

# Model Description

## WaSiM-ETH

(Water balance Simulation Model ETH)

- **description of the most important equations for WaSiM-ETH version 1 (TOPMODEL-approach) and WaSiM-ETH version 2 (RICHARDS-equation for the unsaturated zone; with an integrated multi-layer 2D-groundwater model, irrigation control and tracer and salt transport)**
- **description of data flows**
- **sensitivity analysis of the most important parameters**
- **application: controlling the data flow, data formats, model calibration**
- **software tools for pre- and postprocessing**
- **upgrades**

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# Content

<b>FOREWORD .....</b>	<b>8</b>
<b>1 DESCRIPTION OF THE WASIM-ETH MODULES.....</b>	<b>9</b>
1.1 CORRECTION OF PRECIPITATION .....	10
1.2 INTERPOLATION OF METEOROLOGICAL INPUT DATA .....	10
1.2.1 <i>Altitude dependent regression</i> .....	10
1.2.2 <i>Inverse distance weighting interpolation</i> .....	11
1.3 TOPOGRAPHY DEPENDENT ADJUSTMENT OF RADIATION AND TEMPERATURE .....	12
1.3.1 <i>Calculation of sun coordinates, sunset and sunrise, radiation correction</i> .....	12
1.3.2 <i>Modification of temperature</i> .....	13
1.4 EVAPOTRANSPIRATION.....	14
1.4.1 <i>Potential Evapotranspiration after Penman-Monteith</i> .....	14
1.4.2 <i>Potential Evapotranspiration after Wendling</i> .....	18
1.4.3 <i>Potential Evapotranspiration after HAMON</i> .....	18
1.5 CALCULATING THE REAL EVAPOTRANSPIRATION .....	19
1.5.1 <i>WaSiM-version using the Topmodel-approach</i> .....	19
1.5.2 <i>WaSiM-version using the Richards-equation</i> .....	19
1.6 SNOW ACCUMULATION AND MELT .....	20
1.6.1 <i>Snow accumulation</i> .....	20
1.6.2 <i>Snow melt</i> .....	20
1.7 INTERCEPTION.....	22
1.8 INFILTRATION.....	22
1.9 SOIL MODEL FOR THE WASIM-ETH VERSION USING THE TOPMODEL-APPROACH .....	23
1.9.1 <i>Introduction</i> .....	23
1.9.2 <i>The course of water within the soil model</i> .....	24
1.10 DISCHARGE ROUTING .....	26
1.11 PERFORMANCE CRITERIA $R^2$ AND $EV$ .....	30
1.12 SOIL MODEL FOR THE WASIM-ETH VERSION USING THE RICHARDS-EQUATION .....	31
1.12.1 <i>Introduction</i> .....	31
1.12.2 <i>Parameterization</i> .....	32
1.12.3 <i>Numerical solution (vertical fluxes, interflow, infiltration/exfiltration in rivers)</i> .....	32
1.12.4 <i>Withdrawal of evaporating water</i> .....	39
1.12.5 <i>Considering irrigation</i> .....	41
1.12.6 <i>Considering artificial drainage</i> .....	42
1.12.7 <i>Considering clay horizons</i> .....	42
1.12.8 <i>Considering ponding water</i> .....	42
1.12.9 <i>Groundwater table elevation</i> .....	42
1.12.10 <i>Groundwater recharge</i> .....	43

1.12.11	Calculating baseflow .....	45
1.12.12	Coupling with the groundwater model .....	45
1.13	MODELING OF GROUNDWATER FLOW AND (LATERAL) TRANSPORT .....	46
1.14	COUPLING THE SOLUTE TRANSPORT TO THE WATER FLUXES .....	50
<b>2</b>	<b>OVERVIEW OF REQUIRED INPUT DATA, PARAMETERS AND DATA FLOW CHARTS.....</b>	<b>52</b>
2.1	INPUT DATA REQUIREMENTS FOR SOME MODEL SETUPS.....	52
2.2	OVERVIEW OF THE MOST IMPORTANT MODEL PARAMETERS .....	54
2.3	THE INTERNAL DATA FLOW .....	57
2.3.1	Spatially distributed data (Grids) .....	57
2.3.2	Time series .....	58
2.3.3	Internal data flow.....	59
<b>3</b>	<b>USING WASIM-ETH.....</b>	<b>67</b>
3.1	SUBDIVIDING THE BASIN HORIZONTALLY .....	67
3.1.1	Basic subdivision into a regular raster.....	67
3.1.2	Delineating of the basin .....	68
3.1.3	Zonal statistics .....	68
3.2	INPUT DATA (PREPROCESSING).....	70
3.2.1	Geographical Data .....	70
3.2.1.1	Data requirements.....	70
3.2.1.2	File formats.....	71
3.2.2	Meteorological data.....	71
3.2.3	Hydrological Data .....	73
3.2.4	Initial conditions (storage contents) .....	73
3.3	OUTPUT DATA .....	74
3.3.1	Grids .....	74
3.3.2	Zonal averages.....	76
3.4	TEMPORAL SCHEME.....	77
3.4.1	specifying the time step .....	77
3.4.2	Organization of the space/time/submodel-loops.....	77
3.4.3	Modeling over very long times.....	77
3.5	CONTROLLING THE MODEL RUN BY CONTROL FILE .....	78
3.5.1	structure of the control file.....	78
3.5.2	coding of routing descriptions in WaSiM-ETH.....	89
3.6	SENSITIVITY ANALYSIS.....	94
3.6.1	Introduction .....	94
3.6.2	Parameters of the evaporation model.....	94
3.6.3	Parameters of the interception model.....	95
3.6.4	Parameters of the snow model.....	96
3.6.5	Parameters of the soil model for model version 1 (Topmodel-approach).....	99

3.6.6	<i>Parameters of the soil model for model version 2 (Richards-equation)</i> .....	104
3.6.7	<i>Spatial resolution</i> .....	105
3.6.8	<i>Conclusion</i> .....	106
3.7	<b>CALIBRATING THE MODEL</b> .....	106
3.7.1	<i>Introduction</i> .....	106
3.7.2	<i>Calibrating the soil model for model version 1 (Topmodel-approach)</i> .....	107
3.7.3	<i>Calibrating the soil model for model version 2 (Richards-equation)</i> .....	113
<b>4</b>	<b>SOFTWARE FOR PRE- AND POSTPROCESSING</b> .....	<b>117</b>
4.1	<b>WORKING WITH SPATIALLY DISTRIBUTED DATA (GRIDS)</b> .....	117
4.1.1	<i>ASCIGRID</i> .....	117
4.1.2	<i>FIELDGEN</i> .....	117
4.1.3	<i>FOCLMEAN</i> .....	117
4.1.4	<i>GRIDADD</i> .....	118
4.1.5	<i>GRIDASCI</i> .....	118
4.1.6	<i>GRIDCOLM</i> .....	118
4.1.7	<i>GRIDDIFF</i> .....	118
4.1.8	<i>GRIDEDIT</i> .....	118
4.1.9	<i>GRIDGAUS</i> .....	118
4.1.10	<i>GRIDGRID</i> .....	119
4.1.11	<i>GRIDMASK</i> .....	119
4.1.12	<i>GRIDMULT</i> .....	119
4.1.13	<i>GRIDQUOT</i> .....	119
4.1.14	<i>GRIDRAND</i> .....	119
4.1.15	<i>GRIDSTAT</i> .....	120
4.1.16	<i>GRIDSURF</i> .....	120
4.1.17	<i>MAKEGRID</i> .....	120
4.1.18	<i>MF2WASIM</i> .....	120
4.1.19	<i>RECLASS</i> .....	120
4.1.20	<i>REFINE</i> .....	120
4.1.21	<i>REMAP</i> .....	121
4.1.22	<i>RESAMPLE</i> .....	121
4.1.23	<i>RESIZE</i> .....	122
4.1.24	<i>SURFGRID</i> .....	122
4.1.25	<i>TANALYS</i> .....	122
4.1.26	<i>TOPOFACT</i> .....	127
4.1.27	<i>ZONESTAT</i> .....	128
4.2	<b>WORKING WITH STATION DATA (METEOROLOGICAL TIME SERIES)</b> .....	128
4.2.1	<i>IDWP</i> .....	128
4.2.2	<i>STRLKORR</i> .....	129
4.2.3	<i>REGRESS</i> .....	129

4.2.4	<i>REGR</i> .....	129
4.2.5	<i>REGRASCI</i> .....	130
4.2.6	<i>ASCIREGR</i> .....	130
4.2.7	<i>GMDtoTAB</i> .....	130
4.2.8	<i>QtoSPEND</i> .....	130
4.2.9	<i>SPENDINV</i> .....	130
4.2.10	<i>SONNEREL</i> .....	131
4.3	SOFTWARE FOR VISUALIZATION .....	131
4.3.1	<i>REGRESS</i> .....	131
4.3.2	<i>GRIDSHAD</i> .....	131
4.4	OTHER PROGRAMS .....	132
4.4.1	<i>MAKEGWN</i> .....	132
4.4.2	<i>POLYGRID</i> .....	133
4.4.3	<i>POLYGONE</i> .....	133
4.4.4	<i>RESAGGR</i> .....	133
4.4.5	<i>RESAGG</i> .....	133
4.4.6	<i>RESMEAN</i> .....	133
4.4.7	<i>RESMEANI</i> .....	133
4.4.8	<i>QUANTIL</i> .....	134
4.4.9	<i>LOWFLOW</i> .....	134
4.4.10	<i>FLOODS</i> .....	134
4.4.11	<i>FLOWROUT</i> .....	134
<b>5</b>	<b>EXAMPLE OF A CONTROL FILE FOR WASIM</b> .....	<b>135</b>
<b>6</b>	<b>EXAMPLE OF A CONTROL FILE FOR TANALYS</b> .....	<b>149</b>
<b>7</b>	<b>REFERENCES</b> .....	<b>153</b>
<b>8</b>	<b>ERROR CODES OF THE MODEL</b> .....	<b>155</b>
<b>9</b>	<b>MODEL EXTENSIONS AND UPGRADES</b> .....	<b>157</b>
9.1	GLACIER MODEL .....	157
9.2	EXTENSIONS FOR COUPLING WASIM-ETH TO CLIMATE MODELS AND FOR MODELING LARGE REGIONS .	160
9.2.1	<i>Using multiple regression parameter sets for multiple regions</i> .....	160
9.2.2	<i>Using bilinear interpolation for one-way-coupling with climate model results</i> .....	164
9.2.3	<i>Using a linear combination of bilinearly interpolated gradients and residuals</i> .....	165
9.2.4	<i>Bicubic spline interpolation</i> .....	165
9.2.5	<i>Applying monthly scenario grids</i> .....	166
9.2.6	<i>Using variable cell sizes</i> .....	166
9.2.7	<i>Tolerating additional columns in meteorological input files</i> .....	167
9.3	THE STORAGE CONTENT FILE .....	167

9.4	CONSIDERING MULTI-LAYERED VEGETATION .....	169
9.4.1	<i>[multilayer_landuse] table</i> .....	169
9.4.2	<i>[landuse_table]</i> .....	170
9.5	UPGRADING THE SOIL TABLE.....	171
9.5.1	<i>Macropore runoff</i> .....	172
9.5.2	<i>Horizon-dependent soil parametrization</i> .....	173
9.6	COUPLING WASiM-ETH TO AN EXTERNAL MODEL.....	173
9.7	ADDITIONAL WASiM-ETH OUTPUTS.....	174
9.8	DYNAMIC CALCULATION OF PLANT DEVELOPMENT .....	174
9.8.1	<i>DynamicPhenology_1 (DP1)</i> .....	175
9.8.2	<i>DynamicPhenology_2 (DP2)</i> .....	176
9.8.3	<i>DynamicPhenology_3 (DP3)</i> .....	177
9.8.4	<i>Considering the influence of soil moisture on phenology</i> .....	179
9.8.5	<i>Handling of phenological output data</i> .....	179
9.9	DYNAMIC TIME STEP CONTROL.....	180

## Foreword

This documentation contains the description of the latest version of WaSiM-ETH, the Runoff and Water balance Simulation Model, for both, version 1 using the TOPMODEL-approach and version 2 using RICHARDS-equation. It is dealt with the theoretical bases (complete set of equations) as well as with aspects of the practical application. Some examples of model applications can be taken from the literature, e.g. SCHULLA (1997).

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## 1 Description of the WaSiM-ETH modules

Figure 1 shows the model scheme of WaSiM-ETH. In addition to the original version 1 (TOPMODEL-approach), the version 2 offers considerably extended possibilities for modeling the hydrologic cycle.

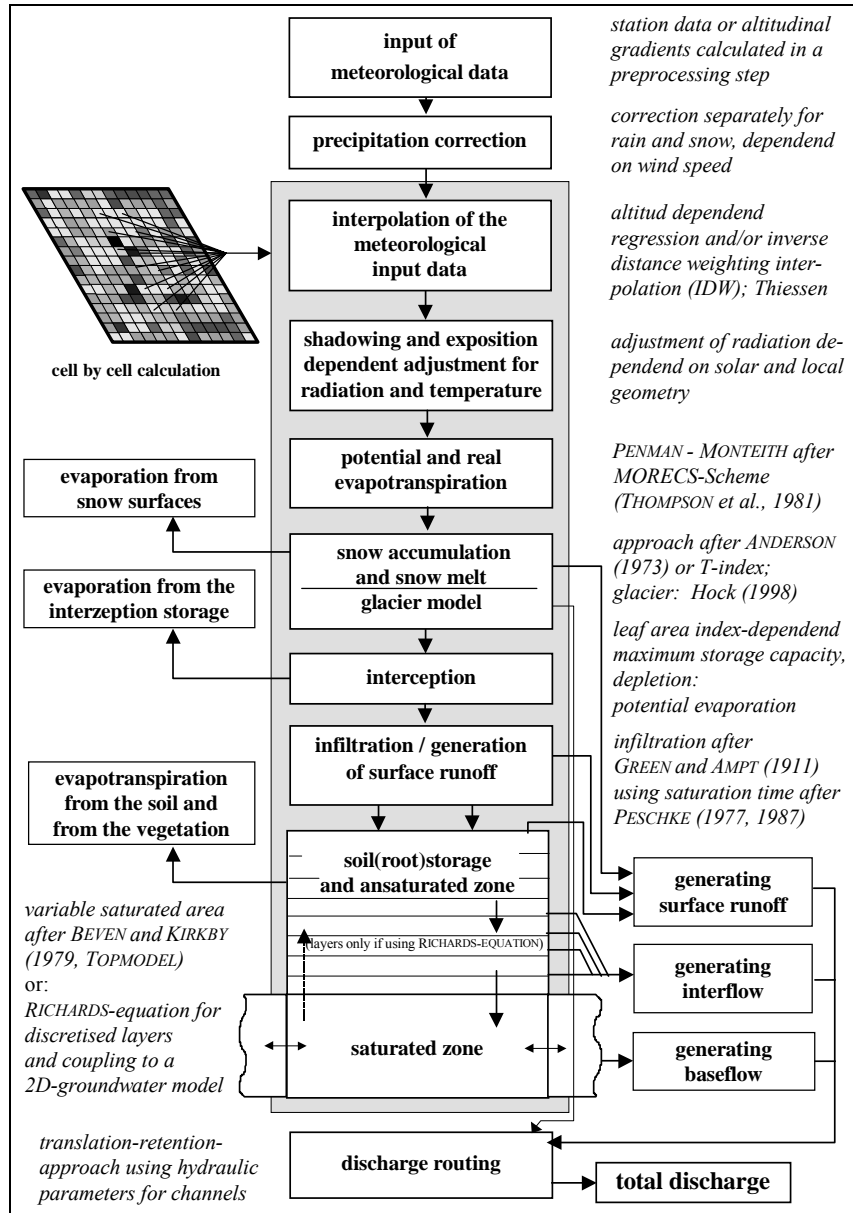


figure 1: model structure of WaSiM-ETH

The most important change is the new soil model using the RICHARDS-equation for describing the water flow within the unsaturated soil rather than the old conceptual TOPMODEL-approach after BEVEN and KIRKBY (1979). Furthermore a simple 2D-groundwater flow and transport model for layered aquifers was implemented which is coupled directly to the RICHARDS-model of the unsaturated zone. There are also possibilities for modeling irrigation using surface water as well as pumped groundwater. It is possible to consider ponding of water (e.g. at rice fields), artificial drainage, and clay layers within the soil.

A substantial extension was done by integrating transport algorithms into the model. It is possible to consider transport, mixing and de-mixing for ideal tracers like  $^{18}\text{O}$  and tritium or for salts. Up to 9 tracers can be considered at the same time but there will be no consideration of the effects of the tracers on each other.

However, such chemical or bio-chemical processes like retardation and denitrification or multi phase flow are not taken into account.

## 1.1 Correction of Precipitation

The correction of precipitation is carried out separately for rain and snow using the wind speed as a parameter. The differentiation between rain and snow is done using a threshold temperature.

$$\begin{aligned} P_{korr} &= P \cdot (a_l + b_l \cdot u_w) & T &\geq T_{grenz} \\ P_{korr} &= P \cdot (a_s + b_s \cdot u_w) & T &< T_{grenz} \end{aligned} \quad (1)$$

with	$P$	observed precipitation [mm]
	$P_{korr}$	corrected precipitation [mm]
	$T_{grenz}$	threshold temperature snow/rain [°C]
	$u_w$	wind speed [m/s]
	$a_l, b_l$	correction parameters for liquid precipitation [-]
	$a_s, b_s$	correction parameters for solid precipitation [-]

*precipitation correction if using inverse-distance-weighting interpolation of precipitation:*

If using IDW for interpolating the precipitation data (see chapter 1.2) the station data are read in directly. These station data are then corrected using equation (1) by interpolating wind speed and temperature to the locations of the meteorological stations used for precipitation data. Both data are interpolated using the method specified in the control file for these variables.

*precipitation correction if using altitude dependent regression for interpolation of precipitation:*

If using altitude dependent regression for interpolating the precipitation, the real positions of the meteorological stations are unknown (only altitude profiles of the variables). In these cases the correction is done by correcting the gradients in a way, that in a first step all of the three altitudinal ranges are subdivided into 10 subranges. For the middle of each of these subranges the temperature and wind speed are interpolated using the appropriate method specified in the respective section of the control file. Then the correction equation (1) is applied to the precipitation value of the subrange center. The corrected precipitations are then used to calculate new altitudinal gradients. Since the gradients of wind speed and temperature doesn't have to be linear nor parallel it is not possible to correct the gradients by shifting or rotating.

## 1.2 Interpolation of meteorological input data

### 1.2.1 Altitude dependent regression

Using this method, the interpolation result is estimated using the altitude dependence of a variable. If there are data of more than three station available, an additional trend surface is estimated in order to correct shifts in the horizontal directions. The trend surface uses only the residuals of the altitude dependent regression. To use this method within WaSiM it is necessary to generate the appropriate files containing the altitudinal gradients for each of these variables using the programs "regress" or "regr". The gradients can be given for at maximum three variable ranges separated by inversions from each other. The estimation of the altitude of these inversions is done semi automatically by searching for cross sections of the regressions of neighboring altitudinal ranges. As initial values typical altitudinal ranges of inversions has to be specified for each of the two possible inversions. Separate regressions are then estimated for the range below the lower inversion and for the range above the lower inversions. If there is a cross section of both regressions between the lower and the upper (theoretical) inversion, then it is assumed that there is only one inversion at all. Otherwise, i.e. if the regressions are crossing outside of the range between the two inversions, a twofold inversion is assumed making the lower regression valid below the lower inver-

sion only and the upper regression above the upper inversion. In-between a third gradient is assumed to link both regressions linearly.

