn	route	Reach outputs
75	Res/rvQ.prn	route	Reach outputs (from route)
76	Res/rvaddQ.prn	add	Reach outputs (from add)
70	Res/rvQ-mn.prn	main	Monthly reach outputs (from route)
80	Res/rvQ-ev.out	xnash	Evaluation of hydrological results
MONTHLY, ANNUAL & AVERAGE ANNUAL WATER and N FLOWS			
77	Flo/floMON.prn	flomon	Monthly water and N flows for 3 hydrotopes
78	Flo/floANN.prn	floann	Annual water and N flows for 3 hydrotopes
79	Flo/floAVE.prn	floave	Average water and N flows for 9 hydrotopes
MONTHLY WATER and N FLOWS for 9 CHOSEN SOILS/HYDROTOPES			
81	Flo/fm-s1	main, flomon	Monthly water and N flows for a chosen hydrotope
82	Flo/fm-s2	main, flomon	Monthly water and N flows for a chosen hydrotope
83	Flo/fm-s3	main, flomon	Monthly water and N flows for a chosen hydrotope
84	Flo/fm-s4	main, flomon	Monthly water and N flows for a chosen hydrotope
85	Flo/fm-s5	main, flomon	Monthly water and N flows for a chosen hydrotope
86	Flo/fm-s6	main, flomon	Monthly water and N flows for a chosen hydrotope
87	Flo/fm-s7	main, flomon	Monthly water and N flows for a chosen hydrotope
88	Flo/fm-s8	main, flomon	Monthly water and N flows for a chosen hydrotope
89	Flo/fm-s9	main, flomon	Monthly water and N flows for a chosen hydrotope
ANNUAL WATER and N FLOWS for 9 CHOSEN SOILS/HYDROTOPES			
91	Flo/fa-s1	floann	Annual water and N flows for a chosen hydrotope
92	Flo/fa-s2	floann	Annual water and N flows for a chosen hydrotope
93	Flo/fa-s3	floann	Annual water and N flows for a chosen hydrotope
94	Flo/fa-s4	floann	Annual water and N flows for a chosen hydrotope
95	Flo/fa-s5	floann	Annual water and N flows for a chosen hydrotope
96	Flo/fa-s6	floann	Annual water and N flows for a chosen hydrotope
97	Flo/fa-s7	floann	Annual water and N flows for a chosen hydrotope
98	Flo/fa-s8	floann	Annual water and N flows for a chosen hydrotope
99	Flo/fa-s9	floann	Annual water and N flows for a chosen hydrotope
GIS OUTPUTS			
33	GIS/yld-gis.out	crop_gis	Crop yield for all hydrotopes – as GRASS input
34	GIS/wat-gis.out	crop_gis	Water stress factor for hydrotopes – as GRASS input
35	GIS/tem-gis.out	crop_gis	Temperature stress factor for hydrotopes – as GRASS input
36	GIS/pre-gis.out	hydro_gis	Annual precipitation for hydrotopes – as GRASS input

37	GIS/eva-gis.out	hydro_gis	Annual evapotranspiration for hydrotopes – as GRASS input
38	GIS/run-gis.out	hydro_gis	Annual runoff for hydrotopes – as GRASS input
39	GIS/gwr-gis.out	hydro_gis	Annual groundwater recharge for hydrotopes – as GRASS input
CROP OUTPUT			
58	Res/cryld.prn	operat	Original calculated crop yield for every year and for every hydrotope in cropland (sub-basin, soil) (considering all applied crop types)
59	Res/cryld-av.prn	main	Averaged crop yield over period a) for every soil and sub-basin, b) for every soil, and c) for the basin (considering all applied crop types)
66	Res/yld-dst.prn	cryld_brb	Distribution function for crop yield
67	Res/yldkr-1.prn	cryld_brb	Crop yield for kreise in BRB with the weighting coefficients accounting for wheat areal distribution
68	Res/yldkr-2.prn	cryld_brb	Crop yield for kreise in BRB with the weighting coefficients accounting for barley areal distribution

3.4 Input Parameters

In this Section input parameters are described. They are arranged in accordance with the input files. Almost all files listed in **Tab. 3.10** are included, except files .CIO, climate and hydrological files. The files .CIO are not included, because they are created by SWIM/GRASS interface and do not need any editing. The format of the climate and hydrological input data is to a certain extent flexible, and preparation of this data is described in Section 4.3.

3.4.1 INPUT FILE - .cod

The *xxx.cod* file includes program codes (where xxx is the basin name given when using GRASS interface). An example of the *xxx.cod* input file format is presented in the following Table:

```
PROGRAM CODES:
nbyr  iyr idaf idal   lu irch nsim msim  ign  ipd iprn iwst isst
   6 1983    1  365   64    1    4    4    5    1    0    1    1
HYDROTOPE PRINT: sub No & hyd No
isb1 ih1  isb2 ih2  isb3 ih3  isb4 ih4  isb5 ih5  isb6 ih6  isb7 ih7
   1   5     1  10     1   7    12  14     1   5     2   8     4   8
SUBBASIN PRINT: sub No
isu1  isu2  isu3
   0     0     0
PROCESS PRINT: 1/0 print/not print, sub No & hyd No
   0     1            icurn       icursb
   0     1            isolt       isosb
   0                  itran
   0     1     5      iperc       ipesb      ipehd
   0     1     5      ievap       ievsb      ievhd
   0     2     26     icrop       icrsb      icrso
   0     7            ieros       iersb
   0     1     1      inutr       inusb      inuhd
   0                  irout
   0     1     5      iswu        iwssb      iwshd
SPECIAL PRINT:
   0                  igis   - print to GIS output?
   0                  iflom  - print monthly water and N flows?
    0                 ifloa  - print annual water and N flows?
```

Parameters included in the *.cod* file are:

nbyr Number of years of simulation. It can range from 1 to 100 years.

iyr Beginning year of simulation. Usually the actual beginning year of record is used.

idaf Beginning (julian) day of simulation. Usually equal to 1.

idal Last (julian) day of simulation. Usually equal to 365 or 366.

lu Number of subbasins in the basin. Corresponds to the subbasin map specified for SWIM/GRASS interface and can be taken from .cod file created by the interface.

irch Reach of measured water and sediment yields. Usually equal to 1 (corresponds to the subbasin in the basin outlet).

nsim Code for rainfal input, if weather generator is used as climate input (clicon).
[2] = simulated single precipitation for entire basin,
[4] = simulated multiple precipitation for entire basin.

msim Code for temperature input, if weather generator is used as climate input (clicon).
[2] = simulated single temperature for entire basin,
[4] = simulated multiple temperature for entire basin.

ign number of times to cycle random number generator (used in main). The random number generator seeds are contained in the SWIM program data statements. If IGN = 0, the simulation begins with these seeds. Setting IGN>0 allows the user to start each simulation with different seeds, if desired. Each time the generators cycle, they produce a new set of seeds. This feature is convenient for simulating several different weather sequences at a particular location.

ipd Print code for general results (in genres) (0= monthly, 1=daily, 2=yearly).

iprn Print code for rin.out and wgen.out files
[0] = print subbasin parameters in the file rin.out (from readsub),
[1] = print weather parameters in the file wgen.out (from readwet).

iwst Code for stat collection on monthly water yield
[0] = to skip statistical comparison,
[1] = to calculate statistics on the simulated water yield.

isst Code for stat collection on monthly sediments yield
[0] = to skip statistical comparison,
[1] = to calculate statistics on the simulated sediment yield.

isb1, isb2, isb3, isb4 subbasin number for hydrotope output (used in *subbsin*).

isb5, isb6, isb7 subbasin number for hydrotope output (used in *vegmd*).

ih1, ih2, ih3, ih4 hydrotope number for hydrotope output (corresponding to subbasins is1, is2, is3, and is4, used in *subbsin*)

ih5, ih6, ih7 hydrotope number for hydrotope output (corresponding to subbasins is5, is6, is7, used in *vegmd*)

isu1,isu2, isu3 subbasin number for subbasin output (used in *subbasin*)

icurn code = 1/0 to print or not from the subroutines *curno* and *volq*

icursb subbasin number for printing from the subroutines *curno* and *volq*

isolt code = 1/0 to print or not from the subroutine *solt*

isosb subbasin number for printing from the subroutine *solt*

itran code = 1/0 to print or not from the subroutine *tran*

iperc code = 1/0 to print or not from the subroutine *purk()*

ipesb subbasin number for printing from the subroutine *purk()*

ipehd hydrotope number for printing from the subroutine *purk()*

ievap code = 1/0 to print or not from the subroutine *evap*

ievsb subbasin number for printing from the subroutine *evap*

ievhd hydrotope number for printing from the subroutine *evap*

icrop code = 1/0 to print or not from the subroutine *crpmd*

icrsb subbasin number for printing from the subroutine *crpmd*

icrso soil number for printing from the subroutine *crpmd*

ieros code = 1/0 to print or not from the subroutines *ecklsp(), ysed()*

iersb subbasin number for printing from the subroutines *ecklsp(), ysed()*

inutr code = 1/0 to print or not from the subroutine *ncycle()*

inusb subbasin number for printing from the subroutine *ncycle(),* and for printing water and nutrient flows from subroutines *flomon(), floann(),* and *floave()*

inuhd hydrotope number for printing from the subroutine *ncycle(),* and initial hydrotope number for printing water and nutrient flows from subroutines *flomon(), floann(),* and *floave().* Water and nutrient flows will be written for hydrotopes inuhd, inuhd+1, ... inuhd+8.

irout code = 1/0 to print or not from the subroutines *rthyd()* and *rtsed()*

iwstr code = 1/0 to print or not from the subroutine *wstress()*

iwssb subbasin number for printing from the subroutine *wstress()*

iwshd hydrotope number for printing from the subroutine *wstress()*

igis code = 1/0 to call or not *crop_gis()* and *hydro_gis()* from the subroutine *subbasin*. If igis = 1, *crop_gis()* and *hydro_gis()* will print crop yield and hydrological flows for GRASS input.

iflom code = 1/0 to call or not *flomon()* from *main*. If iflom = 1, monthly water and nutrient flows will be written for the subbasin inusb and the hydrotopes inuhd, ... , inuhd+8.

ifloa code = 1/0 to call or not *floann()* and *floave()* from *main*. If ifloa = 1, annual and average annual water and nutrient flows will be written for the subbasin inusb and the hydrotopes inuhd, ... , inuhd+8.

3.4.2 INPUT FILE - .fig

The *xxx.fig* file describes the basin routing structure (where xxx is the basin name given when using GRASS interface). An example of the *xxx.fig* input file format is presented in the following Table. The first line includes parameter names used by SWIM. The first two lines are not included in the actual files.

	icodes()	ihouts()	inum1s()	inum2s()	inum3s()	inum4s()
subbasin	1	1	1	1		
subbasin	1	2	2	2		
subbasin	1	3	3	3		
subbasin	1	4	4	4		
subbasin	1	5	5	5		
subbasin	1	6	6	6		
subbasin	1	7	7	7		
subbasin	1	8	8	8		
subbasin	1	9	9	9		
subbasin	1	10	10	10		
add	5	11	7	8	8	1
route	2	12	6	11	6	3
add	5	13	12	6	6	3
add	5	14	13	9	6	3
route	2	15	5	14	5	5
add	5	16	15	5	5	5
add	5	17	16	4	5	5
route	2	18	3	17	3	7
add	5	19	18	3	3	7
add	5	20	19	10	3	7
route	2	21	2	20	2	9
add	5	22	21	2	2	9
route	2	23	1	22	1	10
add	5	24	23	1	1	10
finish	0					

Parameters included in the *.fig* file are:

icodes() code to switch between routing subroutines
[1] = subbasin
[2] = route flow
[5] = add flows

ihouts() Hydrological Storage Location

inum1s() Subbasin No. (if subbasin), or Reach No. (if route), or Inflow hydrograph 1 (if add)

inum2s() Inflow Hydrograph (if route), or Inflow hydrograph 2 (if add)

inum3s() Subbasin No. (if add and route)

inum4s() Fractional Dimension (if add and route)

3.4.3 INPUT FILE - .bsn

The *xxx.bsn* file includes general basin parameters and calibration parameters (where xxx is the basin name given when using GRASS interface). An example of the *xxx.bsn* input file format is presented in the following Table.

```
SWITCH PARAMETERS
1         isc            =0/1, SC: read/calc
0         icn            =0/1, CN: dif for soils/cnum1,cnum3 for all soils
0         idlef          =0/1, day length effect in crop: without/with
0.6       thc            =0...1., evap correction on sky emissivity
BASIN, INITIALIZATION & CALIBRATION PARAMETERS
da        p2(1)     bff       brt       ffcb  Original basin parameters
574.76    1.000     1.000     0.500     0.000
cnum1     cnum2     cnum3                     Curve number, if icn=1
50.       55.       80.
gwq0      abf0                                Groundwater parameters
0.200     0.5
ekc0      prf       spcon     spexp           Erosion parameters
1.0       1.000     0.0001    1.000
snow1     storc1    stinco                    Initial water storage
0.        0.5         0.90
chwc0     chxk0     chcc0                     Channel parameters
0.700     0.05      0.0
roc1      roc2      roc3      roc4            Routing coefficients
0.        3.0       0.        13.0
sccor     prcor     rdcor                     Correction factors
1.20      1.00      1.00
```

Parameters included in the *.bsn* file are:

isc code for saturated conductivity
[0] – read from database
[1] – calculated in SWIM from clay content, sand content and porosity using the method of Brakensiek

icn code for curve number method
[0] – modified CN-method as in SWAT,
[1] – CN = const for all soil and land use categories.
In the case icn = 1 the user can set CN for conditions 1 equal to cnum1, and CN for conditions 3 equal to cnum3. The parameters cnum1 and cnum3 can be used as calibration parameters.

idlef code for taking into account day length effect on crop development
[0] – without the day length effect on crop development (as in SWAT),
[1] – with the day length effect on crop development.

thc correction factor for potential evapotranspiration on sky emissivity
[0] – without the sky emissivity factor,
[1] – with the sky emissivity factor.
The user can set also thc to intermediate values in the range 0 – 1 and use this parameter for calibration.

da basin area in km^2. This parameter should be taken from .bsn file produced by GRASS interface.

p2(1) rainfall correction factor, equal to the ratio of average rainfall to average annual rainfall for the gage in the basin outlet. When daily rainfall data is taken from a rain gauge located at a considerable distance from the basin, it may be necessary to use a rainfall correction factor other than one. If the difference between annual precipitation in the basin and rain gauge is known, a rainfall correction factor from 0.5 to 1.5 can be used.This parameter should be taken from .bsn file produced by GRASS interface. Usually is not used in SWIM.

bff baseflow factor for basin, is used to calc return flow travel time. The return flow travel time is then used to calculate percolation in soil from layer to layer. The bff factor is given in **Tab. 3.12** for different streams:

Table 3.12 Baseflow factor bff

Flow Characteristics	*BFF*
Perennial streams, flow >75% time	1.00
Flow 55-75% time	0.75
Flow 40-55% time	0.50
Flow 20-40% time	0.25
Ephemeral streams	0.00

brt basin lag time in days. Basin lag time lags the subsurface flow. For BRT= 0 all subsurface flow reaches the sub-basin outlets on the day it occurs. Judgment is required to set BRT to as many days as subsurface flow from a precipitation event is expected to contribute to streamflow.This parameter should be taken from .bsn file produced by GRASS interface. It is not used in the current model version.

ffcb fraction of field capacity as initial water storage. This parameter should be taken from .bsn file produced by GRASS interface. It is not used in the current SWIM version.

cnum1 CN, conditions 1 for the case if icn = 1.

cnum2 CN, conditions 2 for the case if icn = 1.

cnum3 CN, conditions 3 for the case if icn = 1.

gwq0 initial groundwater flow contribution to streamflow, mm/day

abf0 alpha factor for grounwater. This parameter characterizes the groundwater recession (the rate at which groundwater flow is returned to the stream).

ekc0 soil erodibility correction factor. This parameter is used to correct all values ek() of soil erodibility obtained from soil database.

prf coefficient to estimate peak runoff in stream, used in calculation of sediment routing.

spcon rate parameter for estimation of sediment transport (between 0.0001 and 0.01).

spexp exponent for estimation of sediment transport (between 1. and 1.5).

snow1 initial snow content in the basin (mm).

storc1 initial water storage in streams correction coefficient.

stinco initial water content in the basin as a fraction of field capacity.

chwc0 coefficient to correct the channel width for all reaches. The channel width is estimated by GRASS interface.

chxk0 correction coefficient for channel USLE K factor

chcc0 correction coef. for channel USLE C factor

roc1, roc2 routing coefficients to calculate the storage time constant for the reach for the surface flow, xkm, from the initial estimation phi(10) and phi(13) based on channel length and celerity (in subroutine ttcoefi(j))

roc3, roc4 routing coefficients to calculate the storage time constant for the reach for the subsurface flow, xkm, from the initial estimation phi(10) and phi(13) based on channel length and celerity (in subroutine ttcoefi(j))

sccor correction factor for saturated conductivity (applied for all soils)

prcor correction factor for precipitation. Usually is not used in SWIM.

rdcor correction factor for the maximum plant root depth. Used in subroutine *readcrp*.

3.4.4 INPUT FILE - .str

The *xxx.str* file includes basin hydrotope structure parameters (where xxx is the basin name given when using GRASS interface), considering sub-basin, land use and soil. An example of the *xxx.str* input file format is presented in the following Table. The first line includes parameter names used by SWIM. The first two lines are not included in the actual files.

j	n	k	ar()	ncell
1	1	26	40000	1
1	2	12	120000	3
1	5	12	1160000	29
1	5	26	1760000	44
1	8	26	840000	21
1	9	12	1040000	26
1	9	26	80000	2
1	12	12	160000	4
1	12	26	40000	1
2	5	12	200000	5
2	5	26	320000	8
2	9	12	200000	5
2	12	12	80000	2
3	1	12	40000	1
3	2	17	40000	1
3	4	26	40000	1
3	5	12	760000	19
3	5	17	800000	20
3	5	19	480000	12
3	5	26	5400000	135
3	7	17	40000	1
3	7	26	40000	1
3	8	19	120000	3
3	9	26	840000	21
3	12	12	80000	2
4	1	26	80000	2
4	5	12	160000	4
4	5	26	680000	17
4	8	26	40000	1
4	9	26	80000	2
4	12	26	40000	1
5	1	26	320000	8
5	4	26	240000	6
5	5	19	40000	1
5	5	26	6560000	164
5	8	26	760000	19
5	9	26	2120000	53
5	12	26	160000	4
6	5	26	80000	2
6	8	26	40000	1
6	9	26	40000	1
6	12	26	40000	1

Parameters included in the *.str* file are:

j subbasin number (from SWIM/GRASS interface)

n land use category number (from SWIM/GRASS interface)
n = 1 - water
n = 2 - settlement
n = 3 - industry
n = 4 - road
n = 5 - cropland
n = 6 - set-aside
n = 7 - grassland, extensive use (meadow)
n = 8 - grassland, intensive use (pasture)
n = 9 - forest mixed
n = 10 - forest evergreen
n = 11 - forest deciduous
n = 12 - wetland nonforested
n = 13 - wetland forested
n = 14 - heather (grass + brushland)
n = 15 - bare soil

k soil type (from SWIM/GRASS interface)

ar hydrotope area, corresponding to the hydrotope with the land use n and the soil k in the subbasin j. (from SWIM/GRASS interface)

ncell number of cells, corresponding to the hydrotope with the land use n and the soil k in the subbasin j. (from SWIM/GRASS interface)

3.4.5 INPUT FILE - sub-prst.dat

The *sub-prst.dat* file establishes the correspondence between sub-basins and precipitation stations in case if only one precipitation station is used for every sub-basin. It lists all sub-basins and the corresponding precipitation stations numbered from 1 to nst, where nst is the total number of precipitation stations used.

is1() subbasin No.

ip2() precip. stat No., corresponding to the subbasin is1() (chosen as the closest the the subbasin central point)

3.4.6 INPUT FILE - crop.dat

The *crop.dat* file provides crop/vegetation parameters for 71 crops/vegetation types, including some aggregated types of vegetation, like deciduous forest. This is the standard file. It is presented in **Tab. 3.13**. Then **Tab. 3.14** lists abbreviated crop names, full crop names, and land cover categories.

Table 3.13 Crop data base (file crop.dat)

icnum	cpnm	ird	be	hi	to	tb	blai	dlai	dlp1	dlp2	bn1	bn2	bn3	bp1	bp2	bp3	cnyld	cpyld	rdmx	cvm	almn	sla	pt2	hun	cpnm
1	AGRL	1	40.0	0.50	25.0	8.0	5.0	0.80	15.05	50.95	0.0440	0.0164	0.0128	0.0062	0.0023	0.0018	0.0175	0.0025	2.0	0.200	0.0	0.0	660.44	1500	AGRL
2	ASPR	1	90.0	0.80	35.0	10.0	4.2	1.00	25.23	40.86	0.0620	0.0500	0.0400	0.0050	0.0040	0.0020	0.0700	0.0065	1.5	0.200	0.0	0.0	660.95	1500	ASPR
3	BROC	1	26.0	0.80	24.0	4.0	4.2	1.00	25.23	40.86	0.0620	0.0090	0.0070	0.0050	0.0040	0.0030	0.0530	0.0073	0.7	0.200	0.0	0.0	660.95	1500	BROC
4	CABG	1	19.0	0.80	24.0	4.0	3.0	1.00	25.23	40.86	0.0620	0.0070	0.0040	0.0050	0.0035	0.0020	0.0270	0.0033	0.7	0.200	0.0	0.0	660.95	1500	CABG
5	CANT	1	30.0	0.50	32.0	16.0	3.0	0.60	15.05	50.95	0.0663	0.0255	0.0148	0.0053	0.0020	0.0012	0.0250	0.0022	1.3	0.030	0.0	0.0	660.39	1500	CANT
6	CAUF	1	21.0	0.80	24.0	7.0	2.5	1.00	25.23	40.86	0.0620	0.0070	0.0040	0.0050	0.0035	0.0020	0.0400	0.0057	0.7	0.200	0.0	0.0	660.95	1500	CAUF
7	CELR	1	27.0	0.80	24.0	7.0	2.5	1.00	25.23	40.86	0.0620	0.0150	0.0100	0.0060	0.0050	0.0030	0.0220	0.0052	0.7	0.200	0.0	0.0	660.95	1500	CELR
8	CORN	1	40.0	0.50	25.0	8.0	5.0	0.80	15.05	50.95	0.0440	0.0164	0.0128	0.0062	0.0023	0.0018	0.0175	0.0025	2.0	0.200	0.0	0.0	660.44	1500	CORN
9	CORN	1	39.0	0.55	35.0	8.0	3.0	0.50	15.05	50.95	0.0470	0.0177	0.0138	0.0048	0.0018	0.0014	0.0210	0.0070	2.0	0.200	0.0	0.0	660.44	1500	CORN
10	COTP	1	15.0	0.40	27.5	10.0	4.0	0.95	15.01	50.95	0.0580	0.0192	0.0177	0.0081	0.0027	0.0025	0.0190	0.0029	2.2	0.200	0.0	0.0	660.19	1500	COTP
11	COTS	1	15.0	0.50	27.5	10.0	4.0	0.95	15.01	50.95	0.0580	0.0192	0.0177	0.0081	0.0027	0.0025	0.0140	0.0020	2.2	0.200	0.0	0.0	660.19	1500	COTS
12	CRRT	1	30.0	1.12	24.0	7.0	3.5	0.60	15.01	50.95	0.0550	0.0075	0.0012	0.0060	0.0030	0.0020	0.0130	0.0037	1.1	0.200	0.0	0.0	660.20	1500	CRRT
13	CUCM	1	30.0	0.27	32.0	16.0	1.5	0.60	15.05	50.95	0.0663	0.0075	0.0048	0.0053	0.0025	0.0012	0.0200	0.0042	1.1	0.030	0.0	0.0	660.39	1500	CUCM
14	EGGP	1	30.0	0.59	35.0	18.0	3.0	0.60	15.05	50.95	0.0663	0.0255	0.0075	0.0053	0.0020	0.0015	0.0220	0.0041	1.1	0.030	0.0	0.0	660.39	1500	EGGP
15	GRSG	1	35.0	0.50	27.5	10.0	5.0	0.80	15.05	50.95	0.0440	0.0164	0.0128	0.0060	0.0022	0.0018	0.0200	0.0028	2.0	0.200	0.0	0.0	660.38	1500	GRSG
16	HMEL	1	30.0	0.55	35.0	16.0	4.0	0.60	15.05	50.95	0.0070	0.0040	0.0020	0.0026	0.0020	0.0017	0.0080	0.0010	1.1	0.030	0.0	0.0	660.39	1500	HMEL
17	ONIO	1	30.0	1.25	29.0	7.0	1.5	0.60	15.01	50.95	0.0400	0.0300	0.0020	0.0021	0.0020	0.0019	0.0210	0.0032	0.7	0.200	0.0	0.0	660.20	1500	ONIO
18	PEPR	1	30.0	0.60	27.0	18.0	5.0	0.60	15.05	50.95	0.0600	0.0350	0.0250	0.0053	0.0020	0.0012	0.0030	0.0020	1.1	0.030	0.0	0.0	660.39	1500	PEPR
19	POTA	1	30.0	0.95	18.0	7.0	5.0	0.60	15.01	50.95	0.0550	0.0200	0.0120	0.0060	0.0025	0.0019	0.0130	0.0020	2.0	0.200	0.0	0.0	660.20	1500	POTA
20	POTA	1	30.0	1.41	18.0	3.0	5.0	0.95	15.01	50.95	0.0550	0.0200	0.0120	0.0060	0.0025	0.0019	0.0130	0.0020	2.0	0.200	0.0	0.0	660.20	2000	POTA
21	RICE	1	25.0	0.50	25.0	10.0	6.0	0.80	30.01	70.95	0.0500	0.0200	0.0100	0.0060	0.0030	0.0018	0.0200	0.0030	0.9	0.030	0.0	0.0	660.31	1500	RICE
22	SBAR	1	30.0	0.42	15.0	0.0	6.0	0.90	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.010	0.0	0.0	660.45	1900	SBAR
23	SGBT	1	30.0	2.00	18.0	4.0	5.0	0.60	5.05	50.95	0.0550	0.0200	0.0120	0.0060	0.0025	0.0019	0.0130	0.0020	2.0	0.200	0.0	0.0	660.20	1500	SGBT
24	SGHY	1	35.0	0.50	27.5	10.0	5.0	0.85	15.01	50.95	0.0440	0.0164	0.0128	0.0060	0.0022	0.0018	0.0200	0.0028	2.0	0.030	0.0	0.0	660.38	1500	SGHY
25	SLMA	1	60.0	1.00	20.0	5.0	8.0	0.70	15.05	50.95	0.0440	0.0164	0.0128	0.0062	0.0023	0.0018	0.0175	0.0025	1.0	0.200	0.0	0.0	660.44	2400	SLMA
26	SPIN	1	30.0	0.95	24.0	4.0	4.2	0.95	10.05	90.95	0.0620	0.0400	0.0300	0.0050	0.0040	0.0035	0.0580	0.0061	0.7	0.200	0.0	0.0	660.95	1500	SPIN
27	STRW	1	30.0	0.45	32.0	10.0	3.0	0.60	15.05	50.95	0.0663	0.0255	0.0148	0.0053	0.0020	0.0012	0.0120	0.0024	0.7	0.030	0.0	0.0	660.39	1500	STRW
28	SUGC	1	25.0	0.50	25.0	11.0	6.0	0.75	15.01	50.95	0.0100	0.0040	0.0025	0.0075	0.0030	0.0019	0.0000	0.0000	2.0	0.001	0.0	0.0	660.40	1500	SUGC
29	SUNF	1	35.0	0.40	25.0	6.0	5.0	0.55	15.01	50.95	0.0500	0.0230	0.0146	0.0063	0.0029	0.0023	0.0280	0.0061	2.2	0.200	0.0	0.0	660.45	1500	SUNF
30	SWHT	1	30.0	0.40	15.0	0.0	6.0	0.80	15.01	50.95	0.0600	0.0231	0.0130	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.030	0.0	0.0	660.39	1500	SWHT
31	TOBC	1	39.0	0.55	25.0	8.0	4.5	0.70	15.05	50.95	0.0470	0.0177	0.0138	0.0048	0.0018	0.0014	0.0140	0.0016	2.0	0.200	0.0	0.0	660.44	1500	TOBC
32	TOMA	1	30.0	0.33	27.0	10.0	3.0	0.95	15.05	50.95	0.0663	0.0300	0.0250	0.0053	0.0035	0.0025	0.0240	0.0038	1.5	0.030	0.0	0.0	660.39	1500	TOMA
33	WMEL	1	30.0	0.50	35.0	18.0	1.5	0.60	15.05	50.95	0.0663	0.0075	0.0048	0.0053	0.0025	0.0012	0.0110	0.0014	1.1	0.030	0.0	0.0	660.39	1500	WMEL
icnum	cpnm	ird	be	hi	to	tb	blai	dlai	dlp1	dlp2	bn1	bn2	bn3	bp1	bp2	bp3	cnyld	cpyld	rdmx	cvm	almn	sla	pt2	hun	cpnm