The interpolation to a specified spot in the model is then done by :

$$T(h_M) = a_{r,i} + b_{r,i} \cdot h_M \quad (2)$$

with  $h_M$  altitude [m a.s.l.]  
 $T$  variable (e.g. air temperature)  
 $i$  index for lower, medium resp. upper regression (i=1..3)  
 $a_{r,i}, b_{r,i}$  parameter of the respective regression

with  $a_{r,i}$  (if data of more than 3 stations are fitted using also a trend surface through the residuals):

$$a_{r,i} = u_r + v_1 x_r + v_2 y_r \quad (3)$$

with  $a_{r,i}$  trend surface through the residuals of the regressions after equation (2)  
 $u_r, v_1, v_2$  regression parameter;  
 $x_r, y_r$  coordinates

### 1.2.2 Inverse distance weighting interpolation

For distance weighted interpolation there are two possibilities offered in WaSiM-ETH: the inverse distance weighting method and the THIESSEN-polygone method, whereby THIESSEN-polygons can be seen as a special case of IDW using only the nearest station for getting an “interpolation” result.

The input data are read in as a WaSiM-table. Regression gradient files cannot be processed since they contain no station data but only gradients. For the IDW-method all stations within a specified search radius are used for the interpolation. If all stations have identical values, the interpolation is skipped and the constant value is taken instead. If all stations have nodata values, the interpolation is skipped and the results from the last time step is taken instead.

The interpolation result is the sum of all contributing weighted station data:

$$\hat{z}(u) = \sum_j (w_j \cdot z(u_j)) \quad (4)$$

$$\text{with } w_j = \frac{1}{d(u, u_j)^p} \cdot \frac{1}{C} \quad \text{and} \quad C = \sum_j \frac{1}{d(u, u_j)^p} \quad \text{follows: } \sum_j w_j = 1.0$$

with  $\hat{z}(u)$  interpolated value at location  $u$   
 $w_j$  weight of the observed value at the station  $j$   
 $z(u_j)$  observed value at the station  $j$   
 $d(u, u_j)$  distance to the station  $j$   
 $p$  weighting power of the inverse distance (between 1 and 3, 2 is recommended)

WaSiM-ETH offers the possibility to change the parameter  $p$ , to specify a maximum distance  $d_{max}$  as well as two parameters specifying the anisotropy, which can be seen as an ellipse with a specified slope of the main axis against the horizontal (west-east-line, using mathematically positive rotation orientation) and with a specified length ratio of the long (main) axis to the short axis. The slope of the main axis may range from 0 to  $<90^\circ$ , the axis length ratio may range from greater than zero to 1 (the latter would indicate that there is no anisotropy at all).

### 1.3 Topography dependent adjustment of radiation and temperature

#### 1.3.1 Calculation of sun coordinates, sunset and sunrise, radiation correction

The impacts of the topography on radiation and air temperature is considered using the scheme after OKE (1987). The symbols meaning is:

$\phi$	geographical latitude (positive north, negative south)
$\delta$	declination of the sun (angle between sun equatorial plane of the earth)
$Z$	zenith angle (angle between the direction to the sun and the local zenith)
$h_s$	hour angle
$\Omega_s$	azimuth angle (angle between the projection of the direction to the sun and the north direction)
$t_J$	Julian day (1 <sup>st</sup> of January = 1, 31 <sup>st</sup> of December = 365)
$t$	true local sun time (from average sun time corrected using: Jan: -3.2, Feb: -13.6, Mar: -2.6, Apr: -4.2, May: +2.8, Jun: +2.5, Jul: -3.5, Aug: -6.3, Sep: -0.3, Oct: +10.0, Nov: +16.4, Dec: +11.3 min)
$\Theta_s$	incidence angle between the normal to the local slope and the direction to the sun
$\beta_t$	local slope angle
$\hat{\beta}$	height of the sun above the horizon (as angle)
$\hat{\Omega}$	azimuth angle of the local slope (aspect, clockwise from north=0 to north=360)

The equations for calculating the zenith and azimuth angles are given by:

$$\cos Z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h_s = \sin \beta_t \quad (5)$$

$$\cos \Omega_s = (\sin \delta \cos \phi - \cos \delta \sin \phi \cos h) / \sin Z \quad (6)$$

$$\delta = -23.4 \cdot \cos[360(t_J + 10) / 365] \quad (7)$$

$$h_s = 15(12 - t) \quad \text{in Grad} \quad (8)$$

$$\begin{aligned} \text{with } \Omega_s &= \arccos(\cos \Omega) & (t < 12, h_s > 0) \\ \Omega_s &= 360^\circ - \arccos(\cos \Omega) & (t > 12, h_s < 0) \\ \Omega_s &= 180^\circ & (t = 12, h_s = 0) \end{aligned}$$

The relations for calculating sun rise and sun set for use within the shadowing routine and within the evaporation routine are given by:

$$\cos h_s = \frac{\sin \phi \sin \delta}{\cos \phi \cos \delta} \rightarrow h_{sr} = \frac{12}{\pi} \cdot \arccos(\cos h_s) = \frac{12}{\pi} \cdot h_s \quad \text{und} \quad h_{ss} = 24 - h_{sr} \quad (9)$$

$$\begin{aligned} \text{with } h_{ss} & \text{ time of sun set [h]} \\ h_{sr} & \text{ time of sun rise [h]} \end{aligned}$$

The incoming clear sky direct shortwave radiation  $I_{max}$  on a plain perpendicular to the direction to the sun can be estimated using an approach for the atmospheric extinction given by OKE (1987):

$$I_{max} = I_{tof} \cdot \psi_a^{\frac{p/p_0}{\cos Z}} \quad \text{in W} \cdot \text{m}^{-2} \quad (10)$$

$$\begin{aligned} \text{with } I_{tof} & \text{ incoming shortwave radiation at the top of atmosphere [W} \cdot \text{m}^{-2}] \\ & \text{(solar constant } \approx 1368 \text{ W} \cdot \text{m}^{-2}) \\ p & \text{ air pressure for the place of interest [hPa]} \\ p_0 & \text{ air pressure at sea level } (\approx 1013 \text{ hPa)} \\ \psi_a & \text{ transmissivity of the atmosphere [-]} \end{aligned}$$

A horizontal plane will then get a normal irradiation  $I_{norm}$  given by:

$$I_{norm} = I_{max} \cdot \cos Z \quad (11)$$

This type of irradiation estimation is used also in the evaporation module if no sunshine duration data is available.

The angle between the direction to the sun and the normal to a given grid cell (the incidence angle  $\hat{\Theta}$ ) and hence the correction factor for the direct irradiation is given by:

$$\cos \hat{\Theta} = \cos \beta_t \cdot \cos Z + \sin \beta_t \cdot \sin Z \cdot \cos(\Omega_s - \hat{\Omega}) \quad (12)$$

For an horizontal plane the correction is then given by:

$$I_{korr} = I_{norm} \cdot \frac{\cos \hat{\Theta}}{\cos Z} \quad (13)$$

This correction factor can be applied only with some restrictions:

1. the sun have to be risen over the horizon,
2. the elevation angle of the sun should be greater than  $12^\circ$ , because smaller angles results in a too fast decreasing optical density of the atmosphere (exponent in equation (13)); if the sun is less than  $12^\circ$  above the horizon, the correction factor is limited to  $\pm 5$ .
3. the considered grid cell may not be in the shadow of another cell and  $\hat{\Theta} < 90^\circ$  must hold.
4. the relative sunshine duration has to exceed 0.1, otherwise only diffuse radiation is assumed which will not be corrected

If the model time step is too large for a reasonable radiation correction (e.g. if using daily time steps) the time step is subdivided into sub-time-steps. Then, a radiation correction is carried out for each of these sub-time-steps. The effective correction factor for the entire time step is then found as the weighted average of all sub-time-step correction factors. The weights for each sub-time-step are then calculated by the fraction of the normal irradiation for the sub-time-step of the normal irradiation for the entire time step which is the sum of the normal irradiation of all sub-time-steps.

$$f_d = \frac{\sum_{i=1}^n \frac{\cos \hat{\Theta}_i}{\cos Z_i} I_{norm,i}}{\sum_{i=1}^n I_{norm,i}} \quad (14)$$

with  $f_d$  average correction factor for a day [-]  
 $i$  sub-time-step index 1...n

The correction of the interpolated global radiation itself (in opposition to the calculation of the correction factor) is done within the evaporation calculation scheme by:

$$RG_{eff} = RG \cdot \left( 1 + (1 - cr_0) \cdot SSD \cdot \left[ \frac{\cos \hat{\Theta}}{\cos Z} - 1 \right] \right) \quad (15)$$

with  $RG_{eff}$  effective (corrected) global radiation [ $\text{Wh} \cdot \text{m}^{-2}$ ]  
 $cr_0$  empirical factor for consideration of diffuse shortwave radiation  
 (for the Thur-basin around 0.23, see SCHULLA, 1997)  
 $SSD$  relative sun shine duration (interpolated, without(!) impacts of topographic shadowing)

Besides the correction of radiation, the azimuth angle  $\Omega_s$  and the zenith angle  $Z$  are used for the analyzing of shadowing of cells by other cells.

### 1.3.2 Modification of temperature

Using the radiation correction term of equation (13) it is also possible to modify the air temperature. As parameters will be needed the sunshine duration and an empirical parameter  $c_t$ :

$$\begin{aligned}
T_{korr} &= T_{mess} + c_t \cdot SSD \cdot \ln \frac{\cos \hat{\Theta}}{\cos Z} & \text{if } 0.2 \leq \cos \hat{\Theta} \cdot (\cos Z)^{-1} \leq 5.0 \\
T_{korr} &= T_{mess} + c_t \cdot SSD \cdot 1.609 & \text{if } \cos \hat{\Theta} \cdot (\cos Z)^{-1} > 5.0 \\
T_{korr} &= T_{mess} - c_t \cdot SSD \cdot 1.609 & \text{if } \cos \hat{\Theta} \cdot (\cos Z)^{-1} < 0.2
\end{aligned} \tag{16}$$

By using the sunshine duration it is taken into account that the radiation correction factor is valid for clear sky conditions only. But, differences between cells with various aspects will become smaller with higher cloudiness (resp. shorter sunshine duration). If the sky is fully clouded, no temperature modification is done. The value of  $c_t$  should be calibrated or taken from serious measurements of temperatures of plots with different aspects. Usually  $c_t$  should be less than 5K.

## 1.4 Evapotranspiration

### 1.4.1 Potential Evapotranspiration after Penman-Monteith

The approach after PENMAN-MONTEITH (MONTEITH, 1975; BRUTSAERT, 1982) is used:

$$\lambda E = \frac{3.6 \cdot \frac{\Delta}{\gamma_p} \cdot (R_N - G) + \frac{\rho \cdot c_p}{\gamma \cdot r_a} (e_s - e) \cdot t_i}{\frac{\Delta}{\gamma_p} + 1 + r_s / r_a} \tag{17}$$

- with  $\lambda$  latent vaporization heat  $\lambda = (2500.8 - 2.372 \cdot T)$  KJ·Kg<sup>-1</sup>,  $T$ : temperature in °C  
 $E$  latent heat flux in mm·m<sup>-2</sup>  $\equiv$  kg·m<sup>-2</sup> ( $\rightarrow [\lambda E] = \text{KJ} \cdot \text{m}^{-2}$ )  
 $\Delta$  tangent of the saturated vapor pressure curve [hPa·K<sup>-1</sup>] (see eq. (18))  
 $R_N$  net radiation, conversion from Wh·m<sup>-2</sup> to KJ·m<sup>-2</sup> by a factor 3.6 [Wh·m<sup>-2</sup>]  
 $G$  soil heat flux (here:  $0.1 \cdot R_N$ ) [Wh·m<sup>-2</sup>]  
 $\rho$  density of dry air =  $p/(R_L \cdot T)$  (at 0 °C and 1013,25 hPa:  $\rho = 1.29$  [Kg·m<sup>-3</sup>])  
 $c_p$  specific heat capacity of dry air at constant pressure  
 $c_p = 1.005$  [KJ·(Kg·K)<sup>-1</sup>]  
 $e_s$  saturation vapor pressure at the temperature  $T$  [hPa] (see eq. (18))  
 $e$  actual vapor pressure (observed) [hPa]  
 $t_i$  number of seconds within a time step  
 $\gamma_p$  psychrometric constant [hPa·K<sup>-1</sup>]  
 $r_s$  bulk-surface resistance [s·m<sup>-1</sup>]  
 $r_a$  bulk-aerodynamic resistance [s·m<sup>-1</sup>]

Equation (17) has units of energy flux, i.e. the flux of latent heat in KJ·m<sup>-2</sup>. The denominator has no units. Both terms of the nominator are given in units of KJ·m<sup>-2</sup> (1Wh·m<sup>-2</sup> = 3.6 KJ·m<sup>-2</sup>). By dividing of  $\lambda E$  by the latent heat  $\lambda$  [KJ·Kg<sup>-1</sup>] the unit changes into Kg·m<sup>-2</sup>, which is the height of water in mm. The model uses for each land use type monthly values for a minimum bulk-surface resistance. To get the real evaporation ETR, the potential evaporation is then reduced according to the actual soil moisture.

The slope  $\Delta$  of the vapor pressure function, given in hPa·K<sup>-1</sup>, is found as first derivative of e.g. the MAGNUS-Formula (TETENS, 1932)

$$\begin{aligned}
e_s &= 6.1078 \cdot e^{\frac{17.27 \cdot T}{237.3 + T}} \\
\Delta &= \frac{\partial e_s}{\partial T} = \frac{25029}{(237.3 + T)^2} \cdot e^{\frac{17.27 \cdot T}{237.3 + T}}
\end{aligned} \tag{18}$$

with  $T$  air temperature [°C]

The psychrometric-„constant“  $\gamma_p$ , given in  $\text{hPa} \cdot \text{K}^{-1}$ , is a function of pressure and temperature:

$$\gamma_p = f(p, T) = \frac{c_p \cdot p}{0.622 \cdot \lambda} \quad (19)$$

with  $p$  air pressure (e.g. from barometric formula) [hPa]  
 $0.622$  relation of the molecular weights of water vapor and dry air

The air pressure  $p$  in (19) may get from a barometric formula (using an average pressure at sea level):

$$p \approx 1013 \cdot e^{-\frac{h_M}{7991 + 29.33 \cdot T_v}} \quad (20)$$

with  $p$  air pressure at level  $h_M$  [hPa]  
 $h_M$  altitude [m a.s.l.]  
 $T_v$  average, virtual temperature of the air column [ $^{\circ}\text{C}$ ]

The net radiation  $R_N$  is the difference of shortwave ( $R_K$ ) and long wave radiation ( $R_L$ ). Shortwave direct and diffuse radiation are the global radiation  $RG$ . The reflected radiation  $R_{reflex}$  is estimated using the albedo  $\alpha$ :

$$R_N = \underbrace{(R_{Sun} + R_{sky} - R_{reflex})}_{R_K} - \underbrace{(R_{out} - R_{in})}_{R_L} \quad (21)$$

$$R_N = (1 - \alpha)RG - R_L \quad (22)$$

with  $R_N$  net radiation [ $\text{Wh} \cdot \text{m}^{-2}$ ]  
 $\alpha \cdot RG$  reflected shortwave radiation  $R_{reflex}$  [ $\text{Wh} \cdot \text{m}^{-2}$ ]  
 $\alpha$  albedo [-]

If no global radiation is observed, it can be estimated using the sunshine duration by:

$$RG = I_{norm} \cdot (cr_0 + cr_1 \cdot SSD + cr_2 \cdot SSD^2 + cr_3 \cdot SSD^3) \quad (23)$$

with  $I_{norm}$  theoretical clear sky global radiation [ $\text{Wh} \cdot \text{m}^{-2}$ ] after eq. (11)  
 $SSD$  relative sunshine duration (ranging from 0 to 1) [-]  
 $cr_0 \dots cr_3$  empirical constants [-]  
 $cr_0 = 0.23$ ,  $cr_1 = 1.77$ ,  $cr_2 = -2.28$ , and  $cr_3 = 1.28$  for the Thur-basin

$I_{norm}$  is calculated using equations (10) and (11). For daily time steps,  $I_{norm}$  is calculated for a number of bright sub-time-steps.

If no sunshine duration is observed but only global radiation (one of them must be measured), sunshine duration can be modeled using a polynomial relation between sunshine duration and the fraction of observed to theoretical global radiation:

$$SSD_{rel} = cs_0 + cs_1 RG_{rel} + cs_2 RG_{rel}^2 + cs_3 RG_{rel}^3 \quad (24)$$

with  $cs_0 \dots cs_3$  polynomial-coefficients ( $cs_0 = 0.072$ ,  $cs_1 = -0.808$ ,  $cs_2 = 2.112$ ,  $cs_3 = -0.239$ )  
 $RG_{rel}$  relative global radiation [ $\text{Wh} \cdot \text{m}^{-2}$ ]

where

$$RG_{rel} = RG_{mess} / RG_{max} \quad (25)$$

with  $RG_{mess}$  observed global radiation (or interpolated) [ $\text{Wh} \cdot \text{m}^{-2}$ ]  
and:

$$RG_{max} = \sum_{i=1}^n I_{toa} \cdot \psi_a(t_j) \cdot \frac{p(h_M)/p_0}{\cos Z_i} \cdot \cos Z_i \cdot t_i \quad (26)$$

with	$RG_{max}$	maximum possible global radiation [ $\text{Wh}\cdot\text{m}^{-2}$ ]
	$I_{toa}$	incoming shortwave radiation at the top of atmosphere [ $\text{Wh}\cdot\text{m}^{-2}$ ] (solar constant $\approx 1368 \text{ W}\cdot\text{m}^{-2}$ )
	$\psi_a(t_J)$	extinction coefficient after equation (27) [-]
	$p(h_M)$	air pressure at altitude $h_M$ after equation (20) [hPa]
	$p_0$	average air pressure at sea level (1013 hPa) [hPa]
	$n$	number of sub-time-steps within a day [-]
	$Z_i$	zenith angle of the sun for sub-time-step $i$ [rad]
	$t_i$	length of sub-time-step $i$ (max. 1 h) [h]

In equation (27) the extinction coefficient is given by:

$$\psi_a(t) = \bar{\psi}_a + 0.5 \cdot \Delta\psi_a \cdot \cos((t_J + 10) / 365 \cdot 2 \cdot \pi) \quad (27)$$

with	$\psi_a(t)$	extinction coefficient for a given time $t$ [-]
	$\bar{\psi}_a$	temporal mean extinction coefficient (e.g. 0.88) [-]
	$\Delta\psi_a$	range of the extinction coefficient (e.g. 0.1) [-]
	$t_J$	Julian day (1 <sup>st</sup> January = 1, 31 <sup>st</sup> December = 365 resp. 366) [-]

The long wave net radiation is given by:

$$R_L = \Delta t \cdot \sigma T^4 \cdot (0.48 - 0.065\sqrt{e}) \cdot (cr_0 + (1 - cr_0) \cdot SSD) \quad \text{in } \text{Wh}\cdot\text{m}^{-2} \quad (28)$$

with	$\Delta t$	time step $\rightarrow$ conversion from power to energy (time related) [h]
	$cr_0$	empirical parameter (Thur: $cr_0 \approx 0.23$ ) [-]
	$T$	air temperature [K]
	$e$	actual vapor pressure [mbar]
	$\sigma$	Boltzmann-constant $\sigma = 5.67 \cdot 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$

The aerodynamic resistances  $r_a$  are estimated by:

$$r_a = \frac{4.72 \cdot \left( \ln \frac{z}{z_0} \right)^2}{1 + 0.54u} \quad \text{in } \text{s}\cdot\text{m}^{-1} \quad (29)$$

with	$z$	sampling elevation above ground [m]
	$z_0$	aerodynamic roughness length as parameter for each land use type $z_0 \approx 0.125 \cdot (\text{crop height} - \text{shift height } d)$ [m]
	$u$	wind speed [ $\text{m}\cdot\text{s}^{-1}$ ]