Tab. 3.13, continued

icnum	cpnm	ird	be	hi	to	tb	blai	dlai	dlp1	dlp2	bn1	bn2	bn3	bp1	bp2	bp3	cnyld	cpyld	rdmx	cvm	almn	sla	pt2	hun	cpnm
34	**BARL**	2	30.0	0.40	15.0	0.0	6.0	0.80	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.030	0.0	0.0	660.45	1500	**BARL**
35	**BARL**	2	35.0	0.42	25.0	0.0	3.5	0.60	20.10	49.95	0.0590	0.0226	0.0131	0.0057	0.0022	0.0013	0.0210	0.0017	2.0	0.010	0.0	0.0	660.39	1500	**BARL**
36	**BARL**	2	30.0	0.42	15.0	0.0	6.0	0.90	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.010	0.0	0.0	660.45	2300	**BARL**
37	**LETT**	2	23.0	0.80	18.2	0.0	4.2	1.00	25.23	40.86	0.0360	0.0250	0.0210	0.0084	0.0032	0.0019	0.0260	0.0049	0.8	0.010	0.0	0.0	660.25	1500	**LETT**
38	**LETL**	2	19.0	0.80	18.2	0.0	4.2	1.00	25.23	40.86	0.0360	0.0250	0.0210	0.0084	0.0032	0.0019	0.0260	0.0049	0.8	0.010	0.0	0.0	660.25	1500	**LETL**
39	**OATS**	2	30.0	0.35	15.0	0.0	6.0	0.80	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.030	0.0	0.0	660.45	1500	**OATS**
40	**RAPE**	2	35.0	0.30	14.0	0.0	4.5	0.60	15.01	50.95	0.0500	0.0200	0.0110	0.0070	0.0025	0.0015	0.0350	0.0067	2.0	0.050	0.0	0.0	660.40	1500	**RAPE**
41	**RYE**	2	35.0	0.40	12.5	0.0	6.0	0.80	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.030	0.0	0.0	660.45	1500	**RYE**
42	**RYE**	2	35.0	0.40	12.5	0.0	6.0	0.80	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.300	0.0	0.0	660.45	2000	**RYE**
43	**WHTD**	2	30.0	0.40	15.0	0.0	6.0	0.80	15.01	50.95	0.0600	0.0231	0.0130	0.0084	0.0032	0.0019	0.0209	0.0050	2.0	0.030	0.0	0.0	660.45	1500	**WHTD**
44	**WWHT**	2	30.0	0.40	15.0	0.0	6.0	0.60	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.030	0.0	0.0	660.39	1500	**WWHT**
45	**WWHT**	2	30.0	0.42	15.0	0.0	6.0	0.80	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.030	0.0	0.0	660.39	2300	**WWHT**
46	**HAY**	3	35.0	0.01	25.0	12.0	5.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.38	1500	**HAY**
47	**PAST**	3	35.0	0.01	25.0	12.0	5.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.38	1500	**PAST**
48	**SPAS**	3	35.0	0.01	25.0	8.0	5.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.38	1500	**SPAS**
49	**WPAS**	3	30.0	0.01	15.0	0.0	5.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.39	1500	**WPAS**
50	**RNGB**	3	30.0	0.01	25.0	8.0	5.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.33	1500	**RNGB**
51	**COVC**	3	35.0	0.01	25.0	8.0	5.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.38	1500	**COVC**
52	**URBN**	3	8.0	0.01	25.0	8.0	4.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.33	1500	**URBN**
53	**WATR**	3	0.0	0.01	25.0	8.0	0.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.33	1500	**WATR**
54	**WETL**	3	30.0	0.01	25.0	8.0	3.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.33	1500	**WETL**
55	**WETN**	3	30.0	0.01	25.0	8.0	3.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	0.0	0.0	660.33	1500	**WETN**
56	**FRSD**	4	16.0	0.01	20.0	6.0	2.0	0.85	10.50	25.99	0.0060	0.0020	0.0015	0.0007	0.0004	0.0003	0.0015	0.0003	2.0	0.001	0.0	18.0	660.20	1500	**FRSD**
57	**FRSE**	4	16.0	0.01	20.0	2.0	6.0	0.85	10.50	25.99	0.0060	0.0020	0.0015	0.0007	0.0004	0.0003	0.0015	0.0003	2.0	0.001	1.8	4.5	660.20	1500	**FRSE**
58	**FRST**	4	16.0	0.01	20.0	2.0	5.0	0.85	10.50	25.99	0.0060	0.0020	0.0015	0.0007	0.0004	0.0003	0.0015	0.0003	2.0	0.001	1.2	11.0	660.20	1500	**FRST**
59	**FORD**	4	16.0	0.01	20.0	2.0	5.0	0.85	10.50	25.99	0.0060	0.0020	0.0015	0.0007	0.0004	0.0003	0.0015	0.0003	2.0	0.001	0.0	18.0	660.20	2500	**FORD**
60	**FORE**	4	16.0	0.01	20.0	2.0	3.0	0.85	10.50	25.99	0.0060	0.0020	0.0015	0.0007	0.0004	0.0003	0.0015	0.0003	2.0	0.001	1.8	4.5	660.20	2500	**FORE**
61	**FORM**	4	16.0	0.01	20.0	2.0	4.0	0.85	10.50	25.99	0.0060	0.0020	0.0015	0.0007	0.0004	0.0003	0.0015	0.0003	2.0	0.001	1.2	11.0	660.20	2500	**FORM**
62	**PINE**	4	16.0	0.75	20.0	2.0	5.0	0.85	10.50	25.99	0.0060	0.0020	0.0015	0.0007	0.0004	0.0003	0.0015	0.0003	2.0	0.001	1.8	4.5	660.20	1500	**PINE**
63	**WETF**	4	30.0	0.01	25.0	8.0	3.0	0.99	15.01	50.95	0.0600	0.0231	0.0134	0.0084	0.0032	0.0019	0.0234	0.0033	2.0	0.003	1.2	11.0	660.33	1500	**WETF**
64	**GRBN**	5	25.0	0.10	27.0	10.0	1.5	0.90	10.05	80.95	0.0040	0.0030	0.0015	0.0040	0.0035	0.0015	0.0290	0.0038	1.1	0.200	0.0	0.0	660.34	1500	**GRBN**
65	**LIMA**	5	25.0	0.30	27.0	10.0	2.5	0.90	10.05	80.95	0.0040	0.0030	0.0015	0.0035	0.0030	0.0015	0.0360	0.0045	1.5	0.200	0.0	0.0	660.34	1500	**LIMA**
66	**PEAS**	5	25.0	0.30	27.0	7.0	2.5	0.60	10.05	80.95	0.0040	0.0030	0.0015	0.0030	0.0020	0.0015	0.0410	0.0051	1.1	0.200	0.0	0.0	660.34	1500	**PEAS**
67	**PNUT**	5	20.0	0.40	25.0	13.5	5.0	0.75	15.01	50.95	0.0524	0.0265	0.0258	0.0074	0.0037	0.0035	0.0650	0.0091	2.0	0.200	0.0	0.0	660.25	1500	**PNUT**
68	**SOYB**	5	25.0	0.30	25.0	10.0	5.0	0.90	15.01	50.95	0.0524	0.0265	0.0258	0.0074	0.0037	0.0035	0.0650	0.0091	2.0	0.200	0.0	0.0	660.31	1500	**SOYB**
69	**LEN1**	6	20.0	0.55	14.0	1.0	4.0	0.90	15.02	50.95	0.0524	0.0320	0.0286	0.0074	0.0037	0.0035	0.0400	0.0050	2.0	0.200	0.0	0.0	660.25	1500	**LEN1**
70	**WPEA**	6	20.0	0.55	14.0	1.0	4.0	0.90	15.02	50.95	0.0400	0.0260	0.0232	0.0070	0.0040	0.0030	0.0380	0.0050	2.0	0.050	0.0	0.0	660.25	1500	**WPEA**
71	**ALFA**	7	20.0	0.01	15.0	1.0	5.0	0.90	15.01	50.95	0.0500	0.0300	0.0200	0.0071	0.0042	0.0028	0.0250	0.0035	2.0	0.010	0.0	0.0	660.25	1500	**ALFA**

Table 3.14 Crop abbreviated names, full names and the corresponding land cover categories

Crop number	Abbreviated crop name	***Crop seasonality identificator***	Crop name	Land cover category
		Annual crops		
1	AGRL	1	agricultural land	row crop
2	ASPR	1	asparagus	row crop
3	BROC	1	broccoli	row crop
4	CABG	1	cabbage	row crop
5	CANT	1	cantaloupe	row crop
6	CAUF	1	cauliflower	row crop
7	CELR	1	celery	row crop
8	CORN	1	corn for grain	row crop
9	CORN	1	corn for grain	row crop
10	COTP	1	cotton, stripped	row crop
11	COTS	1	cotton, picked	row crop
12	CRRT	1	carrot	row crop
13	CUCM	1	cucumber	row crop
14	EGGP	1	eggplant	row crop
15	GRSG	1	sorghum	row crop
16	HMEL	1	honey melon	row crop
17	ONIO	1	onion	row crop
18	PEPR	1	pepper	row crop
19	POTA	1	potatoes	row crop
20	POTA	1	potatoes	row crop
21	RICE	1	rice	small grain
22	SBAR	1	spring barley	small grain
23	SGBT	1	sugar beet	row crop
24	SGHY	1	sorghum hay	row crop
25	SLMA	1	silage maize	row crop
26	SPIN	1	spinach	row crop
27	STRW	1	strawberries	row crop
28	SUGC	1	sugarcane	row crop
29	SUNF	1	sunflower	row crop
30	SWHT	1	spring wheat	small grain
31	TOBC	1	tobacco	row crop
32	TOMA	1	tomato	row crop
33	WMEL	1	water melon	row crop
		Annual winter crops		
34	BARL	2	barley	small grain
35	BARL	2	barley	small grain
36	BARL	2	winter barley	small grain
37	LETT	2	lettuce	row crop
38	LETL	2	lettuce, leaf	row crop
39	OATS	2	oats	small grain
40	RAPE	2	rape	row crop
41	RYE	2	rye	small grain
42	RYE	2	winter rye	small grain
43	WHTD	2	durum wheat	small grain
44	WWHT	2	winter wheat	small grain
45	WWHT	2	winter wheat	small grain

		Perennial land cover (non-forested)		
46	HAY	3	hay	perennial grass
47	PAST	3	pasture	perennial grass
48	SPAS	3	summer pasture	perennial grass
49	WPAS	3	winter pasture	perennial grass
50	RNGB	3	range-brush	brush
51	COVC	3	cover crop	grass
52	URBN	3	urban	urban
53	WATR	3	water	water
54	WETL	3	wetland	perennial grass
55	WETN	3	wetland nonforested	perennial grass
		Woods		
56	FRSD	4	forest deciduous	woods
57	FRSE	4	forest evergreen	woods
58	FRST	4	forest	woods
59	FORD	4	forest deciduous	woods
60	FORE	4	forest evergreen	woods
61	FORM	4	forest mixed	woods
62	PINE	4	pine	woods
63	WETF	4	wetland forested	woods
		Annual legumes		
64	GRBN	5	green beans	row crop
65	LIMA	5	lima	row crop
66	PEAS	5	peas	row crop
67	PNUT	5	peanut	row crop
68	SOYB	5	soybean	row crop
		Annual winter legumes		
69	LEN1	6	lentil	row crop
70	WPEA	6	winter peas	row crop
		Perennial legumes		
71	ALFA	7	alfalfa	perennial grass

Parameters included in the *crop.dat* file are:

icnum(ic) crop number. This is a reference number only

ic crop number in the database (file crop.dat)

cpnm(ic) crop name. This is a four character name to represent the crop.

ilcc(ic) land cover category:
[1] annual crop (row crop / small grain)
[2] annual winter crop (row crop / small grain)
[3] perennial (grass, brush, urban, water)
[4] woods
[5] annual legumes (row crop)
[6] annual winter legumes (row crop)
[7] perennial legumes (grass)

be(ic) biomass-energy ratio. This is the potential (unstressed) growth rate (including roots) per unit of intercepted photosynthetically active radiation. This parameter should be one of the last to be adjusted. Adjustments should be based on research results. This parameter can greatly change the rate of growth, incidence of stress during the season and the resultant crop yield. Care should be taken to make adjustments in the parameter only based on data with no drought, nutrient or temperature stress.

hi(ic) harvest index. This crop parameter is based on experimental data where crop stresses have been minimized to allow the crop to attain its potential. The model adjusts hi() as water stress occurs in the period near flowering.

to(ic) optimal temperature for plant growth, degrees C. This parameter is very stable for cultivars within a species. It should not be changed once it is determined for a species. Varietal or maturity type differences are accounted for by different sums of heat units.

tb(ic) base temperature for plant growth, degrees C. This parameter is very stable for cultivars within a species. It should not be changed once it are determined for a species. Varietal or maturity type differences are accounted for by different sums of heat units.

blai(ic) Maximum potential leaf area index. BLAI may need to be adjusted for drought-prone regions where planting densities are much smaller or irrigated conditions where densities are much greater.

dlai(ic) Fraction of growing season when leaf area declines. The fraction of the growing season in heat units in divided by the total heat units accumulated between planting and crop maturity. If the date at which leaf area normally declines is known, one of the drought options in SWIM can be used to estimate the fraction of heat units accumulated. The estimated heat units at maximum leaf area can then be divided by the heat units at maturity to estimate the fraction of the growing season at which leaf-area-index start to decline.

dlp1(ic) complex number: before decimal: fraction of growing season, after decimal: max corresponding LAI. First point on optimal leaf area development curve.

dlp2(ic) complex number: before decimal: fraction of growing season, after decimal: max corresponding LAI. Second point on optimal leaf area development curve. Explanation: Two points on optimal (non-stress) leaf area development curve. Numbers before decimal are % of growing season. Numbers after decimal are fractions of maximum potential LAI. These two points are based on research results on the % of maximum leaf area at two points in the development of leaf area.

bn1(ic) nitrogen uptake parameter #1: normal fraction of N in crop biomass at emergence, kg N/kg biomass.

bn2(ic) nitrogen uptake parameter #2: normal fraction of N in crop biomass at 0.5 maturity, kg N/kg biomass.

bn3(ic) nitrogen uptake parameter #3: normal fraction of N in crop biomass at maturity, kg N/kg biomass.

bp1(ic) phosphorus uptake parameter #1: normal fraction of P in crop biomass at emergence, kg P/kg biomass.

bp2(ic) phosphorus uptake parameter #2: normal fraction of P in crop biomass at 0.5 maturity, kg P/kg biomass.

bp3(ic) phosphorus uptake parameter #3: normal fraction of P in crop biomass at maturity, kg P/kg biomass.

cnyld(ic) fraction of nitrogen in crop yield, kg N/kg yield.

cpyld(ic) fraction of phosphorus in crop yield, kg P/kg yield.

rdmx(ic) maximum plant rooting depth (m)

cvm(ic) minimum value of C factor for water erosion. This parameter should be adjusted with intercropping or no-tillage simulations to reflect the added cover.

almn(ic) LAI minimum (for forest and natural perennial vegetation).

sla(ic) specific leaf area (m^2/kg). It is in SWIM used for forest and natural perennial vegetation.

pt2(ic) 2nd point on radiation use efficiency curve: complex number: The value to the left of the decimal is a CO^2 atmospheric concentration higher than the ambient (in units of microliters CO^2/liter air, i.e. 450 or 660). The value to the right of the decimal is the corresponding biomass-energy ratio divided by 100. Typical values of the ratio are 1.1 to 1.2 for C4 crops and 1.3 to 1.4 for C3 crops. (Kimball, B.A. 1983).

3.4.7 INPUT FILE - wgen.dat

The *wgen.dat* file includes monthly statistical weather parameter for basin or sub-basins. An example of the *wgen.dat* input file is presented in the following Table. The lines 3 – 13 include 12 monthly values.

```
 SYTHETIC WEATHER DATA
 45.000  66.000  54.000  31.770
 2.28  2.09  6.13 12.10 18.09 19.70 22.28 21.85 17.36 13.16  6.42  4.16
-2.33 -3.22   .10  3.65  7.92 10.25 12.66 12.42  9.84  6.73  1.76   .15
 0.18  0.14  0.11  0.10  0.09  0.08  0.07  0.07  0.08  0.10  0.13  0.15
56.  104.  213.  267.  512.  471.  417.  351.  282.  152.   74.   42.
 7.    7.    9.    9.   10.   10.   10.   10.    9.    9.    7.    7.
 0.37  0.34  0.35  0.33  0.32  0.29  0.35  0.41  0.51  0.55  0.56  0.38
 0.69  0.67  0.69  0.64  0.64  0.61  0.65  0.70  0.72  0.78  0.79  0.4577
 0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
 2.7   2.6   2.7   3.2   4.2   5.0   4.9   5.0   3.7   3.2   3.0   3.0
 3.3   3.05  2.54  2.79  2.54  3.30  5.08  5.84  4.57  4.57  3.81  3.05
 2.86  4.07  3.49  2.19  1.70  2.02  2.51  1.84  2.00  2.90  2.14  2.04
```

The next Table describes format of the example file *wgen.dat*, including parameter names given above the values.

```
 SYTHETIC WEATHER DATA
tp5     tp6     tp24    ylt
45.000  66.000  54.000  31.770
obmx(mo,j)
 2.28  2.09  6.13 12.10 18.09 19.70 22.28 21.85 17.36 13.16  6.42  4.16
obmn(mo,j)
-2.33 -3.22   .10  3.65  7.92 10.25 12.66 12.42  9.84  6.73  1.76   .15
cvt(mo,j)
 0.18  0.14  0.11  0.10  0.09  0.08  0.07  0.07  0.08  0.10  0.13  0.15
obsl(mo,j)
56.  104.  213.  267.  512.  471.  417.  351.  282.  152.   74.   42.
wim(mo)
 7.    7.    9.    9.   10.   10.   10.   10.    9.    9.    7.    7.
prw(1,mo,j)
 0.37  0.34  0.35  0.33  0.32  0.29  0.35  0.41  0.51  0.55  0.56  0.38
prw(2,mo,j)
 0.69  0.67  0.69  0.64  0.64  0.61  0.65  0.70  0.72  0.78  0.79  0.4577
wvl(mo,j)
 0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
rst(mo,1,i)
 2.7   2.6   2.7   3.2   4.2   5.0   4.9   5.0   3.7   3.2   3.0   3.0
rst(mo,2,j)
 3.3   3.05  2.54  2.79  2.54  3.30  5.08  5.84  4.57  4.57  3.81  3.05
rst(mo,3,j)
 2.86  4.07  3.49  2.19  1.70  2.02  2.51  1.84  2.00  2.90  2.14  2.04
```

Parameters included in the *wgen.dat* file are:

tp5(j) 10 year frequency of 0.5 h rainfall (mm). Maybe basin- or subbasin-specific.

tp6(j) 10 year frequency of 6.0 h rainfall (mm). Maybe basin- or subbasin-specific.

tp24(j) Number of years of records for estimating max 0.5 h rainfall. Maybe basin- or subbasin-specific.

ylt(j) latitude of the basin or subbasin centre

obmx(mo,j) average monthly maximum air temperature, degree C.

onmn(mo,j) average monthly minimum air temperature, degree C.

cvt(mo,j) coefficient of variation for monthly temperature

obsl(mo,j) monthly average of daily solar radiation (ly)

wim monthly maximum 0.5 h rainfall (mm) for the period of record

prw(1,mo,j) monthly probability of wet day after dry day.

prw(2,mo,j) monthly probability of wet day after dry day.

wvl(mo,j) monthly number days of precipitation in a month.

rst(mo,1,j) monthly mean event of daily rainfall.

rst(mo,2,,j) monthly standard deviation of daily rainfall.

rst(mo,3,,j) monthly skew coefficient of daily rainfall.

3.4.8 INPUT FILE - .sub

The *xxxNN.sub* file includes sub-basin parameters (where xxx is the basin name given when using GRASS interface, NN is the sub-basin number -1). An example of the *xxxNN.sub* input file format is presented in the following Table.

```
SUBBasin DATA 15 16
   0.006   0.000   0.150   0.000   3.785   0.002   2.494   0.370   0.075   0.150
   0.000 500.000   0.500 104.573   0.007
```

The next Table describes format of the example file *xxxNN.sub* , including parameter names given above the values.

```
SUBBasin DATA 15 16
   flu(j)  dum    salb(j)  sno(j) chl(1,j) chs(j) chw(1,j) chk(1,j) chn(j) ovn(j)
   0.006   0.000   0.150   0.000   3.785   0.002   2.494   0.370   0.075   0.150
   rt(j)  css(j)   ecp(j) sl(j)    stp(j)
   0.000 500.000   0.500 104.573   0.007
```

Parameters included in the *xxxNN.sub* file are:

flu(j) fraction of subbasin area in the whole basin

salb(j) soil albedo.

sno(j) initial water content of snow (mm). For long-term simulations the water content of snow on the ground at the beginning of simulation, SNO is usually not known, but in most cases the estimate is not critical after the first year. If a measured value of SNO is available at the beginning of the simulation, it should be used.

chl(1,j) main channel length (km). The channel length is the distance along the channel from the sub-basin outlet to the most distant point in the sub-basin. It is estimated from a topographic map by GRASS interface and used to calculate the sub-basin time of concentration.

chs(j) main channel slope (m/m). The average channel slope is computed by dividing the difference in elevation between the sub-basin outlet and the most distant point in the sub-basin. It is estimated from a topographic map by GRASS interface and used to calculate the sub-basin time of concentration.

chw(1,j) average width of main channel (m). It is estimated from a topographic map by GRASS interface. Not used by the current model version.

chk(1,j) effective hydraulic conductivity in channel alluvium (mm/hr). It is set to a default value of 0.37 by GRASS Interface. Not used by the current model version.

chn(j) Channel N value. The channel "n" value is Mannings's "n" value. It is set to a default value 0.075 by GRASS interface and used to calculate the sub-basin time of concentration. This value may be corrected by user.

ovn(j) Overland flow N value. The surface roughness factor is Manning's "n" values. It is set to a default value 0.150 by GRASS interface and used to calculate the sub-basin time of concentration. This value may be corrected by user. The following **Tab. 3.15** contains suggested values of Manning's "n" for various condition.

Table 3.15 Values of Manning's "n" for overland flow

Overland Flow	Value Chosen	Range
Fallow, no residue	0.0100	0.008-0.012
Conventional tillage, no residue	0.0900	0.06-0.12
Conventional tillage, residue	0.1900	0.16-0.22
Chisel plow, no residue	0.0900	0.06-0.12
Chisel plow, residue	0.1300	0.10-0.16
Fall disking, residue	0.4000	0.30-0.50
No-till, no residue	0.0700	0.04-0.10
No-till, (0.5-1.0 t/ha)	0.1200	0.07-0.17
No-till (2.0-9.0 t/ha)	0.3000	0.17-0.47
Rangeland (20% cover)	0.6000	0.40-0.70
Short grass prairie	0.1500	0.10-0.20
Dense grass	0.2400	0.17-0.30
Bermuda grass	0.4100	0.30-0.48

rt(j) Return flow travel time(days). Return flow travel time is required for subsurface flow from the centroid of the sub-basin to reach the sub-basin outlet. The value of RT is input for each sub-basin by the SWIM user, or can be calculated by SWIM if rt=0.0 from soil hydraulic properties and flow characteristics. Experienced hydrologists familiar with the base flow characteristics of watersheds within a region should have little problem assigning reasonable values to RT. However, if the user is not familiar with the watershed, SWIM will estimate RT based on the soil's saturated conductivity and a parameter called the baseflow factor.

css(j) Sediment concentration in return flow (ppm). Sediment concentration in return flow is usually very low and does not contribute significantly to total sediment yields unless return flow is very high. Unless the user is aware of unusual situations where CSS is extremely high, a value of [500.] ppm is a good estimate and will yield realistic results.

ecp(j) USLE erosion control practice factor P. Values of the USLE erosion control practice factor provided by Wischmeier and Smith are contained in **Tab. 3.16**.

Table 3.16 Water erosion control practice factor P and slope-length limits for contouring

Land Slope (%)	P Value	Max length* (ft.)
1 to 2	0.60	400
3 to 5	0.50	300
6 to 8	0.50	200
9 to 12	0.60	120
13 to 16	0.70	80
17 to 20	0.80	60
21 to 25	0.90	50

* Limit may be increased by 25% if residue cover after crop seedlings will regularly exceed 50%.

sl(j) Average slope length (m). The average slope length is estimated for each sub-basin with the Contour-Extreme Point Method (Williams and Berndt, 1977).

stp(j) Average slope steepness (m/m)-

rsdin(j) Initial residue cover (kg/ha). The RSDIN is the initial residue cover at the start of simulation

3.4.9 INPUT FILE - .gw

The *xxxNN.gw* file includes groundwater parameters (where xxx is the basin name given when using GRASS interface, NN is the sub-basin number -1). An example of the *xxxNN.gw* input file format is presented in the following Table.

```
Groundwater DATA 15 16
    1.0000    0.5000    0.0480    0.0030  200.0000    0.2000    0.0500    0.0000
```

The next Table describes the format of the example file *xxxNN.gw*, including parameter names given above the values.

```
Groundwater DATA 15 16
    gwht(j)   gwq(j)    abf(j)    syld(j) delay(j)    revapc(j) rchrgc(j)
revapmn(j)
    1.0000    0.5000    0.0480    0.0030  200.0000    0.2000    0.0500    0.0000
```

Parameters included in the *xxxNN.gw* file are:

gwht(j) Initial groundwater height (m)

gwq(j) Initial groundwater flow contribution to streamflow (mm/day)
In SWIM: gwq(j) = gwq0

abf(j) alpha factor for groundwater. ABF characterizes the groundwater recession and the rate at which groundwater flow is returned to the stream.
In SWIM: abf(j) = abf0

syld(j) Specific yield

delay(j) groundwater delay (days). The time it takes for water leaving the bottom of the root zone until it reaches the shallow aquifer where it can become groundwater flow.
In SWIM: delay(j) = exp(-1./(delay(i)+1.e-6))

revapc(j) Revap coefficient (0-1) is the fraction of recharge (root zone percolation) that goes to REVAP. The amount of evaporation from the shallow aquifer is determined by multiplying potential ET by REVAPC.

rchrgc(j) Deep aquifer percolation coefficient (0-1). The amount of water that percolates into the deep aquifer (from the shallow aquifer) is determined by multiplying root zone percolation by RCHRGC.

revapmn(j) Revap storage (mm). Shallow aquifer storage must exceed REVAPMN before groundwater flow can begin.

3.4.10 INPUT FILE - .rte

The *xxxNN.rte* file includes channel routing parameters (where xxx is the basin name given when using GRASS interface, NN is the sub-basin number -1). An example of the *xxxNN.rte* input file format is presented in the following Table.

```
SUBBasin Routing DATA 15 16
  19.447   0.793   0.002   3.785   0.050   1.000   0.280   1.000
```

The next Table describes format of the example file *xxxNN.rte*, including parameter names given above the values.

```
SUBBasin Routing DATA 15 16
  chw(2,j) chd(j) chss(j) chl(2,j) chnn(j) chk(2,j) chxk(j) chc(j)
  19.447   0.793   0.002   3.785   0.050   1.000   0.280   1.000
```

Parameters included in the *xxxNN.rte* file are:

chw(2,j) Average channel width (m). It is estimated from a topographic map by GRASS interface and used for routing. May be substituted by actual channel width if available.

chd(j) Average channel depth (m). If detailed channel cross-section data is unavailable, this parameter is estimated from a topographic map by GRASS interface and used for routing. May be substituted by actual channel depth if available.

chss(j) Channel slope (m/m). If detailed channel cross-section data is unavailable, this parameter is estimated from a topographic map by GRASS interface and used for routing. May be substituted by actual channel slope if available.

chl(2,j) Channel length (km). If detailed channel data is unavailable, this parameter is estimated from a topographic map by GRASS interface and used for routing. May be substituted by actual channel length if available.

chnn(j) Channel n value (mm/hr). The channel "n" value is Mannings' "n" value. It is set to a default value 0.050 (as for natural streams with few trees, stones and brush) by GRASS interface and used to calculate routing. This value may be corrected by user. The typical values of chnn() are given in **Tab. 3.17** for different streams.

Table 3.17 Values of Manning's "n" for channels

Channel Flow	*Value Chosen*	*Range*
Excavated or dredged		
Earth, straight and uniform	0.0250	0.016-0.033
Earth, winding and sluggish	0.0350	0.023-0.05
Not maintained, weeds and brush	0.0750	0.04-0.14
Natural streams		
Few trees, stones, or brush	0.0500	0.025-0.065
Heavy timber and brush	0.1000	0.05-0.15

chk(2,j) Effective hydraulic conductivity in channel alluvium (mm/hr). It is set to a default value 1.0 (as for very low loss rate) by GRASS interface and used to calculate routing. This value may be corrected by user. Effective hydraulic conductivity of the channel alluvium is given in **Tab. 3.18** for various channel bed material.

Table 3.18 Effective hydraulic conductivity of the channel alluvium

Bed Material Group	Bed Material Characteristics	Effective Hydraulic Conductivity (mm/hr)
1 Very high loss rate	Very clean gravel and large sand d50>2 mm	>127
2 High loss rate	Clean sand and gravel under field conditions, d50>2 mm	51-127
3 Moderate high loss rate	Sand and gravel mixture with less than a few percent silt-clay	25-76
4 Moderate loss rate	Mixture of sand and gravel with significant amounts of silt-clay	6.4-25
5 Very low loss rate	Consolidated bed material with high silt-clay content	0.025-2.5

chxk(j) erodibility of stream channel, or USLE soil factor K for channel (range: 0-1). chxk=0 indicates a nonerosive channel, while chxk = 1 indicates no resistance to erosion. It is set to a default value 0.28 by GRASS interface and used in calculating routing. This value may be corrected by user.

chc(j) Cover factor for stream channel, or USLE soil factor C for channel (range: 0-1). If there is no vegatative cover, chc = 1. It is set to a default value of 1.0 (no vegetative cover) by GRASS interface and used to calculate routing. This value may be corrected by user.

3.4.11 INPUT FILE - wstor.dat

The *wstor.dat* file sets initial storage values for the reaches. It lists all reaches and the corresponding initial water storage in m^3. The values for initialisation can be obtained from a test run, considering the simulated water storage at the end of the first year.

i1 reach, corresponding to the subbasin i1

sdtsav initial water storage in the reach i1

3.4.12 INPUT FILE - soilNN.dat

The *soilNN.dat* files include soil parameters (where, NN is the soil type number). An example of the *soilNN.dat* input file format is presented in the following Table.

```
  36   5
Tschernosem aus Loess
  Ap      Ap Ahl    AhBt     Bt
  Ut3     Ut3       Ut3      Lu      Ut3
  10.    300.0   600.0  1000.0  1100.0
  15.     15.     15.     25.     15.
  75.     75.     75.     60.     75.
  10.     10.     10.     15.     10.
   1.40    1.40    1.50    1.70    1.6
  52.5    52.5    50.5    45.5    40.5
  26.5    26.5    26.     17.5    23.5
  41.5    41.5    40.     39.     36.
   2.0     2.0     1.2     0.9     0.
   0.2     0.2     0.1     0.      0.0


   0.56
  16.7    16.7    10.4     4.2    10.4
```

The next Table describes format of the example file *soilNN.dat,* including parameter names given above the values.

```
  k   ns(k)
  36   5
  sname(k)
 Tschernosem aus Loess
  Ap      Ap Ahl    AhBt     Bt
  Ut3     Ut3       Ut3      Lu      Ut3
  z(l,k)
  10.    300.0   600.0  1000.0  1100.0
  cla(l,k)
  15.     15.     15.     25.     15.
  sil(l,k)
  75.     75.     75.     60.     75.
  san(l.k)
  10.     10.     10.     15.     10.
  por(l,k)
   1.40    1.40    1.50    1.70    1.6
  poros(l,k)
  52.5    52.5    50.5    45.5    40.5
  awc(l,k)
  26.5    26.5    26.     17.5    23.5
  fc(l.k)
  41.5    41.5    40.     39.     36.
  cbn(l,k)
  2.0     2.0     1.2     0.9     0.
  wn(l,k)
  0.2     0.2     0.1     0.      0.0

  ek(k)
   0.56
  sc(l,k)
  16.7    16.7    10.4     4.2    10.4
```

Parameters included in the soilNN.dat file are:

k soil type number in a database

ns(k) number of soil layers for soil k. Number of soil layers for soil. The number of soil layers is assigned by the user. Usually the depths to the bottom of the layers are assigned in accordance with available database. Up to 10 layers are allowed, the first layer should be a depth of 10 mm.

snam(k) name of soil k

z(l,k) depth to bottom of layers l=1,...,ns(k) in mm

cla(l,k) clay content in %

sil(l,k) silt content %

san(l,k) sand content, %

por(l,k) bulk density (g/cm^3) (input), then recalculated to porosity

poros(l,k) porosity, % (if available). If available water capacity, field capacity or total porosity values are missing, they can be estimated based on texture as in **Tab. 3.19**.

awc(l,k) available water capacity, %. If available water capacity, field capacity or total porosity values are missing, they can be estimated based on texture as in **Tab. 3.19**.

fc(l,k) field capacity, %. If available water capacity, field capacity or total porosity values are missing, they can be estimated based on texture as in **Tab. 3.19**.

cbn(l,k) organic carbon content (%)

wn(l,k) organic nitrogen content (%)

wno3(l,k) initial NO3-N content (kg/ha), if available. Otherwise, it will be estimated from wn().

ap(l,k) labile (soluble) phosphorus (g/t), if available. Otherwise, it will be estimated.

ek(k) soil erodibility factor K (for USLE)

sc(l,k) saturated conductivity (mm/h)

The following **Tab. 3.19** may be useful, if all necessary soil parameters are not available.

Table 3.19 Mean physical properties of soils (from Svetlosanov and Knisel, 1982)

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Texture	*Volume (m/m)*				
	Bulk Density (gm/cm)	*Total Porosity*	*Field Capacity 1/3 bar*	*Wilting Point 15 bar*	*Available Water Capacity*
Coarse sand	1.600	0.40	0.11	0.03	0.080
Sand	1.600	0.40	0.16	0.03	0.130
Fine sand	1.500	0.43	0.18	0.03	0.150
Very fine sand	1.500	0.43	0.27	0.03	0.250
Loamy coarse sand	1.600	0.40	0.16	0.05	0.110
Loamy sand	1.600	0.40	0.19	0.05	0.140
Loamy fine sand	1.600	0.40	0.22	0.05	0.180
Loamy very fine sand	1.600	0.40	0.37	0.05	0.320
Coarse sandy loam	1.600	0.40	0.19	0.08	0.110
Sandy loam	1.600	0.40	0.22	0.08	0.140
Fine sandy loam	1.700	0.36	0.27	0.08	0.190
Very fine sandy loam	1.600	0.40	0.37	0.08	0.290
Loam	1.600	0.40	0.26	0.11	0.150
Silt loam	1.500	0.43	0.32	0.12	0.200
Silt	1.400	0.47	0.27	0.03	0.240
Sandy clay loam	1.600	0.40	0.30	0.18	0.120
Clay loam	1.600	0.40	0.35	0.22	0.130
Silty clay loam	1.400	0.47	0.36	0.20	0.160
Sandy clay	1.600	0.40	0.28	0.20	0.130
Silty clay	1.500	0.48	0.40	0.30	0.140
Clay	1.400	0.47	0.39	0.28	0.110

3.4.13 BLOCK DATA in the file init.f

Curve Numbers for 15 land use categories are initialized in block data (file init.f). The following values summarized in **Tab. 3.20** are assigned for land use categories and soil groups in SWIM. **Tab. 3.21** presents SCS runoff curve numbers for a variety of land use/land cover categories.

Table 3.20 Curve Numbers for land use categories and four soil groups used in SWIM

Land Use No.	*Land use category*	*Soil group*				*Source in SCS Tables*
		A	*B*	*C*	*D*	
1	Water	100.	100.	100.	100.	
2	Settlement	72.	79.	85.	88.	Urban areas, medium density
3	Industry	81.	88.	91	93	Industrial
4	Road	98.	98.	98.	98.	Paved streets and roads
5	Cropland	65.	75.	82.	86.	Row crops, contoured
6	Set-aside	66.	77.	85.	89.	Rotation meadow
7	Extensive grassland (meadow)	30.	58.	71	78.	Meadow, continuous grass
8	Intensive grassland (pasture)	49.	69.	79.	84.	Pasture, continuous forage for grazing
9	Mixed forest	36.	60.	73.	79.	Woods, fair
10	Evergreen forest	36.	60.	73.	79.	Woods, fair
11	Deciduous forest	36.	60.	73.	79.	Woods, fair
12	Wetland nonforested	85.	85.	85.	85.	
13	Wetland forested	85.	85.	85.	85.	
14	Heather (grass + brushland)	35.	56.	70.	77.	Brush-weed-grass mixture with brush the major element
15	Bare soil	77.	86.	91.	94.	

Table 3.21 SCS Curve Numbers for a variety of land use/land cover categories

Land Use/Crop	Cover	Condition	A	B	C	D
Fallow	Straight row	---	77.0	86.0	91.0	94.0
Row crops	Straight row	Poor	72.0	81.0	88.0	91.0
		Good	67.0	78.0	85.0	89.0
	Contoured	Poor	70.0	79.0	84.0	88.0
		Good	65.0	65.0	82.0	86.0
	Contoured and terraced	Poor	66.0	74.0	80.0	82.0
		Good	62.0	71.0	78.0	81.0
Small grain	Straight row	Poor	65.0	76.0	84.0	88.0
		Good	63.0	75.0	83.0	87.0
	Contoured	Poor	63.0	74.0	82.0	85.0
		Good	61.0	73.0	81.0	84.0
	Contoured and terraced	Poor	61.0	72.0	79.0	82.0
		Good	59.0	70.0	78.0	81.0
Close-seeded legumes* or rotation meadow	Straight row	Poor	66.0	77.0	85.0	89.0
		Good	58.0	72.0	81.0	85.0
	Contoured	Poor	64.0	75.0	83.0	85.0
		Good	55.0	69.0	78.0	83.0
	Contoured and terraced	Poor	63.0	73.0	80.0	83.0
		Good	51.0	67.0	76.0	80.0
Pasture or range	Straight row	Poor	68.0	79.0	86.0	89.0
		Fair	49.0	69.0	79.0	84.0
		Good	39.0	61.0	74.0	80.0
	Contoured	Poor	47.0	67.0	81.0	88.0
		Fair	25.0	59.0	75.0	83.0
		Good	6.0	35.0	70.0	79.0
Meadow		Good	30.0	58.0	71.0	78.0
Woods		Poor	45.0	66.0	77.0	83.0
		Fair	36.0	60.0	73.0	79.0
		Good	25.0	55.0	70.0	77.0
Farmsteads		---	59.0	74.0	82.0	86.0
Roads (dirt)**		---	72.0	82.0	87.0	89.0
Roads (hard surface)**		---	74.0	84.0	90.0	92.0

4. How to Prepare Data and Run SWIM

The model runs under the UNIX environment with the daily time step. The SWIM/GRASS interface is used to initialise the model by extracting spatially distributed parameters of elevation, land use, soil types, closest climate/precipitation station, and the routing structure.

The preparation to the modelling consists of the following steps:

- preparation of spatial data in GRASS (described in 4.1),
- run SWIM/GRASS interface using the spatial data in GRASS (described in 4.2),
- preparation of relational data (described in 4.3), which includes:
    - climate data (in 4.3.2),
    - soil data (4.3.3),
    - crop management data (4.3.4)
    - hydrological and water quality data (4.3.5)
- copy all input data in the working directory and modification of several data-handling routines, if necessary (described in 4.4).

After that the model can be run. The calibration parameters and some examples of the model sensitivity studies are given in 4.5.

4.1 Spatial Data Preparation

First, an overview of necessary spatial data in given in 4.1.1. After that, two important questions: how the resolution of the Digital Elevation Model is related to the basin area, and how the average sub-basin area must be chosen, are discussed in 4.1.2 and 4.1.3. Then a short overview of GRASS GIS is given in 4.1.4, and some GRASS operations, useful for spatial data preparation, are described in 4.1.5 and 4.1.6. A specific program for watershed analysis *r.watershed* is described separately in 4.1.7. A DEMO data set is given in 4.1.8

4.1.1 GIS Data Overview

The full list of necessary spatial data (digitised maps) is the following:
1. Digital Elevation Model (DEM),
2. land use map,
3. soil map,
4. map of basin and sub-basins boundaries,
5. map of river network,
6. map of river gage stations,
7. alpha-factor map for groundwater,
8. map of climate stations,
9. map of Thiessen polygons for climate stations,
10. map of precipitation stations,
11. map of Thiessen polygons for precipitation stations
12. map of point sources of pollution.

All the maps can be provided in ARC/INFO or GRASS format.

The first four maps: DEM, land use, soil and sub-basins are absolutely necessary to run the SWIM/GRASS ínterface and initialise the model (see, for example, **Fig. 4.1**).

For the DEM resolution is important (see 4.1.2). The soil map has to be connected to soil parameters (see a detailed description in 4.3.3). The land use map has to be reclassified for SWIM to a map with the following categories:

n = 1 - water
n = 2 - settlement
n = 3 - industry
n = 4 - road
n = 5 - cropland
n = 6 - set-aside
n = 7 - grassland, extensive use (meadow)
n = 8 - grassland, intensive use (pasture)
n = 9 - forest mixed
n = 10 - forest evergreen
n = 11 - forest deciduous
n = 12 - wetland nonforested
n = 13 - wetland forested
n = 14 - heather (grass + brushland)
n = 15 - bare soil

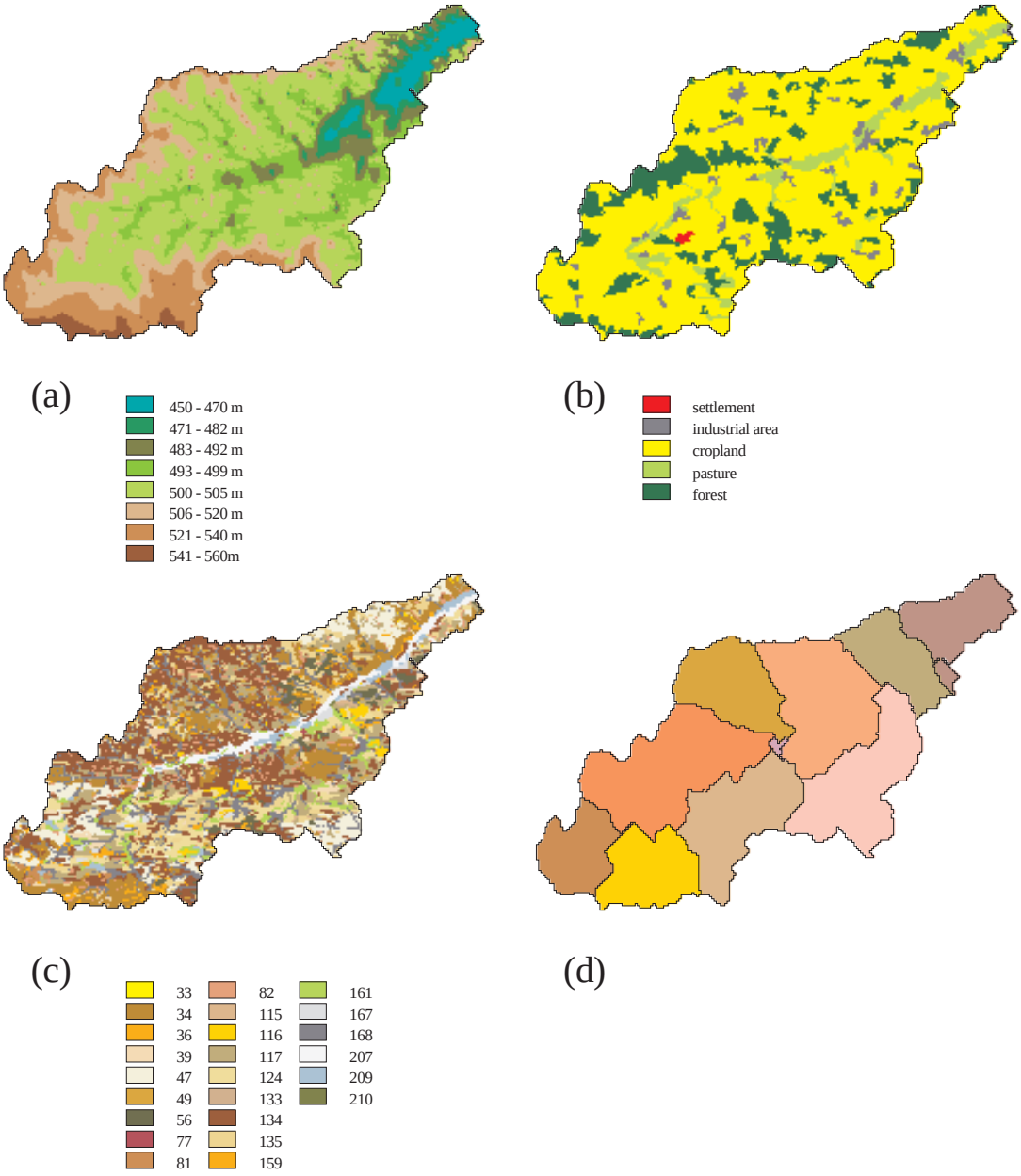


Fig 4.1 A set of four maps: Digital Elevation Model (a), land use (b), soil (c), and sub-basins (d) that are necessary to run SWIM/GRASS interface

The fourth, sub-basin map, can be created in GRASS based on the DEM map using the *r.watershed* program. Here the DEM resolution is important (see 4.1.2 for more details). There is a certain restriction on the average sub-basin area in SWIM, which has to be kept (see more details in 4.1.4). Together with sub-basins, the virtual river network can be calculated, which is useful for checking the routing structure.

The map of river network (5) is useful for comparison with the virtual river network calculated by *r.watershed*, and for checking the routing structure. Comparison of river networks calculated in GRASS and digitazed is demonstrated in **Fig. 4.2** for the Mulde basin.

The map of river gage stations (6) can be used for delineation of the basin boundaries, if the sub-basin map is created in GRASS.

The alpha-factor map for groundwater (7) is useful, if the ground water table has to be modelled specifically for the basin under study.

Maps of climate and precipitation stations and the corresponding maps of Thiessen polygons (8-11) are more important for larger basins, having several climate/precipitation stations. For smaller basins this information can be extracted directly from available paper maps. The Thiessen polygons can be also calculated in GRASS version 4.2 using the functions *s.geom* or *v.geom*.

A map of point sources of pollution (12) is necessary in case of water quality modelling, when the simulated load is compared with the observed load, and the point sources of pollution contribute a significant part in the river load and must be taken into account.

An important question is how to choose an adequate spatial resolution for the mesoscale river basin under study. This problem is of fundamental significance for hydrological and hydrochemical process modelling.

First of all, the spatial resolution and the time increment of the model are interrelated. SWIM is not designed for detailed modelling of flood processes with $\Delta T < 1$ day. Also, we exclude very flat areas with many lakes, where travelling time becomes too large. These problems require specific modelling tools. With these exceptions, the problem of spatial resolution appears in at least two very important questions:

- how the resolution of the Digital Elevation Model (DEM) is related to the watershed area, and
- whether an upper limit of a sub-basin area exists below which the effect of the river network can be neglected.

These two questions are discussed in 4.1.2 and 4.1.3.

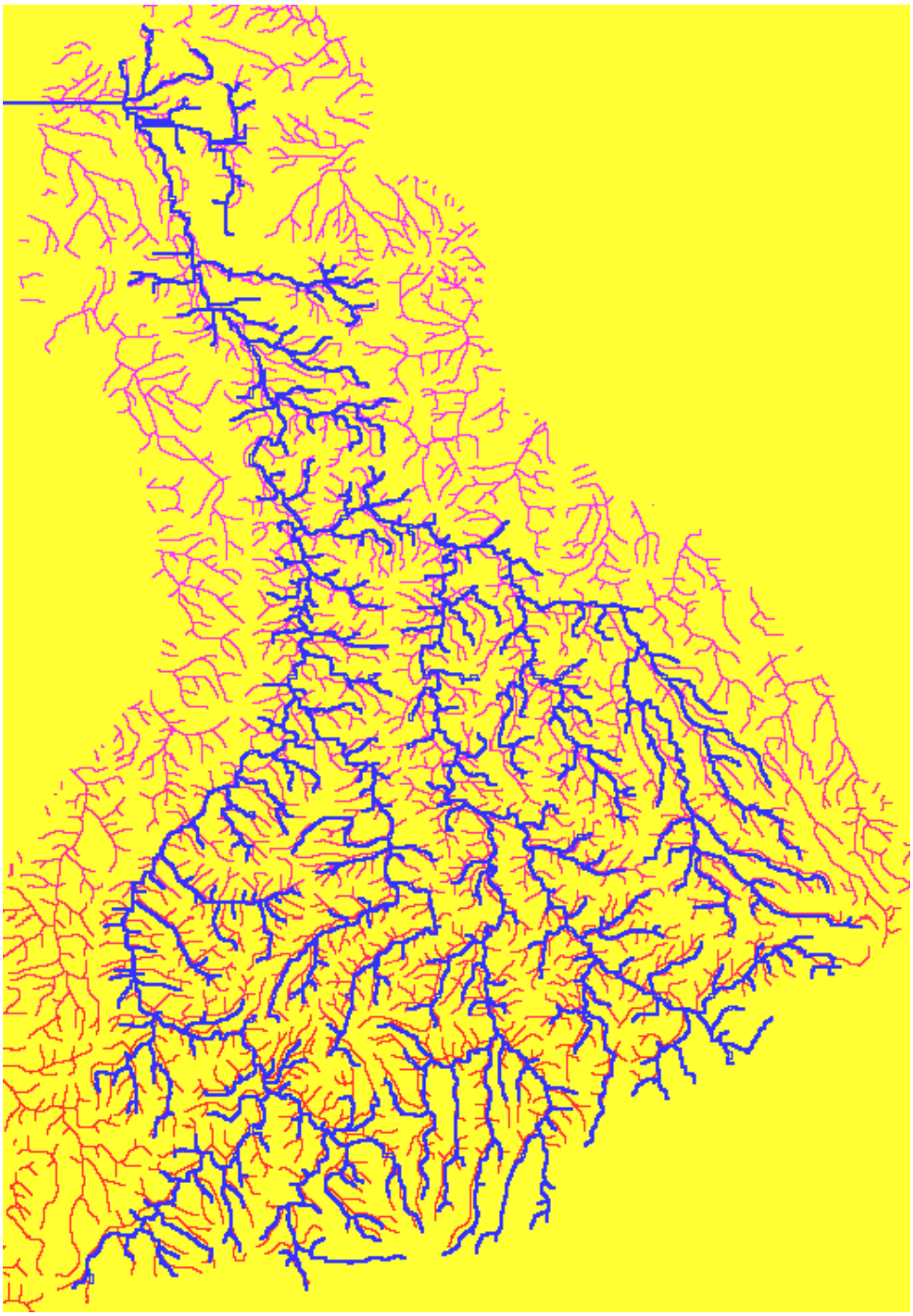


Fig. 4.2 Comparison of a virtual river networks produced by GRASS (blue) and a digitazed river network (red)

4.1.2 How to Choose Spatial Resolution?

Answering the first question, Maidment (1996) suggests using the so-called „thousand-million“ rule as a rough guide: take the area of the region under study and divide it by one million to give the appropriate cell size (area) to be used, then multiply the cell size chosen by one thousand which is then the minimum drainage area of watersheds that should be delineated from this DEM. This rule should not be understood as an absolute one, but should be treated with a certain level of approximation.

According to this rule, 930 m resolution should be used for delineation of a watershed with the drainage area of 4000 km^2, 460 m resolution for a 1000 km^2 watershed, 90 m for a 40 km^2 watershed, and 30 m for a 5 km^2 catchment. This is in agreement with our modelling experience from the studies performed in the Elbe drainage basin, where 100 m resolution was acceptable to represent a catchment of 64 km^2, 200 m resolution was sufficient to delineate a watershed with an area of 535 km^2, and 1000 m resolution was satisfactory for extracting watersheds with an area of 3,000-4,000 km^2.

Maidment (1996) also provides a useful Table showing the recommended cell size of DEM for some typical applications. For example, for a region size of 1000 km^2 a linear cell size of 30 m, and a sub-basin size of 5 km^2 are recommended. In the region with an area of 8000 km^2 the sub-basins of 40 km^2 can be delineated based on 90 m resolution. For a region size of 200,000 km^2 the recommended resolution is 460 m, and the sub-basin size 4000 km^2.

Following this rule more strictly, we can suggest the following **Tab. 4.1** for some commonly used resolutions:

Table 4.1 Recommended resolution of DEM for some typical applications

Linear cell size, m	*Cell area, km^2*	*Sub-basin area, km^2*	*Region or basin size, km^2*
30	0.0009	1	1,000
100	0.01	10	10,000
200	0.04	40	40,000
500	0.25	250	250,000
1000	1.	1,000	1,000,000

Of course, in practice these recommendations should be used with some degree of freedom.

4.1.3 How to Choose the Average Sub-basin Area?

The second question relates to the upper limit of the sub-basin area, below which the effect of the river network can be neglected, and the choice of the average sub-basin area when creating the sub-basin map.

According to Beven and Kirkby (1979), the effect of the channel network becomes important for basins larger than about 10 km^2, where the time constant of the network (i.e. travel time through it) becomes as long as for the infiltration phase. This is especially important for lowland, where the time constant may be very large.

On the other hand, in mountainous areas, where the time constant is rather low, the sub-basin area must be restricted due to climate gradients, because, as it was already explained in Chap. 1, the climate input in SWIM is considered to be homogeneous in sub-basins.

It is also known that 5 to 10 km (or 25 to 100 km^2) appears to be the minimum scale, above which inhomogeneities in land surface properties can trigger specific mesoscale atmospheric circulation systems, which have a definite impact on interactions between land surface and the atmosphere (Kuchment, 1992).

So the following pragmatic conclusion might be drawn: an average sub-basin area, where the effect of the river network may be neglected, should be in a range of 10 to 100 km^2 and definitely not larger than 100 km^2.

The restrictions on average sub-basin area and time step influence the computing time, and, taken together with the data availability, define the upper limit of the sub-basin area for the model application. An adequate spatial disaggregation should allow the applicability of the model to be extended to larger basins.

4.1.4 GRASS GIS Overview

GRASS (Geographic Resource Analysis Support System) (GRASS4.1, 1993) is a public domain raster GIS originally developed by the Environmental Division of the US Army Construction Engineering Research Laboratory (USA-CERL) as a general-purpose spatial modelling and analysis package. Since then, GRASS has evolved into a powerful tool with a wide range of applications in many different areas of scientific research. The new headquarters for GRASS support, research, and development is at Baylor University, the Department of Geology. Recently GRASS was upgraded to version 4.2, and the version 5.0 is underway.

GRASS is highly interactive and graphically oriented, providing tools for developing, analysing, and displaying spatial information. GRASS runs through the use of standardised command line input or under the X Window system under the UNIX environment. The following data formats are supported by GRASS:

- raster,
- vector,
- sites,
- satellite and air-photo image,
- import from ASCII, DXF, Image, and others,
- export to ASCII, DXF, Image, and others.

Though GRASS is the raster-based GIS, it can handle different data representations:

- raster (or grid cell) data can be analysed, overlayed, recalculated,
- vector data can be combined with raster data for display or analysis,
- point data can be used to represent the locations of significant sites.

New maps can be digitised or scanned. Maps can also be transferred from other GIS systems like ARC/INFO. Data files can be developed for large or small geographic regions at any scale desired within the limits of the source data and the storage capacity of the hardware.

GRASS was successfully coupled with a number of hydrological and water quality models, like ANSWERS, AGNPS, TOPMODEL, SWAT, and SWIM (Srinivasan and Engel, 1991; Rewerts and Engel, 1991; Chairat and Delleur, 1993; Srinivasan and Arnold, 1994; Krysanova *et al*., 1998a) in order to facilitate input of spatially-distributed information and enhance the use and utility of the models.

First of all, GRASS raster capabilities are very attractive for the use in spatially-distributed hydrological modelling, because spatial data can be easily translated from the GIS to the model in order to initialise it, and the model outputs can be transferred to GIS again for visualisation and analysis purposes. Second, GRASS is a public domain GIS, all program codes are available. This is different from other packages like ARC/INFO, and significantly facilitates further software development. Third, GRASS is written in the C programming language, which is also widely used for modelling. Forth, GRASS is flexible enough for a variety of applications, as soon as data layers can be transported to and from several other GIS, including ARC/INFO. Last, but not least, GRASS has specific programs for hydrological modelling and interpolation, which can be very useful.

According to our experience the combination of ARC/INFO and GRASS packages can be especially powerful, when ARC/INFO is used mainly for preparation and editing of basic map layers, and afterwards GRASS is used for analysis, reclassification, overlaying, recalculation and application of specific hydrological tools.

4.1.5 Useful GRASS Programs and Functions

GRASS includes special programs and functions for Display (starting with d.), General functions (g.), Raster functions (r.), Vector functions (v.), Sites functions (s.), Imagery functions (i.), as well as some other contributed programs and shell scripts.

Import/Export programs There are a number of transformation programs between GRASS and different other formats: ASCII (*v.in.ascii, v.out.ascii, r.in.ascii, r.out.ascii*), ARC/INFO (*v.in.arc, v.out.arc, r.in.ascii, r.out.ascii*), DXF (*v.in.dxf, v.out.dxf*), DLG (*v.import*), DLG-3 (*v.in.dlg, v.out.dlg*), MOSS (*v.out.moss*). When a map layer has been converted to a GRASS raster format, all raster support files (cellhd, cell_misc, cats, colr, and hist) must be checked for accuracy and completeness. The *r.support* program must be run to modify these files if necessary. Transformation routines sometimes do not work smoothly. It can be due to the fact that the requirements and steps are not sufficiently described in the Manual.

Conversion programs A GRASS database can be based upon one of four different coordinate systems: UTM, SPCS (State Plane Coordinate System), latitude/longitude, or Cartesian coordinate (x/y) system. The map projection that is most commonly used for maps in a GRASS database is the Transverse Mercator projection which is the basis for the to Universal Transverse Mercator (UTM) coordinate system. There are five programs available for conversion purposes:

m.ll2u	- converts geographic coordinates to Universal Transverse Mercator (UTM) coordinates for a number of spheroids,
m.u2ll and *m.region.ll*	- convert Universal Transverse Mercator (UTM) coordinates falling within the current geographic region to geographic (latitude/longitude) coordinates,
m.gc2ll	- converts geocentric to geographic coordinates for a number of possible spheroids,
m.ll2gc	- converts geographic coordinates to geocentric.

The use of geographic coordinates in GRASS is still rather restricted.

Display and printout It is not so easy to create the good-quality printed maps in GRASS that look professional. There is no automatic way to create legend with user-specified options, bar scale, north arrow. The *p.map* script file has to be created in advance in order to create a postscript file and then a map can be printed. The other possibility is to use any *screendump* or *grab* procedure, which is available in a number of packages, and then to add additional features using these tools. Some new capabilities in the map printing program are designed now.

Special hydrological support programs There are several programs in GRASS, which provide support for hydrological modelling. The program *r.watershed* is the main tool for delineation of basin and sub-basin boundaries based on DEM, and for calculating the LS (slope length and steepness) and S (slope steepness) factors of the Revised Universal Soil Loss Equation (RUSLE) (see more detailed description in 4.1.6). There are some more hydrologically-oriented programs in GRASS, like *r.basins.fill, r.cost, r.drain* as well as the useful interpolation tools.

The *r.basins.fill* program is similar to *r.watershed* but does not require DEM. It generates a raster map layer depicting sub-basins, based on two maps: 1) the coded stream network (each channel segment is „coded“ with a unique category value) and 2) the ridges within the given watershed (including the ridge which defines the perimeter of the watershed). The resulting output raster map layer codes the sub-basins with category values matching those of the channel segments passing through them.

The *r.cost* program determines the cumulative cost of moving to each cell on a cost surface (the input raster map) from other specified cell(s) whose locations are specified by their coordinates, and the *r.drain* program traces a flow through a least-cost path in an elevation model. The results for cells are similar to those obtained when using the *seg* version of the *r.watershed* program.

Interpolation programs There are two programs in GRASS for the interpolation from point data (*s.surf.idw* and *s.surf.tps*) and two programs for the interpolation from raster data (*r.surf.idw* and *r.surf.idw2*). The *s.surf.idw* fills a raster matrix with interpolated values generated from a set of irregularly spaced data points using numerical approximation (weighted averaging) techniques. The interpolated value of a cell is determined by values of nearby data points and the distance of the cell from those input points. In comparison

with other methods, numerical approximation allows representation of more complex surfaces (particularly those with anomalous features), and restricts the spatial influence of any errors.

The *s.surf.tps* interpolates and computes topographic analysis from given site data (digitised contours, climatic stations, drill holes, etc.) to GRASS raster format using spline with tension. As an option, simultaneously with interpolation, topographic parameters like slope, aspect, profile curvature (measured in the direction of the steepest slope), tangential curvature (measured in the direction of a tangent to a contour line) or mean curvature are computed and saved as raster files. Topographic parameters are computed directly from the interpolation functions so that the important relationships between these parameters are preserved. The equations and their interpretation are described in Mitasova et al., 1996.

Two programs *r.surf.idw* and *r.surf.idw2* fill a grid cell (raster) matrix with interpolated values generated from a set of input layer data points or irregularly spaced data points. They use a numerical approximation technique based on distance squared weighting of the values of nearest data points. The number of nearest data points used to determine the interpolated value of a cell can be specified by the user (default: 12 nearest data points). Unlike *r.surf.idw2*, which processes all input data points in each interpolation cycle, *r.surf.idw* attempts to minimise the number of input data for which distances have to be calculated. Execution speed is therefore a function of the search effort and does not increase appreciably with the number of input data points. The r.surf.idw2 does not work with latitude/longitude data, in such a case the r.surf.idw should be used.

There are a number of useful GRASS commands, which are necessary for any SWIM user. They are needed for visualisation, recalculation, and reclassification of map layers. In the **Appendix I** the most useful GRASS commands are listed, which are needed for spatial data preparation.

4.1.6 Map Export from ARC/INFO to ASCII Format

Raster Data in ARC/INFO A raster data set in ARC/INFO is called a "Grid". All operations on grids are performed in the module with the same name. The resolution (or cell size) of any existing grid can be changed using the resample function, which offers different algorithms for categorial and continuous data. Conversion from vector to raster data in ARC/INFO can be either done on the Arc prompt, or within Grid. Both procedures are similar and can be performed with polygon, line or point input data. The user has to define the desired cell size, because one coverage can be gridded using different resolutions. By defining the coordinates of a lower left corner and a desired number of rows and columns, the processing can be focussed on a certain part of the coverage, if necessary. As GRASS version 4.2 does not yet support the NODATA data format, it is recommended to select ARC/INFO's ZERO option using "0" as NODATA (or background) value.

Data Exchange between ARC/INFO and GRASS As neither GRASS 4.2 can import ARC/INFO grids, nor ARC/INFO can read GRASS raster maps directly, the data exchange between both systems should be performed using ASCII format. Both systems can produce and read ASCII files containing the data as a continuous stream of values separated by blanks. The information about how to produce a raster map for the system is stored in a header section containing the coordinates of the corner (or north, south, east west coordinates) and the number of rows and columns. ARC/INFO's header format looks like

NCOLS xxx
NROWS xxx
XLLCORNER xxx
YLLCORNER xxx
CELLSIZE xxx
NODATA_VALUE xxx,

whereas GRASS uses the following header:

north: xxx
south: xxx
east: xxx
west: xxx
rows: xxx
cols: xxx

An example of data conversion Let us assume that we want to grid a polygon coverage called "lupoly" containing land use information (item lu-code) with cell size 50 and a line coverage "fgw" containing the stream network of the same region. The necessary commands are listed below (the comments are between **).

Step 1:
Usage: POLYGRID <in_cover> <out_grid> {value_item} {lookup_table} {weight_table}
Arc: POLYGRID lupoly lugrd lu-code

Converting polygons from lupoly to grid lugrd
Cell Size (square cell): 50
Convert the Entire Coverage? (Y/N): y
Number of Rows = 648 ** the value is calculated by the program**
Number of Columns = 604 ** the value is calculated by the program**

Step 2:
Usage: LINEGRID <in_cover> <out_grid> {value_item} {lookup_table} {weight_table}
Arc: LINEGRID fgw fgwgrd

Converting arcs from fgw to grid fgwgrd
Cell Size (square cell): 50
Convert the Entire Coverage(Y/N)?: y
Enter background value (NODATA | ZERO): zero
Number of Rows = 493 ** the value is calculated by the program**
Number of Columns = 553 ** the value is calculated by the program**

An example of changing the cellsize of an existing grid Let us assume that we want to change the cell size of lugrd from its original size of 50 cells to 100 cells using the nearest-neighbour assignment as default option. (N.B.: This of course could be done earlier when prompted during POLYGRID).

Arc: grid ** starts the grid module**

Grid: lugrd2 = resample(lugrd,100)
Resample ...
Grid: quit ** leaves the grid module**

An example of export to ASCII file Let us assume that now we want to export lugrd and fgwgrd to ASCII files.

Usage: GRIDASCII <in_grid> <out_ascii_file> {item}
Arc: GRIDASCII lugrd lugrd.txt
Arc: GRIDASCII fgwgrd fgwgrd.txt

The header of lugrd.txt is:

```
ncols         604
nrows         648
xllcorner     4492676.68
yllcorner     5884875.398
cellsize      50
NODATA_value  -9999
```

The header of fgwgrd.txt is:

```
ncols         553
nrows         493
xllcorner     4494452.5
yllcorner     5886652
cellsize      50
NODATA_value  -9999
```

It is obvious that although both grids have the same cell size, they do not match, because their llcorners' coordinates' difference is not a multiple of their cell size. In such a case it is recommended to use the coordinates of lugrd as an input to LINEGRID as shown in the following example.

An example of producing matching grids The following commands should be done:

Usage: DESCRIBE <geo_dataset>
Arc: DESCRIBE lugrd

```
        Description of Grid LUGRD
 Cell Size =  50.000              Data Type: Integer
Number of Rows  =  648            Number of Values =  14
Number of Columns = 604           Attribute Data (bytes) =  8

         BOUNDARY                      STATISTICS
 Xmin =  4492676.680        Minimum Value =  111.000
Xmax =  4522876.680         Maximum Value =  512.000
Ymin =  5884875.398         Mean  =  225.421
Ymax =  5917275.398         Standard Deviation =  42.130
```

Arc: LINEGRID fgw fgwgrd
Converting arcs from fgw to grid fgwgrd
Cell Size (square cell): 50

```
Convert the Entire Coverage(Y/N)?: n          **in Example 1 we entered y **
Grid Origin (x, y): 4492676.680,5884875.398   **values taken from lugrd **
Grid Size (nrows, ncolumns): 648,604          **values taken from lugrd **


Enter background value (NODATA | ZERO): zero
Number of Rows    = 648
Number of Columns = 604
Arc: GRIDASCII fgwgrd fgwgrd.txt
```

Now fgwgrd.txt's header looks as follows:

```
ncols         604
nrows         648
xllcorner     4492676.68
yllcorner     5884875.398
cellsize      50
NODATA_value  -9999
```

After the header information has been changed, both ASCII files are almost ready to be imported to GRASS running r.in.ascii (after changing the header).

An example of changing the header information The map exported from ARC/INFO in ASCII format has the heading, which consists of six lines, describing coordinates of the lower left corner, number of columns and rows, and the cell size, e.g.:

```
ncols         349
nrows         542
xllcorner     69367.3
yllcorner     37980.7
cellsize      1000
NODATA_value  -9999
```

However GRASS requires slightly different format for its *r.in.ascii* program, describing the coordinates of north, south, east and west, and the number of rows and columns, like:

```
north:579980.7
south: 37980.7
east: 418367.3
west: 69367.3
rows: 542
cols: 349
```

The ARC/INFO export file in ASCII format can be transformed to GRASS input ASCII format using the program arc2grass, which is included in the SWIM model package.

4.1.7 Watershed Analysis Program r.watershed

Delineation of watersheds from the Digital Elevation Model (DEM) is the first necessary step in many hydrological applications. A procedure that has become a standard one is based on the eight-direction basis in which each grid cell is connected to one of its eight neighbour cells according to the direction of steepest descent. Another possibility is to use the four-direction procedure for watershed delineation.

Based on an elevation grid, a grid of flow direction is built, and then a map of flow accumulation is derived from the flow direction map, counting the number of cells upstream of a given cell. Streams are identified as lines of cells whose flow accumulation exceeds a specified threshold number of cells and thus a specified upstream drainage area. This threshold number must be specified in advance. Watershed is delineated as the set of all cells draining through a given cell.

GRASS program *r.watershed* is the main tool for delineation of basin and sub-basin boundaries and calculating the LS (slope length and steepness) and S (slope steepness) factors of the Revised Universal Soil Loss Equation (RUSLE) in GRASS.

There are two versions of this program available in GRASS: *ram* and *seg*. Which of them is run depends on whether the -m flag is set or not. The *ram* version uses virtual memory managed by the operating system to store data and is much faster than the *seg* version. The *seg* version (with the -m flag) uses the memory on disk which allows larger maps to be processed but is considerably slower.

The *seg* version uses the AT least-cost search algorithm (Ehlschlaeger, 1989) to determine the flow of water over the landscape and is more reliable than *ram*. In addition to the elevation map, maps of depressions in the landscape and blocking terrain can be provided to assure more reliable watershed boundaries.

Due to memory requirements of both *seg* and *ram* versions of the program, it is quite easy to run out of memory. If the resolution of the current region cannot be increased, more memory needs to be added to the computer. GRASS Reference Manual provides recommendations on how to use the coarser resolution. Masking out unimportant areas is another means to reduce processing time significantly if the watershed of interest occupies only a part of the overall area. According to our experience, the *seg* version of the program is much more reliable. Our recommendation is to use only this version for watershed delineation (using the -m flag).