For effective crop heights  $z_0 > 2 \text{ m}$   $r_a$  is given by:

$$r_a = 25 / (1 + 0.54u) \quad (30)$$

The surface resistances  $r_s$  are estimated for the bright day by:

$$\frac{1}{r_s} = \frac{(1 - A)}{r_{sc}} + \frac{A}{r_{ss}} \quad (31)$$

with	$r_s$	minimum surface resistance [ $\text{s}\cdot\text{m}^{-1}$ ]
	$r_{sc}$	minimum surface resistance of the plant if fully supplied with water [ $\text{s}\cdot\text{m}^{-1}$ ]
	$r_{ss}$	surface resistance for bare soil ( $\approx 150 \text{ s}\cdot\text{m}^{-1}$ ) [ $\text{s}\cdot\text{m}^{-1}$ ]
	$1-A$	evaporation effective vegetation coverage $A = f^{LAI}$ with $LAI$ leaf area index, $f \approx 0.6 \dots 0.7$

At night the following relation is valid:



$$\frac{1}{r_s} = \frac{LAI}{2500} + \frac{1}{r_{ss}} \quad (32)$$

The parameters  $z_0$  and  $LAI$  and the root depth have a specific annual course, which is given as 4 values for each crop at 4 specific days. These 4 days are given as Julian days. In order to consider a time shift with increasing altitude, these days are shifted (to later days at the beginning and to former days at the end of the year) according to:

$$\begin{aligned} d_1 &= d_{1,400} + 0.025 \cdot (h_M - 400) \\ d_2 &= d_{2,400} + 0.025 \cdot (h_M - 400) \\ d_3 &= d_{3,400} - 0.025 \cdot (h_M - 400) \\ d_4 &= d_{4,400} - 0.025 \cdot (h_M - 400) \end{aligned} \quad (33)$$

with  $h_M$  altitude [m a.s.l.]  
 $d_1, d_2, d_3, d_4$  Julian days;  $d_1$ : start of vegetation,  $d_2$ : fully developed vegetation;  
 $d_3$ : start and  $d_4$ : end of autumn  
resp. of the shutdown of vegetation  
 $d_{1,400}$  to  $d_{4,400}$  initial values for 400 m a.s.l (examples see SCHULLA, 1997)

If the model is driven in daily time steps, a subdivision into day and night is automatically performed for the Penman-Monteith approach in order to modify the temperature:

$$ETP_{24h} = ETP_{day} + ETP_{night} \quad (34)$$

$$ETP_{day} = \frac{\Delta_{day} (R_{N,day} - G) + \rho \cdot c_p (e_{s,day} - \bar{e})}{\Delta_{day} + \gamma(1 + r_{s,day} / r_a)} \cdot d \quad (35 a)$$

$$ETP_{night} = \frac{\Delta_{night} (R_{N,night} - G) + \rho \cdot c_p (e_{s,night} - \bar{e})}{\Delta_{night} + \gamma(1 + r_{s,night} / r_a)} \cdot (1 - d) \quad (35 b)$$

with  $\Delta_{day}, \Delta_{night}$  slope of the saturated vapor pressure curve for temperatures at day ( $T_{day}$ ) resp. at night ( $T_{night}$ ) [hPa·K<sup>-1</sup>]  
 $R_{N,day}, R_{N,night}$  net radiation for day and night, resp. [Wh·m<sup>2</sup>]  
 $R_{N,day} = (1 - \alpha) \cdot RG - R_L$  with  $R_L$  after (28) with  $T = T_{day}$  (36 a)  
 $R_{N,night} = -R_L$  with  $R_L$  after (28) with  $T = T_{night}$  (36 b)  
 $e_{s,day}, e_{s,night}$  Saturation vapor pressure as function of  $T_{day}$  resp.  $T_{night}$  [hPa]  
 $r_{s,day}, r_{s,night}$  surface resistance of the vegetation for the bright day [s·m<sup>-1</sup>]  
and for the night after eq. (31) and eq. (32), resp.  
 $d$  relative duration of the bright day  $(h_{ss} - h_{sr})/24$  after eq.(9) [-]

The temperatures  $T_{day}$  and  $T_{night}$  are given by:

$$T_{day} = T_{24h} + c_{T,day} \cdot \Delta T \quad (37 a)$$

$$T_{night} = T_{24h} - c_{T,night} \cdot \Delta T \quad (37 b)$$

$c_{T,Day}$  and  $c_{T,Night}$  are calculated as follows:

$$c_{T,day} = c_T + \Delta c_T \cdot \cos((t_J + 10) / 365 \cdot 2 \cdot \pi) \quad (38 a)$$

$$c_{T,night} = 1 - c_{T,day} \quad (38 b)$$

with  $c_{T,Day}$  fraction of  $\Delta T$ , which is added to the daily average  $T$  to get  $T_{day}$   
 $c_{T,Night}$  fraction of  $\Delta T$ , which is subtracted from the daily average  $T$  to get  $T_{Night}$   
 $c_T$  mean fraction of  $\Delta T$  for  $T_{day}$   
 $\Delta c_T$  range of the fraction  $c_T$  during a year (0.1 ... 0.15)

The temperature fluctuation range  $\Delta T$  is given by:

$$\Delta T = f(t_J, h_M, SSD) = \Delta T_{Meer, t_J} \cdot e^{-h_M / k_T} \cdot SSD \quad (39)$$

with  $\Delta T_{Meer, t_J}$  temperature range valid for sea level and for Julian day  $t_J$  (1 ... 365),  
interpolated using values like from table 1 [K]  
 $k_T$  recession constant valid for all days of an year [m]  
 $SSD$  relative sunshine duration as daily value [-]  
 $h_M$  altitude above sea level [m]

The recession constant  $k_T$  was empirically found to be around 1654 m, valid for northern Switzerland. Table 1 contains the monthly values of differences between average day and average night temperatures.

Table 1: monthly differences between day and night average temperatures, referring to sea level, valid for northern Switzerland

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\Delta T_{Meer}$ [K]	3.3	4.4	6.1	7.9	9.4	10.0	9.9	9.0	7.8	6.0	4.2	3.2

#### 1.4.2 Potential Evapotranspiration after Wendling

The estimation of potential evapotranspiration after both WENDLING (1975) and HAMON (in FEDERER and LASH, 1983) is applicable only if using a time step of one day or larger. The potential evapotranspiration using this approach is then given by:

$$ETP = (RG(1.1 - \alpha) + 93 \cdot f_k) \frac{T + 22}{150(T + 123)} \quad (40)$$

with  $RG$  global radiation in  $J \cdot cm^{-2} \cdot d^{-1}$ , converted from  $Wh \cdot m^{-2} \cdot d^{-1}$  by multiplication with 0.36 [ $J \cdot cm^{-2} \cdot d^{-1}$ ]  
 $\alpha$  albedo (0 ... 1) [-]  
 $f_k$  empirical correction factor, (coastal regions of northern Germany  $\approx 0.6$ , other flat regions  $\approx 1$ , value for northern Switzerland found by comparison with Penman-Monteith evaporation: 0.5 [-])  
 $T$  daily mean value of air temperature [ $^{\circ}C$ ]

The global radiation  $RG$  in the above formula can be derived as described in chapter 1.4.2 if it is not measured (resp. interpolated).

#### 1.4.3 Potential Evapotranspiration after HAMON

$$ETP = 0.1651 \cdot f_i \cdot h_d / 12 \cdot \frac{216.7 \cdot e_s}{T + 273.3} \quad (41)$$

with  $f_i$  empirical factor, monthly values (see table below)  
 $h_d$  day length [h]  
 $e_s$  Saturation vapor pressure at temperature  $T$  [hPa]  
 $T$  temperature [ $^{\circ}C$ ]

Die correction factors  $f_i$  contained in equation (41) are listed in Table 2.

table 2: Monthly correction factors  $f_i$  for HAMON-Evapotranspiration (valid for northern Switzerland)

month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct.	Nov	Dec
$F_i$	0.5	0.6	0.8	1.1	1.2	1.3	1.2	1.1	1.0	0.9	0.7	0.5

## 1.5 Calculating the real evapotranspiration

### 1.5.1 WaSiM-version using the Topmodel-approach

This model version uses a relative simple reduction function of potential evaporation to get the real evaporation. The real evaporation is reduced compared to the potential evaporation if the content of the soil moisture storage drops below a specified level  $\eta$ :

$$\begin{aligned} ETR &= ETP \cdot SB / (\eta \cdot SB_{\max}) & SB < \eta \cdot SB_{\max} \\ ETR &= ETP & SB \geq \eta \cdot SB_{\max} \end{aligned} \quad (42)$$

with  $ETR$  real evaporation after eq. (17) resp. eqs. (40/41) [mm]  
 $ETP$  potential evaporation [mm]  
 $SB$  actual content of the soil water storage [mm]  
 $SB_{\max}$  maximum capacity of the soil water storage [mm]  
 $\eta$  threshold value for the soil moisture; below the evaporation is reduced compared to the potential evaporation ( $\eta \approx 0.6$  after MENZEL, 1997b)

### 1.5.2 WaSiM-version using the Richards-equation

The more physically based soil moisture modeling within WaSiM-ETH version 2 allows another kind of estimating real evaporation by using the relation between the soil water content  $\Theta$  and the actual capillary pressure (suction) as given by the VAN GENUCHTEN parameters of the actual soil.

Besides a reduction as a result of dry soils ( $\Theta(\psi) < \Theta_{\psi_g}$ ) also the impact of too wet soils ( $\eta \cdot \Theta_{sat} < \Theta(\psi) < \Theta_{sat}$ ) is considered.

$$\begin{aligned} ETR_i &= 0 & \Theta(\psi) < \Theta_{wp} \\ ETR_i &= ETP_i \cdot (\Theta(\psi)_i - \Theta_{wp}) / (\Theta_{\psi_g} - \Theta_{wp}) & \Theta_{wp} \leq \Theta(\psi) \leq \Theta_{\psi_g} \\ ETR_i &= ETP_i & \Theta_{\psi_g} \leq \eta \cdot \Theta_{sat} \\ ETR_i &= ETP_i \cdot (\Theta_{sat} - \Theta(\psi)_i) / (\Theta_{sat} - \eta \cdot \Theta_{sat}) & \eta \cdot \Theta_{sat} < \Theta(\psi) < \Theta_{sat} \end{aligned} \quad (43)$$

with  $i$  index of the soil layer (see the soil model description for WaSiM-ETH Version 2 using the RICHARDS-equation)  
 $ETR$  real evaporation [mm]  
 $ETP$  potential evaporation [mm]  
 $\Theta(\psi)$  actual relative soil water content at suction  $\psi$  [-]  
 $\psi$  actual suction (capillary pressure) [m]  
 $\eta$  maximum relative water content without partly or total anaerobe conditions ( $\approx 0.9 \dots 0.95$ )  
 $\Theta_{sat}$  saturation water content of the soil [-]  
 $\Theta_{\psi_g}$  soil water content at a given suction  $\psi_g$   
 $\Theta_{wp}$  water content of the soil at permanent wilting point ( $\psi = 1.5 \text{ MPa} \approx 150 \text{ m}$ )

The parameters for equation (43) are (I) the relative soil water content at the beginning of the reduction of evaporation due to dry soil and (II) the relative soil water content at the beginning of reduction due to anaerobe conditions. Both parameters are given as suction for each crop type in order to make differences between various crop types. This way the reduction of evaporation depends not only on the soil but also

on the crop type and it can easily be converted into a time dependent parameter as well. The extraction of water over the depth profile is described in chapter 1.12.

## 1.6 Snow accumulation and melt <sup>1</sup>

### 1.6.1 Snow accumulation

The type of precipitation is estimated for each grid cell using the interpolated air temperature during the event. Within a transition range there will be both kinds of precipitation. The fraction of snow is given by:

$$p_{Schnee} = \frac{T_{R/S} + T_{trans} - T}{2 \cdot T_{trans}} \quad \text{for } (T_{R/S} - T_{trans}) < T < (T_{R/S} + T_{trans}) \quad (44)$$

with  $p_{Snow}$  fraction of snow on the total precipitation (0..1)  
 $T$  air temperature [°C]  
 $T_{R/S}$  temperature, at which 50 % of precipitation are falling as snow [°C]  
 $T_{trans}$   $\frac{1}{2}$  of the temperature-transition range from snow to rain [K]

### 1.6.2 Snow melt

- temperature-index-approach

$$M = c_0 \cdot (T - T_{0,m}) \cdot \frac{\Delta t}{24} \quad \text{for } T > T_{0,m}, \text{ else } M = 0 \quad (45)$$

with  $M$  melting rate in mm per time step  
 $c_0$  temperature dependent melt factor [mm·°C<sup>-1</sup>·d<sup>-1</sup>]  
 $T$  air temperature, casually using modification after equations (37) to (39) [°C]  
 $T_{0,m}$  temperature for beginning with snow melt [°C]  
 $\Delta t$  time step [h]

- temperature-wind-index-approach

$$M = (c_1 + c_2 \cdot u) \cdot (T - T_{0,m}) \cdot \frac{\Delta t}{24} \quad \text{for } T > T_{0,m}, \text{ else } M = 0 \quad (46)$$

with  $M$  melt rate [mm/time step]  
 $c_1$  temperature dependent melt factor [mm·°C<sup>-1</sup>·d<sup>-1</sup>]  
 $c_2$  wind dependent melt factor [mm·(°C·m·s<sup>-1</sup>·d<sup>-1</sup>)-1]  
 $u$  wind speed [m·s<sup>-1</sup>]  
 $T$  air temperature, casually using modifications after equations (37) to (39) [°C]  
 $T_{0,m}$  temperature for beginning with snow melt [°C]  
 $\Delta t$  time step [h]

- Combination approach after ANDERSON (1973) and extended combination approach after Braun (1985)

This approach was developed for daily time steps. Using it in WaSiM-ETH requires a time step of one day or larger. The water equivalent of the snow cover is subdivided into a snow and a water fraction. A coefficient  $c_l$  is used to control the maximum capacity of the water storage as fraction on the total storage (usually around 10 % of the water equivalent). The effective melt is the amount of water exceeding the water holding capacity, where rain and melt are superposed before doing this calculation. Because the storage for the liquid fraction does not have to be empty at the beginning of a time step, it is required to calculate a refreezing  $M_{neg}$  at temperatures below  $T_{0,m}$ .

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<sup>1</sup> Chapter 9 contains the description of the integrated glacier model

$$M_{neg} = c_{rfr} \cdot RMF \cdot (T - T_{0,m}) \cdot \frac{\Delta t}{24} \quad (47)$$

with  $M_{neg}$  „negative melt“ (refreezing water) [mm]  
 $c_{rfr}$  coefficient for refreezing [-]  
 $RMF$  season dependent radiation melt coefficient [ $\text{mm} \cdot (\text{°C} \cdot \text{d})^{-1}$ ]  
 $T$  air temperature, eventually modified after equation (16) [ $\text{°C}$ ]  
 $T_{0,m}$  threshold temperature for beginning with snow melt [ $\text{°C}$ ]  
 $\Delta t$  time step [h]

After calculating negative melt, the storage's of liquid ( $S_l$ ) and solid ( $S_s$ ) fractions on the water equivalent are balanced. The re-frozen amount of liquid water is added to the solid fraction and subtracted from the liquid fraction (limited by the amount of water in the liquid fraction storage).

Melt is calculated only at air temperatures above the threshold temperature  $T_{0,m}$ . For time steps with precipitation ( $P \geq 2 \text{ mm} \cdot \text{d}^{-1}$ ) melt is composed of radiation melt, melt from sensible heat, melt from latent heat, and melt from energy import from precipitation:

$$M = (M_R + M_S + M_E + M_P) \cdot \frac{\Delta t}{24} \quad (48a)$$

with  $M_R$  radiation melt [mm]  
 $M_S$  melt by sensible heat [mm]  
 $M_E$  melt by latent heat [mm]  
 $M_P$  melt by import of energy by precipitation [mm]  
 $\Delta t$  time step [h]

The melt fractions in equation (48) are parameterized by:

$$\begin{aligned} M_R &= 1.2 \cdot T \\ M_S &= (c_1 + c_2 \cdot u) \cdot (T - T_{0,m}) \\ M_E &= (c_1 + c_2 \cdot u) \cdot (E - 6.11) / \gamma \\ M_P &= 0.0125 \cdot P \cdot T \end{aligned} \quad (48b)$$

with  $T$  air temperature [ $\text{°C}$ ]  
 $T_{0,m}$  threshold temperature for melt [ $\text{°C}$ ]  
 $c_1$  temperature dependent melt factor [ $\text{mm} \cdot (\text{°C} \cdot \text{d})^{-1}$ ]  
 $c_2$  wind dependent melt factor [ $\text{mm} \cdot (\text{°C} \cdot \text{m/s} \cdot \text{d})^{-1}$ ]  
 $u$  wind speed [ $\text{m} \cdot \text{s}^{-1}$ ]  
 $\gamma$  psychrometric constant, see equation (19) [ $\text{hPa} \cdot \text{K}^{-1}$ ]  
 $E$  saturation vapor pressure at air temperature  $T$  [hPa]  
 (extended approach after BRAUN, 1985: observed vapor pressure  $e$ )  
 $P$  precipitation [mm]

In a time step without precipitation melt is calculated like in equation (45) by:

$$M = RMF \cdot (T - T_{0,m}) \cdot \frac{\Delta t}{24} \quad (49)$$

with  $M$  melt [mm]  
 $RMF$  radiation melt factor [ $\text{mm} \cdot (\text{°C} \cdot \text{d})^{-1}$ ]  
 $T$  air temperature [ $\text{°C}$ ]  
 $T_{0,m}$  threshold temperature for melt [ $\text{°C}$ ]  
 $\Delta t$  time step [h]

## 1.7 Interception

A simple bucket approach is used with a capacity depending on the leaf area index, the vegetation coverage degree, and the maximum height of water at the leaf surfaces:

$$SI_{\max} = v \cdot LAI \cdot h_{SI} + (1 - v) \cdot h_{SI} \quad (50)$$

with	$SI_{\max}$	maximum interception storage capacity [mm]
	$v$	degree of vegetation covering (crop specific annual course) [ $\text{m}^2/\text{m}^2$ ]
	$LAI$	leaf area index (crop specific annual course) [ $\text{m}^2/\text{m}^2$ ]
	$h_{SI}$	maximum height of water at the leaf surfaces [mm]

In WaSiM-ETH, the interception is calculated after the snow model, so the snow melt is flowing into the interception storage in order to be able to store melt water (as well as rain water) at the soil surface in small ponds etc.

The extraction of water out of the interception storage by evaporation is assumed to be at potential rate. If there is a sufficient amount of water in the storage, the storage content is reduced by the potential evaporation and no evaporation will be taken from the soil. If the storage content is smaller than the potential evaporation rate, the remaining rate will be taken from the soil (if the soil is not too dry or too wet).

$$\begin{aligned} EI &= ETP & (\text{for } SI \geq ETP \text{ in mm}), & & ETR &= 0 \\ EI &= SI & (\text{for } SI < ETP \text{ in mm}), & & ETR &= ETP - SI \end{aligned} \quad (51)$$

with	$EI$	interception evaporation [mm]
	$ETP$	potential evaporation [mm]
	$ETR$	remaining evaporation from soil and vegetation, a reduction after eq. (42) or (43) dependent on soil moisture is possible [mm]
	$SI$	content of the interception storage [mm]

If the interception storage is filled, further precipitation or snow melt will fall directly to the soil surface. This amount is the input for the infiltration and soil model.

## 1.8 Infiltration

The infiltration model is an integrated part of the soil model. It uses an approach after PESCHKE (1977, 1987) which is based on the approach of GREEN and AMPT (1911). The soil is assumed to be homogeneous and unlayered. matrix flow is assumed to dominate, the wetting front is approximated as a step function. The precipitation intensity is assumed to be constant over the entire time step. The approach consist of two phases. Within the first phase the time of saturation is calculated (if any saturation will occur within the time step at all). Within the second phase, the cumulated infiltration until the end of the time step is calculated. If the soil surface is saturated at the end of the time step, in the next time step only the cumulated infiltration will be calculated (if the precipitation intensity is sufficiently high) without calculating the saturation time. The exceeding amount (the not infiltrated water) is surface runoff. Using a parameter  $x_f$  the amount of re-infiltrating water can be controlled (0... 1). This may be important to consider inhomogeneities of the soil properties if using larger grid cells (e.g. for grid cell sizes of some hundreds of meters).