After the watersheds are delineated for a certain region, an analysis of output maps has to be done in order to identify the basin under study and its sub-basins. For this purpose the basin, accumulation, and streams output maps are needed, as well as any available digitised maps of the basin boundaries or river network. Comparison of digitised and calculated rivers, digitised and calculated watershed boundaries can be very helpful in order to find some mistakes or inconsistencies in the DEM. An example of resulted sub-basin map with the river network is given in **Fig. 4.3.**

After correction of the DEM the procedure *r.watershed* can be repeated. It is also quite difficult to find an appropriate threshold value from the very beginning. Usually, it is necessary to repeat the procedure several times with different thresholds. The user has to remember that LS and S factors are multiplied by 100 for the GRASS output map layer, since they are usually small numbers.

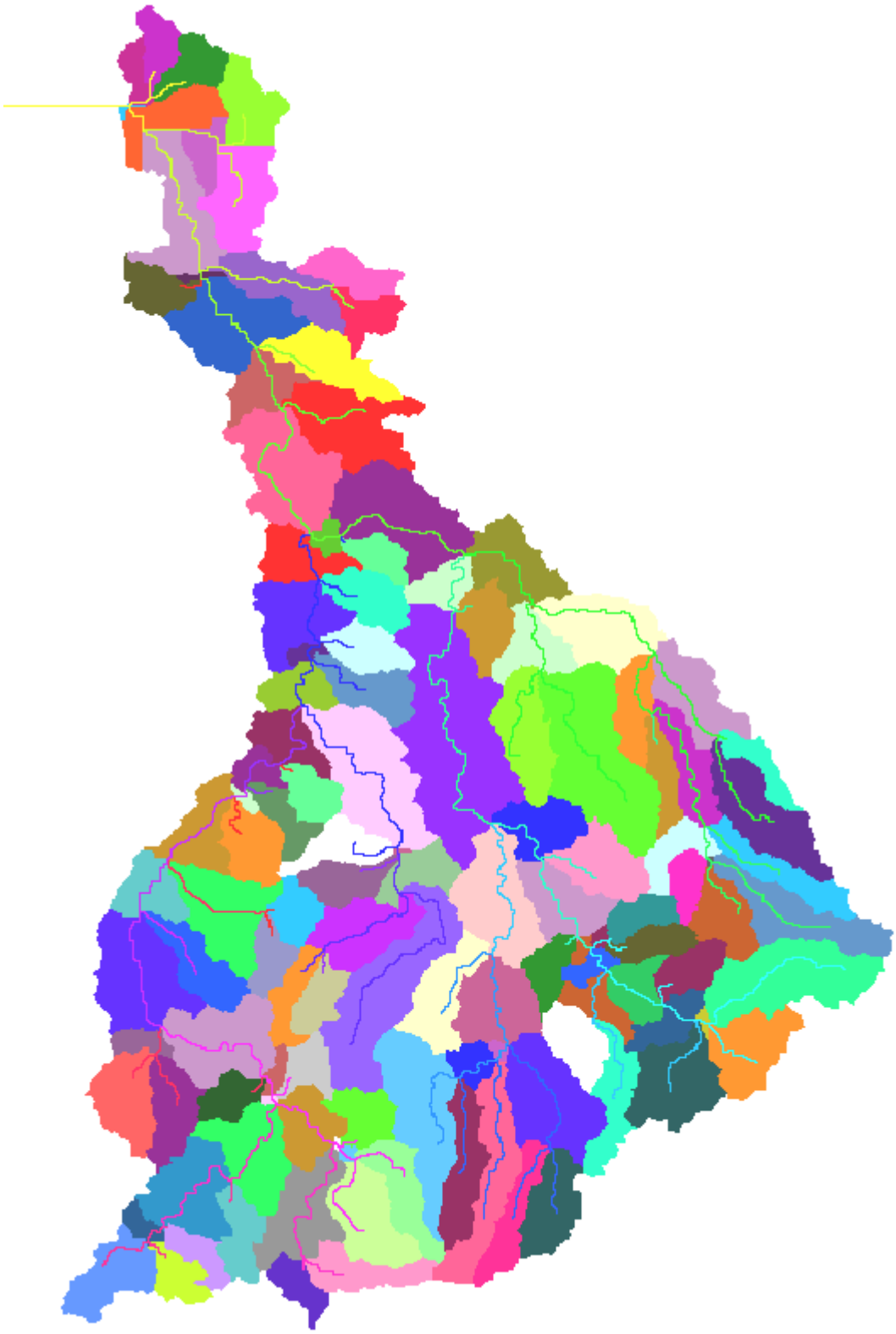


Fig. 4.3 Virtual subbasins obtained by applying r.watershed function in GRASS for the Mulde river basin

4.1.8 DEMO Data Set

Here the DEMO data set for spatial data preparation is described. The maps for the Glonn basin in Bavaria (drainage area 392 km^2) were used for that.

Input data in ASCII format The exemplary export files in ASCII format produced in ARC/INFO are located in the directory */grassdata*. They are: the Digital Elevation Model map in the file

glonn160-dem.asc,

and the soil map in the file

glonn160-soil.asc.

The program *arc2grass* can be used for converting the ARC/INFO export files to GRASS format. The resulting ASCII files for these two and other maps, which are ready for GRASS import, are located in the same directory

- glonn160-dem.txt - DEM map,
- glonn160-lus.txt - land use map,
- glonn160-soil.txt - soil map,
- glonn160-fluss.txt - a river map,
- glonn160-rivnet.txt - a more detailed river map,
- glonn160-pegel.txt - gage station map,
- glonn160-clst.txt - climate stations map
- glonn160-prst.txt - precipitation stations map
- glonn160-clst-this.txt - a map with Thiessen polygons for climate stations,
- glonn160-prst-this.txt - a map with Thiessen polygons for precipitation stations.

Geographic location Let us assume that the geographic location with the name *glonn160* is created by the user *usern* in the directory */usern/databases*. Here 160 indicates the resolution of maps in this location (which was chosen in accordance with the resolution of available DEM map). The directory */usern/databases* contains at least two subdirectories: */PERMANENT* and */usern*. The directory */PERMANENT* describes the name (file *MYNAME*) and coordinates (file *WIND*) of the geographic location. In our case the file *WIND* looks as following:

proj:	0
zone:	0
north:	6098669
south	6064429
east:	123951
west:	73871
cols:	313
rows:	214
e-w resol:	160
n-s resol:	160

The directory */usern/databases/glonn160/usern* is designated for all GRASS files in this geographic location, which will be stored under subdirectories: *cats, catts_dig, cell, cell_misc, cellhd, colr, dig, dig_ascii, dig_att, dig_cats, hist*. Here the user name *usern* corresponds to the name of MAPSET, which is asked always when starting GRASS session. All files from this directory can be copied by any other user and used independently.

Map input to GRASS As a first step, a number of maps can be created by introducing data in ASCII format to GRASS using *r.in.ascii* command. For example, the following maps listed in **Tab. 4.2** can be introduced from available ASCII data:

Table 4.2 List of source ASCII files and the corresponding maps in GRASS

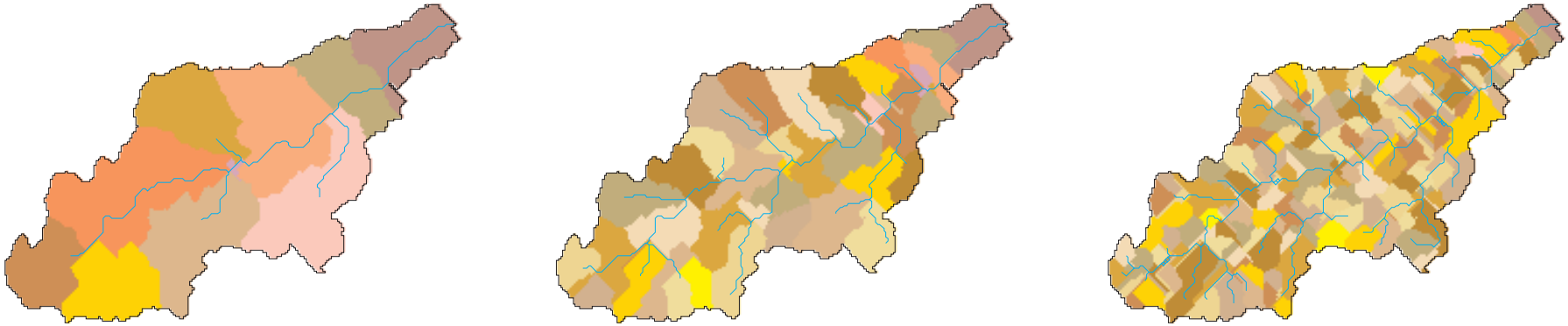
GRASS map	*Map description*	*The corresponding source ASCII file*
dem	DEM	glonn160-dem.txt
lus	Land use	glonn160-lus.txt
soil	Soil	glonn160-soil.txt
fluss	River network	glonn160-fluss.txt
flussnet	Detailed river network	glonn160-rivnet.txt
pegel	Gage station	glonn160-pegel.txt
clst	Climate stations	glonn160-clst.txt
prst	Precipitation stations	glonn160-prst.txt
clstthis	Thiessen polygons for climate stations	glonn160-clst-this.txt
prstthis	Thiessen polygons for precipitation stations	glonn160-prst-this.txt

Program r.watershed After that the program *r.watershed* can be applied to the Digital Elevation Model *dem* in order to create sub-basin maps. Let us assume that we applied this program six times (always with a flag *–m*) with different thresholds. The threshold is defined as a minimum size of the exterior watershed basin. As a result, a number of sub-basin maps (*basN*) and stream network maps (*rivN*) will be created as listed in **Tab. 4.3**:

Table 4.3 Maps created with *r.watershed* using different thresholds

Threshold (number of cells)	*Corresponding area, km^2*	*Created maps*
3600	92.16	bas1, riv1
1800	46.08	bas2, riv2
900	23.04	bas3, riv3
200	5.12	bas4, riv4
100	2.56	bas5, riv5
50	1.26	bas6, riv6

We can compare the average, minimum and maximum sub-basin area for three different sub-basin maps *bas3, bas4,* and *bas6*, created with different thresholds (see **Fig. 4.4** and **Tab. 4.4**).



(a) (b) (c)

Fig 4.4 A set of sub-basin and river network maps produced with *r. watershed* using different thresholds: 900 (a), 200 (b) and 50 (c)

Table 4.4 Comparison of three sub-basin maps created with different thresholds

Raster map name	*Number of sub-basins*	*Average sub-basin area, km^2*	*Minimum sub-basin area, km^2*	*Maximum sub-basin area, km^2*
bas3	10	40.6	1.02	72.2
bas4	42	9.7	0.36	19.1
bas6	162	2.5	0.05	11.2

As we can see, 10 sub-basins with an average area of 40.6 km^2 were created with threshold 900 cells, or 23.04 km^2, 42 sub-basins with an average area of 9.7 km^2 were created with threshold 200 cells, or 5.12 km^2, and 162 sub-basins with an average area of 2.5 km^2 were created with threshold 50 cells, or 1.26 km^2. In other words, the threshold corresponds approximately to ½ of the average area of created sub-basins. This has to be taken into account when estimating the threshold values. Finally, the three sub-basin maps: bas36, bas44 and bas64 were chosen for model application.

Reclassification and analysis The original land use map *lus* has to be reclassified to SWIM land use categories. The latter one, as well as the *dem* and *soil* maps have to be clipped using a mask (e.g. corresponding to the *bas3* map), to get the final maps *dem3, lus3, soil3*, which can be used by Interface. Finally, the four maps (e.g. *dem3, lus3, soil3* and *bas3*) are ready for SWIM/GRASS interface.

The programs *r.stats* and *r.report* (see **Appendix I**) are useful for the analysis of obtained maps. For example, using the function *r.report* as

```
r.report -z map=soil3 units=k,p output=gl160-soil.rep
```

we can get the following report about the soil map soil, indicating areal distribution of soil categories (in km^2 and in percent). For example, **Tab. 4.5** includes GRASS report about the soil map soil3, indicating areal distribution of soil types.

Fig. 4.5 demonstrates an overlay of sub-basins (bas3), precipitation stations (prst2), and Thiessen polygons for precipitation stations. The report about two of these maps:

```
r.report -z map=bas3,prstthis units=k,p output=glonn-bas36-prstthis.rep
```

is given in **Tab. 4.6**.Such a report can be very helpful in establishing the connection between sub-basins and precipitation stations (weighting coefficients).

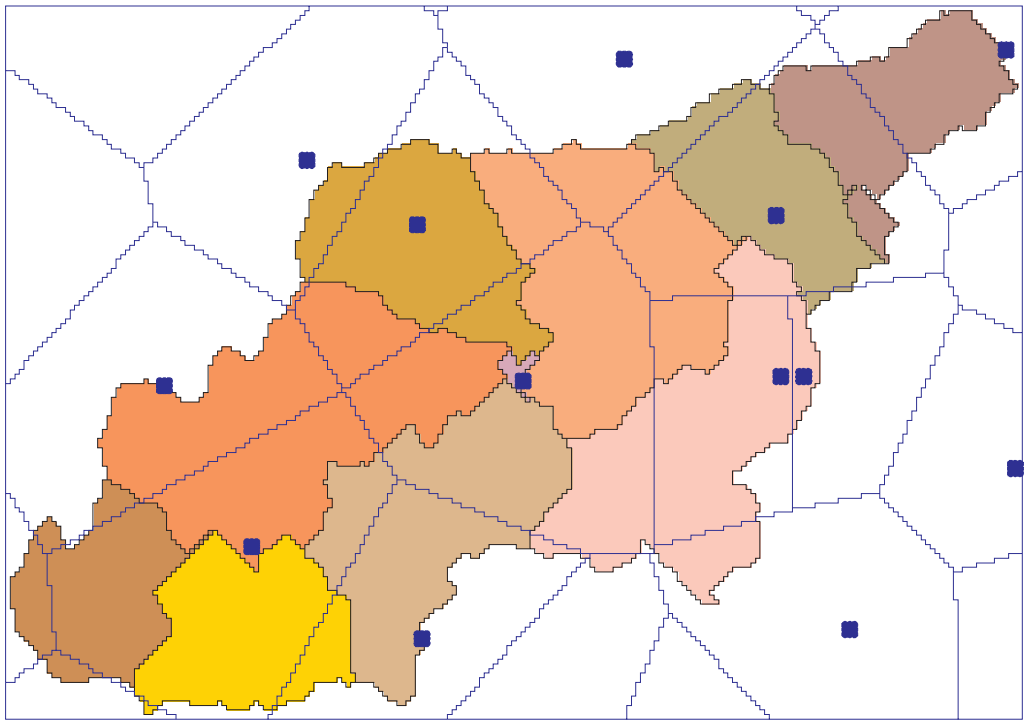
Table 4.5 GRASS report about the soil map soil3, indicating areal distribution of soil types

RASTER MAP CATEGORY REPORT

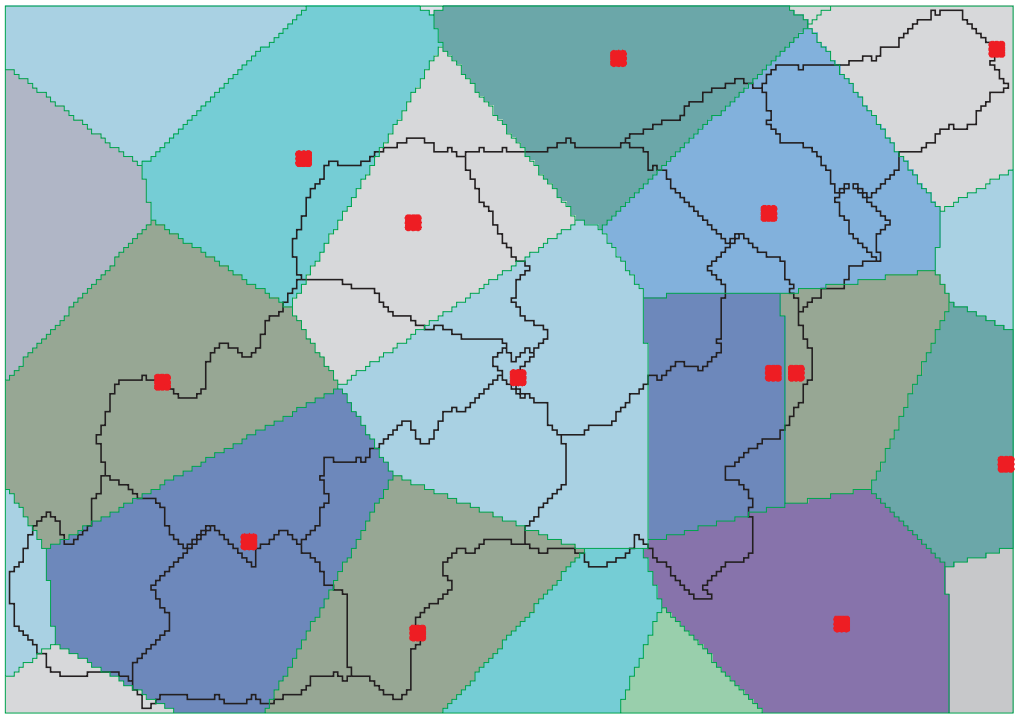
LOCATION: glonn160 — Tue Apr 20 12:09:32 1999

REGION: north: 6092269 east: 113711; south: 6067469 west: 78351; res: 160 res: 160

#	description	square kilometers	% cover
33	. . . . .	49.433600	12.24
34	. . . . .	6.809600	1.69
36	. . . . .	6.604800	1.64
39	. . . . .	31.308800	7.75
47	. . . . .	4.940800	1.22
49	. . . . .	11.468800	2.84
56	. . . . .	1.536000	0.38
77	. . . . .	0.307200	0.08
81	. . . . .	2.355200	0.58
82	. . . . .	11.878400	2.94
105	. . . . .	1.382400	0.34
115	. . . . .	4.377600	1.08
116	. . . . .	47.462400	11.75
117	. . . . .	27.750400	6.87
124	. . . . .	0.358400	0.09
133	. . . . .	87.782400	21.73
134	. . . . .	23.680000	5.86
135	. . . . .	2.611200	0.65
159	. . . . .	14.054400	3.48
161	. . . . .	3.430400	0.85
167	. . . . .	43.264000	10.71
168	. . . . .	11.648000	2.88
207	. . . . .	6.707200	1.66
209	. . . . .	0.128000	0.03
210	. . . . .	2.662400	0.66
TOTAL		403.942400	100.00



(a)



(b)

Fig 4.5 An overlay of the sub-basin map, the precipitation station map and the Thiessen polygon map for the Clonn basin (a, b)

Table 4.6 GRASS report about sub-basin map bas3 and the map of Thiessen polygons for precipitation stations

RASTER MAP CATEGORY REPORT

LOCATION: glonn160 — Thu Apr 1 10:07:56 1999

REGION: north: 6093229 east: 114831; south: 6067469 west: 78351; res: 160 res: 160

#	description	square kilometers	% cover
1		32.256000	3.43
	92164	15.308800	47.46
	92165	16.947200	52.54
2		30.771200	3.27
	90661	4.096000	13.31
	92156	0.537600	1.75
	92164	26.137600	84.94
3		60.851200	6.48
	90661	8.217600	13.50
	92160	25.292800	41.56
	92162	8.627200	14.18
	92164	11.929600	19.60
	92169	6.784000	11.15
4		39.040000	4.15
	90634	5.017600	12.85
	92160	5.939200	15.21
	92162	28.083200	71.93
5		1.024000	0.11
	92160	1.024000	100.00
6		72.192000	7.68
	90625	25.318400	35.07
	92160	14.361600	19.89
	92161	23.040000	31.91
	92162	9.472000	13.12
7		28.211200	3.00
	90624	4.300800	15.25
	90625	2.252800	7.99
	92135	1.305600	4.63
	92161	20.352000	72.14
8		33.920000	3.61
	92141	5.094400	15.02
	92161	28.825600	84.98
9		50.508800	5.37
	92141	23.168000	45.87
	92160	19.865600	39.33
	92161	7.475200	14.80
10		57.292800	6.10
	92141	1.536000	2.68
	92142	5.785600	10.10
	92156	3.046400	5.32
	92160	14.771200	25.78
	92164	3.788800	6.61
	92169	28.364800	49.51
TOTAL		939.724800	100.00

4.2 SWIM/GRASS Interface

Throughout SWIM/GRASS, two primary types of interface input are used:

1) Text input that can be completed by hitting the RETURN key. In most cases, if no text was entered, the given question or operation is cancelled. Most often the text input will consist of the name of a new or existing map or project name, in which case entering the word "list" will provide a list of currently used names.

2) Text or menu options that can be completed by hitting the ESC (escape) key. This type of interface is used for menus or for entering tables of parameters. All menus have a default answer of Exit (0), so that by simply hitting ESC one may leave the program's menus.

The following **Tab. 4.7** provides a keystroke guide, which is helpful when using the parameter entry worksheets that use this interface:

Table 4.7 Keystroke guide for using the interface

key	*the function*
<RETURN>	moves the cursor to next prompt field
<CTRL-K>	moves the cursor to previous prompt field
<CTRL-H>	moves the cursor backward non-destructively within the field
<CTRL-L>	moves the cursor forward non-destructively within the field
<CTRL-A>	copies the screen to a file named "visual_ask" in the users home directory
<CTRL-C>	where indicated (on the bottom line of the screen) can be used to cancel operation

Starting GRASS and SWIM_INPUT Before running SWIM/GRASS interface, GRASS has to be started. For that, the user has to start GRASS:

```
grass4.2.1
```

The following information window will appear:

```
GRASS 4.2.1

LOCATION: This is the name of an available geographic location.
          spearfish is the sample data base for which all tutorials
          are written.

MAPSET:   Every GRASS session runs under the name of a MAPSET.
          Associated with each MAPSET is a rectangular COORDINATE
          REGION and a list of any new maps created.

DATABASE: This is the unix directory containing the geographic
          databases

          The REGION defaults to the entire area of the chosen
          LOCATION. You may change it later with the command: g.region
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

LOCATION:   glonn160______       (enter list for a list of locations)
MAPSET:     usern_________       (or mapsets within a location)

DATABASE:   usern/databases_________________


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

The Location and Database names are the last entered. If you need another ones, please change the names. After entering GRASS, the user can open the monitor with the command *d.mon*. After that SWIM/GRASS interface can be started:

```
cd  usern/swiminput
swim_input
```

The following window will appear:

```
SWIM / GRASS Project Manager

  This program is designed to help you use information in
  GRASS raster layers to create an input file to run on a
  standard version of the SWIM basin simulation program.
  All steps of this process are recorded in data files
  stored under a project name in your GRASS database.

                   Choose desired option:

                  0.  Exit
                  1.  Create new project
                  2.  Work on an existing project
                  3.  Copy an existing project
                  4.  Remove an existing project

          Option: 0_

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

Options of the main menu The user can use option 1 to create a new project, or option 2 to continue working on an existing project. If you want to create a new project, choose the option 1. After that you have to enter the project name. The name should correspond to the basin name, but it has to be not too long (maximum 8 letters), for example, we choose ‚gl‘:

```
Enter project name:

Enter 'list' for a list of existing SWIM / GRASS project files
Hit RETURN to cancel request
> gl
```

Then the following Data Extraction Menu will appear:

```
SWIM / GRASS Project Data Extraction Menu
    Project Name:  gl

                    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 Hydrotop 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)
```

Data Extraction Steps 3 to 7 have to be run one after another, after that option 0 has to be chosen. Steps 8 and 9 are not up to date, they have to be modified.

When the option 3 is chosen to extract basin attributes, the name of the basin and sub-basin map is asked. Assuming that we use the maps described in the previous section, the name ‚bas36‘ has to be entered:

```
Basin and Subbasin Map
Enter 'list' for a list of existing raster files
Enter 'list -f' for a list with titles
Hit RETURN to cancel request
> bas36
```

When the option 4 is chosen to extract the hydrotope structure, the names of three maps: 1) basin and sub-basin, 2) land use and 3) soil are asked:

```
Basin and Subbasin Map
Enter 'list' for a list of existing raster files
Enter 'list -f' for a list with titles
Hit RETURN to cancel request
> bas36
<bas36>
```

```
Landuse Map
Enter 'list' for a list of existing raster files
Enter 'list -f' for a list with titles
Hit RETURN to cancel request
> lus36
<lus36>

Soil Map
Enter 'list' for a list of existing raster files
Enter 'list -f' for a list with titles
Hit RETURN to cancel request
> soil36
```

When the option 5 is chosen to extract topographic attributes, the name of the elevation map has to be entered:

```
Elevation Map
Enter 'list' for a list of existing raster files
Enter 'list -f' for a list with titles
Hit RETURN to cancel request
> dem36
```

When the option 6 is chosen to extract groundwater attributes, the name of the groundwater alpha map is asked. If the user does not have such a map, an option ‚n' has to chosen:

```
Do you have groundwater alpha parameter map?(y/n) [y]
n
```

The next step is to choose 7 in order to compute routing structure of the basin. If the routing structure is calculated without problems, the user gets a message about the outlet sub-basin, like:

```
outlet subbasin number is 1
```

Please note that the outlet sub-basin has to numbered with 1, otherwise the user has to recode the output. After that the user has to choose ‚0' to quit the SWIM/GRASS interface. The results will be stored in the directory:

```
in usern/databases/glonn160/usern/swim/gl,
```

which corresponds to the DATABASE/LOCATION/MAPSET/swim/projectname. In our case the full list of resulting files is the following:

```
file.cio  gl.str gl.fig gl.proj str.cio  gl.cod gl.bsn
gl0.sub gl0.gw gl0.rte
gl1.sub gl1.gw gl1.rte gl2.sub gl2.gw gl2.rte
gl3.sub gl3.gw gl3.rte gl4.sub gl4.gw gl4.rte
gl5.sub gl5.gw gl5.rte gl6.sub gl6.gw gl6.rte
gl7.sub gl7.gw gl7.rte gl8.sub gl8.gw gl8.rte
gl9.sub gl9.gw gl9.rte
```

‚where the number n corresponds to the sub-basin number n+1.

Possible problem In some cases, option 7 runs not so smoothly, and the message like

```
Start checking the aspect through each subbasin
More than one outlet from subbasins 1 and 40
More than one outlet found from subbasins 40 1
Do you agree with this?(y/n) [y]
```

can appear. If the user chooses ‚y', the routing structure file will be created, but without sub-basin 40. In such a situation ‚n' has to be chosen in order to edit aspect. After choosing ‚n', the programs asks:

```
Would you like to continue?(y/n) [y]
```

When the user answers: ‚y', the following Sub-basin Aspect Editing menu will appear:

```
Subbasin Aspect Editing/Error Checking Menu
   Project Name:  gl

                  Choose desired option:
        0   Return to Previous Menu
        1   Check for Errors in Subbasin Aspect
        2   Edit Subbasin Aspect Using Key board
        3   Edit Subbasin Aspect Using Graphic Monitor
        4   Display Subbasin Number on the Graphic Monitor
```

Please choose the option 3, and point on two sub-basins sequentially. For example, if you know that stream in sub-basin 40 flows to sub-basin 38, then point two sub-basins: first sub-basin 40, then sub-basin 38. After that click on non-basin area to finish.

Working on existing project If the user wants to continue working on an existing project, he/she can start from that point, where the project was stopped the former time.

4.3 Relational Data Preparation

4.3.1 An Overview of Relational Data

The full list of necessary relational data is the following:
1. Climate data: average, minimum and maximum daily air temperature, daily precipitation, and daily solar radiation,
2. soil geophysical and geochemical parameters,
3. crop types, crop rotation and crop management,
4. river discharge at the basin outlet,
5. water quality parameters (N, P, suspended solids) at the basin outlet,
6. river cross-sections or mean river width and depth,
7. rainfall intensity parameters.

The climate and soil data (1-4) are absolutely necessary to run the model.

Information about crop types in the basin, crop rotation and crop management (dates of planting and harvesting, dates and rates of fertilization) (5) is needed to initialise the model. If detailed information about crop management is not available for the studied basin, at least expert knowledge should be used in this case.

Measured river discharge and water quality parameters (6-7) are necessary for model validation.

River cross-sections (8) or mean river width and depth in several points of a basin (approximately one per sub-basin) can facilitate the model verification, especially for lateral processes (water and chemicals routing). The other way is to use the default stream width and depth parameters extracted from DEM by SWIM/GRASS interface.

Rainfall intensity parameters (9), which include
- ten years frequency of I_{30} - the maximum annual half-an-hour rainfall,
- ten years frequency of I_{360} - the maximum annual six-hours rainfall, and
- long-term monthly maximum of the half-an-hour rainfall,

are necessary for erosion modelling.

In the following sections specific data requirements for climate, soil, crops, curve numbers are considered with some more detail.

4.3.2 Climate Data

The climate parameters necessary to drive the model are daily precipitation, air temperature (maximum, average, and minimum), and solar radiation. Usually, the climate data must be taken from meteorological and precipitation stations. This is absolutely necessary in the case of model validation for a specific basin. Note that the climate data have to be corrected, no missing values in form of –999 are allowed.

Usually, climate input is considered to be homogeneous at the level of sub-basins. The precipitation data has to be provided for as many stations as possible (approximately 1 station per 100 km^2 area), while this is less important for the air temperature and solar radiation parameters.

According to our experience, the best is to use data from all available climate stations (parameters 1-3), located inside and close to the basin, in a combination with precipitation data from all available precipitation stations, also located inside the basin and close to it.

The following **Tables 4.8, 4.9 and 4.10** demonstrate the format of temperature, precipitation, and radiation data for SWIM. The other possibility is to put all climate data in one file, if the number of stations is not too large.

Table 4.8 Format of temperature data

YYYY	MON	DAY	4116tmx	4116tav	4116tmn
1981	1	1	3.5	0.4	-1.7
1981	1	2	1.0	0.5	-1.3
1981	1	3	5.8	3.9	0.7
1981	1	4	4.0	1.4	0.4
1981	1	5	0.5	-1.6	-3.5
1981	1	6	-1.3	-3.0	-3.6
1981	1	7	-3.4	-6.8	-10.5
1981	1	8	-5.8	-15.5	-21.4
1981	1	9	-4.8	-7.8	-21.8
1981	1	10	-0.2	-2.8	-6.6
1981	1	11	-1.2	-2.6	-4.3
1981	1	12	-2.0	-3.9	-4.6
....	..	..	...	...	....

Table 4.9 Format of precipitation data

YYYY	MON	DAY	90625	90661	92141	92160	92161	92162
1981	1	1	12.2	12.4	7.6	10.4	7.6	8.5
1981	1	2	7.7	8.0	4.2	8.5	4.2	9.1
1981	1	3	7.8	4.5	8.3	5.4	8.3	6.2
1981	1	4	8.8	6.6	6.8	7.1	6.8	8.8
1981	1	5	9.0	6.0	6.2	7.8	6.2	5.6
1981	1	6	3.2	3.3	2.4	3.4	2.4	3.0
1981	1	7	1.7	2.1	1.4	1.4	1.4	1.5
1981	1	8	0.6	0.0	0.3	0.4	0.3	0.3
1981	1	9	0.0	1.4	0.4	0.0	0.4	0.9
1981	1	10	1.2	1.4	0.4	0.2	0.4	0.9
1981	1	11	0.0	0.0	0.0	0.0	0.0	0.0
1981	1	12	0.0	0.0	0.0	0.0	0.0	0.0
....	..	..	...	...	...	...	...	...

Table 4.10 Format of radiation data

YYY	MON	DAY	4117rad
1981	1	1	171.0
1981	1	2	173.0
1981	1	3	186.6
1981	1	4	178.0
1981	1	5	173.0
1981	1	6	174.0
1981	1	7	241.0
1981	1	8	485.8
1981	1	9	170.0
1981	1	10	183.0
1981	1	11	171.0
1981	1	12	479.0
....	..	..	.....

Climate input in the model is not fully automatised at the moment. Therefore, the subroutine cliread() has to be recompiled for new applications to take into account specific climate input: number of climate and precipitation stations, and their 'attachment' to sub-basins with specific weighting coefficients. Later, this routine has to be rearranged to allow fully automatised climate data input.

The other way is to use weather generator instead of actual climate parameters. The weather generator is attached to the model and can be initialised using monthly statistical data for the station(s) (see, e.g., **Tab. 4.11**):

- average monthly maximum temperature (e.g., line 3 in **Tab.4.11**),
- average monthly minimum temperature (line 4),
- coefficient of variation for monthly temperature (line 5),
- average monthly solar radiation (line 6),
- monthly maximum 0.5 hour rain for period of record (line 7),
- monthly probability of wet day after dry (line 8),
- monthly probability of wet day after wet (line 9),
- monthly days with precipitation in a month (line 10) (can be used instead of monthly probabilities),
- monthly mean event rainfall (line 11),
- monthly standard deviation of rainfall (line 12),
- monthly skew coefficient of daily rainfall (line 13).