If  $PI > K_s$  (otherwise there will be no saturation at all), the saturation time  $t_s$  is calculated by:

$$t_s = \frac{l_s \cdot n_a}{PI} = \frac{\frac{\psi_f}{PI / K_s - 1}}{PI} \quad (52)$$

with	$t_s$	saturation time from the beginning of the time step [h]
	$l_s$	saturation depth [mm]
	$n_a$	fillable porosity ( $n_a = \Theta_s - \Theta$ ) [-]

$\psi_f$  suction at the wetting front ( $\approx 1000 n_a$ ) [mm]  
 $PI$  precipitation intensity [mm/h]  
 $K_S$  saturated hydraulic conductivity [mm/h]

The infiltrated amount of water up to this time  $F_S$  is given by:

$$F_S = l_S \cdot n_a = t_S \cdot PI \quad (53)$$

Finally, the cumulated amount of infiltration after saturation until the end of the time step is calculated after PESCHKE (in DYCK, PESCHKE [1989]) by:

$$F = \frac{A}{2} + \left[ \frac{A^2}{4} + AB + F_S^2 \right]^{1/2} \quad (54)$$

with  $A = K_S(t - t_s)$   
 $B = F_S + 2 \cdot n_a \cdot \psi_f$

The exceeding amount of precipitation  $PI \cdot \Delta t - F - F_S$  is surface runoff  $Q_{D,I}$ .

## 1.9 Soil model for the WaSiM-ETH version using the Topmodel-approach

### 1.9.1 Introduction

The modeling of the soil water balance and of runoff generation is done using a modified variable saturated area approach after BEVEN and KIRKBY (1979) extended by capillary rise and interflow. The calculation is done separately for each of the grid cells opposed to the modeling of classes of similar indices like in the original TOPMODEL. The base for the model is the spatial distribution of the topographic index  $c_s$ . Using this index, the potential extent of saturation areas can be estimated depending on the mean saturation deficit within the basin:

$$c_s = \ln \frac{a_t}{T_0 \tan \beta_t} \quad (55)$$

with  $c_s$  topographic index [-]  
 $a_t$  specific catchment area per unit length of a grid cell;  
 this is the area draining through one meter of the edge of a grid cell [ $\text{m}^2 \cdot \text{m}^{-1}$ ]  
 $T_0$  saturated local hydraulic transmissivity ( $T_0 = \int K_s dh$ ) [ $\text{m}^2 \cdot \text{s}^{-1}$ ]  
 $\beta_t$  slope angle [ $\text{m} \cdot \text{m}^{-1}$ ]

It is presumed, that (i) the groundwater table is parallel to the topographic slope, that (ii) the dynamic of the saturated zone can be approximated by subsequent quasi stationary states, and that (iii) the local hydraulic transmissivity  $T_h$  is a exponential function of the saturation deficit  $S$ :

$$T_h = T_0 e^{-S/m} \quad (56)$$

The spatial distribution of saturated areas or, more general, the distribution of the saturation deficit can be found by:

$$S_i = S_m - m \left( \ln \frac{a_t}{T_0 \cdot \tan \beta_t} - \gamma \right) \quad (57)$$

with  $S_m$  mean saturation deficit of the basin (arithmetic average of all  $S_i$ ) [mm]  
 $m$  model parameter [mm]  
 $\gamma$  mean topographic index of the (sub-)catchment

At places where  $S_i$  is negative or zero, any further liquid precipitation (or snowmelt) will immediately generate surface runoff. The mean saturation deficit is newly calculated in each time step as average value

of all local saturation deficits from the previous time step and from the balance of all inflows into an outflows out of the basin. After estimating all runoff components for the entire subbasin, the new mean saturation deficit is calculated by:

$$S_{m,i} = S_{m,i-1} + Q_B + Q_{rück} - Q_{SUZ} \quad (58)$$

with  $S_{m,i}$  spatially averaged Saturation deficit in the actual time step [mm]  
 $S_{m,i-1}$  spatially averaged Saturation deficit in the previous time step [mm]  
 $Q_B$  base flow in the actual time step (is always a mean value for the (sub-)catchment)  
[mm]  
 $Q_{rück}$  capillary rise as a mean value for the (sub-)catchment in the actual time step [mm]  
 $Q_{SUZ}$  groundwater recharge from the unsaturated zone as a mean value for the (sub-)catchment [mm]

### 1.9.2 The course of water within the soil model

#### *surface runoff from snowmelt*

If there is a sufficient snow cover on the ground (>10 mm water equivalent), a specified fraction of snow melt is taken as surface runoff directly from this melt (and is not given to the infiltration module):

$$Q_{D,S} = Q_{snow.out} \cdot QD_{Schnee} \quad (59)$$

with  $Q_{D,S}$  surface runoff (fraction from snow melt) [mm]  
 $Q_{snow.out}$  snow melt [mm]  
 $QD_{Snow}$  factor defining the fraction of surface runoff on the snow melt [-]

#### *partitioning of the water reaching the soil*

Depending on the precipitation intensity, a greater or lesser fraction of precipitation can flow directly into deeper soil regions without going into the root zone storage (from where evaporation could remove the water again). The fraction is specified by a threshold value for the precipitation intensity:

$$P_{grenz} = P_{grenz,1h} \cdot \Delta t^{a_p} \quad (60)$$

with  $P_{grenz}$  threshold precipitation intensity, if  $P > P_{grenz}$ , all exceeding precipitation is routed into the deep soil by macro pores [mm/ $\Delta T$ ]  
 $P_{grenz,1h}$  threshold precipitation intensity for time step  $\Delta t = 1h$  [mm/h]  
 $\Delta t$  time step [h]  
 $a_p$  empirical value, describing the decrease of the variance of the precipitation intensity with larger time steps ( $\approx 0.6$ , static value in the model source code) [-]

All precipitation below the threshold value  $P_{grenz}$  flows into the root zone storage, which is also called soil storage, from where it can be withdrawn by evaporation after equation (42). The exceeding fraction is flowing into deeper soil regions immediately:

$$q_v = K_{korr} \cdot k_f \cdot e^{-S_i/m} \quad (61)$$

with  $q_v$  vertical flow rate (percolation) [mm]  
 $K_{korr}$  scaling parameter for considering unsaturated soils as well as preferred flow paths [-]  
 $S_i$  local saturation deficit [mm]  
 $m$  recession parameter (see generation of baseflow) [mm]  
 $k_f$  saturated hydraulic conductivity [mm/h]

**Important:** The parameter  $K_{korr}$  is used in the original-TOPMODEL as a parameter for considering unsaturated conditions. In WaSiM-ETH, this parameter is used also for considering preferential flow paths. Thus, this parameter can be within a wide range of values.  $K_{korr}$  should therefore be calibrated. For soils with much macro pores, it should be much greater than for compact soils, otherwise the water will not going down fast enough within the model.



**also Important:** If starting the model calibration with a combination of a much too large  $K_{kor}$  and a too large initial saturation deficit  $S_m$ , this will lead to a kind of hydraulic “stop bar” as a result of the exponential function in equation (61). No water is able to percolate and all precipitation will leave the cell as evaporation or as surface runoff. It is therefore save to set  $K_{kor}$  at the beginning to a large number (e.g. 1000) and to set  $S_m$  to a rather small number ( $\geq 0$ )

*generation of interflow and surface runoff from saturated areas*

Interflow may be generated between soil layers of different hydraulic conductivities or porosities. There must be a sufficient slope, otherwise no interflow but water logging will be the result.

The WaSiM-ETH version with the TOPMODEL-approach considers interflow using a conceptual approach. Like the surface runoff, the interflow storage is filled dependent on the local saturation deficit:

$$Q_{SH,in} = (S - SUZ) - SH_{max} \quad (62)$$

with  $Q_{SH,in}$  inflow into the interflow storage (for each grid cell one storage) [mm]  
 $S$  actual local saturation deficit [mm]  
 $SUZ$  content of the storage of the unsaturated zone (pore volume, which is not accessible by plant roots down to the saturated zone) [mm]  
 $SH_{max}$  maximum content of the interflow storage [mm], this is a model parameter

Surface runoff  $Q_{D,sat}$  is generated only if the interflow storage is completely filled (what means also, that the unsaturated zone is filled, too, and hence there is no unsaturated zone at all). The original TOPMODEL with only one fast runoff component is get if  $SH = 0$  mm. The total surface runoff is the sum of all possible three components:  $Q_{D,S}$  from snow melt,  $Q_{D,I}$  from infiltration excess and  $Q_{D,sat}$  from saturated areas.

*capillary rise from the saturated zone into the soil water storage and into the interflow storage*

In order to allow evaporation with potential rates at places with high groundwater, the deficit in the soil water storage (root zone storage) caused by evaporation can be replaced by water from the saturated zone and/or from the interflow storage. The first re-flow is taken from the interflow storage proportional to its filling ( $Q_{rück}$ ). Then, the capillary rise will take water from the saturated zone until the evaporation losses are refilled ( $Q_{kap}$ ). A hydraulic contact between the root zone and the saturated zone is required for this flow to take place. Two assumptions are made:

1. there is no capillary fringe above the groundwater – the decision, if capillary rise will take place depends only on the saturation deficit compared to the root zone capacity.
2. the extraction of water by evaporation is done using an unique intensity for the entire soil profile, thus avoiding a subdivision of the soil into layers.

A parameter  $r_k$  is used to quantify the re-flow into the soil storage (to scale the saturation deficit to the root zone depth). This is required due to the fact that the modeled groundwater table (given by the saturation deficit) doesn't fits well the real groundwater table as observed in the catchment:

$$Q_{rück} = (ETR - Q_{kap}) \cdot \frac{SH}{SH_{max}} \cdot r_k \quad (0 \leq SH \leq SH_{max}) \quad (63)$$

$$Q_{kap} = \left( 1 - \frac{S}{r_k \cdot n_e \cdot z_w} \right) \cdot ETR \quad (0 \leq S \leq r_k \cdot n_e \cdot z_w) \quad (64)$$

with  $Q_{rück}$  amount of water flowing back from the interflow storage into the soil storage [mm]  
 $Q_{kap}$  capillary rise from groundwater [mm]  
 $ETR$  evaporation withdrawal from the soil [mm]  
 $SH$  content of the interflow storage [mm]  
 $SH_{max}$  maximum content of the interflow storage [mm]  
 $S$  local saturation deficit [mm]  
 $r_k$  scaling parameter (there will be no capillary rise for cells with  $S > r_k \cdot n_e \cdot z_w$ ) [-]

$n_e$	drainable porosity [-]
$z_w$	root depth [mm]

### calculating baseflow

The baseflow is calculated for each subbasin as a whole:

$$Q_B = e^{-\gamma + \ln T_{kor}} \cdot e^{-S_m/m} = T_{kor} \cdot e^{-\gamma} \cdot e^{-S_m/m} \quad (65)$$

with $Q_B$	baseflow [mm/time step]
$\gamma$	mean value of the topographic index [-]
$S_m$	mean saturation deficit for a (sub-)basin [mm]
$m$	model parameter [mm]
$T_{kor}$	scaling factor for transmissivities as well as for scale dependent shifts in the distribution function of the topographic index $c$ [-]

For estimating the parameter  $m$  it is recommended to fit some appropriate recession periods in an inverted graph (in h/mm or days/mm) of the observed discharge by a linear regression. The slope of this inverted recessions give the parameter  $m$ . **Important:** If modeling interflow, the parameter  $m$  usually has to be much larger than without using interflow (often the factor 2 or 3 has to be applied), because then the fast runoff components are handled by the interflow storage and  $m$  is responsible for the slower components only.

$$\frac{t}{m} + \frac{1}{Q_0} = \frac{1}{Q_B(t)} \quad (66)$$

### flow concentration within the subbasin

The base flow is generated for an entire subbasin as average value. Interflow is generated for each grid cell separately and then averaged over space. The third component, the surface runoff, is routed to the subbasin outlet using a subdivision of the basin into flow time zones. Flow time zones are zones of equal flow times for surface runoff to reach the subbasin outlet, where all grid cells belonging to the same zone have the same flow time (rounded up to the next integer number of time steps). The fraction of each of these zones on the total area, ordered by the zone number, can be seen as a system response. At the beginning of a new time step, the surface runoff of each flow time zone is given to the next lower flow time zone, only the content of the lowest zone is taken as effective surface runoff for the actual time step and added to base flow and interflow to get the total runoff. For considering retention, a single linear storage approach is applied to the surface runoff in the last flow time zone, using a storage constant  $k_D$ :

$$Q_{D_i} = Q_{D_{i-1}} \cdot e^{-\Delta t/k_D} + \hat{Q}_D \cdot (1 - e^{-\Delta t/k_D}) \quad (67)$$

with $Q_{D,i}$	transformed (by a single linear storage) surface runoff in the time step $i$ [mm]
$Q_{D,i-1}$	transformed (by a single linear storage) surface runoff in the time step $i-1$ [mm]
$\hat{Q}_D$	surface runoff in the time step $i$ within the lowest flow time zone [mm]
$\Delta t$	time step [h]
$k_D$	recession constant for surface runoff single linear storage [h]

At the begin of the next time step, the uppermost flow time zone is empty, whereas in the other flow time zones is already the water coming from the upper flow time zones. If there is newly generated surface runoff, it will be added to the amount which is already contained in the flow time zones.

## 1.10 Discharge routing

WaSiM-ETH does the routing based on a hydraulic calculation of the of the flow velocities. Some channel characteristics are needed for describing the geometry. The approach neglects effects of inertia and diffusion. It is a cinematic wave approach using different flow velocities for different water levels in the

channel. After the translation of the wave a single linear storage is applied to the routed discharge in order to consider the effects of diffusion and retardation. The approach can be seen as a three step process: In the first step the translation is done for all channels, in the second step the storage approach is applied and in the third step the discharges from different subbasins are superposed.

#### *Translation of discharge in the channel*

The flow process in the channel is seen as stationary within a time step (but not between time steps). The flow velocity depends then for a given discharge on the stationary channel properties only (slope, roughness, width, depth a.s.o.). Each Inflow into the channel can be assigned to a specific water level and to a specific translation time for the channel link (if regular turbulent flow is assumed and no nonlinear effects from downstream occur). After the translation time, the inflow flows out of the channel as translated outflow. To avoid an “overtaking” of slower “discharge packets” by faster “discharge packets” as it may be so in the case of a fast rising water level, the channel is subdivided automatically in as much subchannels as needed to make sure that the fastest packet is not earlier at the outlet than the slowest packet which was processed one time step before the fastest packet. The number of subchannels depends on the lengths and the hydraulic properties of the channel as well as on the length of the time step. The spectrum of flow velocities is like all other secondary data, calculated during the model initialization and stored in so called flow time tables, one for each channel. The actual translation times are interpolated using the entries in this table and rounded up to the next integer number interpretable as a multiple of the time step length.

#### *Calculating the flow time table*

The flow times are calculated using the equation after Manning-Strickler:

$$v_l = M \cdot R_h^{2/3} \cdot I^{1/2} \quad (68)$$

with  $v_l$  flow velocity [ $\text{m}\cdot\text{s}^{-1}$ ]  
 $M$  roughness parameter [ $\text{m}^{1/3}\cdot\text{s}^{-1}$ ]  
 $R_h$  hydraulic radius [ $\text{m}$ ]  
 $I$  slope in the direction of the flow [ $\text{m}\cdot\text{m}^{-1}$ ]

The profile of the channel is assumed to be double-rectangular. So the discharge can be mean channel discharge and flood plain discharge. The borders between both components are the vertical extensions of the side walls of the mean channel. For each discharge  $Q = Q_v + Q_h$  the discharge depths  $T_v$  and  $T_h$ , the flow velocities  $v_v$  and  $v_h$  as well as the translation time  $t$  for the actual channel and the relation of flood plain to mean channel flow are calculated. The index  $v$  stands for flood plains, the index  $h$  for the mean channel.

To get a better resolution in time it is possible to subdivide the time step into a specified number of subintervals. Thus it is possible to consider also non-integer multiples of a time step as translation times, because also the discharge is then subdivided into the same number of subintervals.

The flow time table is generated by calculating flow velocities for given discharges. Because not only the flow velocity but also the thereon dependent hydraulic radius is a unknown variable in equation (68), both the flow velocities and the hydraulic radius' have to be calculated by iteration. The initial guess for the flow velocity is  $v_0 = 1 \text{ m}\cdot\text{s}^{-1}$  for each discharge  $Q [\text{m}^3\cdot\text{s}^{-1}]$ , which results in an initial hydraulic  $R_k$  radius after equation (68).

$$R_h = \frac{A_h}{U_h} = \frac{A_h}{B_h + 2 \cdot T_h} = \frac{Q_h / v_h}{B_h + \frac{2 \cdot Q_h}{v_h \cdot B_h}} \quad (69)$$

with  $Q_h/v_h$  channel cross section area  $A_h [\text{m}^2]$   
 $B_h$  width of the main channel [ $\text{m}$ ]  
 $T_h$  flow depth in the main channel [ $\text{m}$ ]  
 $U_h$  effective perimeter of the main channel  $U_h = B_h + 2 \cdot T_h [\text{m}]$

$v_h$  flow velocity in the main channel [ $\text{m}\cdot\text{s}^{-1}$ ]

combined with (68) follows the iterative equation:

$$v_h = M \cdot \left( \frac{Q_h/v_h}{B_h + \frac{2 \cdot Q_h}{v_h \cdot B_h}} \right)^{\frac{2}{3}} \cdot \sqrt{I} \quad (70)$$

with  $M$  Manning-parameter [ $\text{m}^{1/3}\cdot\text{s}$ ]  
 $I$  slope of the channel [ $\text{m}\cdot\text{m}^{-1}$ ]

The iteration is finished if two following iteration steps show no greater difference in the flow velocity than  $0.01 \text{ m}\cdot\text{s}^{-1}$ . The flow depth  $T_h$  is then given by:

$$T_h = \frac{A_h}{B_h} = \frac{Q_h}{v_h \cdot B_h} \quad (71)$$

If there is more discharge than the capacity of the main channel may carry, the discharge is splitted up into main channel and flood plain flow. Then a twofold nested iteration is required – one for the mean channel and the flood plains, respectively, and one for both flows together in order to join their water levels. It should be noted that the hydraulic radius for the mean channel is the width of the main channel plus 2 times the full water depth, whereas the hydraulic radius of the flood plains is only the sum of the flood plains width and the flow depth there. This implies no friction at the border from the viewpoint of the flood plains but full friction from the viewpoint of the main channel. If the water level enters the flood plains and both water levels are calculated, the difference between the water tables in the main channel and in the flood plains must be minimized iteratively. This is done in the way that in each iteration step 50 % of the flow volume difference is shifted to the flow with the lower water table. Like in equation (70) after calculating the flow velocities  $v_v$  and  $v_h$  the flow depths for the floodplains and for the main channel are calculated:

$$T_h = \frac{Q_h}{v_h \cdot B_h} \quad T_v = \frac{Q_v}{v_v \cdot B_v} \quad (72)$$

with  $T_h$  Flow depth in the main channel [m]  
 $T_v$  Flow depth on the flood plains [m]  
 $Q_h$  discharge in the main channel [ $\text{m}^3\cdot\text{s}^{-1}$ ]  
 $Q_v$  discharge on the flood plains [ $\text{m}^3\cdot\text{s}^{-1}$ ]  
 $v_h$  flow velocity in the main channel [ $\text{m}\cdot\text{s}^{-1}$ ]  
 $v_v$  flow velocity on the flood plains [ $\text{m}\cdot\text{s}^{-1}$ ]  
 $B_h$  width of the main channel [m]  
 $B_v$  width of the flood plains (sum of left and right flood plain) [m]

If  $T_h$  and the sum of  $T_v$  and the maximum mean channel depth  $T_m$  differ from each other more than by 1 cm ( $|T_h - (T_v + T_m)| > 0.01 \text{ m}$ ), the discharge  $\Delta Q$  to be shifted to the other flow is calculated by:

$$\begin{aligned} \Delta Q &= -\min(B_h v_h (T_h - (T_v + T_m)), B_v v_v (T_h - (T_v + T_m))) & \text{for } T_h > T_v + T_m \\ \Delta Q &= \min(B_h v_h (T_v + T_m - T_h), B_v v_v (T_v + T_m - T_h)) & \text{for } T_h < T_v + T_m \end{aligned} \quad (73)$$

Thus, the new values for  $Q_h$  and  $Q_v$  are given by:

$$\begin{aligned} Q_{h,i} &= Q_{h,i-1} + \Delta Q \\ Q_{v,i} &= Q_{v,i-1} - \Delta Q \end{aligned} \quad (74)$$

with  $i$  index of the iteration step

After calculating the resulting new flow velocities  $v_v$  and  $v_h$  the new flow depths can be estimated after equation (72). The iteration stops, if the water level on the flood plains and the water level in the main channel differ by not more than 1 cm. The flow velocity for the total flow, which is also the velocity taken for the translation time of the discharge is given by a weighted average of both flow velocities:

$$v_l = v_v \cdot \frac{Q_v}{Q_v + Q_h} + v_h \cdot \frac{Q_h}{Q_v + Q_h} \quad (75)$$

with  $v_l$  effective flow velocity of mean channel flow and flood plain flow [m/s]

#### *doing the translation itself*

The calculated translation times are rounded up to the next integer multiple of a (sub) time step. Then the inflow for that (sub) time step is shifted through the channel. Because of the differences in velocities it is possible to generate overlapped flows or even spaces in-between single discharge packets. Spaces and overlappings are balanced at each other (the overlappings are used to fill the spaces), so the balance is zero at the end of a sufficiently long period.

#### *wave flattening by retention and diffusion*

After doing the translation for a channel, which can also be only a part of a link between two subbasins, the retention is considered. This is done by applying single linear storages to each of the two flow components, the main channel flow and the flood plain flow. Usually, the flood plains will have larger recession constants than the main channel, so it is possible to consider the different retention behavior. The sum of both retention results is the inflow into the next routing channel.

$$Q_{out} = (Q_{v,i-1} \cdot e^{-\Delta t/k_v} + Q_{v,i} \cdot (1 - e^{-\Delta t/k_v})) + (Q_{h,i-1} \cdot e^{-\Delta t/k_h} + Q_{h,i} \cdot (1 - e^{-\Delta t/k_h})) \quad (76)$$

with  $i$  interval number  
 $\Delta t$  time step [h]  
 $k_v$  storage coefficient flood plains [h]  
 $k_h$  storage coefficient main channel [h]  
 $Q_{out}$  outflow of the channel during time step  $i$  [mm]  
 $Q_v$  discharge on flood plains after eqs. (72) to (74) [mm]  
 $Q_h$  discharge in the main channel after eqs. (72) to (74) [mm]

#### *superposing discharges from different subbasins of a larger basin*

Large basins are usually subdivided into hydrological subbasins. There are source basins and in-between basins. A source basin is a subbasin without any inflows from other basins (a so called headwater basin). An in-between basin is a subbasin getting at least one inflow from other source or in-between basins. However, once the routing and superpositioning of discharges for a subbasin is done, its resulting total discharge is seen in the next lower in-between basin as coming from a source basin. After the routing scheme, the runoff from the subbasin (in both in-between and source basins) itself is superposed to the total discharge routed from the tributaries. This total discharge flows into the next in-between basin, where it is handled as inflow from a source basin.

#### *possibilities of parameter calibration*

The hydraulic parameters often can not be measured exactly. Therefore, but also because of the high variance of these parameters along a river, effective parameters have to be found. Like all effective parameters they have to be calibrated. To avoid a propagation of errors down the stream network it is possible to calibrate single routing channels by using observed instead of modeled inflows. This is done simply by replacing the calculated routed discharge by the observed value of a river gauging station and it can be controlled by a single switch in the control file.

### *external inflows, abstractions, and reservoirs*

For each subbasin any number of external or internal inflows and abstractions as well as reservoirs can be defined. External inflows are read from files which in case of modeling also tracer concentrations should contain not only the discharge rates, given in m<sup>3</sup>/s, but also the tracer concentrations, one column per tracer. External abstractions will also be written into files. For each reservoir, a abstraction rule as a relation between reservoir content and allowed outflow must be defined, additionally, in the case of considering tracer concentrations, initial values for all tracer concentrations must be given. The abstraction water is taken from the lowest (last) reservoir in a subbasin, even if there are multiple reservoirs. If there are more than one abstractions, they are handled in the order in which they appear in the control file until there is not enough water to satisfy the abstraction demand or until all abstractions were satisfied. If there is no reservoir, abstractions are taken from the river applying the same rule of order. Also irrigation water is taken from the last reservoir or from the river. Irrigation is ranked before the abstractions.

**Important!** For considering reservoirs the initial content as well as the initial tracer concentrations for all of the at maximum 9 possible tracers have to be specified in the control file, even if no tracer/solute transport is considered. This is true also for the WaSiM-ETH version 1 (TOPMODEL approach)!

### **1.11 Performance criteria $R^2$ and $EV$**

In order to evaluate the performance of the model a series of performance criteria is calculated. For this it is required to incorporate observed runoffs into the modeling process. The outlets of selected modeled subcatchments should match the locations of the flow gauging stations at the rivers. The first performance criteria is the  $R^2$ .

$$R^2 = 1 - \frac{\sum_i \varepsilon_i^2}{\sum_i (x_i - \bar{x})^2} = 1 - \frac{\sum_i (y_i - x_i)^2}{\sum_i x_i^2 - \frac{1}{n} \left( \sum_i x_i \right)^2} \quad (77)$$

with $y_i$	simulated value (e.g. runoff [mm])
$x_i, \bar{x}$	observed value (e.g. runoff [mm]), mean observed value
$\varepsilon_i$	derivation observed - modeled ( $y_i - x_i$ ) at time step $i$
$n$	number of time steps used for calculating $R^2$

In order to be able to recognize impacts of a systematic time shift of the modeled to the observed data the performance criteria are calculated as a series of 21 values shifted by  $\pm 10$  time steps with respect to the central value. The location of the maximum  $R^2$  within this series can be useful to re-calibrate routing parameters.

Because runoff data usually does not fulfill the theoretical requirement of normal distribution the impact of flood peaks is over estimated. If the purpose of the modeling is in simulating low flows or the entire flow spectrum the performance criteria should be taken from normal distributed data sets. Therefore in WaSiM there is the possibility to calculate a performance criteria of the logarithms of the runoff values.

Another performance criteria is the explained variance ( $EV$ ). It is able to eliminate the impact of systematic shifts of the data along the y-axis in the performance criteria (e.g. systematically to large or to small modeled data, even if they are right in time). A comparison between the  $EV$  and the  $R^2$ , which itself does not consider systematic shifts, may show these effects. If the explained variance  $EV$  is larger than the corresponding  $R^2$ , then it is highly probable that there are systematic errors in the modeled data.

$$EV = 1 - \frac{\sum_i (\varepsilon_i - \mu_\varepsilon)^2}{\sum_i (x_i - \bar{x})^2} = 1 - \frac{\sum_i \varepsilon_i^2 - \frac{1}{n} \left( \sum_i \varepsilon_i \right)^2}{\sum_i x_i^2 - \frac{1}{n} \left( \sum_i x_i \right)^2} \quad (78)$$

with  $\varepsilon_i$  derivation of the modeled from the observed value ( $y_i - x_i$ ) like in equ. (77)  
 $\mu_\varepsilon$  mean derivation of the model from the observed values =  $E(\varepsilon_i)$   
 $x_i, \bar{x}$  observed value at time step  $i$  (e.g. runoff [mm]), mean observed value  
 $n$  number of time steps used for  $EV$ -calculation

Like for the  $R^2$  it is also possible for the  $EV$  to use the logarithms of the runoff values. Thus there are in fact 4 types of performance criteria: the  $R^2$  for linear and for logarithmic values and the explained variances  $EV$  for linear and logarithmic values. Each of these criteria is calculated for a time shift of  $\pm 10$  time steps resulting in a total number of  $4 \times 21 = 84$  criteria numbers for each subbasin.

## 1.12 Soil model for the WaSiM-ETH version using the Richards-equation

### 1.12.1 Introduction

The WaSiM-ETH version 2 uses the RICHARDS-equation for modeling the fluxes within the unsaturated soil zone. The modeling is done one-dimensional in the vertical direction using a soil discretised into several layers. The continuity equation for this type of problem is given by:

$$\frac{\partial \Theta}{\partial t} = \frac{\partial q}{\partial z} = \frac{\partial}{\partial z} \left( -k(\Theta) \frac{\partial \Psi(\Theta)}{\partial z} \right) \quad (79)$$

with  $\Theta$  water content [ $\text{m}^3/\text{m}^3$ ]  
 $t$  time [s]  
 $k$  hydraulic conductivity [m/s]  
 $\Psi$  hydraulic head as sum of the suction  $\psi$  and geodetic altitude  $h$  [m]  
 $q$  specific flux [m/s]  
 $z$  vertical coordinate [m]

The discretised RICHARDS-equation is given by:

$$\frac{\Delta \Theta}{\Delta t} = \frac{\Delta q}{\Delta z} = q_{in} - q_{out} \quad (80)$$

with  $q_{in}$  inflow into the actual soil layer [m/s]  
 $q_{out}$  outflow from the actual soil layer (including interflow and artificial drainage) [m/s]

The dependencies of the hydraulic properties on the water content of the soil are considered in a discrete manner. The flux  $q$  between two layers with indices  $u$  (upper) and  $l$  (lower) is then given by:

$$q = k_{eff} \cdot \frac{h_h(\Theta_u) - h_h(\Theta_l)}{0.5 \cdot (d_u + d_l)} \quad \text{with} \quad \frac{1}{k_{eff}} = \frac{d_u}{d_l + d_u} \cdot \frac{1}{k(\Theta_u)} + \frac{d_l}{d_l + d_u} \cdot \frac{1}{k(\Theta_l)} \quad (81)$$

with  $q$  flux between two discrete layers [m/s]  
 $k_{eff}$  effective hydraulic conductivity [m/s]  
 $h_h$  hydraulic head, dependent on the water content and given as sum of suction  $\psi(\Theta)$  after equation (82) and geodetic altitude  $h_{geo}$  [m]  
 $d$  thickness of the layers under consideration [m]

In equation (81), the effective conductivity is an harmonic average of the conductivities of both layers. It is possible to use layers with any thickness for this approach.

### 1.12.2 Parameterization

In WaSiM-ETH it is possible to take into account the hydraulic properties of the soil by using two different methods. The first method uses look-up-tables for the relations between the hydraulic head  $h_h$  and  $\Theta$  and between the hydraulic conductivity  $k$  and  $\Theta$ , respectively. For each soil type, a free number of table entries  $[\Theta, h_h(\Theta)]$  and  $[\Theta, k_{rel}(\Theta)]$  can be given.  $k_{rel}$  is the relative hydraulic conductivity dependent on the saturation of the soil (0..1). The saturated hydraulic conductivity  $k_s$  can be given for each soil layer. The model interpolates between the table entries. The advantage of this method is the possibility to fit the parameters to any type of soil. However, a lot of observation data is required. Therefore, the second method uses common parameters by applying the method after VAN GENUCHTEN (1976):

$$\psi(\Theta) = \frac{1}{\alpha} \left[ \left( \frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} \right)^{-1/m} - 1 \right]^{1/n} \quad (82)$$

and

$$\frac{k(\Theta)}{k_s} = \left[ \frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} \right]^{1/2} \cdot \left[ 1 - \left\{ 1 - \left( \frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} \right)^{1/m} \right\}^m \right]^2 \quad (83)$$

with  $\psi$  suction [m]  
 $\alpha$  empirical parameter [ $\text{m}^{-1}$ ]  
 $n$  empirical parameter [-]  
 $m$  empirical parameter [-] with  $m = 1 - 1/n$   
 $\Theta$  actual water content [-]  
 $\Theta_r$  residual water content at  $k(\Theta) = 0$  [-]  
 $\Theta_s$  saturation water content [-]  
 $k_s$  saturated hydraulic conductivity [m/s]

Using equation (82) the actual water content is given by the actual suction by:

$$\Theta = \Theta_r + (\Theta_s - \Theta_r) \left( \frac{1}{1 + (\psi\alpha)^n} \right)^m \quad (84)$$

Besides the parameters  $n$  and  $\alpha$  a third parameter  $k_{rec}$  has to be specified for each soil type for describing the recession of the saturated conductivity with depth:

$$k_{s,z} = k_s \cdot k_{rec}^z \quad (85)$$

with  $k_{s,z}$  saturated hydraulic conductivity within depth  $z$  [m/s]  
 $k_s$  saturated hydraulic conductivity at the soil surface [m/s]  
 $k_{rec}$  recession constant [-]  
 $z$  depth [m]

### 1.12.3 Numerical solution (vertical fluxes, interflow, infiltration/exfiltration in rivers)

For solving equation (81) a one dimensional vertical finite difference (FD) scheme is applied. After transforming equation (79) into its discrete form as given by equation (80) the fluxes between the discrete soil layers are calculated followed by the calculation of interflow, drainage, and exfiltration into or infiltration from rivers. The upper boundary condition is the infiltration amount  $F$  estimated after GREEN and AMPT (1911) using the extended approach after PESCHKE (1977, 1987). The FD-scheme starts in the lowest layer which was completely saturated by the infiltration or, if no layer was saturated, in the uppermost layer. The lower boundary condition is the depth of the groundwater layer, which is constant for a specific time step but which is variable in time (due to the groundwater flow as well as due to recharge or capillary rise). The extraction of evaporating water is done before the FD-scheme starts (see chapter



1.12.4). The FD-scheme is done in the following steps 1 to 7, where the points 2 to 7 are iteratively repeated until the scheme is stable, which is determined by the change in water content from step to step or until a maximum number of iteration steps is reached (usually not more than 100 ... 1000).

1. *Calculating infiltration* down to layer  $m$ , it's possible to generate interflow at layer boundaries
2. *flux calculation*: It starts from layer  $m-1$ , the last completely saturated layer (or from layer 1, if  $m = 1$ ) down to the groundwater layer. The flux  $q_m$  (flux between layers  $m$  and  $m + 1$ ) is estimated after equation (81). The actual water content of the layers  $m$  and  $m + 1$  are estimated by:

$$\begin{aligned}\Theta_m &= 0.5(\Theta_{m,i-1} + \overline{\Theta_{m,iter}}) \\ \Theta_{m+1} &= 0.5(\Theta_{m+1,i-1} + \overline{\Theta_{m+1,iter}})\end{aligned}\quad (86)$$

with  $\Theta$  water content [-]  
 $m$  index of the layer (in ascending order from top of soil downwards)  
 $i$  time step  
 $\overline{\Theta_{m,iter}}$  accumulated average of the water content from all iteration steps, beginning with iteration step 4

For reasons of convergence and stability, especially if using large time steps, after the 4<sup>th</sup> time step the water content is calculated as an average using the value from the last time step and the accumulated average from all iteration steps in the actual time step (starting with iteration step 4). For the first iteration step,  $\Theta_m$  and  $\Theta_{m+1}$  are taken from the results of the last time step. For iteration steps 2 and 3, the  $\Theta$ -values are estimated as an average from the last time step  $\Theta_{m,i-1}$  and the result from the last iteration step  $\overline{\Theta_{m,i,iter}}$ .

Using these water content values, the hydraulic conductivities  $k$ , the suction values  $\psi$ , and the hydraulic heads  $h_h$  are estimated for upper and lower layer using equations (82) and (83). It holds  $h_{h,m} = \psi_m + h_{geo,m}$  (see equation 82). Because of the discretization in space and time there is a constraint for the relation of the conductivity values of two adjacent layers: Both, the value of  $k(\Theta_m)/k(\Theta_{m+1})$  and  $k(\Theta_{m+1})/k(\Theta_m)$  has to stay below a maximum value in order to avoid an artificial “flow obstacle” which would be there if, for instance, the layer  $m$  is saturated but layer  $m+1$  is still near by or at wilting point:

$$\left. \begin{aligned} k_m &= k(\Theta_m) \\ k_{m+1} &= k(\Theta_{m+1}) \end{aligned} \right\} \text{limited to } \left\{ \begin{aligned} k_m &= \frac{1}{c_k} k(\Theta_{m+1}) \\ k_{m+1} &= \frac{1}{c_k} k(\Theta_m) \end{aligned} \right\} \text{ if } \left\{ \begin{aligned} k_m &< \frac{1}{c_k} k(\Theta_{m+1}) \\ k_{m+1} &< \frac{1}{c_k} k(\Theta_m) \end{aligned} \right. \quad (87)$$

with  $c_k$  empirical parameter, dependent on the vertical discretization and on the time step ( $c_k \approx 50 \dots 100$  at  $1h \leq \Delta t \leq 5d$  and  $\Delta z \approx 0.33$  m)

3. *Calculating interflow*: Interflow is generated if the suction  $\psi_m$  in a layer  $m$  holds:  $\psi_m < 3.45$  m. The calculation is performed in two steps, in a third step the comparison between the results is done:

a) maximum possible interflow  $q_{ifl,max}$  as drainable water content of the actual layer

$$q_{ifl,max} = (\Theta(\psi) - \Theta_{\psi=3.45}) \cdot \frac{\Delta z}{\Delta t} \quad (88)$$

with  $\Theta(\psi)$  water content at actual suction  $\psi$  [-]  
 $\Theta_{\psi=3.45}$  water content at suction  $\psi = 3.45$  m [-]  
 $\Delta z$  layer thickness [m]  
 $\Delta t$  time step [s]

b) Interflow  $q_{ifl}$  as a result of conductivity, river density and hydraulic gradient:

$$q_{ifl} = k_s(\Theta_m) \cdot \Delta z \cdot d_r \cdot \tan \beta \quad (89)$$

with  $k_s$  saturated hydraulic conductivity [m/s]  
 $\Theta_m$  water content in the actual layer  $m$  [-]  
 $d_r$  scaling parameter used to consider river density as well as effects like a  
anisotropy of  $k_{s,horizontal}$  compared to  $k_{s,vertical}$  [m<sup>-1</sup>]  
 $\beta$  local slope angle (**important:** if  $\beta > 45^\circ$ ,  $\beta$  is limited to  $45^\circ$ )

c) The result is the smaller value of steps a) and b).

#### 4. Infiltration from rivers and exfiltration from groundwater into rivers:

If a grid cell is marked as a river cell (which is done by having valid entries in the river width grid, the river depth grid, and the leakage factor grid), exfiltration into the river bed can be calculated. Infiltration from rivers into groundwater can be calculated only if there is in addition an entry in a so called link grid, a grid containing the ID-number of the tributary which is sending it's water downstream to the actual cell. Thus, infiltration into groundwater is possible only at grid cells which are occupied by real routing channels, whereas exfiltration is possible at each grid cell which is marked as river. This scheme is based on the assumption that in smaller headwater subbasins usually the gradient of flow is directed from the groundwater to the rivers. Only in large stream valleys (which are usually routing channels) this gradient can be reversed if there are large amounts of external inflows from the upper areas.

The estimation of river width and river depth as well as the marking of routing channels is done in the preprocessing using the program TANALYS. It is also possible to use observed values by generating grids from any GIS-Coverage or from other bases.