Table 4.11 Format of monthly statistics for climate stations

SYTHETIC WEATHER DATA FOR ST41017												TITLE
45.000	66.000	54.000	51.000									I_{30},I_{360},N_{yr},Lat
1.80	3.00	8.10	13.40	19.10	22.10	23.70	23.00	19.30	13.30	6.70	2.90	Av Mo Max Temp
-3.30	-2.90	-0.20	3.40	7.90	11.20	13.20	12.70	9.60	5.50	1.30	-1.70	Av Mo Min Temp
0.18	0.14	0.11	0.10	0.09	0.08	0.07	0.07	0.08	0.10	0.13	0.15	Co Var Mo Temp
56.	104.	213.	267.	512.	471.	417.	351.	282.	152.	74.	42.	Av Mo Sol Rad
7.	7.	9.	9.	10.	10.	10.	10.	9.	9.	7.	7.	Mo Max .5h rain
0.37	0.34	0.35	0.33	0.32	0.29	0.35	0.41	0.51	0.55	0.56	0.38	Mo Prob W aft D
0.69	0.67	0.69	0.64	0.64	0.61	0.65	0.70	0.72	0.78	0.79	0.45	Mo Prob W aft W
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Mo days of prec
2.7	2.6	2.7	3.2	4.2	5.0	4.9	5.0	3.7	3.2	3.0	3.0	Mo mean ev rain
3.3	3.05	2.54	2.79	2.54	3.30	5.08	5.84	4.57	4.57	3.81	3.05	Mo st dev rain
2.86	4.07	3.49	2.19	1.70	2.02	2.51	1.84	2.00	2.90	2.14	2.04	Mo skew of rain

4.3.3. Soil Data

In addition, data for soils have to be provided. The soil data should include the following parameters for each of a maximum of ten soil layers:

- depth of the layer (mm),
- clay, silt and sand content (%),
- bulk density (g/cm^3),
- porosity (Vol. %),
- available water capacity (Vol. %),
- field capacity (Vol. %),
- organic carbon content (%),
- organic N content (%),
- saturated conductivity (mm/hr).

According to the model requirements, the depth of the first soil layer should be always 10 mm. The format of soil parameters presentation in the soil database is shown in **Tab. 4.12**. Format inside lines is free, the right column with parameter names is not needed. The read and recalculation of soil parameters is fully automatised.

Table 4.12 Format of soil parameters for SWIM

26	5				SoilNum, Layers
Fahlerde aus sandigen Deckschichten über Geschiebelehm					SoilName
Ap	Ap	Ael	Bt	Cc	Horizon
Sl3	Sl3	Sl2	Ls4	Sl4	Type
10.	240.	400.	800.	1300.	Depth, mm
10.	10.	5.	20.	15.	Clay, %
7.	7.	5.	12.	15.	Silt, %
83.	83.	90.	68.	70.	Sand, %
1.30	1.30	1.45	1.75	1.60	Bulk density,g/cm3
51.	51.	43.	40.	42.	Porosity, Vol. %
23.	23.	18.	16.	16.	AWC, Vol. %
32.	32.	24.	31.	28.	FC, Vol. %
0.6	0.6	0.	0.	0.	C, %
0.07	0.07	0.	0.	0.	N, %
0.25					Erodibility factor
83.4	83.4	29.2	4.2	29.2	SC, mm/h

Saturated conductivity can be either read from the file (like **Tab. 4.12**), or, In case if it is not available (zeros in the soil parameter files), it can be estimated in the model using the method of Rawls & Brakensiek et al. (1985) as dependent on soil texture and porosity:

$$
\begin{aligned}
&SC = 24.\cdot \exp(x_1 + x_2 + x_3 + x_4),\\
&x_1 = 19.52348\cdot PV - 8.96847 - 0.028212\cdot CL\\
&x_2 = 0.00018107\cdot SN^2 - 0.0094125\cdot CL^2 - 8.395215\cdot PV^2 + 0.077718\cdot SN\cdot PV\\
&x_3 = 0.0000173\cdot SN^2\cdot CL + 0.02733\cdot CL^2\cdot PV + 0.001434\cdot SN^2\cdot PV - 0.0000035\cdot CL^2\cdot SN\\
&x_4 = -0.00298\cdot SN^2\cdot PV^2 - 0.019492\cdot CL^2\cdot PV^2
\end{aligned}
\qquad (3.1)
$$

where PV is porosity in m3/m3, CL – clay content in %, and SN – sand content in %. In principle, also the methods of Cosby (1984)

$$
\begin{aligned}
&SC = 60.96\cdot 10^{a},\\
&a = -0.6 + 0.0126\cdot SN - 0.0064\cdot CL
\end{aligned}
\qquad (4.2)
$$

and Vereecken et al., (1989)

$$SC = \exp\left[20.62 - 0.96\cdot \ln(CL) - 0.66\cdot \ln(SN) - 0.46\cdot \ln(OM) - 8.43\cdot BD\right] \qquad (4.3)$$

where *OM* – organic matter content, and *BD* – bulk density in g/cm^3, can be used.

The results produced by three methods may be quite different. The comparison of estimates of saturated conductivity by three methods is given in **Fig. 4.6.** As we can see, usually they produce quite different values of saturated conductivity.

For German soils (BÜK 1000), the estimation of saturated conductivity SC in mm/h can be done using the following **Tab. 4.13** or **Tab. 4.14**.

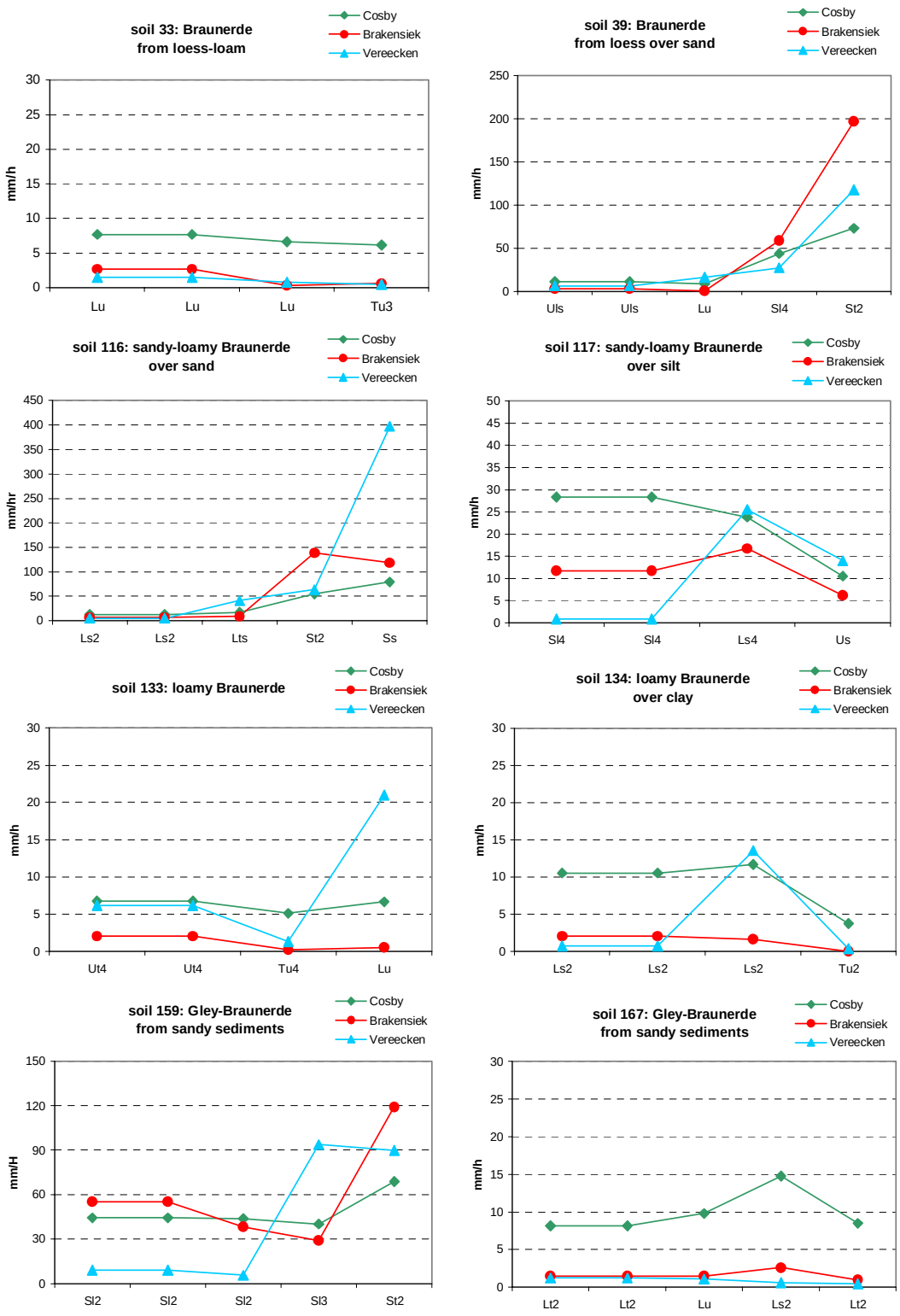


Fig. 4.6 Estimation of saturated conductivity using three different methods for dominant soils in the Glonn basin

Table 4.13 Estimation of saturated conductivity based on soil texture class and bulk density (based on Bodenkundliche Kartieranleitung, 3.)

Bulk density / ***Texture class***	***1.3***	***1.4***	***1.5 – 1.6***	***1.7 – 1.75***	***1.8 – 1.9***	***2.0 – 2.1***	***2.3 – 2.4***
mS	200	125	125	83.4	83.4	42	
fS	83.4	42	29	16.7	10	4.2	
Su,Slu	29	16.7	10.4	4.2	2.3	0.4	
Sl2	83.4	42	29.2	16.7	10.4	4.2	
Sl3,Sl4,St2	83.4	42	29.2	16.7	10.4	2.3	
St3	29.2	16.7	10.4	4.2	2.3	0.4	
U,Us,Uls,Ul2, Ul3,Ut2,Ut3	29.2	16.7	10.4	4.2	2.3	0.2	
Ul4,Ut4	42	16.7	10.4	4.2	2.3	0.2	
Ls2,Ls3,Ls4	83.4	41.7	16.7	4.2	2.3	0.2	
Lu	29.2	16.7	10.4	4.2	2.3	0.2	
Ltu	83.4	42	16.7	4.2	2.3	0.2	
Lts,Lt2,Lt3	42	16.7	10.4	4.2	2.3	0.2	
Tu3,Tu4,Tl,Tu2,T	42	16.7	10.4	4.2	2.3	0.2	0.1
Hh	83.4	16.7	10.4	4.2	2.3	0.2	
Hn	125	42	29.2	16.7	10.4	4.2	

Table 4.14 Estimation of saturated conductivity based on soil texture class and bulk density (based on Bodenkundliche Kartieranleitung, 4.)

Soil texture class	Bulk density <1.6 SC mm/h	Bulk density = 1.6-1.8 SC mm/h	Bulk density >1.8 SC mm/h
Ss	145.4	95.4	52.5
Sl2	45.4	20.4	15.0
Sl3	19.6	13.8	6.3
Sl4	17.9	8.8	5.0
Slu	17.1	4.6	3.3
St2	37.9	32.9	15.4
St3	11.6	7.1	2.9
Su2	65.4	36.7	15.0
Su3	31.3	13.3	7.1
Su4	17.1	10.0	8.3
Ls2	17.1	8.3	5.4
Ls3	5.4	2.9	2.5
Ls4	8.3	5.8	2.5
Lt2	5.4	3.8	1.7
Lt3	4.2	4.2	2.9
Lts	5.0	2.5	1.3
Lu	10.8	7.5	2.5
Uu	6.7	2.9	1.2
Uls	14.6	5.8	2.1
Us	9.2	4.2	1.6
Ut2	12.5	2.9	1.7
Ut3	15.8	3.3	1.3
Ut4	12.9	3.8	1.7
Tt	2.9	0.8	0.4
Tl	4.2	1.3	0.4
Tu2	8.3	2.1	0.4
Tu3	11.3	5.4	2.5
Tu4	14.2	11.7	3.3
gSfs	153.8	54.2	20.8
mS	272.1	177.9	79.1
mSgs	242.1	117.1	29.1
mSfs	129.6	92.1	54.1
fS	71.7	44.2	16.6
fSms	101.7	70.4	25.0
Hhz1	83.3	10.4	2.1
Hhz2	83.3	10.4	2.1
Hhz3	10.4	2.1	0.2
Hhz4	2.1	0.2	0.0
Hhz5	2.1	0.2	0.0
nHv	83.7	10.8	2.5
nHm	83.7	10.8	2.5
nHa	83.7	10.8	2.5
nHt	83.7	10.8	2.5
nHr	83.7	10.8	2.5

4.3.4 Crop Parameters and Crop Management Data

Crop parameters file **crop.dat** has to be included in the model input. It is a standard input file for SWIM. The full description of this data is given in Section 3.3.6.

Crop management data include description of agricultural activities:
- day of operation,
- operation code (planting, harvesting),
- crop number (from the available crop data base, which also include some aggregated categories),
- days of fertilisation,
- amount of N and P in kg applied per hectare.

Cop management input in the model is not fully automatised at the moment. Therefore, the subroutine initcrop() has to be recompiled for new applications to take into account crop rotation and crop management. Three options are available for crop rotation now:
- one crop in cropland,
- 10-11 years rotation scheme, including six crop types and set aside,
- three different rotation schemes for three soil groups (poor, intermediate and high quality soils) with a stochastic crop distributor, so that crop rotation is the same within the soil group, but it is not synchronised for different 'fields' (starting year is chosen stochastically for the 'fields').

Later, this routine has to be rearranged to allow fully automatised climate data input.

4.2.5 Hydrological and water quality data

Additionally, river discharge and concentrations of nitrogen, phosphorus and suspended solids in the basin outlet are needed for model validation. River discharge has to be included in the model input (see format in **Tab. 4.15**), while the measured water quality data can be compared with the model output outside the model. A number of criteria of fit are included in the model, like the Nash & Sutcliffe efficiency (Nash and Sutcliffe, 1970).

Table 4.15 Format of water discharge data for SWIM

YYYY	MON	DAY	Q,m3/s
1981	1	1	3.10
1981	1	2	3.45
1981	1	3	7.92
1981	1	4	13.80
1981	1	5	6.81
1981	1	6	5.39
1981	1	7	4.86
1981	1	8	4.53
1981	1	9	4.13
1981	1	10	4.09
1981	1	11	3.97
1981	1	12	4.06
1981	1	13	3.91
1981	1	14	3.92
1981	1	15	4.17
...	..	..	....

4.4 Model Run

4.4.1. Collect all input data

All input files necessary for the model application were listed in Section 3.3 and described in **Tab. 3.10**. Their preparation is described in Sections 4.1 – 4.3. Here a summary is given on how to collect all prepared data before running SWIM.

The working directory (later called 'main working directory') is usually named by the basin name, It must have the following subdirectories:

/Code – for the model code
/Sub – for sub-basin parameter files
/Soil – for soil data files,
/Struc – for sub-basin structure files,
/Res – for general model results,
/Flo – for specific results on water and nutrient flows,
/GIS – for specific results in GRASS GIS format,
/Clim – for climate and hydrological data files.

After that all prepared files have to be copied in appropriate subdirectories as described below.

Step1. Files created by SWIM/GRASS interface The four files created by SWIM/GRASS interface in the user GRASS directory DATABASE/LOCATION/MAPSET/swim/projectname

file.cio,
str.cio,
xxx.fig ,
xxx.str

have to be copied to the main working directory.

The sub-basin files created by SWIM/GRASS interface in the user GRASS directory DATABASE/LOCATION/MAPSET/swim/projectname

xxxNN.sub – M files, where M is the number of sub-basins,
xxxNN.gw – M files, where M is the number of sub-basins,
xxxNN.rte – M files, where M is the number of sub-basins

have to be copied in the directory **/Sub.**

Step 2. Climate and hydrological data Climate and hydrological data have to be copied to the main working directory: either one file

clim.dat,

which includes all climate and hydrological data (see Sections 4.2.2 and 4.2.5), or four files

prec.dat
temp.dat,
radi.dat
runoff.dat,

which include separately precipitation, temperature, radiation, and runoff data, respectively. The directory /Clim may be used for original climate data sets and for climate data modification (e.g. to prepare two separate climate data sets for the calibration and validation periods).

In the case of large number of sub-basins and direct correspondence '1 sub-basin – 1 precipitation station', the file

sub2prst.dat

may be prepared, which indicates the correspondence between sub-basins and precipitation stations. If necessary, this file may contain weighting coefficients for precipitation stations. This file has to be placed in the main working directory.

Usually the climate read part is organised specifically for the basin under study by user (file cliread.f in the directory /Code), who can specify whether the data are read from one file clim.dat, or from several files, and how the correspondence between sub-basins and precipitation/climate stations is established.

Step. 3 Soil data The user has either use available soil database BÜK-1000 supplied with the model or to prepare all soil data in the same format as described in Section 4.3.3. Soil data

soil04.dat,

soil05.dat, etc

Have to be copied in the directory ***/*Soil**. In addition, the file

soil.cio,

which includes a list of all soil data file names, has to be copied to the main working directory or prepared.

Step 4. Crop data The standard crop database contained in the file

crop.dat,

which is supplied with the model, has to be copied to the main working directory.

Step 5. Files .cod and .bsn An example program codes file

xxx.cod,

which includes program codes for printing, is supplied with the model. The user has to specify the desired period of simulation (parameters nbyr, iyr, idaf, idal), which has to be in correspondence with climate and hydrological data, and the number of sub-basins (parameter lu). The print codes have to established by user, if the hydrotope printout, sub-basin printout, process printout, or special printout are necessary. This file has to be placed in the main working directory.

An example basin parameters file

xxx.bsn,

which includes a set of basin parameters and a set of calibration parameters, is supplied with the model. The user has to introduce the correct basin area (parameter da), which can be taken from .bsn file produced by SWIM/GRASS interface. This file has to be placed in the main working directory.

Step 6. File wstor.dat An example file

wstor.dat,

which includes initial water storages for the reaches is supplied with the model. Here all initial storages may be put to 0, then initial period (1-2 weeks) of simulation has to be ignored. The other option is to take water storage at the end of the first year from the test model run. This file has to be placed in the main working directory.

Step 7. File wgen.dat An example file with monthly statistical climate data

wgen.dat,

is used to run weather generator. Besides this file is needed to establish rain intensity parameters (tp5, tp6, tp24), latitude (parameter ylt), and average monthly maximum and minimum temperature (vectors obmx, obmn). It is assumed that these parameters are

basin-specific. The vectors obmx, obmn can be calculated using an additional program *wgenpar* from the available climate data, taking as long time series of climate for the basin as possible. Then the calculated average monthly maximum and minimum temperatures have to be substituted into the example wgen.dat file. The file wgen.dat has to be placed in the main working directory.

4.4.2 Modification of the code to adjust for specific input data

When all input data are ready, the user has to copy the source code files

```
clicon.f        gwat.f          readcrp.f
cliread.f       hydrotop.f      readsol.f
common.f        init.f          readsub.f
compar.f        initcrop.f      readwet.f
crop.f          main.f          route.f
cropyld.f       ncycle.f        routfun.f
curn.f          open.f          solt.f
eros.f          pcycle.f        stat.f
evap.f          perc.f          subbasin.f
flohyd.f        readbas.f       veget.f
genres.f        readcod.f       vegfun.f
```

and the Makefile from the supplied model package. Some files, which provide initialisation of the model, may be corrected. The correction may be needed in

- climate data read part (files **open.f,** and **cliread.f),**
- crop initialization part (file **initcrop.f**),
- soil parameter read part (file **readsol.f**),
- global model parameter part (file **compar.f**).

As soon as a certain flexibility is allowed regarding the climate data input, the corresponding changes may be necessary in files

open.f, and
cliread.f

Different options are possible: from the simplest variant, when all climate and hydrological data are put in one file **clim.dat**, to another variant, when precipitation, temperature, radiation, and water discharge are put in four different files

prec.dat
temp.dat,
radi.dat
runoff.dat.

Correspondingly, the assignment of precipitation stations to sub-basins may be done differently. Examples are given in **cliread.f.variants** file located in **/Codevar** directory (supplied with the model).

Crop management is initialised in the file

initcrop.f.

Different options are possible in initialisation of crop management:

- single crop on the total cropland area,
- different crop rotations and fertilization schemes,
- crop generator.

The first two options may be used by including desired version of initcrop() subroutine. Examples are given in **initrcrop.f.rotNferN** and **initcrop.f.single** files located in **/Codevar**

directory (supplied with the model). They can be used directly by opening the desired variant of initcrop() and closing the others. The user has to keep in mind that winter crops may start only from the second year of simulation (planting in autumn). That is why the single crop variants with winter crops include summer barley for the first year of simulation.

The third option (crop generator) is usually applied only for regional studies. It requires more changes in the code, and is supplied as a separate model version.

The user may either use the available soil database BÜK-1000, or another soil parameters. In principle, the format should be the same, then no changes are needed in the **readsol.f** file. In case if a new format is used, the corresponding changes have to be made in the file

readsol.f

Two examples: **readsol.f.elbe** and **readsol.f.glonn** are given in the /Codevar directory for the Elbe and Glonn basins, respectively.

Besides, the user may changes global model parameters, like maximum number of sub-basins, *mb*, and maximum number of hydrotopes, *meap*, in the file

compar.f

This is necessary if the maximum number of sub-basins/hydrotopes for the case study basin is larger than in the code, and it is also useful if the maximum number of sub-basins/hydrotopes for the case study basin is significantly smaller than in the code (saves compilation time!).

4.4.3 Sensitivity of the simulated river discharge to model parameters

Sensitivity of the simulated river discharge to model parameters described in this Section is one of the most important sensitivity studies with SWIM as an ecohydrological model. It can be extended by sensitivity analysis of the crop yield or nitrogen flow components to model parameters. The results of the sensitivity analysis are partly basin-specific, because they depend on the basin structure (land use, soil, etc.).

The sensitivity analysis described here was done for the Stepenitz basin (gauge station Wolfshagen, drainage area 575 km^2) for the six years period 1983 - 1988. Most of parameters used for the sensitivity analysis are from the *.bsn* file (see Section 3.4.3). The results are summarised in **Tab. 4.16** and depicted in **Figs 4.7 – 4.24**.

Saturated Conductivity is a very important model parameter. However, it is rarely available in soil databases, and its estimation using pedo-transfer functions or other methods is problematic and often leads to contrasting estimates (see e.g. **Fig. 4.6** in Section 4.3.3). In SWIM the saturated conductivity *sc* can be either read from the database connected to the model (if the parameter *isc* = 0), or calculated using the Rawls & Brakensiek method (if *isc* = 1). The comparison of the effect of the both methods on the simulated river discharge is shown in **Fig. 4.7**. If the parameter *sc* is read, the peaks are higher, and the level of lowflow is lower, the total water discharge for the six years simulation period is 6% higher.

Due to uncertainties in the estimation of saturated conductivity, it is allowed to correct the parameter *sc* in the model globally for all soils and soil layers, using the correction factor *sccor*. The results of model sensitivity to the correction of the parameter *sc* are shown in **Figs. 4.8 and 4.9**. As one can see, the decrease in the sc (sccor = 0.8) leads to a slight increase in peaks and lowering the level (compare with **Fig. 4.7**). The difference in the total

water discharge is rather small. The graphs on the right hand side show changes for shorter periods of several months.

Soil depth Usually there is an uncertainty in the establishing of soil depth in the models. In some models the soil depth is limited by 1 m, in others by 2 m or by the maximum root depth. In our soil database based on BÜK 1000 (Hartwich et al., 1995) the soil depth is limited by the maximum rooting depth defined for the leading soil profile in dry years. This defines the reference case in **Tab. 4.16**. The sensitivity of the model to soil depth is depicted in **Fig. 4.10**, which compares the reference case with the variant, when soil depth is increased by 50%. In the both cases the actual root depth is restricted by the parameter *rdmx* (see **Tab. 3.13**) and the actual soil depth. The increase in soil depth leads to a quite significant decrease (-10.1 %) in the total water discharge (due to higher evapo-transpiration), and lowering of the peaks and the level.

Assignment of hydrological soil groups The analysis of the model sensitivity to the assignment of hydrological soil groups is shown in **Fig. 4.11**. As could be expected, shifting of the soil groups to the higher ones, like A → B, B → C, and C → D leads to the increase in peaks (more explicitly visible in two graphs on the right hand side), but rather small changes in the total water discharge.

Curve Number method The Curve Number method in SWIM ca be used in two different modes: a) in the original mode, differentiating CN parameter for soil types and land use categories, and b) in the other mode, not differentiating for land use and soil types, and putting CN parameter for conditions 1 equal to cnum1, and for conditions 3 equal to cnum3 (cnum1 is not equal to cnum3) for all land use categories and all soil types. The comparison of the reference case (icn = 0) and a number of variants corresponding to the mode b) are given in **Tab. 4.16** and **Figs. 4.12 – 4.14**. When CN is not differentiated, small peaks disappear, and the hydrograph becomes smoother. Though the high peaks can be lower (**Fig. 4.12**), or higher (**Fig. 4.13**), the total discharge is always lower by 5 – 5.5 %.

Baseflow factor for return flow travel time The influence of the baseflow factor *bff* on water discharge is shown in **Figs. 4.15 and 4.16**. When *bff* is decreased from 1.0 to 0.2, the peaks are lower, the level of lowflow is higher, and the total discharge is 3.4% lower. The increase of *bff* leads to the opposite effect.

Groundwater recession rate Alpha factor for groundwater, or groundwater recession rate, which characterises the rate at which groundwater flow is returned to the stream, has quite significant influence on hydrograph, especially in the period of high flow (winter – spring) (**Figs. 4.17 – 4.18**). When the alpha factor *abf0* is higher, peaks in winter and early spring are also higher, while the decrease in *abf0* leads to the 3.5% decrease in the total discharge and the lowering of winter peaks.

Initial conditions The initial conditions in SWIM may be changed by establishing the initial groundwater contribution to streamflow (parameter *gwq0*) and the initial water storage (parameter *stinco*). This influences the hydrograph during the first 3-6 months, as one can see in **Figs. 4.19 – 4.20**.

Routing coefficients Initial estimation of the storage time constants for the reach, *xkm*, in the model is based on the channel length and celerity, which, in their turn, are estimated based on the DEM. This preliminary estimation can be corrected during the model calibration using parameters *roc2* and *roc4*. The increase in these coefficients leads to the lowering of peaks and the smoothing of the dynamics in general (**Figs. 4.21 – 4.22**).

However, the total water discharge does not change significantly. It is recommended to check these parameters always during the model calibration.

Crop type Water discharge is also sensitive to crop types due to their different seasonality and other characteristics (e.g. maximum LAI). Regarding the crop distribution on arable land, SWIM can be applied either

a) with one crop on the whole arable land every year, or
b) applying a predefined crop rotation scheme for the whole arable land, or
c) with crop generator, which distributes different crop types in the basin or region under study in accordance with several predefined crop rotation schemes.

In our sensitivity analysis the simplest option a) was used in order to check the influence of crop types on the simulated hydrograph. Though the change in the total water discharge is rather small (**Tab. 4.16**), there are obvious differences in the discharge dynamics (see **Figs. 4.23 – 4.24**). This confirms the importance of using reliable information on actual crop distribution for the initial parametrisation of the model.

The sensitivity study like one described in this Section can be recommended for inexperienced users in order to gain better understanding of the model performance.

Table 4.16 Results of sensitivity analysis for the Stepenitz basin

method to define saturated conductivity sc	**Reference**: sc calculated (Rawls & Brakensiek method)	sc read from database
Model parameter used	isc = 1	isc = 0
Change in total water discharge		+ 6.0%
Change in peaks		Peaks ↑↑
Change in level		Level ↓↓

Correction of saturated conductivity sc, if sc is read (isc = 0)		**Reference**:	
Model parameter used	sccor =1.2	sccor = 1.	sccor = 0.8
Change in total water discharge	-1.3 %		+1.6 %
Change in peaks	Peaks ↓		Peaks ↑
Change in level			

Correction of saturated conductivity sc, if sc is calculated (isc = 1)		**Reference**:	
Model parameter used	sccor =1.2	sccor = 1.	sccor = 0.8
Change in total water discharge	-1.0 %		+1.2 %
Change in peaks	Peaks ↓		Peaks ↑
Change in level	Level ↑		Level ↓

Soil depth	**Reference**: Soil depth is established according to maximum root depth	Soil depth is established according to maximum root depth + 50%
Change in total water discharge		-10.1 %
Change in peaks		Peaks ↓↓
Change in level		Level ↓↓

Hydrological soil groups	**Reference**: soil groups A, B, C, D	A→ B, B → C, C → D, D = D	A → C, B → C, C → D, D = D
Model parameter used	nsolgr = 1, 2, 3, 4	nsolgr = 2, 3, 4, 4	nsolgr = 3, 3, 4, 4
Change in total water discharge		+0.3 %	+0.9 %
Change in peaks		Peaks ↑	Peaks ↑↑
Change in level		Level ↓	Level ↓

Curve number method: differentiate on land use and soil or not	**Reference**: CN different, icn = 0	icn = 1	icn = 1	icn = 1	icn = 1	icn = 1	icn = 1	icn = 1
Model parameter used: cnum1, cnum3		30, 70	40, 80	50, 90	30, 80	40, 90	40, 70	50, 80
Change in total water discharge		- 5.5 %	- 5.5 %	- 5.0 %	- 5.5 %	- 5.1%	- 5.5 %	- 5.5 %
Change in peaks		Peaks ↓ no small peaks	Peaks ↓ no small peaks	Peaks ↑ no small peaks	Peaks ↓ no small peaks	Peaks ↑ no small peaks	Peaks ↓ no small peaks	Peaks ↓ no small peaks
Change in level		no	no	no	no	no	no	no

Baseflow factor for return flow travel time	**Reference**					
Model parameter used: bff	bff = 1.	bff = 1.5	bff = 2.	bff = 3.	bff = 0.5	bff = 0.2
Change in total water discharge		+ 1.%	+1.6 %	+2.3 %	-1. 5 %	-3.4 %
Change in peaks				Peaks ↑		Peaks ↓
Change in level				Level ↓		Level ↑

Alpha factor for groundwater	**Reference**				
Model parameter used: abf0	abf0 = 0.048	abf0 = 0.1	abf0 = 0.3	abf0 = 0.024	abf0 = 0.012
Change in total water discharge		+ 1 %	+ 1.7 %	- 1.4 %	- 3.5 %
Change in peaks			Peaks ↑ in winter-spring		Peaks ↓ in winter-spring
Change in level			Level ↑ in winter-spring		Level ↓ in winter-spring

Initial groundwater contribution to flow	**Reference**		
Model parameter used: gwq0	gwq0 = 0.5	gwq0 = 0.2	gwq0 = 1.
Change in total water discharge		- 5.1 %	+ 8.4 %
Change in peaks & level		Initial peaks and level ↓	Initial peaks and level ↑

Initial soil water storage	**Reference**		
Model parameter used: stinco	stinco = 0.7	stinco = 0.4	stinco = 1.0
Change in total water discharge		- 3.4 %	+ 3.1 %
Change in peaks & level		Initial peaks and level ↓	Initial peaks and level ↑

Routing coefficients							

Model parameter used: roc2, roc4	3, 3	6, 6	12, 12	24, 24	48, 48	6, 48	96, 96
Change in total water discharge		0 %	- 0.2 %	- 0.6 %	- 1.2 %	- 1 %	- 2.2 %
Change in peaks		Peaks ↓, dynamics - smoother	Peaks ↓, dynamics - smoother	Peaks ↓, dynamics - smoother	Peaks ↓, dynamics - smoother	Peaks ↓, dynamics - smoother	Peaks ↓, dynamics - smoother
Crop type (in the case if only one crop type on cropland)	**Reference:** winter rye	winter wheat	winter barley	summer barley	maize	potatoes	
Model parameter used: ncrp	ncrp =iwr	ncrp =iww	ncrp =iwb	ncrp =isba	ncrp =imai	ncrp =ipo	
Change in total water discharge		- 3.0 %	- 2.2 %	+ 0.4 %	- 0.9 %	+ 1.2 %	
Change in peaks		some peaks - different	some peaks - different	some peaks - different	some peaks - different	some peaks - different	