The equations for estimating exfiltration and infiltration are relatively simple:

*Exfiltration* (which is the base flow), calculation has two steps:

a) calculation of exfiltration using the hydraulic gradient and the colmation (in- and exfiltration resistance) at the river bed:

$$q_{exf,pot} = l_k \cdot \Delta H \cdot b_{rb} / cs \quad (90)$$

with  $q_{exf,pot}$  maximum possible exfiltration (base flow) [m/s]  
 $l_k$  Leakage-factor (colmation resistance) [s<sup>-1</sup>]  
 $\Delta H$  positive difference between groundwater table and river bed  
 $\Delta H = h_{GW} - h_{rb}$  ( $h_{GW}$ : groundwater table [m a.s.l.],  $h_{rb}$ : river bed [m a.s.l.])  
 $b_{rb}$  width of the river bed [m]  
 $cs$  grid cell size [m]

b) partitioning of  $q_{exf,pot}$  to all affected soil layers: From each layer water can be extracted only until the pre-defined suction of 3.45 m is reached:

$$q_{exf,m} = (\Theta_m - \Theta_{\psi=3,45m}) \cdot \Delta z_e / \Delta t \quad \text{for } \text{int}((h_{geo,0} - h_{GW}) / \Delta z) \leq m \leq \text{int}((h_{geo,0} - h_{rb}) / \Delta z) \quad (91)$$

with  $q_{exf,m}$  maximum possible exfiltration from layer  $m$  [m/s]  
 $m$  layer index, starting from the uppermost layer with contact to the groundwater down to the layer the river bed is within [-]  
 $\Theta_m$  water content in layer  $m$  (usually saturation) [-]  
 $\Theta_{\psi=3,45m}$  water content at suction  $\psi = 3.45$  m [-]  
 $h_{geo,0}$  surface altitude [m a.s.l.]  
 $h_{GW}$  groundwater head [m a.s.l.]  
 $h_{rb}$  altitude of the river bed [m a.s.l.]  
 $\Delta z$  layer thickness [m]  
 $\Delta z_e$  effective layer thickness: If the layer is positioned completely between groundwater surface and river bed, then  $\Delta z_e = \Delta z$  (overall layer thickness); if the groundwa-

ter table is positioned within layer  $m$ , then  $\Delta z_e = h_{GW} - h_{geo,m}$ ; if the river bed is positioned within layer  $m$ , then  $\Delta z_e = h_{geo,m-1} - h_{rb}$ ; if both, the groundwater table and the river bed are positioned within layer  $m$ , then  $\Delta z_e = h_{GW} - h_{rb} = \Delta H$

If for the uppermost layer  $m$  the amount  $q_{exf,m}$  is smaller than  $q_{exf,pot}$ , the remaining amount is taken from the next layer (or at least that part which can be taken from the next layer) and so on - as long as this next layers location is at least fractionally above the river bed. On the other side, if  $q_{exf,pot}$  is smaller than  $q_{exf,m}$ , the amount taken from layer  $m$  is limited to  $q_{exf,pot}$ . The amounts taken from each layer are subsumed:

$$q_{exf} = \sum_m q_{exf,m} \quad (92)$$

with  $q_{exf}$  amount of exfiltrated water

*Infiltration:* Like the estimation of exfiltration also the estimation of infiltration is done using equation (90). There are also two steps:

a) potential infiltration as given by the hydraulic gradient and by the transition resistance (colmation):

$$q_{inf,pot} = l_k \cdot \Delta H \cdot b_{rb} / cs \quad (93)$$

with  $q_{inf,pot}$  maximum possible infiltration as given by the gradient [m/s]  
 $l_k$  leakage-factor (transition resistance or colmation resistance) [s<sup>-1</sup>]  
 $\Delta H$  positive difference between river bed altitude and groundwater table  
 $\Delta H = h_{rb} - h_{GW}$ ; if the groundwater table is below the river bed it holds:  
 $\Delta H = h_{rb} - hh_n$ , whereas  $hh_n$  is the hydraulic head of the layer the river bed is positioned within  
 $b_{rb}$  width of the river bed [m]  
 $cs$  grid cells size [m]

b) In analogy to equation (91), the potential infiltration is filled into the soil layers starting with the layer the river bed is located in down to the groundwater table. The fillable porosity is the difference between the saturation water content and the actual water content as valid in the actual iteration step. Darcy's law is not necessarily considered, this means that there may be more infiltration than the hydraulic conductivity would allow. To limit the infiltration amount, the leakage factor should be reduced.

$$q_{inf,m} = (\Theta_{sat} - \overline{\Theta_{m,iter}}) \Delta z / \Delta t \quad (94)$$

with  $q_{inf,m}$  maximum infiltration into the layer  $m$  as given by the fillable porosity [m/s]  
 $\overline{\Theta_{m,iter}}$  actual water content in the layer  $m$  as taken from the actual iteration step  $iter$  [-]

Like for exfiltration, also for infiltration a subsummation is done during the filling of the layers:

$$q_{inf} = \sum_m q_{inf,m} \quad (95)$$

with  $q_{inf}$  infiltration amount which is already filled into empty layers [m/s]

If after the filling of all layers below the river bed this sum  $q_{inf}$  is still less than the potential infiltration  $q_{inf,pot}$ , then the layers in-between the river bed and the water table in the river are filled starting from the river bed up to the water table. If afterwards the potential infiltration is still not completely filled into the soil, the real infiltration  $q_{inf}$  is limited to the actual accumulated value  $\Sigma q_{inf,m}$ . The total infiltration amount (in units of m<sup>3</sup>) is stored in a table with entries for each routing channel. This table contains also the discharge within each routing channel as calculated by the routing-module (results from the previous time step). After calculating the infiltration the infiltration amount for the actual cell is subtracted from the discharge amount of the matching channel in the discharge table. If the infiltration after equations (93) to (95) is larger than the available amount of water in the channel, the infiltration is limited to that available amount in the channel. The channel is drying out.

5. *gradient restrictions*: Because of the discretization in time and space (in WaSiM the time step is constant and usually equal or greater than one hour) some restrictions for the fluxes must be applied. For instance if there is a very large flux from layer  $m$  into layer  $m+1$  over a long time step which leads to a considerable decreasing water content in layer  $m$  and to a increasing water content in layer  $m+1$ , the hydraulic gradient may switch from downwards to upwards within this time step. In order to keep the numbers of iteration steps low, for each calculated flux the resulting water contents are checked and adjusted if required. The first step is a check for oversaturation (later in point 6 further flux restrictions are applied). The balance of inflows and outflows with the water content of the actual layer  $m$  in the time step  $i$  is:

$$\Theta_{m,i+1} = \Theta_{m,i} + (q_{m,i} - q_{ifl,i} - q_{m-1,i} - q_{exf,m} + q_{inf,m}) \frac{\Delta t}{d_m} \quad (96)$$

with  $\Theta_{m,i}$   $\Theta_{m,i+1}$  Water content before and after the actualization with the calculated fluxes  
 $q_{m,i}$  flux between layers  $m$  and  $m+1$  (outflow has a negative sign) [m/s]  
 $q_{ifl,i}$  interflow from layer  $m$  [m/s]  
 $q_{m-1,i}$  flux between layers  $m-1$  and  $m$  (inflow has a negative sign) [m/s]  
 $q_{exf,m}$  exfiltration from the ground water, calculated after equation (90)/(91) [m/s]  
 $q_{inf,m}$  infiltration into the groundwater, calculated after equation (92)/(93) [m/s]  
 $\Delta t$  time step [s]  
 $d_m$  thickness of layer  $m$  [m]

If the balance is greater than the saturation water content, the flow from layer  $m+1$  into layer  $m$  is reduced. The inflow from above (from layer  $m-1$ ) is automatically reduced afterwards when the flux restrictions are applied to the layers above (the flux restriction is done from the lower to the upper layers of the soil column).

Also for layer  $m+1$  a balance is calculated after equation (96) with the resulting water content  $\Theta_{m+1,i+1}$ . Using both water content values, the corresponding hydraulic heads  $hh_{m,i+1}$  and  $hh_{m+1,i+1}$  are calculated:

$$\begin{aligned} hh_{m,i+1} &= 0.5(h_{geo,m-1} + h_{geo,m}) + \psi(\Theta_{m,i+1}) \\ hh_{m+1,i+1} &= 0.5(h_{geo,m} + h_{geo,m+1}) + \psi(\Theta_{m+1,i+1}) \end{aligned} \quad (97)$$

with  $hh$  hydraulic head [m]  
 $h_{geo}$  altitude of the lower boundary of the layer [m a.s.l.]  
 $\psi$  suction [m]  
 $i$  index for time  
 $m$  index for layers

A gradient restriction is applied if equation (98) holds:

$$\begin{aligned} (hh_{m,i} > hh_{m+1,i}) \cap (hh_{m,i+1} < hh_{m+1,i+1}) \cup \\ (hh_{m,i} < hh_{m+1,i}) \cap (hh_{m,i+1} > hh_{m+1,i+1}) \end{aligned} \quad (98)$$

In such cases the time  $t_s$  at which the gradient becomes 0 is estimated. To do so, the balances after equation (96) are calculated for the middle of the time step using  $\Delta t_{neu} = \frac{1}{2} \Delta t$  as  $\Delta t$ . The new water content values are then  $\Theta_{m,i+\frac{1}{2}}$  and  $\Theta_{m+1,i+\frac{1}{2}}$ . After equation (97) the new hydraulic heads are  $hh_{m,i+\frac{1}{2}}$  and  $hh_{m+1,i+\frac{1}{2}}$ . These heads are compared to the heads from the beginning of the time step. If the gradients are still reversed, the time step is divided again into two halves. If the gradient is not reversed but larger than a certain threshold (of e.g. 0.001m), the time step is enlarged by 50 % of the previously cut time slice. Again, the iterative search for the time of gradient reversal is continued. If this time  $t_s$  is found, the fraction of this time on the time step duration is the reduction factor for the calculated fluxes:

$$q_{m,red} = \frac{t_s}{\Delta t} \cdot q_m \quad (99)$$

with  $q_{m,red}$  reduced flux between 2 layers, in order to avoid gradient reversals [m/s]  
 $t_s$  time from the beginning of the time step until the gradient is zero [s]

6. *flux restrictions*: The gradient restriction is applied each time only for two adjacent layers, even if the fluxes out of or into the next layers are considered for the balances, they still can be changed due to the following gradient restriction of the next layer. Therefore the gradient restriction is done a few times in an iterative scheme. In addition after this scheme it is checked if there are cases of “oversaturation” or “undersaturation” (drying,  $\Theta < \Theta_w$ ). Because of the downwards decreasing dynamic of the fluxes in the unsaturated zone the smallest corrections should be at the lower boundary. Also fluxes are usually restricted only from upper to lower layers, what may lead to water logging in the upper layers. Thus it is recommended to perform the flux restriction starting from the lowest unsaturated layer up to the soil surface. There are two possible cases:

6.1  $\Theta_{m,i+1} > \Theta_s$  (balance after equation (96): over saturation, reducing inflows)

a)  $q_m$  and  $q_{m+1}$  are flowing downwards (vertical throughflow); reducing  $q_{m-1}$  and  $q_{inf}$

$$q_{m-1,red} = q_{m-1} + (\Theta_{m,i+1} - \Theta_s) \cdot \Delta z / \Delta t \quad (100a)$$

with  $q_{m-1,red}$  reduced vertical inflow from the upper layer  
 $q_{m-1}$  original value of the inflow from the upper layer  
 $\Delta z$  layer thickness [m]  
 $\Delta t$  time step [s]  
 $q_{inf,m}$  infiltration after equation (94)  
 $\Theta_s$  saturation water content [-]  
 $\Theta_{m,i+1}$  water content as balance after equation (96) from the unrestricted fluxes [-]

If the reduction after (100a) should lead to a inverse sign of  $q_{m-1,red}$  compared to  $q_{m-1}$ , the reduction was to large. The reduction is then splitted into a fraction which reduces  $q_{m-1}$  down to zero and another fraction which is applied to the second possible inflow, to the infiltration from surface water:

$$q_{ifl,m,red} = q_{ifl,m} - q_{m-1,red} \quad \text{and} \quad q_{m-1,red} = 0 \quad (100b)$$

with  $q_{inf,m,red}$  reduced infiltration from a surface water (river) [m/s]  
 $q_{inf,m}$  infiltration after equation (94)

b) inflows from below and from above ( $q_m: \uparrow$ ,  $q_{m-1}: \downarrow$ , additional inflow possible by  $q_{inf,m}$ )

In a first step the inflow from above is reduced after equation (100a):

$$q_{m-1,red} = q_{m-1} + (\Theta_{m,i+1} - \Theta_s) \cdot \Delta z / \Delta t \quad (\text{identical with 100a})$$

If the sign of the inflow from above should be inverted by the reducing, the reduction itself is reduced in a way that the inflow from above is reduced to zero. The inflow from below is reduced by (note that the reduction of the inflow from above is corrected after the reduction of the inflow from below! The sign of  $q_{m-1,red}$  is now positive after the over-reduction!):

$$q_{m,red} = q_m - q_{m-1,red} \quad \text{and} \quad q_{m-1,red} = 0 \quad (100c)$$

If this reduction of the inflow from below also leads to a switch of the sign of the flux  $q_{m,red}$  compared to  $q_m$ , the reduction is again reduced in a way that the flux from below is set to zero. The remaining amount of reduction is then applied to the infiltration from surface water. Note that in equation (100d) the correction term is negative, because during the previous reduction of  $q_m$  to  $q_{m,red}$  the sign of the flux from below has changed from + to -.

$$q_{ifl,m,red} = q_{ifl,m} + q_{m,red} \quad \text{and} \quad q_{m,red} = 0 \quad (100d)$$

- c) only inflow from below and from infiltration, other fluxes are outflows or zero ( $q_m \uparrow$ ,  $q_{m-1} \uparrow$ ,  $q_{inf,m} \geq 0$ ). In a first step the inflow from below is reduced:

$$q_{m,red} = q_m - (\Theta_{m,i+1} - \Theta_s) \cdot \Delta z / \Delta t \quad (100e)$$

Again, if the sign of the flux  $q_m$  is changed, the reduction itself has to be reduced and the remaining reduction has to be applied to the infiltration from surface water:

$$q_{ifl,m,red} = q_{ifl,m} + q_{m,red} \quad \text{und} \quad q_{m,red} = 0 \quad (\text{identical with 100d})$$

- c) only inflow from infiltration from rivers, all other fluxes are outflows ( $q_m \downarrow$ ,  $q_{m-1} \uparrow$ ,  $q_{inf,m} \geq 0$ )  
Only the infiltration from rivers is reduced:

$$q_{ifl,m,red} = q_{ifl,m} - (\Theta_{m,i+1} - \Theta_s) \cdot \Delta z / \Delta t \quad (100f)$$

6.2  $\Theta_{m,i+1} < \Theta_r$  (reducing only outflows, this may happen especially if the time step is very long and there is a considerable amount of interflow or exfiltration into rivers)

- a)  $q_m$  and  $q_{m+1}$  are flowing downwards (vertical throughflow),  $q_{ifl} > 0$  or  $q_{exf,m} > 0$

In a first step the outflow downwards is reduced:

$$q_{m,red} = q_m + (\Theta_r - \Theta_{m,i+1}) \cdot \Delta z / \Delta t \quad (101a)$$

with  $q_{m,red}$  reduced outflow from layer  $m$  to layer  $m+1$  [m/s]  
 $q_m$  unreduced outflow from layer  $m$  to layer  $m+1$  [m/s]  
 $\Theta_r$  residual water content [-]  
 other variables like in equation (100)

If the sign of  $q_m$  is inverted by this reduction (if it will become positive:  $q_m > 0$ ), the reduction itself is reduced. The remaining fraction of the reduction is then applied to the other possible outflows interflow and exfiltration (if they are positive; only one of these components can be there because interflow is generated from layers above the groundwater only and exfiltration is generated from layers within the groundwater only):

$$\begin{aligned} q_{exf,m,red} &= q_{exf,m} - q_{m,red} & \text{and} & \quad q_{m,red} = 0 & \quad (\text{if } q_{exf,m} > 0) \\ q_{ifl,m,red} &= q_{ifl,m} - q_{m,red} & \text{and} & \quad q_{m,red} = 0 & \quad (\text{if } q_{ifl,m} > 0) \end{aligned} \quad (101b)$$

with  $q_{exf,m,red}$  reduced exfiltration from layer  $m$  [m/s]  
 $q_{exf,m}$  original exfiltration after equations (90) to (92) [m/s]  
 $q_{ifl,m,red}$  reduced interflow from layer  $m$  [m/s]  
 $q_{ifl,m}$  original interflow after equation (88) and (89) [m/s]

- b) all Fluxes are outflows ( $q_m: \downarrow$ ,  $q_{m-1}: \uparrow$ ,  $q_{ifl} > 0$  or  $q_{exf,m} > 0$ )  
in addition to  $q_m$  and  $q_{exf,m}$  and  $q_{ifl}$ ,  $q_{m-1}$  is reduced analog equation (101a).
- c) inflow from above and below but also outflow by  $q_{ifl}$  or  $q_{exf,m}$  ( $q_m: \uparrow$ ,  $q_{m-1}: \downarrow$ ,  $q_{ifl} > 0$ )  
only reduction of  $q_{ifl}$  or  $q_{exf,m}$  after equation (101a), replacing there  $q_m$  by  $q_{ifl}$  resp.  $q_{exf}$ .
- d) all fluxes are directed upwards and there is interflow ( $q_m: \uparrow$ ,  $q_{m-1}: \uparrow$ ,  $q_{ifl} > 0$ ; this is rather improbable). In this case all outflows are reduced ( $q_{m-1}$ ,  $q_{ifl}$  or  $q_{exf,m}$ ) in analogy to equation (101), the signs has to be changed according to the direction of flow.

## 7. getting the iteration error and comparison with the break criterion:

After calculating the fluxes the new water content values are calculated for all layers according to equation (85). The maximum change of the water content of two successive iteration steps is compared with the allowed maximum error. If the change in water content is below this threshold for all layers, the scheme is assumed to be stable:

$$\varepsilon_{\max} = \max(\Theta_{m,iter} - \overline{\Theta_{m,iter-1}}) \text{ (for all } m) \quad (102)$$

with  $\varepsilon_{\max}$  maximum change of water content values for all layers between two iteration steps  
 $\Theta_{m,iter}$  water content after iteration step  $iter$  in the layer  $m$   
 $\overline{\Theta_{m,iter-1}}$  accumulated average value of all water content values of the previous iteration steps within the actual time step. If  $iter < 4$  then:  $\overline{\Theta_{m,iter-1}} = \Theta_{m,iter-1}$ , what means that the calculation is done not with the accumulated average but with the real result from the last iteration step. In the first iteration step is  $\overline{\Theta_{m,iter-1}} = \Theta_{m,i-1}$ , the result from the last time step  $i-1$

The iteration is broken if:

$$\begin{aligned} a) \quad & \varepsilon_{\max} < \varepsilon_{zul} \\ b) \quad & iter \geq iter_{zul} \end{aligned} \quad (103)$$

with  $\varepsilon_{zul}$  maximum allowed error:  $\varepsilon_{zul} = 10^{-4}$  for  $iter = 1 \dots 10$ ,  $\varepsilon_{zul} = 5 \cdot 10^{-4}$ , for  $iter > 10$   
 $iter_{zul}$  maximum allowed number of iteration steps (WaSiM-internal: 300)

To avoid too much iteration cycles, the maximum allowed error is increased from  $\varepsilon_{\max} = 0.01 \text{ \%Vol.}$  to  $\varepsilon_{\max} = 0.05 \text{ \%Vol.}$  if the number of iteration steps  $iter$  is greater than 10. Usually this case occurs only for large time steps ( $\Delta t > 1d$ ) when the FD-scheme tends to extreme states because of the strong nonlinearities in the  $k$ - $\Theta$ - and  $\psi$ - $\Theta$ -relations. These nonlinearities in conjunction with long time steps are also the reasons for using the accumulated averages for the soil water content values starting from the 4<sup>th</sup> iteration step instead of the iteration results itself to calculate the new  $k$  and  $\psi$  values.

#### 1.12.4 Withdrawal of evaporating water

The extraction of water from the different soil layers is done separately for soil evaporation and for transpiration before calculating the soil water fluxes. The first extraction step is the extraction of transpiration water which in each layer may be decreased according to the soil moisture. The second step is the extraction of soil evaporation from bare soil. Also the evaporation may be reduced according to the moisture of the uppermost soil level. If the transpiration was reduced according to the soil moisture it is still possible to extract this remaining water (at least fractionally) from the uppermost layer by evaporation until the potential evaporation is satisfied.