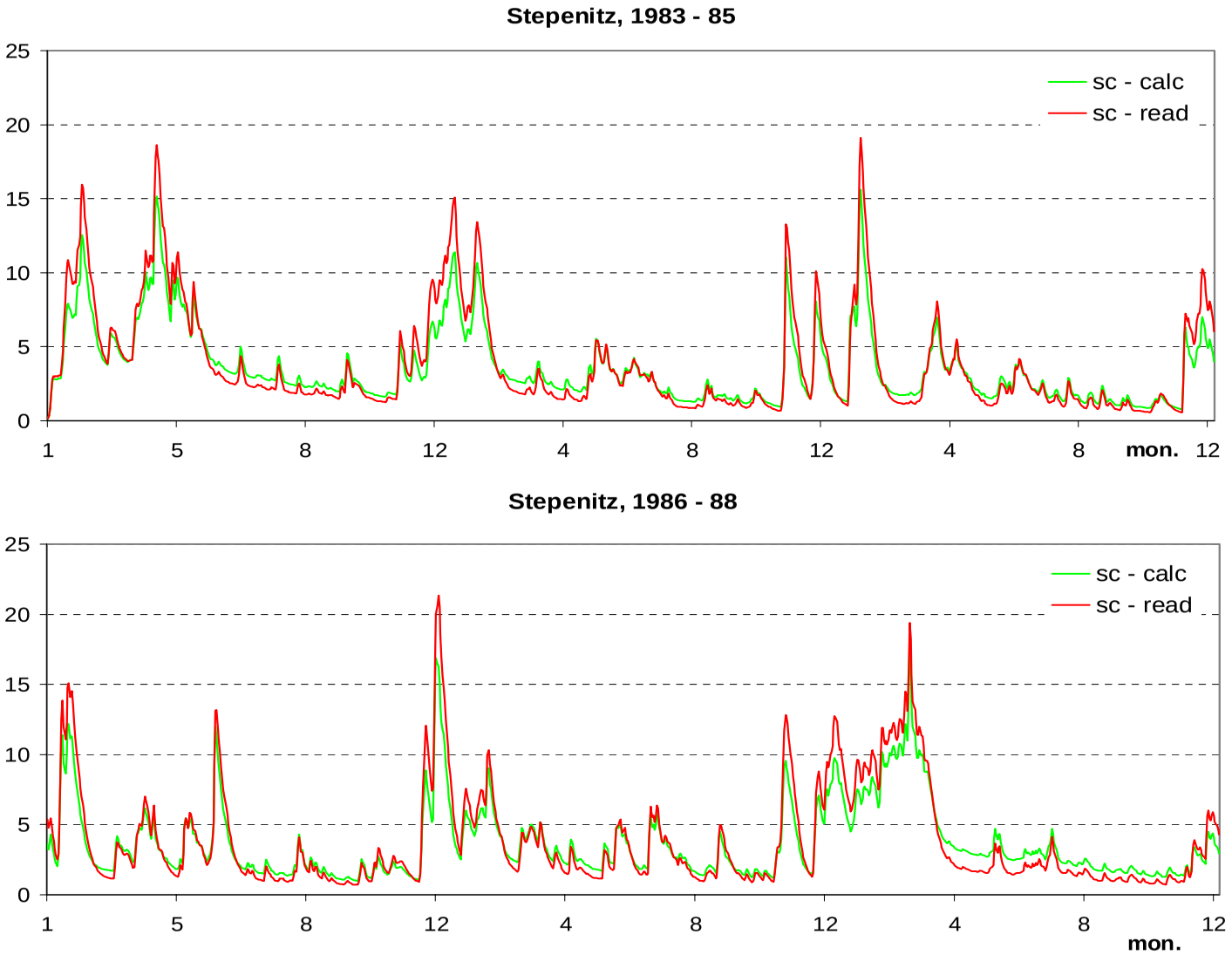
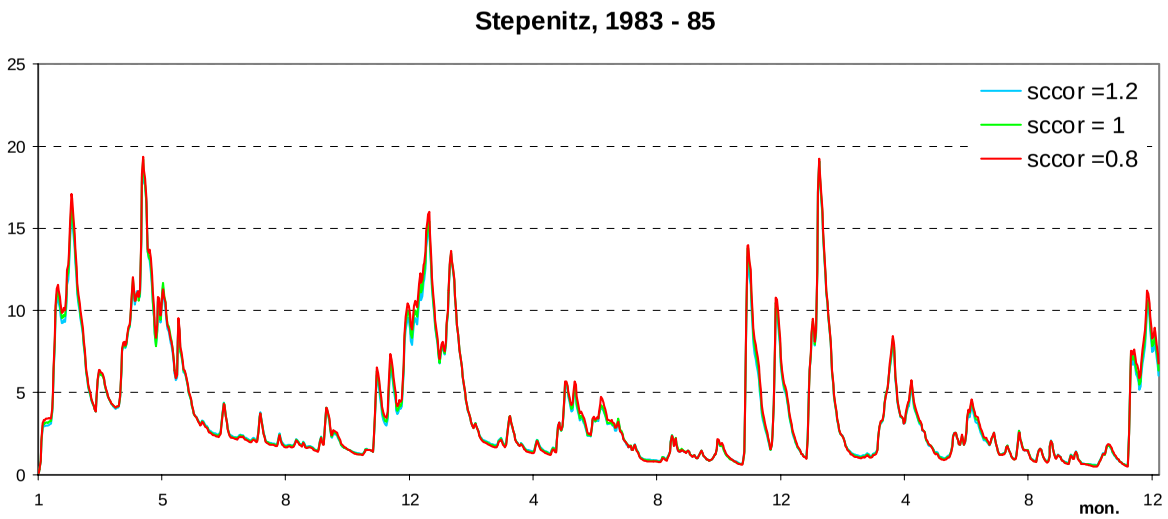


Fig. 4.7 Sensitivity to the method of estimation of saturated conductivity


Stepenitz, 1983 - 85
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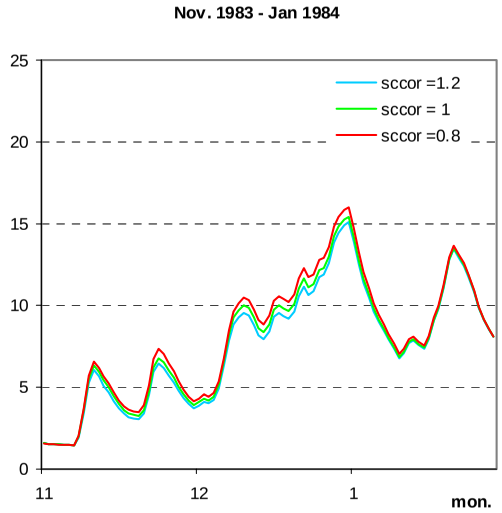
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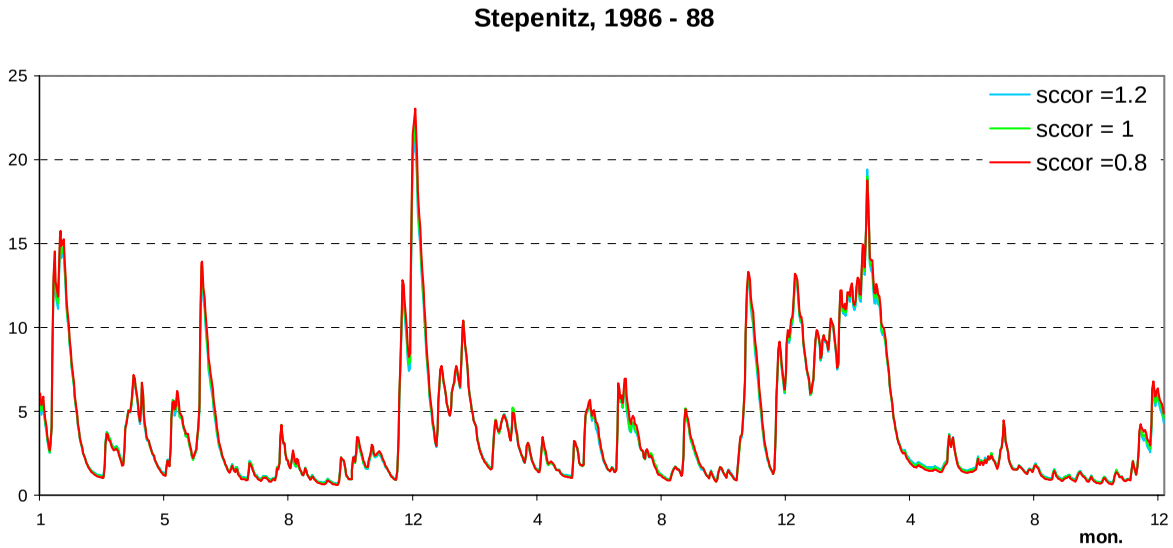
Stepenitz, 1986 - 88
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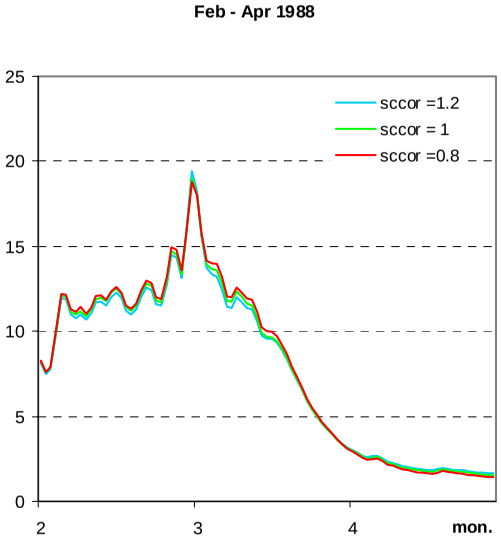
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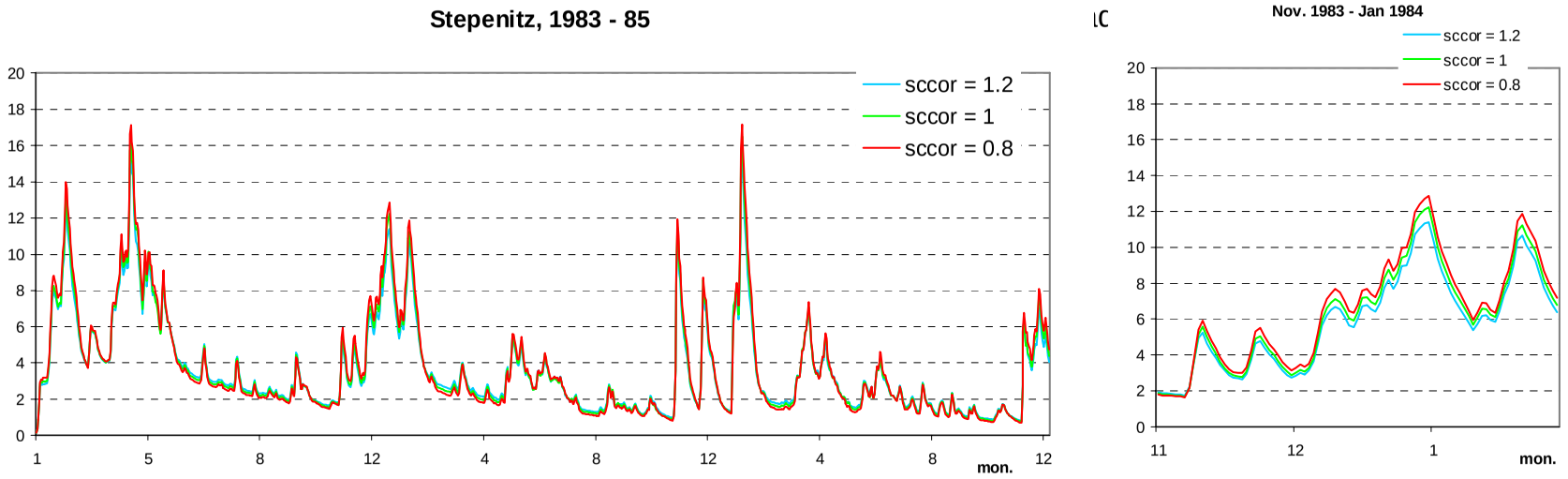
Stepenitz, 1983 - 85
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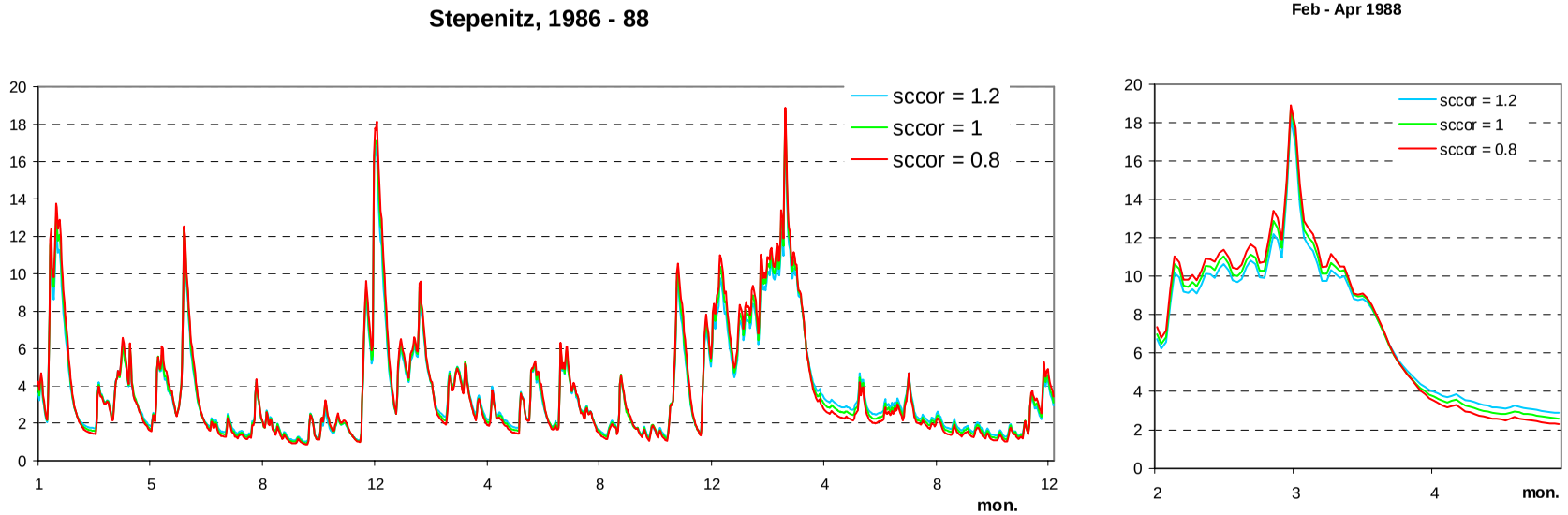
Stepenitz, 1986 - 88
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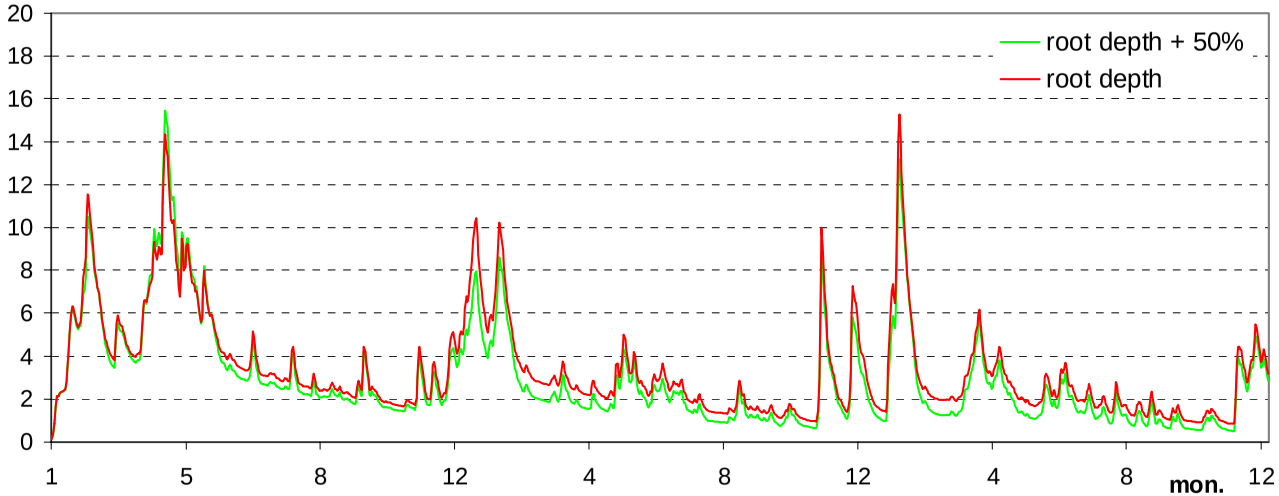
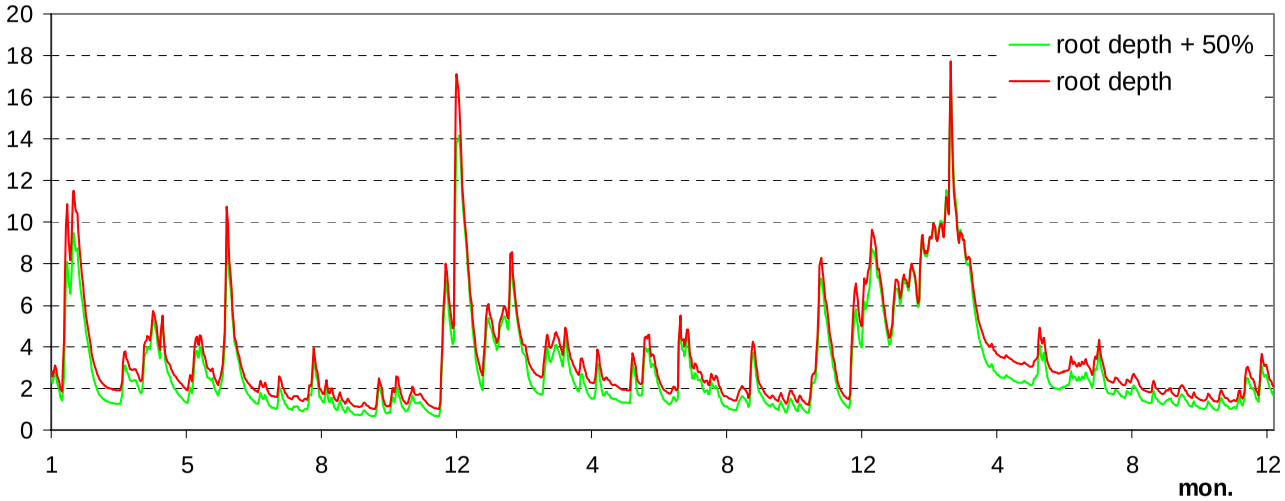
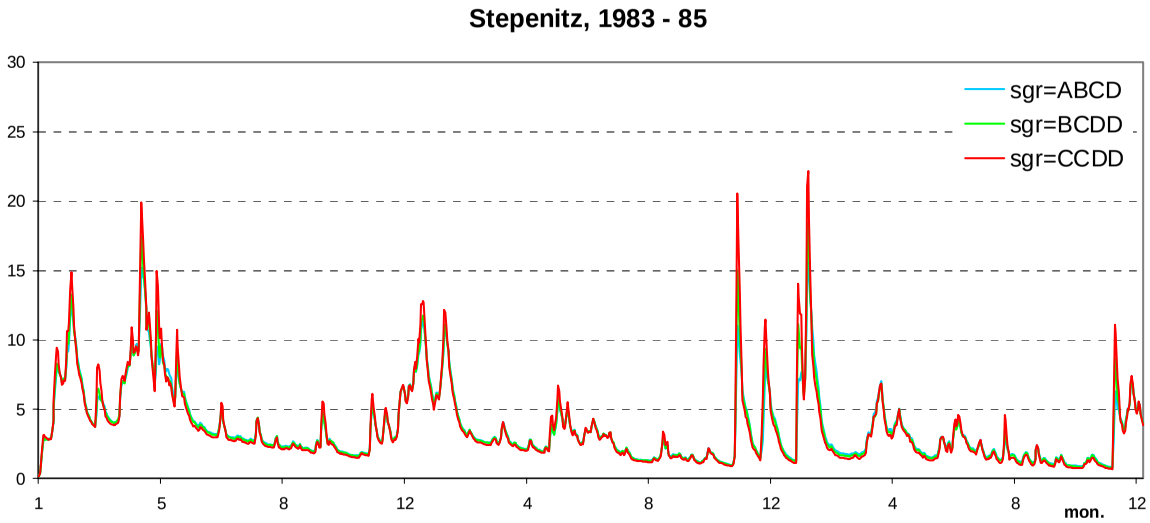
Stepenitz, 1983 - 85



Stepenitz, 1986 - 88




Stepenitz, 1983 - 85
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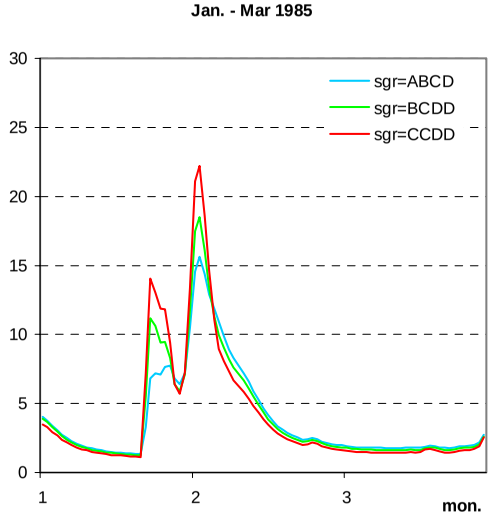
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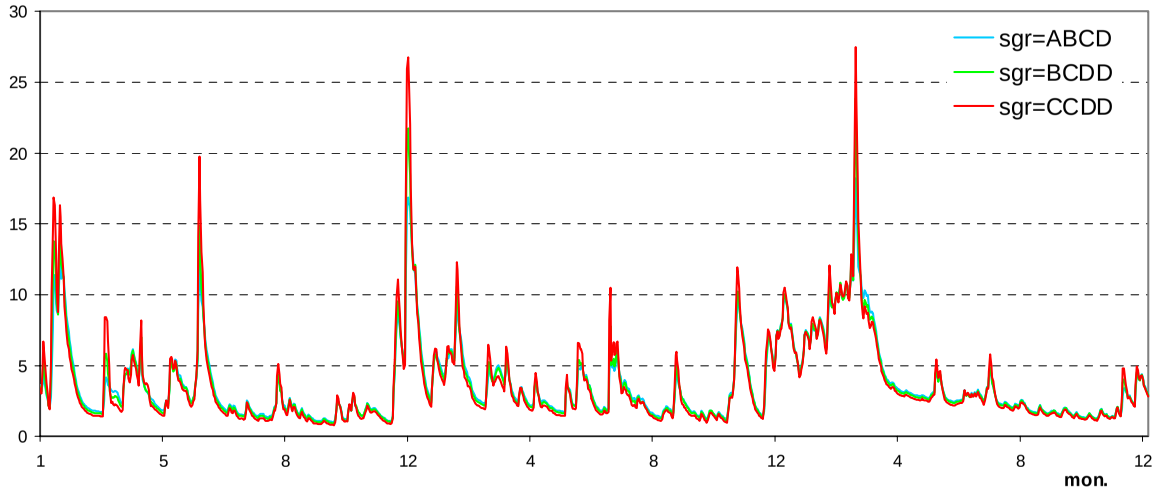
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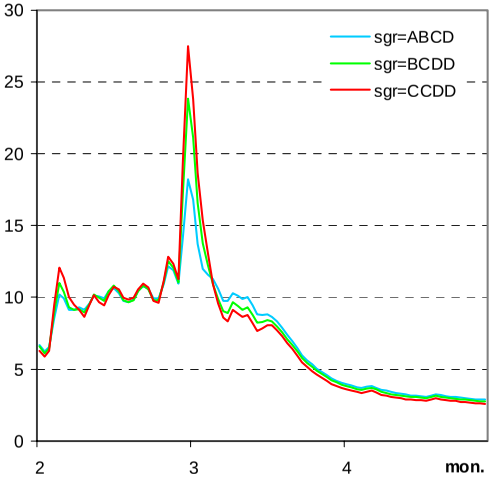
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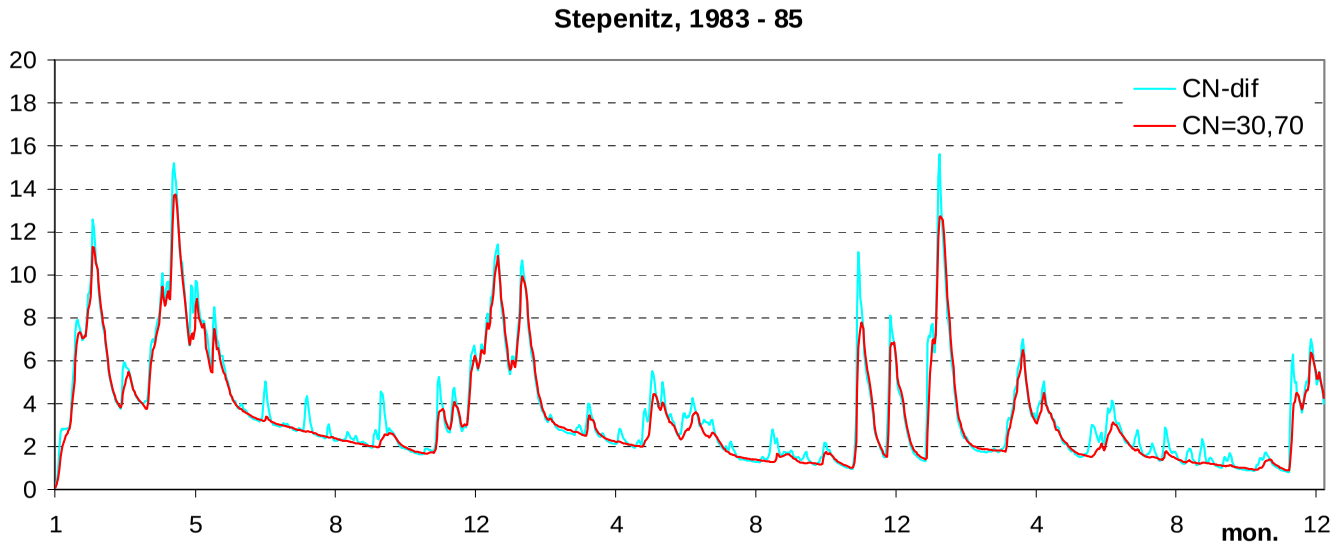
Stepenitz, 1983 - 85
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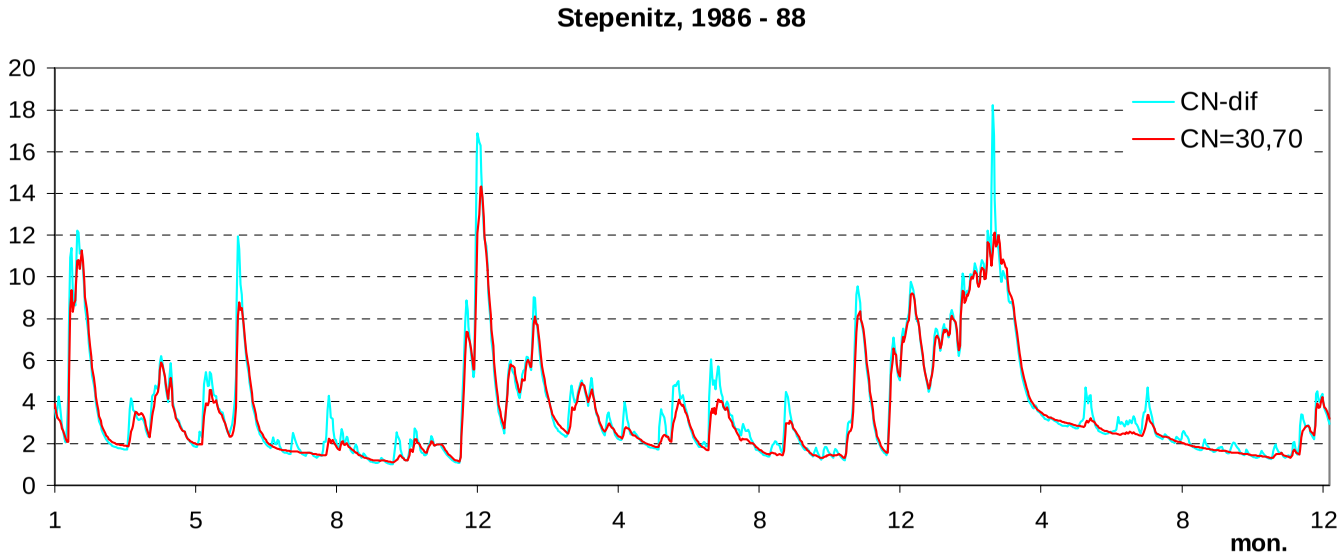
Stepenitz, 1986 - 88
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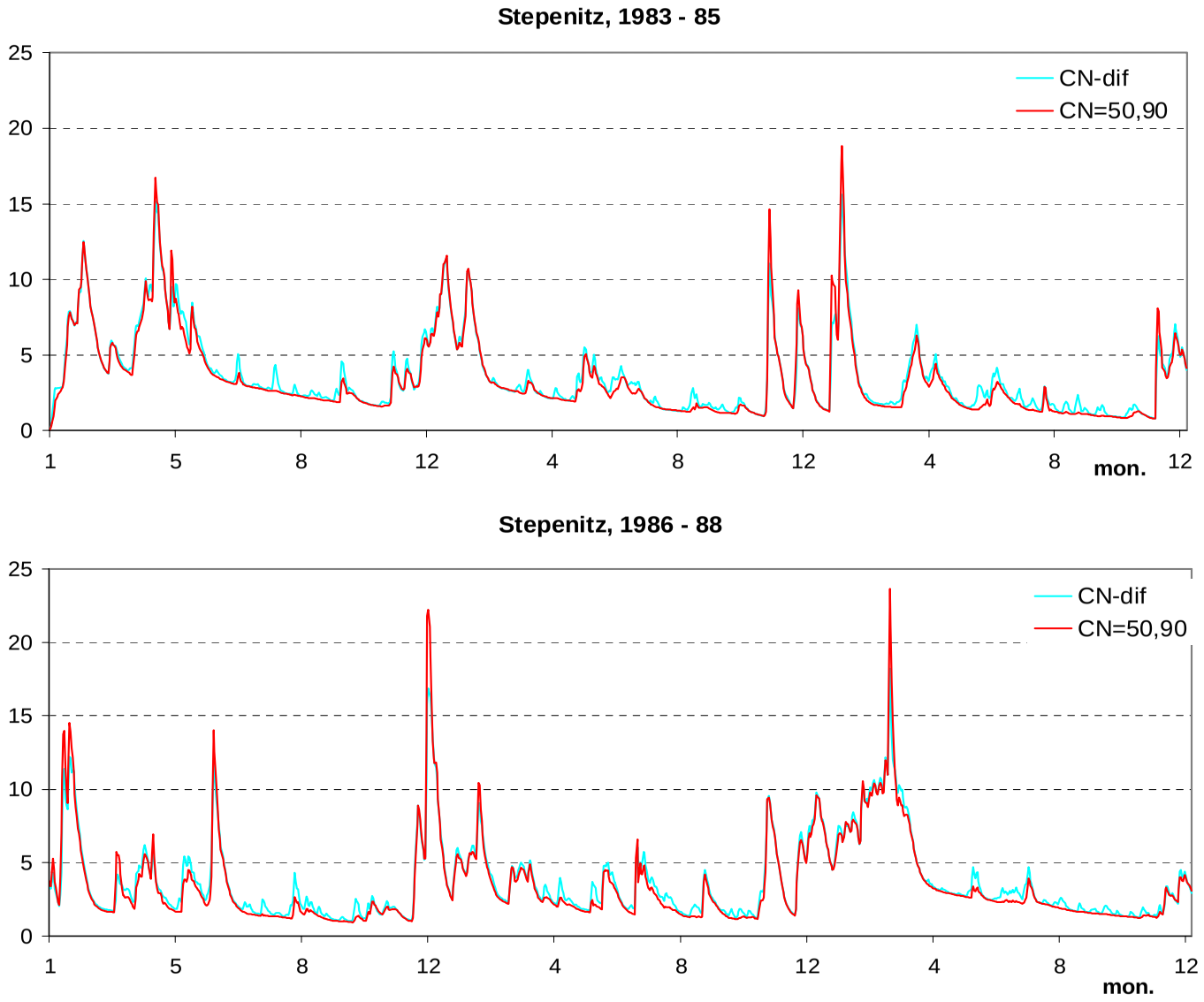
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mon.
Stepenitz, 1986 - 88
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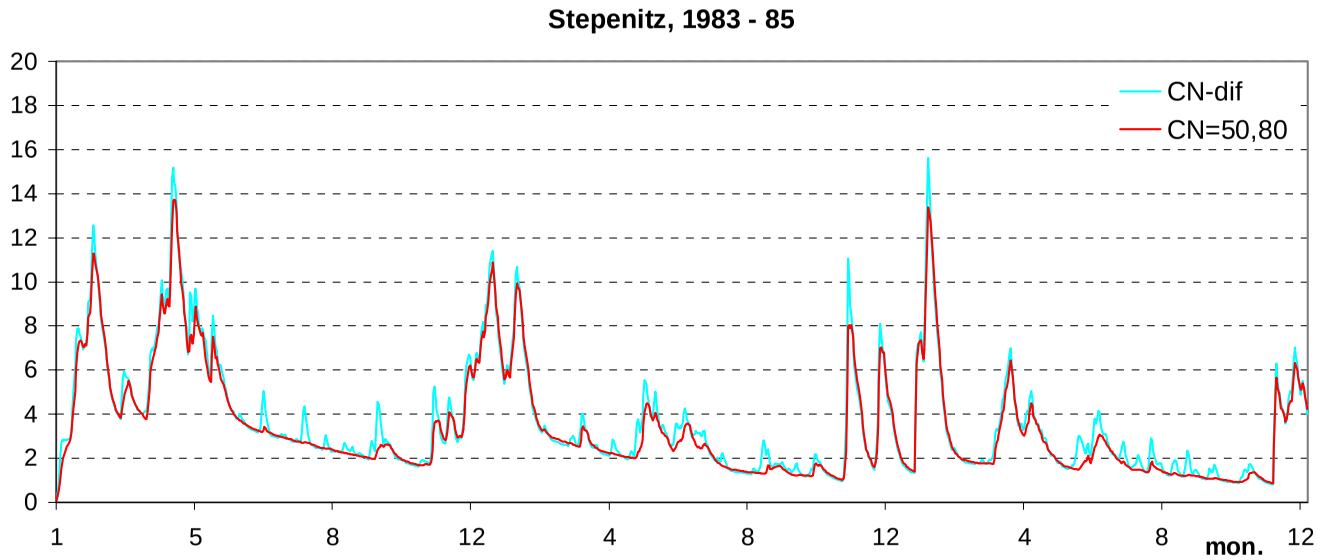
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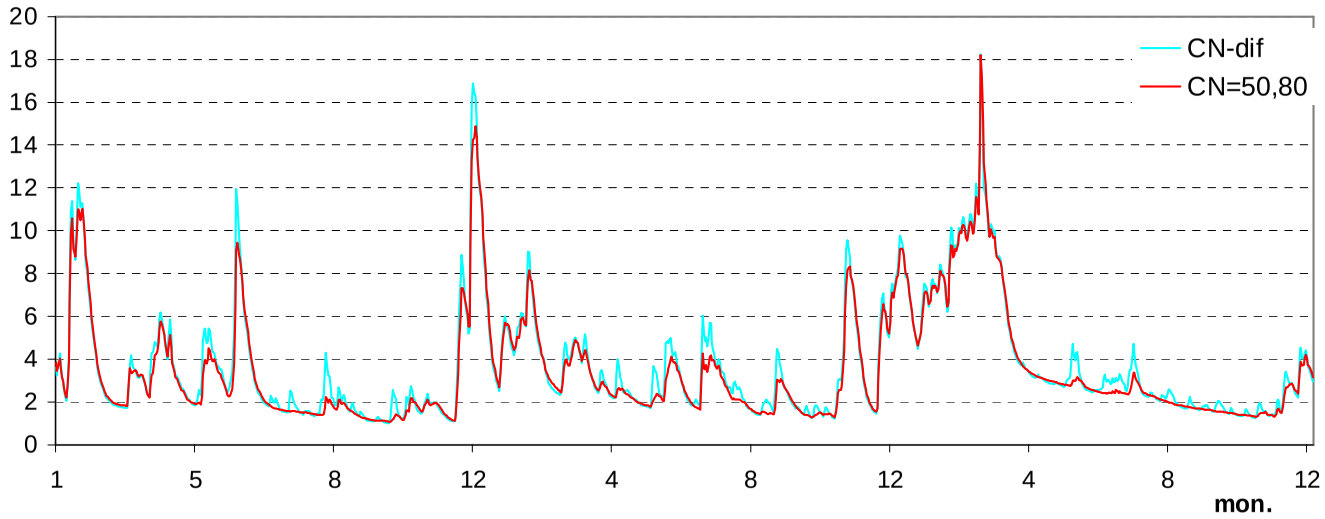
Stepenitz, 1986 - 88
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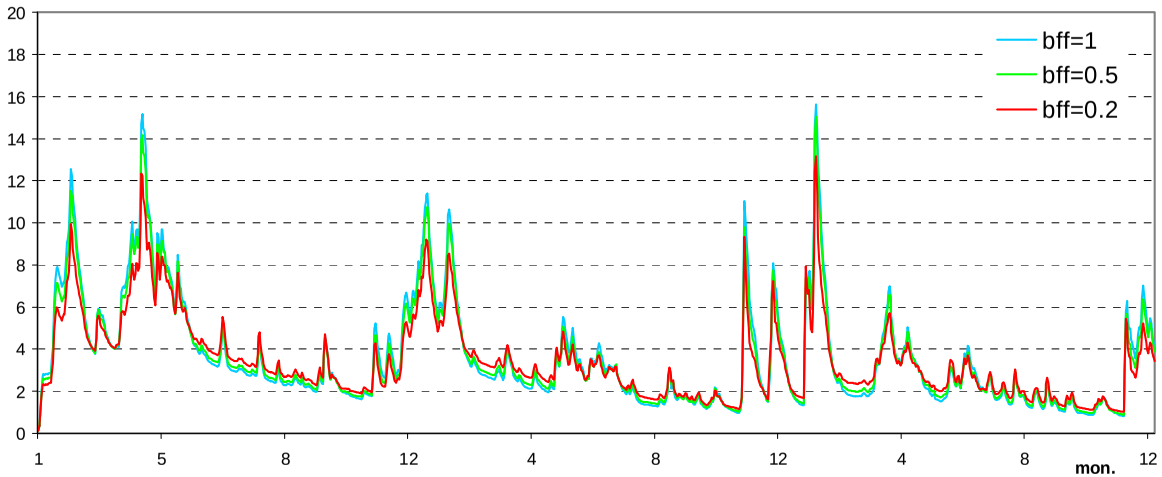
Stepenitz, 1983 - 85