*1. calculating extraction by transpiration:*

For each kind of vegetation there is a parameter for the root density distribution with depth. Another set of parameters describes the annual course of the root depth. The root density distribution can be described after GURTZ (1988) by:

$$d_r(z) = d_{norm} \left( 1 - \frac{z}{z_w} \right) \cdot \left( 1 + \frac{z}{z_w} \cdot \rho \right) \quad (104)$$

with  $d_r$  root density at depth  $z$   
 $z$  depth below soil surface [m]  
 $z_w$  maximum root depth (annual course specific for each crop type)  
 $\rho$  parameter of the root density distribution ( $\rho > -1$ )  
for  $-1 < \rho < 0$  concave shape with extraction mainly from the upper layers  
for  $\rho = 0$  linear decrease of extraction with depth  
for  $\rho > 0$  convex shape, extraction more from the lower layers  
 $d_{norm}$  scaling factor to scale the sums of the discrete extraction densities to 1.0

At first, the extraction density  $d_{r,m}$  are calculated for the centers of all layers 1.. $m$  which are entirely within the root zone. If in the lowest root zone layer the roots does not reach the lower boundary of the layer, the center between the upper boundary  $h_{geo,m-1}$  (expressed in meters below surface) and the maximum root depth  $z_w$  is taken for calculating the extraction density of this layer.

The second step is a check for possibly required reductions of evapotranspiration according to soil moisture. This is done starting at the top layer for each layer down to the lowest root zone layer. If a extraction from one layer is reduced, it is possible to compensate this reduction by increasing the extraction density of the next lower layer up to a certain limit:

$$\hat{d}_{r,m+1} = d_{r,m+1} + (1-x) \cdot d_{r,m} \quad (\text{for } (1-x) \cdot d_{r,m} \leq \lambda \cdot d_{r,m+1}) \quad (105)$$

with  $\hat{d}_{r,m+1}$  increased extraction density for layer  $m+1$  (increased by the reduction amount of the upper layer  $m$ )  
 $d_{r,m+1}$  original extraction density for layer  $m+1$  after eq. (103)  
 $d_{r,m}$  extraction density for layer  $m$  (possibly also increased by reductions from upper layers)  
 $\lambda$  maximum allowed factor for increasing the extraction density of layer  $m+1$  in WaSiM set to 2.0 (this factor is ought to consider a balance between plant flexibility and limits of flexibility due to the given distribution of roots)  
 $x$  reduction factor of the extraction density of layer  $m$  (0..1, 0 means no transpiration is taken from layer  $m$ , 1 means that no reduction at all is applied)

If the reduced amount of the extraction density (in terms of density!) in layer  $m$  is greater than  $\lambda$  times the extraction density of layer  $m+1$ , the extraction density of layer  $m+1$  is increased only by the maximum factor  $\lambda$ . The remaining amount of the reduction is then stored in a variable  $E_{z,m}$  in terms of evaporation in mm and can be taken from the top soil layer by bare soil evaporation (if the total transpiration was less than the potential evaporation):

$$E_{z,m} = ((1-x) \cdot d_{r,m} - (1+\lambda) \cdot d_{r,m+1}) \cdot ETP \cdot v \quad (\text{only for } (1-x) \cdot d_{r,m} > \lambda \cdot d_{r,m+1}) \quad (106)$$

with  $E_{z,m}$  additional available evaporation energy (because saved in layer  $m$ ) for evaporation from the top soil [mm]  
 $v$  vegetation coverage degree, crop specific annual course [-]  
 $ETP$  potential evaporation [mm]

The extraction amounts for each soil layer are then calculated using the now corrected extraction densities, the vegetation coverage degree and the potential evaporation:

$$T_m = \hat{d}_{r,m} \cdot ETP \cdot v \quad (107)$$

with  $T_m$  Transpiration from layer  $m$  [mm or m/s]  
 $\hat{d}_{r,m}$  corrected extraction density after equations (43), (103) and (104)  
 $ETP$  potential evaporation [mm or m/s]  
 $v$  vegetation coverage degree [-]

## 2. evaporation from the top soil layer

Evaporation is only possible from the top soil (down to 0.1 m) and from the fraction of the area which is not covered by vegetation. If the extractions from the soil were effectively reduced, the saved amount of energy  $E_z$  is still available to allow evaporation from the bare soil area. Like the transpiration, also the evaporation may be reduced according to the moisture  $\Theta_1$  within the top soil layer, but following another scheme:

$$E = [(1-v) \cdot ETP + v \cdot E_z] \cdot \left[ 1 - \left( \frac{\Theta_s - \Theta_1}{\Theta_1} \right)^2 \right] \quad (108)$$

with  $E$  evaporation from the top soil layer [mm]



$ETP$	potential evaporation (after reduction by the interception evaporation)
$v$	vegetation coverage degree, crop specific annual course [-]
$E_z$	sum of the uncompensated reductions after equation (105)
$\Theta_{s,1}$	saturation water content of the top soil layer [-]
$\Theta_1$	actual water content of the top soil layer [-]

### 3. updating the soil water content

After extracting the evaporation and transpiration water from the soil layers 1.. $m$ , the water content is updated for all these layers:

$$\begin{aligned}\Theta_{m,i+1} &= \Theta_{m,i} + T_{m,i} \cdot d_m \cdot \Delta t^{-1} & \text{for } m > 1 \\ \Theta_{1,i+1} &= \Theta_{1,i} + (T_{1,i} + E_{1,i}) \cdot d_m \cdot \Delta t^{-1} & \text{for } m = 1\end{aligned}\quad (109)$$

#### 1.12.5 Considering irrigation

Within WaSiM-ETH irrigation can be controlled by two different ways – by an irrigation schedule which contains the irrigation amount for each irrigation day as crop specific values or by a process controlled by the model itself using soil moisture data and crop specific threshold values. For both methods the model needs information about the irrigated areas which is given by a irrigation grid. This grid contains for each irrigated crop type a specific code allowing in this way a localization of irrigated areas. The control file contains a irrigation table which contains for each grid code from the irrigation grid a corresponding irrigation description containing information about

- whether the irrigation is controlled by a schedule or by internal model states (soil moisture),
- whether the irrigation water is taken from the groundwater (from the same cell where irrigation is applied) or from surface water (from the same subbasin the irrigated cell is located in); the water balance is done in every case for groundwater and surface water, respectively
- if irrigation is controlled by a schedule: when is what crop type irrigated with how much water
- or, if irrigation is controlled by soil moisture: what is the threshold suction  $\psi_{dry}$  of each irrigated crop type for starting irrigation and what for stopping irrigation ( $\psi_{wet}$ )

If the irrigation is controlled by soil moisture, the threshold suctions  $\psi_{dry}$  and  $\psi_{wet}$  are converted into corresponding water content values  $\Theta_{dry}$  and  $\Theta_{wet}$  which vary dependent on the soil type the crop is growing on. If the model enters the irrigation module, it compares the mean soil water content within the entire root zone with the lower threshold value  $\Theta_{dry}$ . If this threshold is reached the irrigation amount  $I$  is calculated by:

$$I = (\Theta_{wet} - \Theta_{dry}) \cdot z_w \cdot 1000 \quad (110)$$

with  $I$  irrigation amount [mm]  
 $\Theta_{wet}$  upper threshold for soil water content during irrigation [-]  
 $\Theta_{dry}$  lower soil water content for triggering the irrigation (lower threshold) [-]  
 $z_w$  root depth [m]

The irrigation amount  $I$  is splitted into 24 fraction for the next 24 hourly time steps (if using a time step of one hour) to avoid to high irrigation intensities which could lead to surface runoff. The leakage fraction can not be specified exactly in the control file. To control the leakage fraction, the upper moisture threshold  $\Theta_{wet}$  can be changed using the parameter  $\psi_{wet}$  in the control file. If  $\psi_{wet}$  is greater than the suction at field capacity (around 0.3 ... 0.5 m) there will be no leakage but small values for  $\psi_{wet}$  of e.g. 0.1 to 0.2 m will lead to more or less fast drainage (leakage).

The irrigation water is taken from groundwater or from surface water and is added to the precipitation. The tracer concentrations are mixed with the input concentrations from precipitation.

### 1.12.6 Considering artificial drainage

The effects of artificial drainage's is calculated separately and afterwards added to the interflow. The parameterization is done using two grids – a grid containing the depth  $z_d$  of the drainage tiles or hoses and another grid containing the horizontal spaces  $d_h$  between the drainage devices. If the drainage depth in the depth-grid is zero or the cell has nodata then no drainage is assumed there. The drainage water is added to the interflow of the same layer where the drainage system is located in:

$$q_{\text{drain}} = k(\Theta) \cdot \frac{2d_m}{d_h} \cdot \frac{cs}{d_h} \quad (111)$$

with $q_{\text{drain}}$	drainage from layer $m$ , if drainage tiles or hoses are located in this layer [m/s]
$k(\Theta)$	hydraulic conductivity as a function water content and soil type (83)
$d_m$	layer thickness of the drainage layer $m$ (discretization in $z$ -direction) [m]
$d_h$	horizontal spacing of the drainage tiles [m]
$cs$	grid cell size [m]

The term  $2d_m/d_h$  is the hydraulic gradient within the layer  $m$  which is directed to the drainage system. The term  $cs/d_h$  considers the drainage density in this cell thus making the algorithm scale independent. The drainage is added to the interflow of the same layer and thus included in the flux and gradient restrictions after chapter 1.12.3. (especially the check after equations (88) and (89) must be done in order to get not too much drainage). Because the calculation of drainage is included in the iteration of the unsaturated zone, the drainage can affect also the downward fluxes from the layers above.

### 1.12.7 Considering clay horizons

Clay horizons or horizons with a significant lower conductivity may be generated by a combination of climate, humane impact (cropping technologies), or by the soil genesis. However, in WaSiM-ETH there is a possibility to consider a so called clay-grid which contains for each grid cell the depth of the upper limit of a clay layer. If this depth is zero or if the value is nodata no clay layer is assumed for this cell. If WaSiM-ETH can find this grid during initialization *and* if a flag in the control file is set to 1, then the hydraulic conductivity of that discretization layer which is containing the clay layer is replaced by a constant value given in the control file. This is only an extension of the parameterization of the soil in the control file and does not tangent the finite difference scheme for calculating the unsaturated flow.

### 1.12.8 Considering ponding water

Water ponding, e.g. at rice fields, can be considered by defining a pond depth grid which contains for each grid cell the maximum storage capacity of the pond in mm. If the capacity is zero or if the value is nodata, no ponding is assumed. If there is water in a pond, its amount is added to the precipitation, the tracer concentrations are mixed respectively added (in case of salt masses). Evaporation is taken from ponding water before starting the scheme of unsaturated zone flows, so there will be no transpiration and thus no change in the soil water content if there is enough water in the pond. This avoids numerical problems but another problems may: a enrichment of salt in the pond because there is no flow of water and salt into the soil (e.g. if the soil is unleaky because of a clay layer).

### 1.12.9 Groundwater table elevation

The groundwater table is modeled in both the unsaturated zone module and the groundwater model. The coupling between both modules is done by a net boundary flux between the unsaturated zone and the groundwater. If the groundwater model calculates a change of the groundwater tables for a cell, the rate of change is converted into a vertical flux, positive for a falling groundwater table, negative for a rising groundwater table. This boundary flux and the amounts of infiltration, exfiltration, precipitation and fluxes between the unsaturated layers are considered to estimate the groundwater table. Assuming that the modeled soil column reaches down to the groundwater the groundwater table is located in the lowest partly saturated layer. Its “exact” location is interpolated. Using equation (84) it is possible to calculate

the water content a layer must have if being in a hydrostatic equilibrium with the groundwater at the lower layer boundary.

$$\Theta_{GW,min} = \Theta_r + (\Theta_s - \Theta_r) \left( \frac{1}{1 + (0.5 \cdot d_m \alpha)^n} \right)^m \quad (112)$$

with  $\Theta_{GW,min}$  water content for hydrostatic equilibrium with the groundwater table (referring to the center of the layer)  
 $\Theta_s$  saturation water content of layer  $m$  [-]  
 $\Theta_r$  residual water content of layer  $m$  [-]  
 $\alpha, m, n$  Van Genuchten - parameter  
 $d_m$  layer thickness of layer  $m$  [m]

The actual groundwater table is then interpolated after each time step:

$$h_{GW} = h_{geo,m} + d_m (\Theta_{m,i} - \Theta_{GW,min}) (\Theta_s - \Theta_{GW,min}) \quad (113)$$

with  $h_{GW}$  groundwater level [m a.s.l.]  
 $h_{geo,m}$  geodetic altitude of the lower limit of the lowest partly saturated layer [m]  
 $d_m$  thickness of layer  $m$  [m]  
 $\Theta_{m,i}$  actual water content of layer  $m$  at time step  $i$   
 $\Theta_s$  saturation water content [-]

This equation (113) is valid only if the groundwater table is moving within a single layer. If the groundwater table moves to another layer there must be differentiated between two possibilities:

*1. dropping down to the next lower layer:* The equilibrium water content  $\Theta_{GW,min}$  must be newly calculated for this next layer

*2. entering the upper layer:* As long as the groundwater table rises, the last water content  $\Theta_{m-1}$  of the layer  $m-1$  is stored as  $\hat{\Theta}_{GW,min}$  and used for the interpolation of the groundwater table. Only if the groundwater table is falling again *and* at the same time  $\hat{\Theta}_{GW,min}$  is greater than  $\Theta_{GW,min}$  (calculated after equation (112)), the value of  $\hat{\Theta}_{GW,min}$  has to be adopted to  $\Theta_{GW,min}$ . This is done by adding the balance of inflows and outflows to the actual value of  $\hat{\Theta}_{GW,min}$ :

$$\begin{aligned} \Delta\Theta_{m,i} &= q_{m-1} + Q_B + Q_{ifl} + ETR_m \\ \hat{\Theta}_{GW,min,i+1} &= \hat{\Theta}_{GW,min,i} + \Delta\Theta_{m,i} \quad \text{for } \Delta\Theta_{m,i} > 0 \text{ (falling groundwater table)} \end{aligned} \quad (114)$$

with  $\Delta\Theta_{m,i}$  change of water content of layer  $m$  during time step  $i$  [-]  
 $q_{m-1}$  inflow from layer  $m-1$  (may be positive or negative!) [m/s]  
 $Q_B$  lateral net runoff of layer  $m$  as given by the groundwater model [m/s]  
 $Q_{ifl}$  interflow from layer  $m$  [m/s]  
 $ETR_m$  extraction by transpiration from layer  $m$  [m/s]

If the value of  $\hat{\Theta}_{GW,min}$  becomes smaller than the value of  $\Theta_{GW,min}$ , the latter value is taken for the interpolation of the groundwater table and  $\hat{\Theta}_{GW,min}$  is not considered anymore until the groundwater is entering the layer again from below.

#### 1.12.10 Groundwater recharge

The groundwater recharge is the balance of inflows and outflows to that layer which contains the groundwater level. Recharge can be positive or negative. If the groundwater tables moves to another layer, the balances are calculated including the fluxes of all affected layers. The drained or filled porosity

is balanced with the lateral net flux change from the groundwater model (the rate of rise or fall of groundwater in terms of mm/time step). There are 4 cases for calculating the drained or filled porosity:

*1. groundwater table is falling within the same layer:*

The layer is splitted into an unsaturated and a saturated fraction. The thickness  $d_u$  of the unsaturated fraction is given by  $d_u = h_{geo,m-1} - h_{GW}$  (see equation 108):

$$\Theta_{u,new} = \frac{(d_m \Theta_{m,i} - (h_{GW,i} - h_{geo,m}) \Theta_s)}{h_{geo,m-1} - h_{GW}} \quad (115)$$

with  $\Theta_{u,new}$  water content of the unsaturated fraction of layer  $m$  (the layer the groundwater table is within)  
 $d_m$  thickness of layer  $m$  [m]  
 $h_{GW,i}$  groundwater table at time step  $i$   
 $\Theta_{m,i}$  average water content of layer  $m$  in the actual time step  $i$

The water content for the lower fraction between  $h_{GW}$  and  $h_{geo,m}$  is at saturation:  $\Theta = \Theta_s$ . The drainable porosity is thus given by:

$$\Theta_e = (h_{GW,i} - h_{GW,i-1}) \cdot (\Theta_s - \Theta_{u,new}) \quad (116)$$

with  $h_{GW,i}$  groundwater table in the actual time step  $i$  [m]  
 $h_{GW,i-1}$  groundwater table from the previous time step  $i-1$  [m]

*2. groundwater table is rising within the same layer*

$$\Theta_{u,old} = \frac{(d_m \Theta_{m,i-1} - (h_{GW,i-1} - h_{geo,m}) \Theta_s)}{h_{geo,m-1} - h_{GW,i-1}} \quad (117)$$

with  $\Theta_{u,old}$  water content of the unsaturated fraction of layer  $m$  from the previous time step  $i-1$  [-]  
 $d_m$  thickness of layer  $m$  [m]  
 $h_{GW,i-1}$  groundwater table from the previous time step  $i-1$  [m]  
 $\Theta_{m,i-1}$  average water content of layer  $m$  from the previous time step  $i-1$  [-]

The filled porosity is then given by:

$$\Theta_e = (h_{GW,i} - h_{GW,i-1}) \cdot (\Theta_s - \Theta_{u,old}) \quad (118)$$

with  $h_{GW,i}$  groundwater table in the actual time step  $i$  [m]  
 $h_{GW,i-1}$  groundwater table from the previous time step  $i-1$  [m]

If the groundwater table moves into another layer (over one or more layer boundaries), the results of equations (116) and (118) have to be extended by the drained or filled porosities of the completely drained or filled layers:

*3. groundwater is moving down a layer limit :*

$$\Theta_e = (h_{geo,n} - h_{GW,i-1}) \cdot (\Theta_s - \Theta_{n,i}) + \sum_{k=n+1}^m (d_k (\Theta_{k,i-1} - \Theta_{k,i})) \quad (119)$$

with  $h_{geo,n}$  geodetic altitude of the layer the groundwater table was within in time step  $i-1$   
 $h_{GW,i-1}$  groundwater table in the previous time step  $i-1$   
 $\Theta_{n,i}$  actual water content in the layer  $n$  the groundwater table is within in time step  $i$   
 $n$  index: layer the groundwater was within in time step  $i-1$   
 $m$  index: layer, the groundwater is within in time step  $i$   
 $d$  thickness of the layers [m]  
 $k$  loop index for all completely drained layers

4. groundwater table rises above a layer limit:

$$\Theta_e = (h_{GW,i} - h_{geo,m}) \cdot (\Theta_s - \Theta_{m,i} - \Delta t \cdot Q_{lat} / d_m) + \sum_{k=n+1}^m (d_k (\Theta_{k,i} - \Theta_{k,i-1})) \quad (120)$$

with	$h_{geo,m}$	geodetic altitude of the layer the groundwater table is within in time step $i$
	$h_{GW,i}$	groundwater table in the actual time step $i$
	$\Theta_{m,i}$	actual water content in the layer $m$ the groundwater is within in time step $i$
	$n$	index: layer the groundwater was within in time step $i-1$
	$m$	index: layer, the groundwater is within in time step $i$
	$d$	thickness of the layers [m]
	$\Delta t$	time step [s]
	$Q_{lat}$	lateral Net flow in time step $i$
	$k$	loop index for all completely filled layers

The groundwater recharge is for all 4 cases the sum of the drained respectively the filled porosity  $\Theta_e$  and the lateral net fluxes of the previous time step:

$$GWN = 1000 \cdot \Theta_e + Q_{B,i-1} \quad (121)$$

with	$GWN$	groundwater recharge [mm]
	$\Theta_e$	filled porosity (positive sign) resp. drained porosity (negative sign) [-]
	$Q_{B,i-1}$	base flow/lateral net flow from the previous time $i-1$ [mm]

#### 1.12.11 Calculating baseflow

Base flow is generated in WaSiM-ETH version 2 only as exfiltration from the groundwater into the surface river system. It is generated only at that grid cells which are marked in a number of grids as river cells. The output is written not only as a grid but also as a areal average value for subbasins. For this output files the exfiltration into rivers is not balanced with the infiltration from rivers into the groundwater. This is done during the discharge routing.