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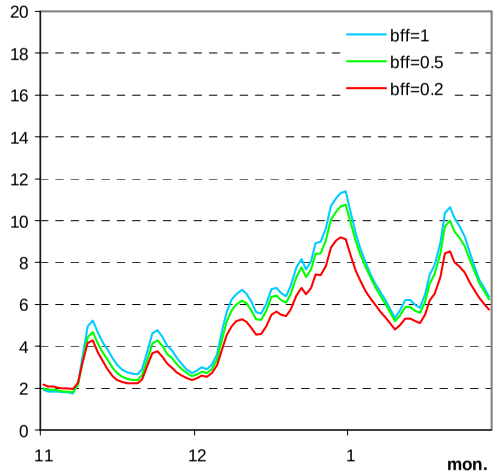
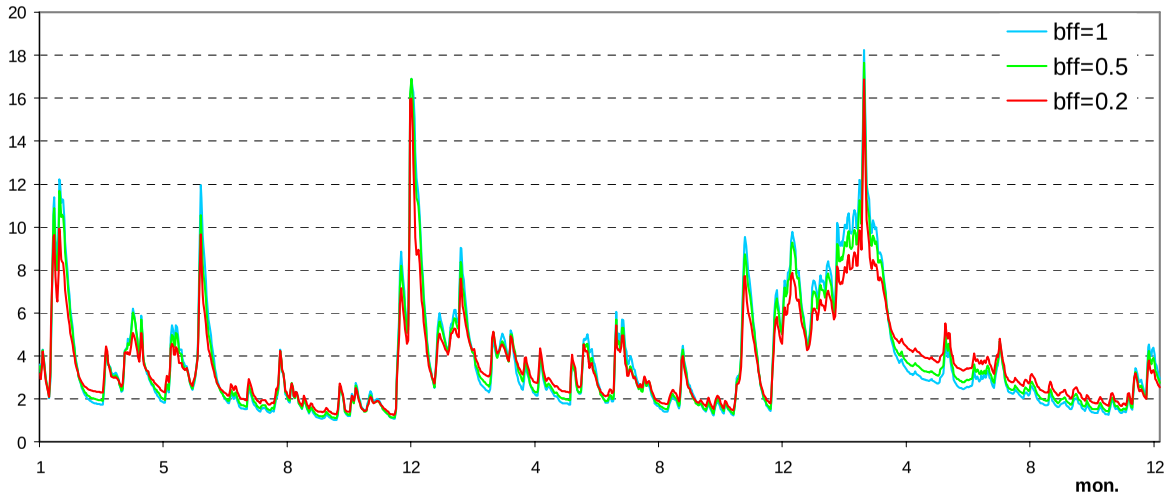


Stepenitz, 1986 - 88



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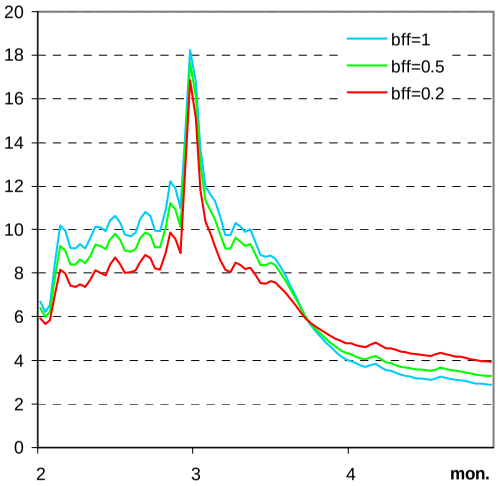
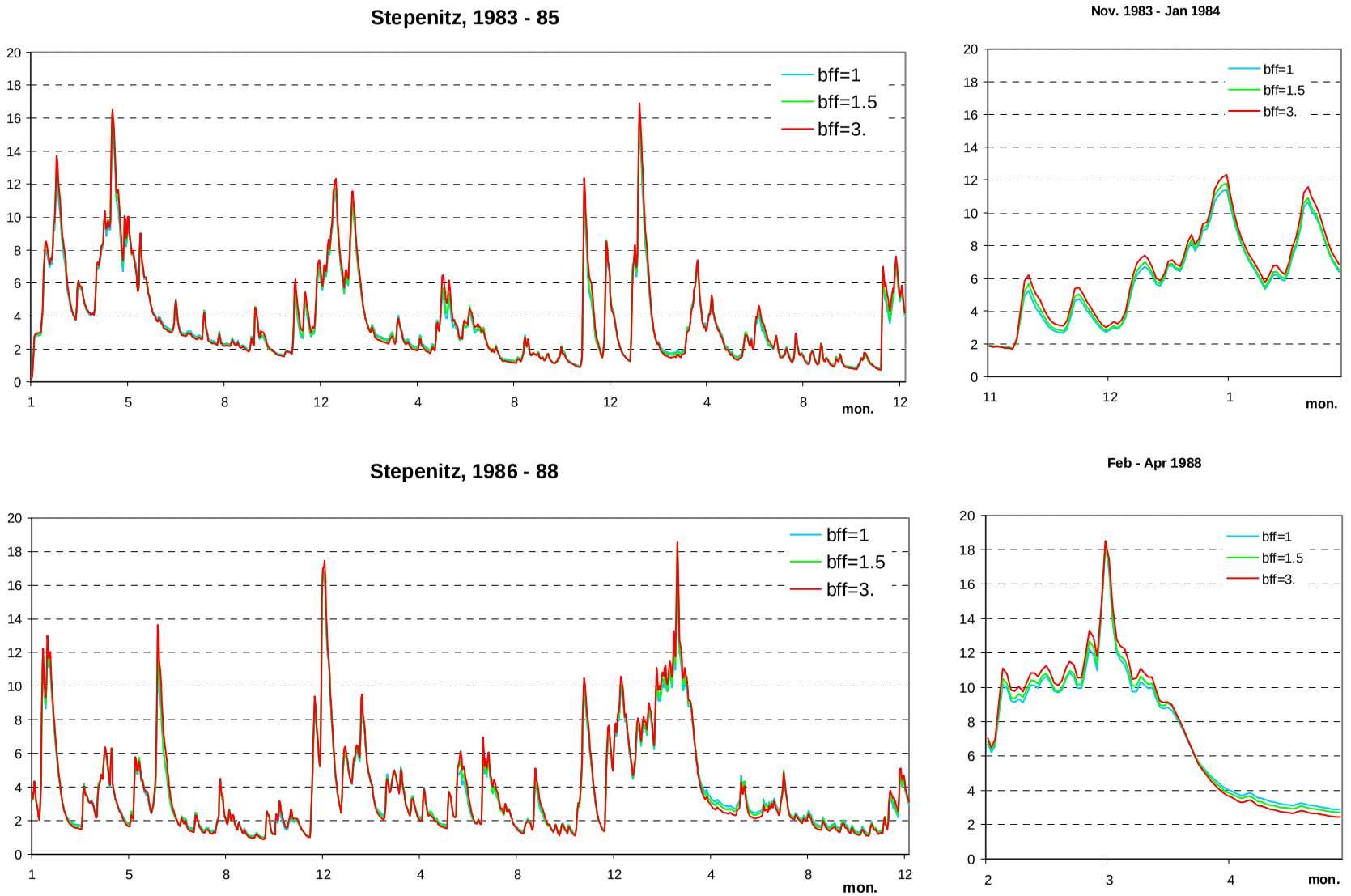
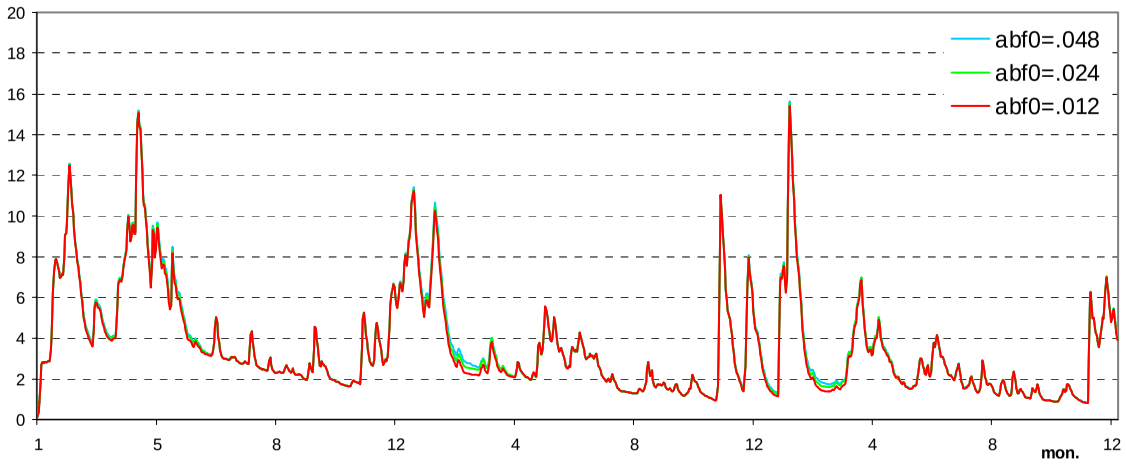


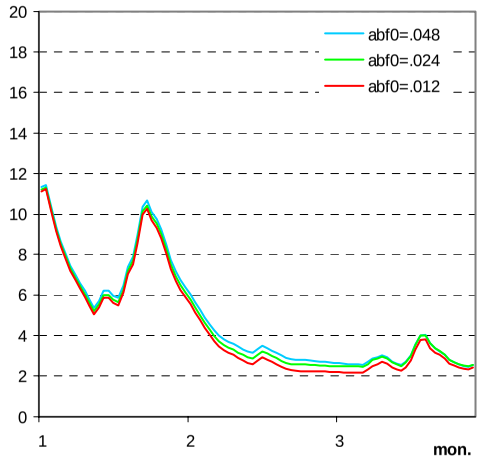
Fig. 4.15 Sensitivity to the baseflow factor (bff = 1; 0.5; 3.0)



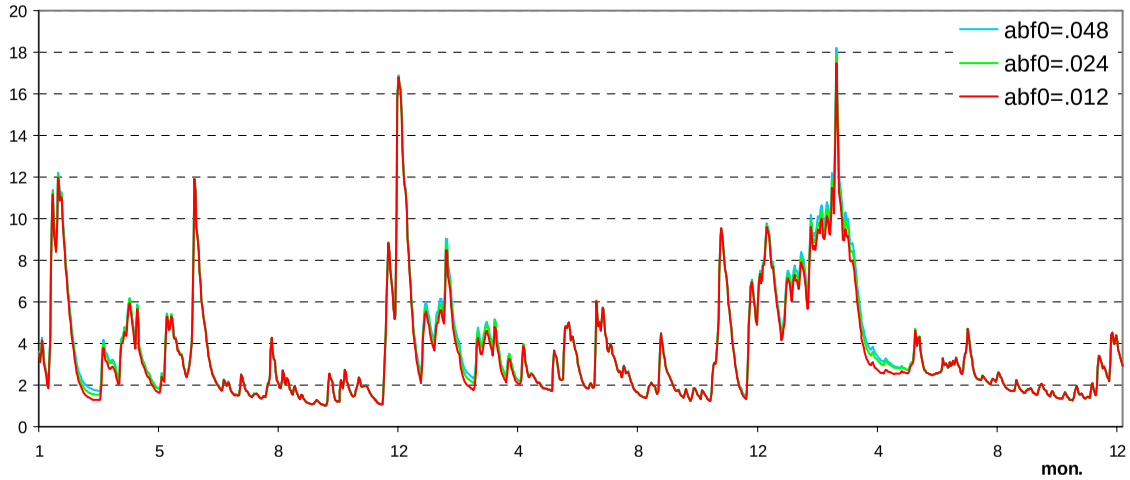
Stepenitz, 1983 - 85



Jan. - Mar. 1984



Stepenitz, 1986 - 88



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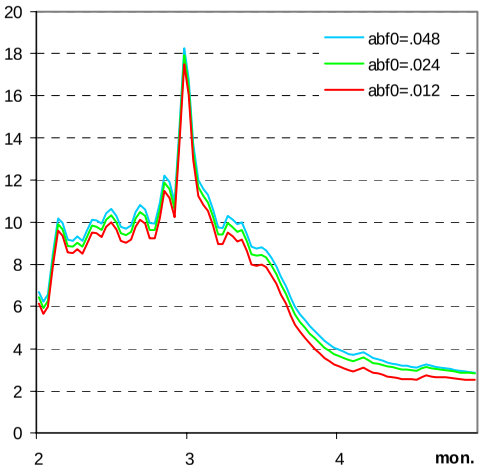
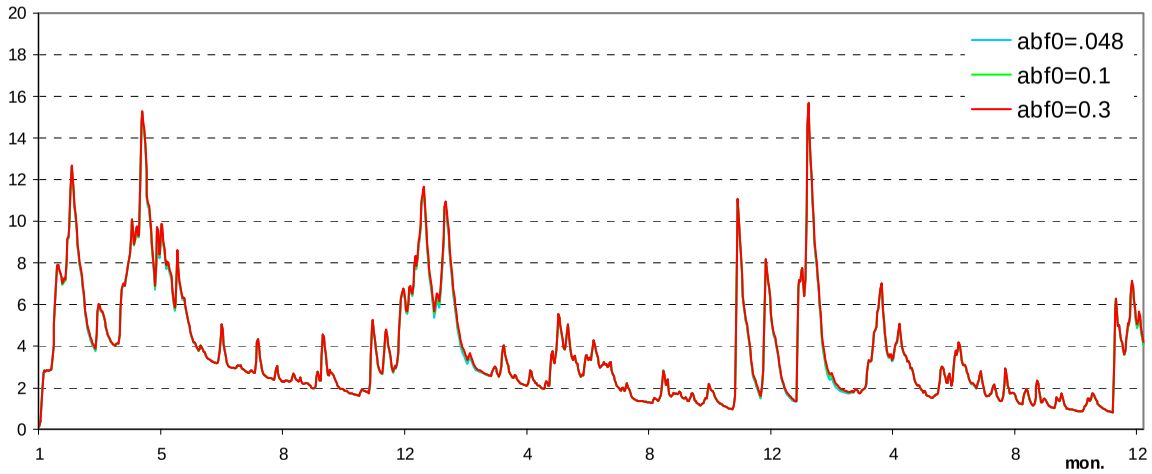


Stepenitz, 1983 - 85



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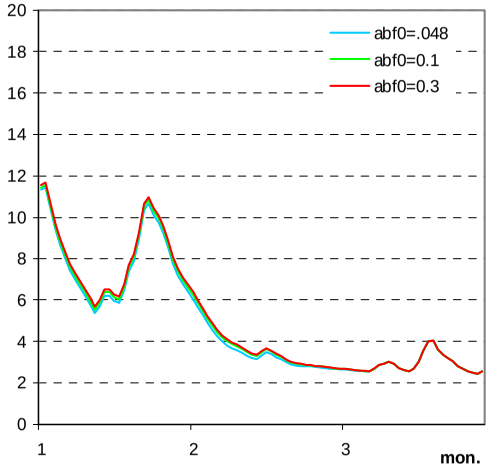
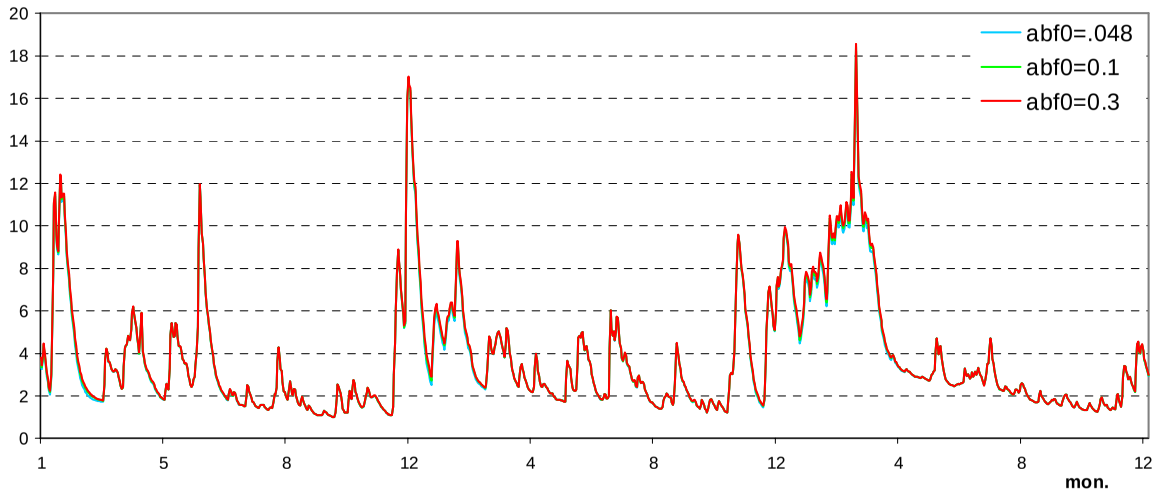
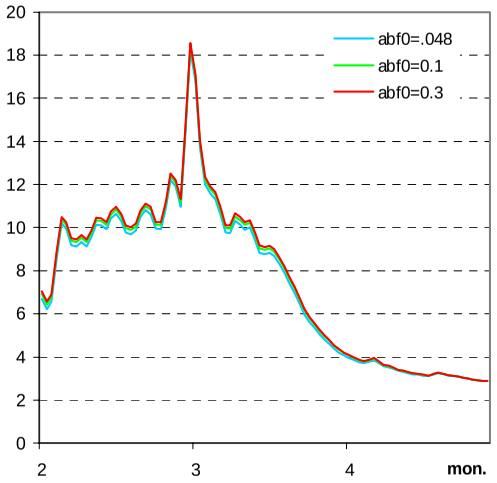
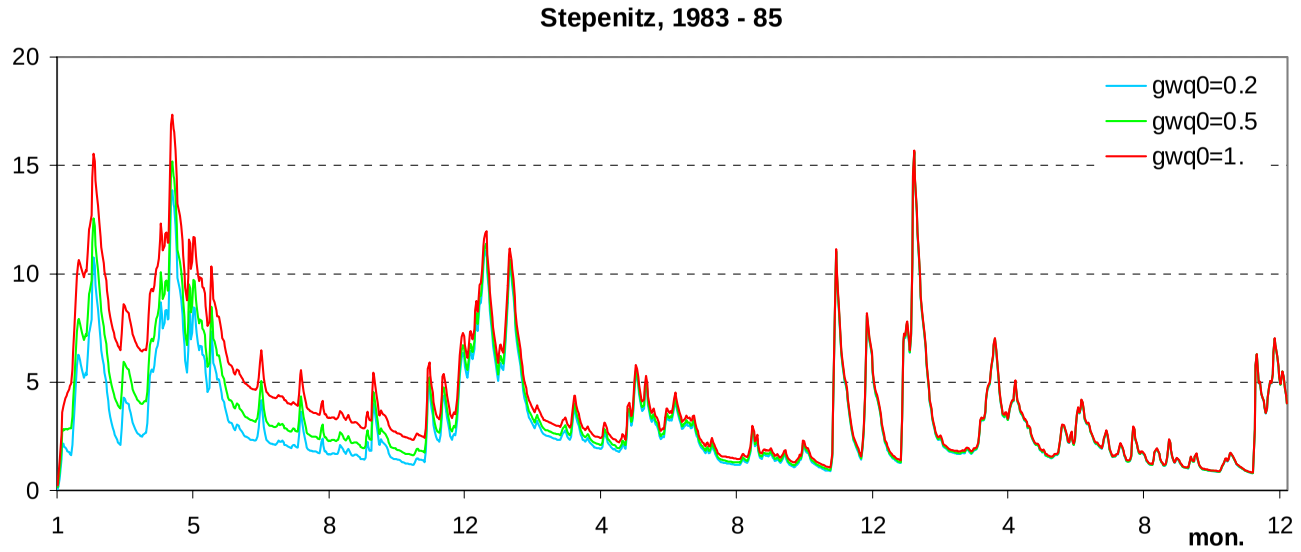


Stepenitz, 1986 - 88



Feb - Apr 1988




Stepenitz, 1983 - 85
20
15
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mon.
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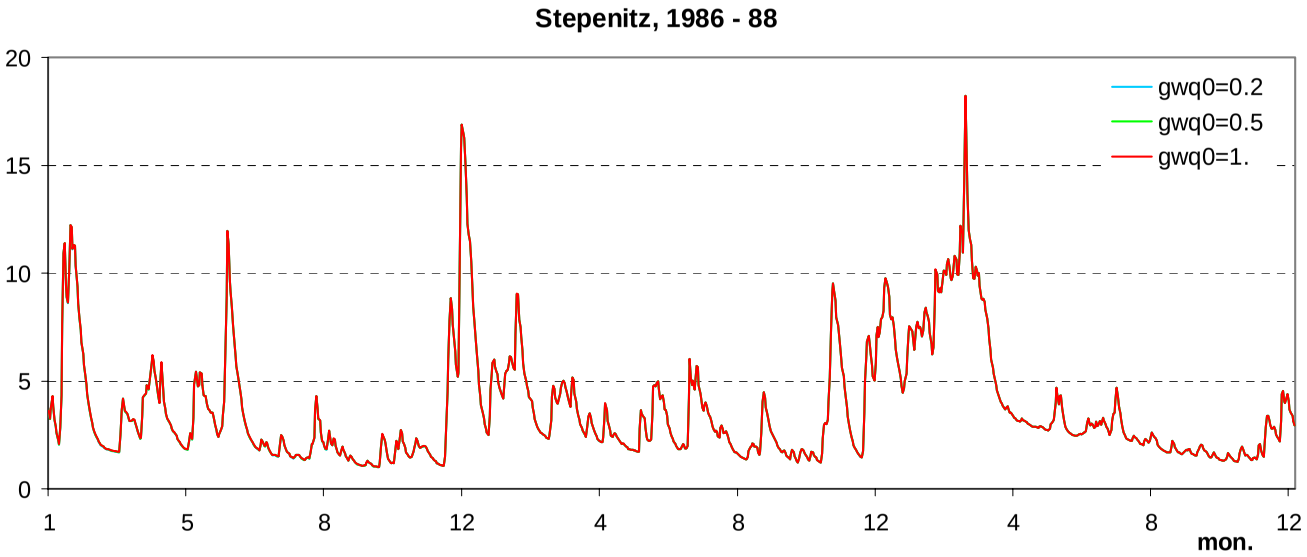
gwq0=0.5
gwq0=1.


Stepenitz, 1986 - 88
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mon.
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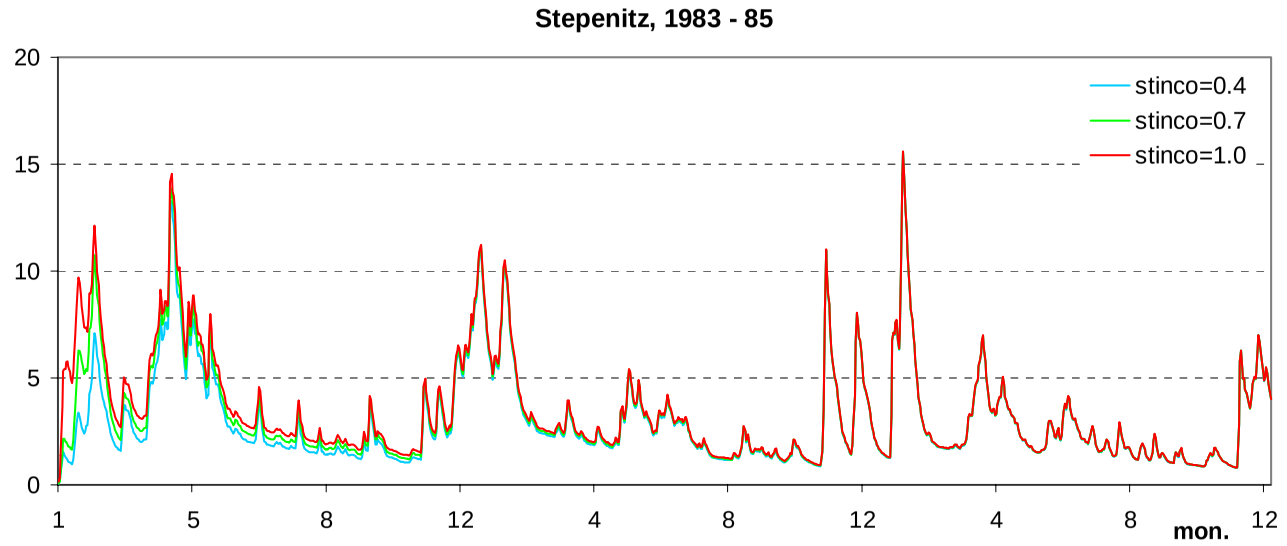
gwq0=0.5
gwq0=1.


Stepenitz, 1983 - 85
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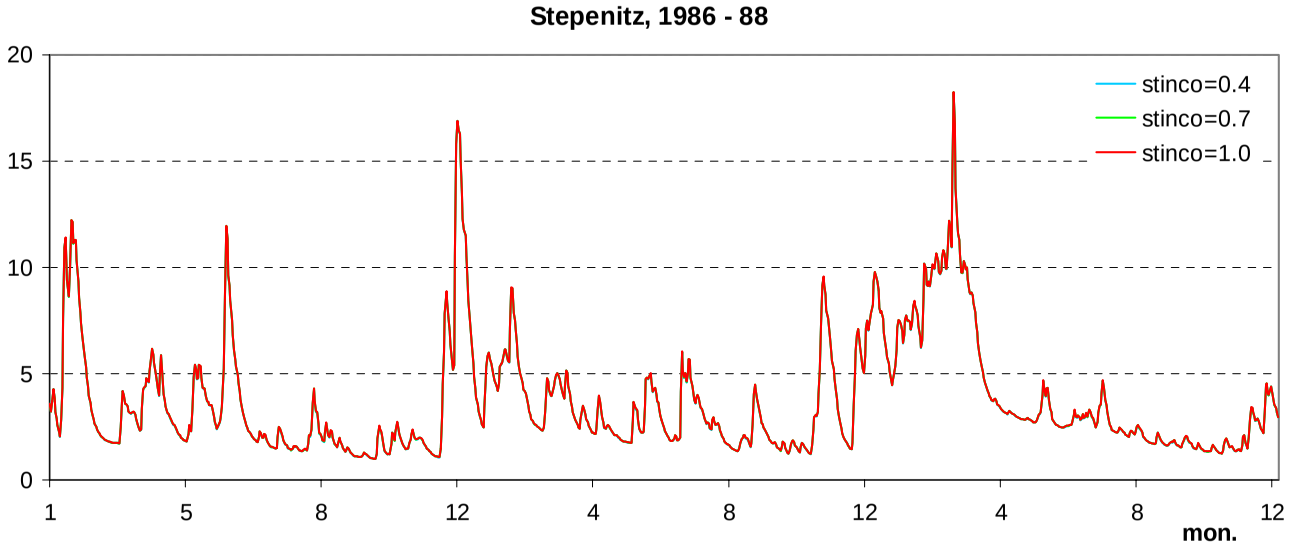
Stepenitz, 1986 - 88
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mon.
stinco=0.4
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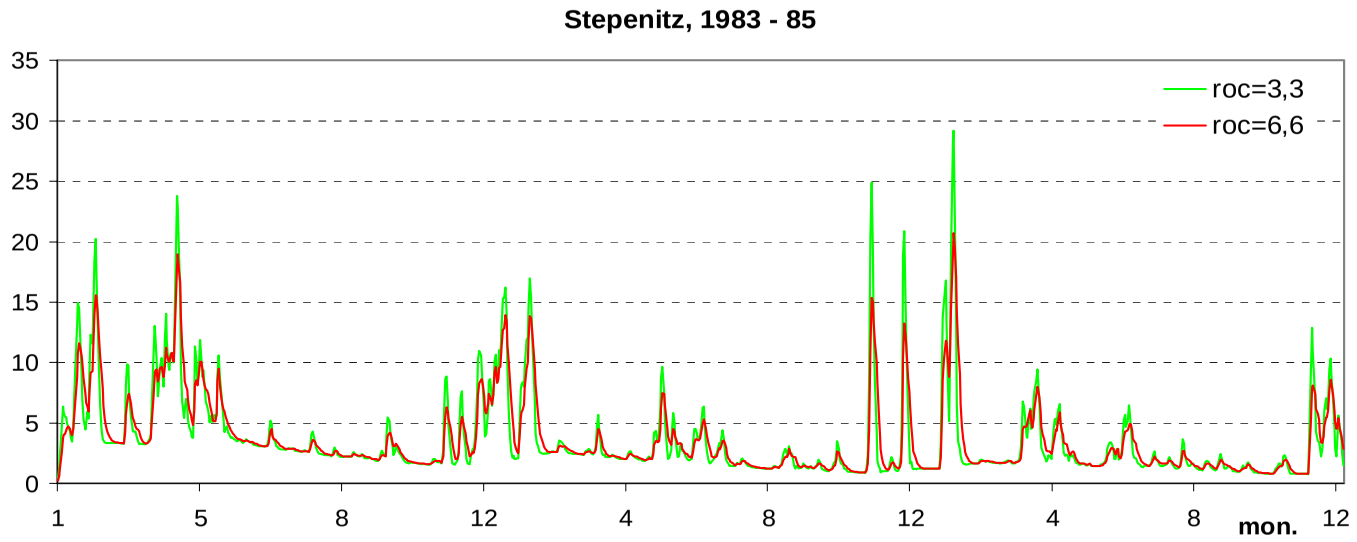
stinco=1.0


Stepenitz, 1983 - 85
roc=3,3
roc=6,6
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20
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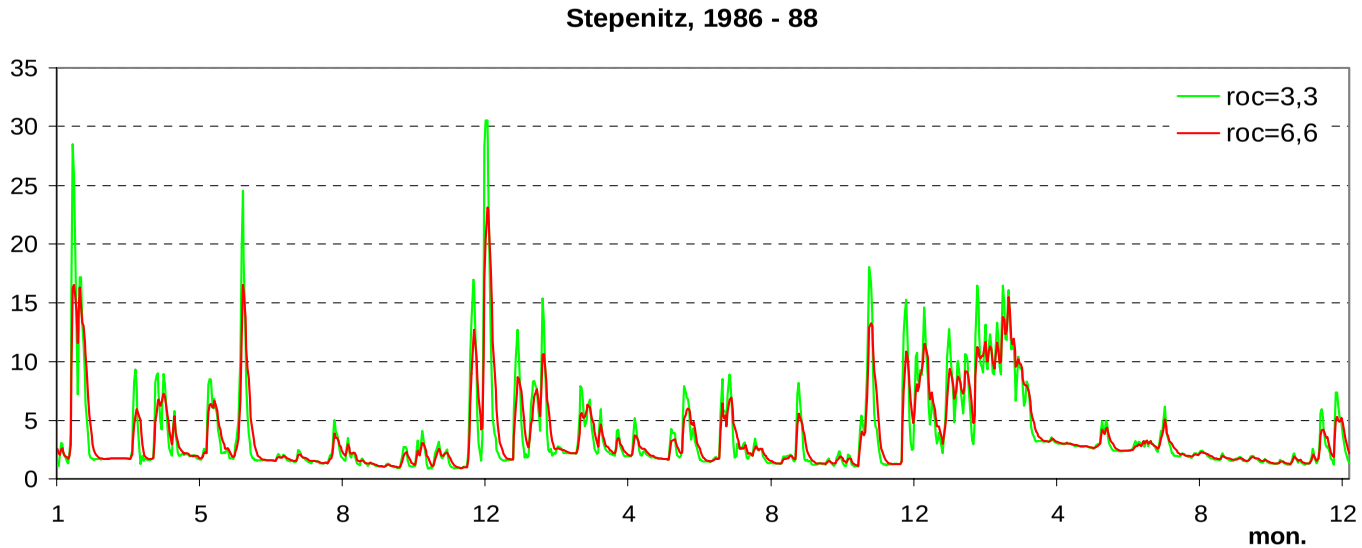
mon.


Stepenitz, 1986 - 88
roc=3,3
roc=6,6
35
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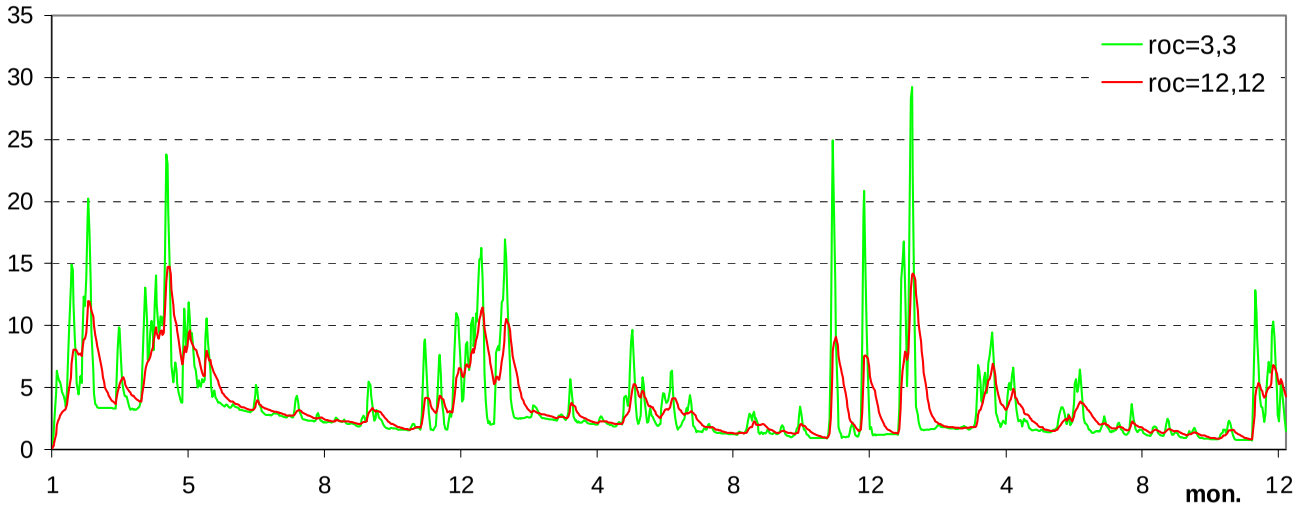
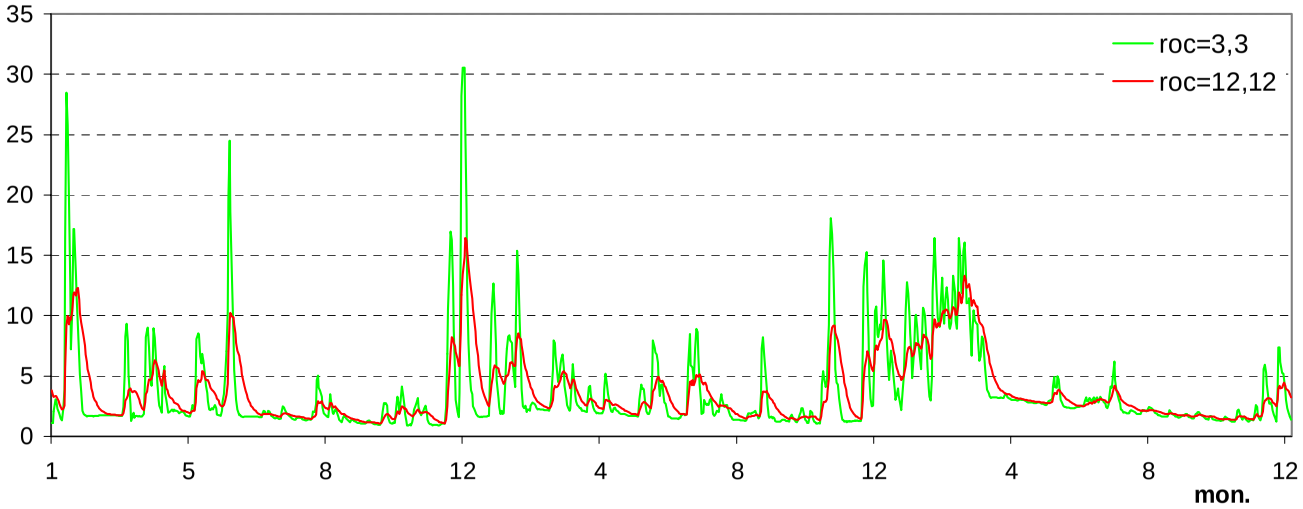
mon.

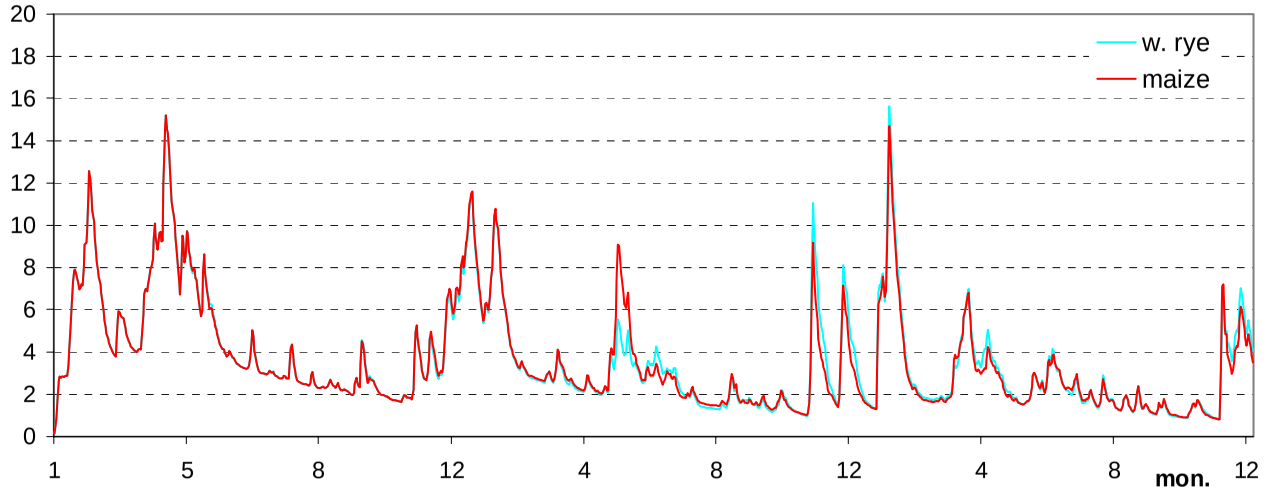
Stepenitz, 1983 - 85



Stepenitz, 1986 - 88



Stepenitz, 1983 - 85



Stepenitz, 1986 - 88

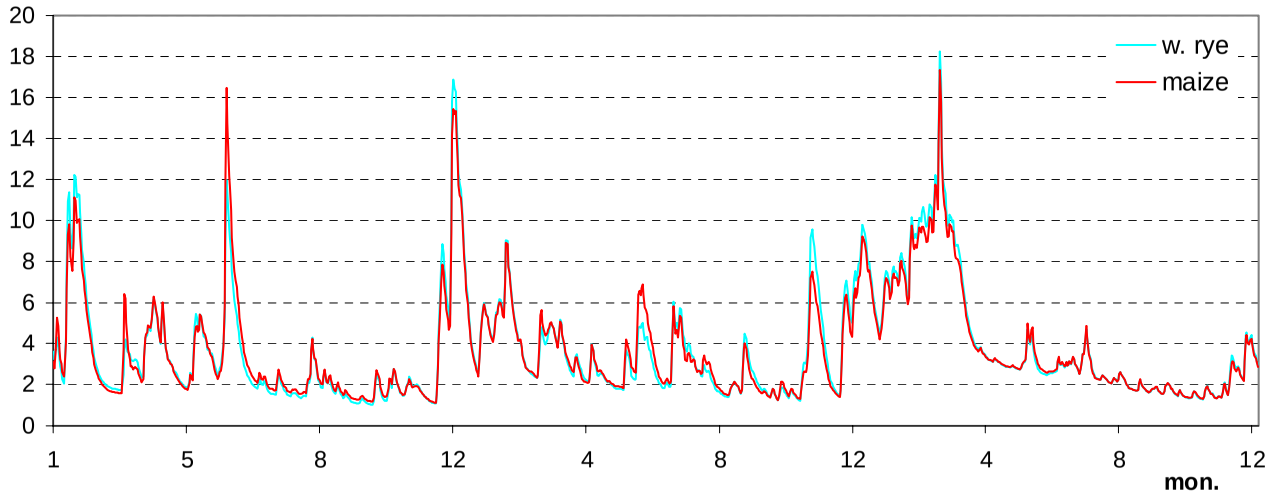


Fig. 4.23 Sensitivity to the crop type: winter rye and maize

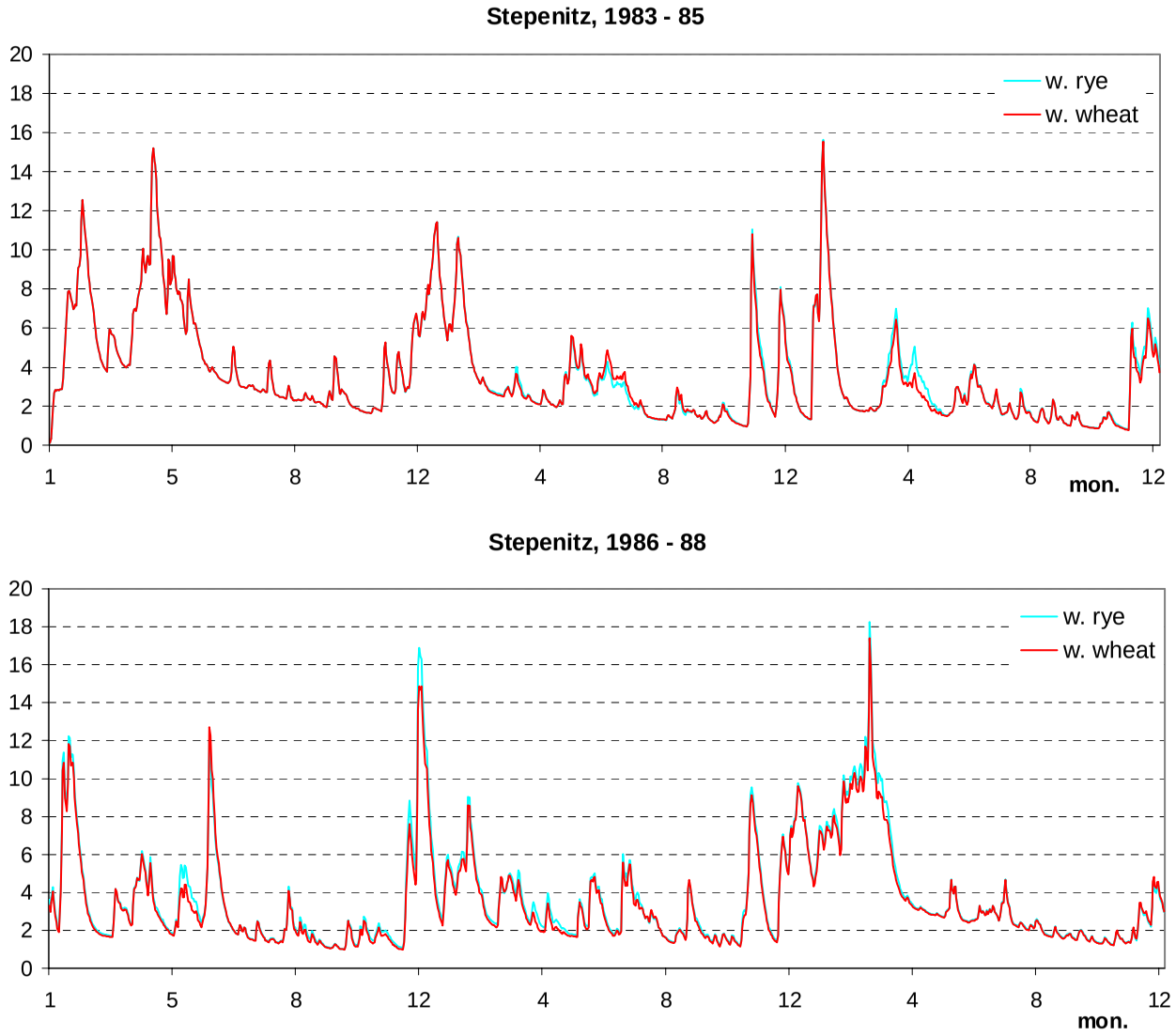


Fig. 4.24 Sensitivity to the crop type:winter rye and winter wheat

4.4.4 Overview of SWIM applications

Model validation SWIM was tested and validated sequentially for hydrological processes, for nitrogen dynamics, crop growth and erosion. First validation for hydrological processes performed for several mesoscale river basins is described in Krysanova *et al.*, 1998a. Preliminary validation of the model for nitrogen dynamics and crop growth is described in Krysanova *et al.*, 1998a. First test for erosion processes was performed for the Mulde basin (area 6171 km^2), and it is described in Krysanova *et al.*, 1998b.

More detailed validation of the model for hydrological processes and nitrogen dynamics in the lowland and mountainous sub-regions of the Elbe was done for the Stepenitz and the Zschopau basins (Krysanova *et al.*, 1999a & b). These two papers include also the analysis of factors affecting nitrogen export from diffuse agricultural sources of pollution.

More elaborate validation of the erosion processes in SWIM was done for the Glonn basin in Bavaria (392 km^2, Krysanova *et al.*, 2001), where more detailed data than for the Mulde basin were available. Results of the model validation are quite satisfactory.

Further development is foreseen for some processes, like nutrient retention in river basins. Besides the validation studies, the model was applied for the land use change and climate change impact studies, which are described below.

Land use change impact study was performed for the state of Brandenburg, Germany. Besides general vulnerability against water stress due to natural conditions, water resources in Brandenburg are strongly affected by brown coal mining, which took place in the south-east of the federal state in the last decades. Now the mining activities are significantly shortened. This results in decreasing river discharge, in particular in the Spree river, and may lead to general shortages in water availability. Land use change is one possible option to counteract this development.

As regards land use change trends, a tendency towards deintensification in the use of agricultural land is observed in Brandenburg during the last decade. The increase in a temporary set-aside within crop rotations was the main measure used to decrease the intensification level on arable land. Another effective way to deintensify crop production and, at the same time, to protect environmentally sensitive areas, is to create buffer zones along river courses (river corridors) by converting the arable land there into grassland or forest (permanent “set-aside”). Besides, the latter is an efficient way to reduce nitrate pollution and sediment load in rivers and to improve water quality.

Therefore, the primary objective of our study was to analyse the effects of these two alternatives of deintensification in the use of arable land on water resources in Brandenburg. Three types of land use change scenarios were developed and applied:

- **modification of the basic rotation scheme by increasing the portion of temporary “set-aside”;**
- introducing river corridors (150 and 500m width) in the original land use map and converting cropland within them into meadows (permanent “set-aside”);
- combinations of temporary and permanent set-aside schemes described above.

Two opposite tendencies were established in our simulation study. The temporary “set-aside” within a crop rotation scheme would result in decreasing evapotranspiration and increasing runoff and groundwater recharge in the region, whereas the permanent set-aside within river corridors would reduce runoff and increase evapotranspiration.

Therefore, land use changes in terms of deintensification may compensate for the expected decrease of discharge in the river Spree over the coming period, only if these changes assume increases in the portion of temporary set-aside areas, and do not include conversion of arable land into meadows (or forests). Runoff increases might be even greater with a decreasing production intensity on the remaining area for arable crops, due to reduction in regional transpiration as consequence of the lowered leaf area index. The land use change impact study is described in Krysanova et al, 1999d, and Wechsung *et al*., 2000.

Climate change impact The analysis of climate change impacts on hydrology and crop yield was performed also for the state of Brandenburg, applying two transient 1.5 K scenarios of climate change. In advance, hydrological validation was performed in three representative mesoscale river basins in the area, and the crop module was validated regionally for Brandenburg, using crop yield data for districts. The CO_2 fertilization effect was studied in two options, considering:

a) adjustment of the potential growth rate per unit of intercepted PAR by a temperature dependent correction factor alpha based on experimental data for C3 and C4 crops;
b) assuming a CO_2 influence on transpiration at the regional scale as the beta factor, which is coupled to the factor alpha.

Two transient 1.5 K scenarios of climate change for Brandenburg were developed in PIK: wet scenario W15 and dry scenario D15. Three periods were compared: 1981 - 1992 (control period A), 2022 - 2030 (period B), and 2042 - 2050 (period C). The atmospheric CO_2 concentration for the reference period and two scenario periods were set to 346, 406 and 436 ppm, respectively. According to the scenario W15, precipitation is expected to increase in Brandenburg: +5.2% and +11.7% on average in periods B and C, respectively. According to the scenario D15, precipitation is expected to decrease slightly in the period B (-1.7%) and quite significantly in the period C (-11.3%).

Evapotranspiration is expected to increase quite significantly under changing climate for the scenario W15, and moderately for the scenario D15. Groundwater recharge is practically the same as that in the control period for scenario W15. On the opposite, the decrease of groundwater recharge is notable for scenario D15, down to -31.5% in the period C. According to scenario W15, runoff is increasing (up to +17.2% in the period C). However it decreases significantly in the period C for scenario D15 (-22.6%).

The crop yield was only slightly altered under the "climate change only" variant of the W15 scenario for barley and maize, and it was reduced for wheat. The D15 scenario lead to the reduced crop yield for all the crops.

The impact of higher atmospheric CO_2 (alpha factor) compensated fully or partly for climate-related crop yield losses, and resulted in an increased yield both for barley and maize in scenario W15 compared to the reference scenario. The negative changes were still preserved in scenario D15 for wheat and maize.

The assumption that in addition stomatal control of transpiration is taking place at the regional scale (beta factor coupled to alpha factor) lead to further increase in crop yield, which was larger for maize than for barley and wheat. A full description of the climate change impact study with scenario W15 is given in Krysanova *et al*. (1999c).

Conclusions **One of the major challenges for BAHC (Biospheric Aspects of Hydrological Cycle) research in the frame of the International Geosphere and Biosphere Program (IGBP) is**

the adequate description and modelling of the complex interactions between climate, hydrological and ecological processes at different scales. SWIM has been developed as a tool to serve this purpose at the mesoscale and regional scale.

Model applications in a number of river basins in the range of about 100 to 24000 km^2 drainage area have shown that the model is capable to describe realistically the basic ecohydrological processes under different environmental conditions, including a) the spatial and temporal variability of main water balance components (evapotranspiration, groundwater recharge, runoff generation), b) the cycling of nutrients in soil and their transport with water considering the dynamics of the controlling climate and hydrological conditions, c) vegetation/crop growth and related phenomena, d) the dynamical features of soil erosion and sediment transport, and e) the effect of changes in climate and land use on all these interrelated processes and characteristics.

APPENDIX I

GRASS commands useful for the spatial data preparation for SWIM

Command format	*Flags and Parameters*	*Command description*
d.colors [map=name]	**Parameters:** map raster map name	To interactively change the color table of a raster map layer
d.display		A menu-driven display program for viewing maps
d.erase [color=name]	**Parameters:** color color to erase with	Erases the contents of the active display frame on the user's monitor
d.frame [-cepsD] [frame=name] [at=bottom,top,left,right]	**Flags**: -c Create a new frame -e Remove all frames and erase the screen -p Print name of current frame -s Select a frame -D Debugging output **Parameters:** frame frame to be created/selected at where to place the frame	Manages display frames on the user's monitor
d.histogram [-zq] map=name [color=name] [style=name]	**Flags**: -z Display zero-data information -q Gather the histogram quietly **Parameters:** map raster map for which histogram will be displayed color color for legend and title options: red, orange, yellow, green, blue, indigo, white, black, brown, magenta, aqua, gray, grey style indicate if a pie or bar chart is desired	Displays a histogram in the form of a pie or bar chart for a user-specified raster file
d.legend map=name [color=name] [lines=value]	**Parameters:** map name of raster map color sets the legend's text color lines number of text lines (useful for truncating long legends)	Displays a legend for a raster map layer in the active frame on the graphics monitor
d.mon [-lLprs] [start=name] [stop=name] [select=name] [unlock=name]	**Flags**: -l List all monitors -L List all monitors (with current status) -p Print name of currently selected monitor -r Release currently selected monitor -s Do not automatically select when starting **Parameters:** start name of graphic monitor to start stop name of graphic monitor to stop select name of graphic monitor to select unlock name of graphic monitor to unlock	To establish and control the use of a graphics display monitor

d.rast [-o] map=name	**Flags**: -o Overlay (non-zero values only) **Parameters:** map name of raster map to be displayed	Displays and overlays raster map layers in the active display frame on the graphics monitor
d.vect [-m] map=name [color=name]	**Flags**: -m Use less memory **Parameters:** map name of vector map to be displayed color color desired for drawing map	Displays vector data in the active frame on the graphics monitor
d.what.rast [-1t] [map=name[,name,...]] [fs=name]	**Flags**: -1 Identify just one location -t Terse output. For parsing by programs. **Parameters:** map name of raster map(s) fs field separator (terse mode only), default: :	Allows the user to interactively query the category contents of multiple raster map layers at user-specified locations within the current geographic region
d.what.vect [-1] map=name	**Flags**: -1 Identify just one location **Parameters:** map name of existing vector map	Allows the user to interactively query the category contents of a (binary) vector map layer at user-specified locations within the current geographic region
d.where [-1] [spheroid=name]	**Flags**: -1 one mouse click only **Parameters:** spheroid name of a spheroid for lat/lon coordinate conversion, options: australian, bessel, clark66, everest, international, wgs72, wgs84	Identifies the geographic coordinates associated with point locations in the active frame on the graphics monitor
d.zoom [-q] [action=name]	**Flags**: -q Quiet **Parameters:** action type of zoom (for latitude/longitude databases only) options: zoom, rotate	Allows the user to change the current geographic region settings interactively, with a mouse
r.average [-c] base=name cover=name output=name	**Flags**: -c cover values extracted from the category labels of the cover map **Parameters:** base base raster map cover cover raster map output resultant raster map	Finds the average of values in a cover map within areas assigned the same category values in a user-specified base map
r.buffer [-q] input=name output=name distances=value[,value,...] [units=name]	**Flags**: -q Quiet **Parameters:** input name of input map output name of output map distances distance zone(s) units units of distance, options: meters, kilometers, feet, miles, default: meters	Creates a raster map layer showing buffer zones surrounding cells that contain non-zero category values

r.cats map=name [cats=range[,range,...]] [fs=character|space|tab]	**Parameters:** map name of a raster map cats category list: e.g. 1,3-8,14 fs output separator character, default: tab	Prints category values and labels associated with user-specified raster map layer
r.coin [-qw] map1=name map2=name units=name	**Flags**: -q Quiet -w Wide report, 132 columns (default: 80) **Parameters:** map1 name of first raster map map2 name of second raster map units unit of measure, options: c,p,x,y,a,h,k,m	Tabulates the mutual occurrence (coincidence) of categories for two raster map layers
r.colors [-wq] map=name color=type	**Flags**: -w Don't overwrite existing color table -q Quietly **Parameters**: map raster map name color type of color table options: aspect, grey, grey.eq, gyr, rainbow, ramp, random, ryg, wave, rules **Where color type** is one of: aspect (aspect oriented grey colors) grey (linear grey scale) grey.eq (histogram equalized grey scale) gyr (green through yellow to red) rainbow (rainbow color table) ramp (color ramp) ryg (red through yellow to green) random (random color table) wave (color wave) rules (create color table by rules) **Valid colors** are: white black red green blue yellow magenta cyan aqua grey gray orange brown purple violet indigo	Creates/modifies the color table associated with a raster map layer
r.combine [-s]	**Flags**: -s Use symbols (instead of graphics)	Allows category values from several raster map layers to be combined
r.cross [-qz] input=name[,name,...] output=name	**Flags**: -q Quiet -z Non-zero data only **Parameters**: input names of 2-10 input raster maps output name of the resulting map	Creates a cross product of the category values from multiple raster map layers
r.describe [-1rqd] map=name	**Flags**: -1 Print the output one value per line -r Only print the range of the data -q Quiet -d Use the current region **Parameters**: map name of raster map	Prints terse list of category values found in a raster map layer

r.in.ascii input=name output=name [title="phrase"] [mult=value]	**Parameters**: input ascii raster file to be imported output name of resultant raster map title title for resultant raster map mult multiplier for ascii data, default: 1.	Convert an ASCII raster text file (e.g., from ARC/INFO) into a binary raster map layer
r.info map=name	**Parameters**: map name of raster map	Outputs basic information about a user-specified raster map layer
r.mapcalc [result=expression]		Raster map layer data calculator, performs arithmetic operations on several raster map layers
r.neighbors [-aq] input=name output=name method=name size=value [title="phrase"]	**Flags**: -a Do not align output with the input -q Run quietly **Parameters**: input name of existing raster file output name of the new raster file method neigborhood operation, options: average, median, mode, minimum, maximum, astdev., variance, diversity, interspersion size neigborhood size, options: 1,3,5,7,9,11,13,15,17,19,21,23,25 title title of the output raster file	Makes each cell category value a function of the category values assigned to the cells around it, and stores new cell values in an output raster map layer
r.out.ascii [-h] map=name [digits=value]	**Flags**: -l Smooth Corners	Converts a raster map layer into an ASCII text suitable for other computer systems
r.poly [-l] input=name output=name	**Flags**: -h Suppress printing of header information **Parameters**: map name of existing raster map digits the minimum number of digits per cell to be printed	Extracts area edges from a raster map layer and converts data to GRASS vector format
r.reclass input=name output=name [title=name]	**Parameters**: input raster map to be reclassified output name for the resulting raster map title title for the resulting raster map	Creates a new map layer with category values based upon the user's reclassification of cate-gories in an existing map
r.report [-hmfqez] map=name[,name,...] [units=name[,name,...]] [pl=value] [pw=value] [output=name]	**Flags**: -h suppress page headers -m report zero values due to mask -f use form feeds between pages -q quiet -e scientific format -z filter out zero category data **Parameters**: map raster map(s) to report on units mi(les), me(tres), k(ilometers), a(cres), h(ectares), c(cells), p(ercent) pl,pw page length, page width output name of an output file	Reports statistics for raster map layers

r.stats [-1aclmqzgx] input=name[,name,...] [fs=character|space] [output=name]	**Flags**: -1 One cell per line -a Print area totals -c Print cell counts -l Print category labels -m Report zero values due to mask -q Quiet -z Non-zero data only will be output -g Print grid coordinates (east and north) (requires -1 flag) -x Print x and y (column and row) (requires -1 flag) **Parameters**: input raster maps(s) fs output field separator, default: space output output file name	Generates area statistics for raster map layers
r.watershed [-m4] elevation=name [depression=name] [flow=name] [disturbed.land=name] [blocking=name] [threshold=value] [max.slope.length=value] [accumulation=name] [drainage=name] [basin=name] [stream=name] [half.basin=name] [visual=name] [length.slope=name] [slope.steepness=name]	**Flags**: -m Enable extend memory option: Operation is slow -4 Allow only horizontal and vertical flow of water **Parameters**: **Input maps**: *elevation* Input map: elevation on which entire analysis is based *depression* Input map: locations of real depressions *flow* Input map: amount of overland flow per cell *disturbed.land* Input map or value: percent of disturbed land, for RUSLE *blocking* Input map: terrain blocking overland surface flow, for RUSLE *threshold* Input value: minimum size of exterior watershed basin *max.slope.length* Input value: maximum length of surface flow, for RUSLE **Output maps:** *accumulation* Output map: number of cells that drain through each cell *drainage* Output map: drainage direction *basin* Output map: unique label for each watershed basin *stream* Output map: stream segments *half.basin* Output map: each half-basin is given a unique value *visual* Output map: useful for visual display of results *length.slope* Output map: slope length and steepness (LS) factor for RUSLE *slope.steepness* Output map: slope steepness (S) factor for RUSLE	Watershed basin analysis program. It generates a set of maps indicating the location of sub-basins and streams, and the LS and S factors of the Revised Universal Soil Loss Equation (RUSLE)

g.remove [rast=name[,name,...]] [vect=name[,name,...]] [icon=name[,name,...]] [labels=name[,name,...]] [sites=name[,name,...]] [region=name[,name,...]] [group=name[,name,...]] [3dview=name[,name,...]]]	**Parameters**: rast rast file(s) to be removed vect vect file(s) to be removed icon icon file(s) to be removed labels labels file(s) to be removed sites sites file(s) to be removed region region file(s) to be removed group group file(s) to be removed 3dview 3dview file(s) to be removed	Removes data base element files from the user's current mapset
g.rename [rast=old,new] [vect=old,new] [icon=old,new] [labels=old,new] [sites=old,new] [region=old,new] [group=old,new] [3dview=old,new]	**Parameters**: rast rast file(s) to be renamed vect vect file(s) to be renamed icon icon file(s) to be renamed labels labels file(s) to be renamed sites sites file(s) to be renamed region region file(s) to be renamed group group file(s) to be renamed 3dview 3dview file(s) to be renamed	To rename data base element files in the user's current mapset
p.map [input=name] [scale=mapscale]	**Parameters**: input file containing mapping instructions (or use input=- to enter from keyboard) scale scale of the output map, e.g. 1:25000 (default: 1panel)	Hardcopy color map output utility

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A short description of SWIM is available in the Register of Ecological Models, University of Kassel:
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