However, if the model is run without the groundwater module, calculation of base flow must be done in a conceptual way, because no lateral exchange between cells is possible. For such cases an approach similar to the TOPMODEL-Approach is used:

$$Q_B = Q_0 \cdot K_s \cdot e^{(h_{GW} - h_{geo,0})/k_B} \quad (122)$$

with	$Q_B$	base flow [m/s]
	$Q_0$	scaling factor for base flow (or maximum baseflow if the soil is saturated) [-]
	$K_s$	saturated hydraulic conductivity [m/s]
	$h_{GW}$	groundwater table [m a.s.l.]
	$h_{geo,0}$	geodetic altitude of the soil surface (upper limit 1 <sup>st</sup> layer) [m a.s.l.]
	$k_B$	recession constant for base flow [m]

This approach is applied to each cell of the model grid – base flow is thus not generated only at river cells. The parameters  $Q_0$  and  $k_B$  have to be calibrated.

#### 1.12.12 Coupling with the groundwater model

Starting from the interpolation all model components including snow, evaporation, interception, irrigation and unsaturated zone were only one dimensional. The generation of interflow is an extension which presumes a sufficiently larger cell size than the natural drainage systems density (small drainage channels can be found usually after at least 10 to 100 meters in hilly regions). Neighboring cells does not communicate in this scheme, otherwise a complete 3-D-model for the unsaturated zone would be required. On the other hand, coupling a horizontally 2-dimensional groundwater model to the unsaturated zone is very easy if the groundwater flux field is calculated independent on the unsaturated zone.

The coupling in WaSiM-ETH (version 2) is done bi-directional.

- The unsaturated zone module calculates the flux between the unsaturated zone and the groundwater. This flux is given to the groundwater module as upper boundary condition (known flux boundary). Tracer concentrations of the net fluxes are balanced with the groundwater and the unsaturated zone.
- The groundwater model calculates the lateral fluxes using the boundary fluxes from the unsaturated zone model. The net change of the groundwater table is converted into a boundary flux (in mm/time step vertical flux) and given to the unsaturated zone to be considered as inflow or outflow.

### 1.13 Modeling of groundwater flow and (lateral) transport

The main features of the groundwater module are:

- The model is a multi layer model. Each layer is modeled horizontally 2-dimensional in a regularly spaced grid. The coupling between the layers is done using leakage factors.
- The uppermost (first) groundwater aquifer is assumed to be unconfined, the lower aquifers can be confined or unconfined (it is determined by comparing the heads with the upper boundaries of the layers)
- It is possible to use anisotropic conductivities but only in x- and y-direction (without rotated anisotropy). If a rotation is required, the coordinate system should be rotated.
- The connection to surface water is done by leakage approaches within the unsaturated zone model. It is possible to calculate infiltration from rivers as well as exfiltration into the rivers (base flow). If the groundwater reaches the surface of the soil, surface runoff is generated (but in the unsaturated zone model).
- The solution of continuity and flux equations is done using an implicit finite difference approach: Gauss-Seidel-Algorithm with automatic or manual estimation of Successive Over Relaxation Factors (SOR factors). It is scheduled to implement some faster solving algorithms like PCG into the model in later versions.
- The substance transport is done as a big-cell-approach without considering diffusion. It is possible to model the substance transport externally by writing all flux fields to external files.
- spatial distributed parameters for the groundwater model:
  - KX saturated horizontal conductivity (x-direction), 1 grid each aquifer [m/s]
  - KY saturated horizontal conductivity (y-direction), 1 grid each aquifer [m/s]
  - S0 specific storage coefficient ( $S_0$ ), 1 grid for each aquifer [ $\text{m}^3/\text{m}^3$ ]
  - GK leakage factors for layer interaction, 1 grid for each layer [ $\text{m}^{-1}$ ]
  - BQ boundary fluxes (referring to the vertical  $\rightarrow$  recharge), 1 grid for each layer [m/s]
  - BH constant head boundary, 1 grid for each layer [m a.s.l.]
  - AQ aquifer thickness, 1 grid for each layer [m]

#### *Solving the flux equation*

The flux equation is get from the continuity equation and from the DARCY-equation. The change of the water storage in a control volume  $\partial x \cdot \partial y$  during a time  $\partial t$  equals the balance of the inflows into and outflows out of the control volume:

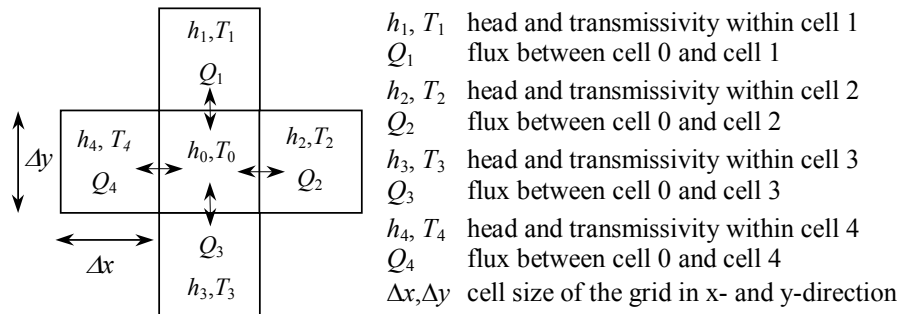
$$\text{div}(T \text{grad} h) + q + l_{up}(h_{up} - h) + l_{lo}(h_{lo} - h) = S_0 \frac{\partial h}{\partial t} \quad (123)$$

with  $T$  transmissivity = aquifer thickness [m] times conductivity  $K_X$  (resp.  $K_Y$ ) [ $\text{m}^2/\text{s}$ ]  
 $h$  hydraulic head in the control volume [m]  
 $q$  boundary fluxes perpendicular to the grid cell surface [m/s]  
 $l_{up}$  leakage factor for fluxes between the actual and the upper aquifer [ $\text{s}^{-1}$ ]

$h_{up}$	hydraulic head in the upper laying aquifer [m]
$l_o$	leakage factor for fluxes between the actual and the lower aquifer [ $s^{-1}$ ]
$h_{lo}$	hydraulic head in the lower laying aquifer [m]
$S_0$	specific storage coefficient [1/1]
$t$	time [s]

Beside the horizontal fluxes equation (123) contains also terms for fluxes between aquifers and the term  $q$ , which is introduced to consider extractions or additional inputs by wells or recharge. In case of unconfined conditions in a aquifer below the top aquifer the storage coefficient  $S_0$  of this lower layer is replaced automatically with the storage coefficient from the top layer. This presumes that the other layers use confined values for the storage coefficient whereas for the top aquifer the effective porosity is given as storage coefficient.

To get a discrete equation, a control volume with discrete cell edges  $\Delta x$  and  $\Delta y$  is defined. Also the time is made discrete to  $\Delta t$ . The following equations use local indices between 0 and 4 according to the following scheme.



If in equation (123) the leakage term is merged together with the perpendicular inflows and outflows (including leakage) through the cells surface to the flux  $Q_0$  and if the divergence of the fluxes is written as balance of the fluxes through the borders of the control volume than a discrete flux equation is given by:

$$\Delta t(Q_1 + Q_2 + Q_3 + Q_4 + Q_0) = [h_0(t + \Delta t) - h_0(t)]S_0\Delta x\Delta y \quad (124)$$

with fluxes  $Q_1$  to  $Q_4$  as

$$\begin{aligned} Q_1 &= \Delta x T_{1,0} \frac{h_1(t') - h_0(t')}{\Delta y} & Q_2 &= \Delta y T_{2,0} \frac{h_2(t') - h_0(t')}{\Delta x} \\ Q_3 &= \Delta x T_{3,0} \frac{h_3(t') - h_0(t')}{\Delta y} & Q_4 &= \Delta y T_{4,0} \frac{h_4(t') - h_0(t')}{\Delta x} \end{aligned} \quad (125)$$

It is assumed that the fluxes during the time step  $\Delta t$  can be represented by the fluxes at the time  $t'$  (with  $t \leq t' \leq t + \Delta t$ ) and thus by the heads valid at this time. The transmissivities  $T_{1,0}$  to  $T_{4,0}$  between the cells 0 and 1, 0 and 2, 0 and 3, and 0 and 4 are averaged as harmonic average of the affected cells:

$$T_{i,0} = 2 \frac{T_i T_0}{T_i + T_0} \quad (126)$$

with  $i$  local indices between 1 and 4

Under confined conditions the local transmissivity in a cell is the product of aquifer thickness and saturated hydraulic conductivity in the matching direction. X- and y-direction may have different conductivities. Under unconfined conditions the local transmissivity is the product of the effective aquifer thickness (only the saturated part of the aquifer) and the saturated hydraulic conductivity in the direction of interest.

The following reformulations presume a regular grid with  $\Delta x = \Delta y$  what leads to simplifications of equation (125). Also the hydraulic heads  $h'$  at time  $t'$  are expressed by  $h(t)$  and  $h(t + \Delta t)$ :

$$h(t') = (1 - \alpha) \cdot h(t) + \alpha \cdot h(t + \Delta t) \quad (127)$$

The parameter  $\alpha$  has a range of 0 to 1. If  $\alpha$  is set to 0 the solution is done explicitly, if  $\alpha$  is set 1 the solution is fully implicit, values between 0 and 1 will cause a partly implicate solution. Explicit solutions are fast because the solution is get in a single step but they tend to numerical instabilities if using long time steps. Implicit solutions can be obtained by using iterative methods or by direct solutions of the linear equation systems. In WaSiM-ETH an iterative scheme, the Gauss-Seidel-Algorithm is applied. It is simple and fast enough also for very large model grids, because the time critical part in the model is the unsaturated zone. Usually the model will be applied with time steps of one hour or one day or even longer time steps, thus the use of the fully implicit approach is strongly recommended. If there are oscillations between successive time steps the model gives messages about this in order to allow the user to change some iteration parameters.

If the fluxes from equation (125) are simplified by  $\Delta x / \Delta y = 1.0$  and put into equation (124) and if the heads  $h_0(t')$  are expressed by equation (127) the head  $h_0(t + \Delta t)$  can be expressed by:

$$h_0(t + \Delta t) = \frac{\frac{\Delta x \Delta y}{\Delta t} S_0 \cdot h_0(t) + (F_1 + F_2 + F_3 + F_4) - (1 - \alpha) \cdot h_0(t) \cdot (T_{1,0} + T_{2,0} + T_{3,0} + T_{4,0})}{\frac{\Delta x \Delta y}{\Delta t} S_0 + \alpha \cdot (T_{1,0} + T_{2,0} + T_{3,0} + T_{4,0})} \quad (128)$$

with

$$F_1 = T_{1,0} h_1(t') \quad F_2 = T_{2,0} h_2(t') \quad F_3 = T_{3,0} h_3(t') \quad F_4 = T_{4,0} h_4(t') \quad (129)$$

Because after a complete step over all grid cells the heads  $h_1(t')$  to  $h_4(t')$  of the neighboring cells 1 to 4 may have changed, equation (129) has to be repeatedly processed for the entire grid until the changes between two iteration steps are nowhere greater than a user-specified threshold  $\varepsilon_{max}$  (of e.g.  $10^{-5}$  m) or until the maximum number of iteration steps  $n_{iter}$  has been reached. Both parameters are specified as global parameters in the control file (global means: they are valid for each cell in the grid). To avoid to many iteration steps, for confined conditions the error threshold  $\varepsilon_{max}$  is automatically increased by a factor 50. This is done in order to consider the much larger effect of very small in- and outflows on the heads compared to unconfined conditions. Thus, a very small flux which is really unimportant for the balance may very well change the heads by e.g. 0.001 m under confined conditions whereas the same flux would change the head under unconfined conditions by e.g. 1e-6 m. Using the Gauss-Seidel iteration scheme it is taken advantage from the fact, that in each iteration step the heads of the cells 1 and 3 (local indices) are already newly calculated values which gives better estimations and thus a faster convergence of the solution.

#### *Acceleration of the convergence of the iteration*

In order to minimize the errors of the iteration even faster it is possible to use acceleration factors, the so called successive over relaxation (SOR). Using this method, the differences in the heads between to iteration steps are multiplied by a SOR-factor. This factor can be specified in the control file or it can be estimated automatically during the model run by indicating a negative value for the SOR-factor in the control file. If it is not automatically estimated, the value should be set with care, because too large values will destabilize the iteration scheme. Manually selected SOR-values should be between 1.1 and 1.4. If the model starts to oscillate, this is messaged to the user in order to change also the SOR-factor. In case of an automatic estimation of the SOR-factor the model uses the heads of the actual and the two last iteration steps to calculate an SOR-factor:

$$SOR = 1 + \frac{h(t) - h(t - \Delta t)}{h(t - \Delta t) - h(t - 2\Delta t)} \quad (130)$$



with  $SOR$  acceleration factor (successive over relaxation), limited to  $1 \leq SOR \leq 2$  [-]

#### *Leakage between aquifers*

Fluxes between different aquifers are considered by a leakage-approach. Using DARCY's Law the flux is calculated according to the hydraulic conductivity and the thickness of the assumed clay layer in-between the aquifers. Because usually both variables are unknown they are replaced by a leakage factor  $l$ :

$$l = \frac{k'}{d'} \quad (131)$$

with  $l$  leakage-factor [ $s^{-1}$ ]  
 $k'$  hydraulic conductivity within the clay layer between the aquifers [ $m \cdot s^{-1}$ ]  
 $d'$  thickness of the clay layer in-between the aquifers [m]

The leakage fluxes are calculated according to equation (123) depending on the head difference and the leakage factor. The results are fluxes in m/s perpendicular to the grid cell surface.

#### *boundary conditions*

It is possible and required to define grids containing boundary conditions. There are two grids for each aquifer, one containing constant heads and one containing constant fluxes into or out of the cells. The boundary conditions can be set separately for each grid cell but they are valid during the entire model run. For cells with a constant head boundary equation (128) is skipped. Inputs (positive sign) or extractions (negative sign) are expected in m/s perpendicular to the cell surface. It is also possible to consider lateral boundary fluxes if they are converted considering the grid cell size into matching vertical fluxes. It is not possible to consider temporally variable boundary conditions. Also boundary conditions which are linear combinations of known heads and known fluxes are not explicitly allowed. However, if both grids (constant flux and constant head) have valid entries for a cell, then this is a kind of a combined boundary condition. Such combinations may lead to serious problems with the water balance especially if the hydraulic properties do not match the boundary conditions (too much extraction/inflow and at the same time a fixed head → problems with the balance).

#### *Balance for the 1<sup>st</sup> aquifer for coupling the unsaturated zone to the groundwater model*

The balance of inflows and outflows across the cell boundaries (all six surfaces including ceiling and floor) is converted into an effective rate of change of the groundwater table in terms of water flux. Thus the model of the unsaturated zone gets information about the change of the groundwater table for inclusion into its algorithms. The rate of change of the groundwater table is estimated by:

$$\Delta_{GW} = \frac{h(t - \Delta t) - h(t)}{\Delta t} S_0 \quad (132)$$

with  $\Delta_{GW}$  rate of change of the groundwater table in terms of a vertical water flux [ $m \cdot s^{-1}$ ]  
 $h(t - \Delta t)$  groundwater head in the previous time step [m]  
 $h(t)$  groundwater head at the end of the actual time step [m]  
 $S_0$  specific storage coefficient [-]  
 $\Delta t$  time step [s]

#### *Substance transport in the groundwater*

The exchange of tracers between unsaturated zone and groundwater and the mixing is considered in the unsaturated zone module. The flux between the last completely unsaturated zone and the groundwater is taken as recharge (or uptake) transporting with it an amount of tracers matching the concentrations of this tracers in the place of the origin of the fluxes. For capillary rise this solute amount is the product of the upwards flow and the concentration of the solute in the groundwater. Mixing and enrichment as well as radioactive decay are described using the equations from chapter (1.14).

Within the groundwater the transport of solutes is estimated using the lateral fluxes and the solute concentrations in their origin cells. The vertical fluxes are handled in analogy to the horizontal fluxes. After calculating the water fluxes, the corresponding masses of transported tracers are calculated. The balance of mass inflows and outflows with the old tracer content of the cell (all units in  $10^3\text{kg}$  or in relative units) is divided by the new water content to get the new tracer concentration:

$$c_0(t + \Delta t) = c_0(t) \cdot \Delta x \cdot \Delta y \cdot n \cdot d + Q_1 \cdot c_{1\cup 0}(t) + Q_2 \cdot c_{2\cup 0}(t) + Q_3 \cdot c_{3\cup 0}(t) + Q_4 \cdot c_{4\cup 0}(t) + Q_{up} \cdot c_{up\cup 0}(t) + Q_{lo} \cdot c_{lo\cup 0}(t) + Q_0 \cdot c_0(t) \quad (133)$$

with $n$	porosity [-]
$d$	aquifer thickness (confined aquifer) resp. effective aquifer thickness (unconfined aquifer) [m]
$c_{1\cup 0} \dots c_{4\cup 0}$	tracer concentrations in the four neighboring cells; depending on the flow direction this may be the central cell (index 0) or one of the neighboring cells (indices 1 to 4), units [ $10^3\text{kg/m}^3$ ] or relative concentrations
$c_{up\cup 0}$	tracer concentrations within the actual or the upper laying aquifer, depending on the flow direction (only if there is an aquifer above, else 0), units like $c_{1\dots 4}$
$c_{lo\cup 0}$	tracer concentrations within the actual or the lower laying aquifer, depending on the flow direction (only if there is an aquifer below, else 0), units like $c_{1\dots 4}$
$c_0$	tracer concentrations in boundary inflows (unimportant for extractions because no concentration changes), units like $c_{1\dots 4}$
$Q_1 \dots Q_4$	fluxes between the cells 1...4 and the actual cell (index 0) [ $\text{m}^3$ ]
$Q_{up}, Q_{lo}$	leakage fluxes, if upper (up) or lower (lo) aquifers are present [ $\text{m}^3$ ]
$Q_0$	boundary flux [ $\text{m}^3$ ]

The fluxes  $Q_1$  to  $Q_4$  in equation (133) are given by:

$$\begin{aligned} Q_1 &= k_{s,1} \frac{h_0 - h_1}{\Delta y} \cdot \Delta x \cdot \Delta t \cdot \frac{d_0 + d_1}{2} \\ Q_2 &= k_{s,2} \frac{h_0 - h_2}{\Delta x} \cdot \Delta y \cdot \Delta t \cdot \frac{d_0 + d_2}{2} \\ Q_3 &= k_{s,3} \frac{h_0 - h_3}{\Delta y} \cdot \Delta x \cdot \Delta t \cdot \frac{d_0 + d_3}{2} \\ Q_4 &= k_{s,4} \frac{h_0 - h_4}{\Delta x} \cdot \Delta y \cdot \Delta t \cdot \frac{d_0 + d_4}{2} \end{aligned} \quad (134)$$

with $k_{s,1} \dots k_{s,4}$	saturated lateral hydraulic conductivity in the neighboring cells [m/s]
$h_0 \dots h_4$	hydraulic heads in the cells 0 to 4 [m]
$d_0 \dots d_4$	effective thickness of the aquifers in cells 0 to 4

The amount of water within the actual cell which is needed for equation (133) may be get as balance of the old water content and the inflows and outflows or it may be estimated from the hydraulic head at the end of the time step. If the latter value differs from the first one, the mass fluxes are reduced to the latter one. Thus numerical errors caused by the use of local hydraulic conductivities can be avoided as well as the tracer balance is hold.

## 1.14 Coupling the solute transport to the water fluxes

In WaSiM-ETH version 2 the modeling of ideal tracers is included. It is possible to consider radioactive decay, mixing and enrichment (for salts). Only advective transport and mixing is considered, no diffusion is taken into account. This is a useful simplification if diffuse sources like salt from irrigation water or tritium from precipitation is modeled. Salts are modeled using the absolute masses, all other tracers are modeled by their concentrations. The advantage is, that for salts no changes in the masses will occur dur-

ing evaporation while for evaporating tracers also no changes in their concentrations will occur. The mixing of water volumes with different concentrations is calculated after:

$$c_{mix} = \frac{c_1 V_1 + c_2 V_2}{V_1 + V_2} \quad (135)$$

with  $V_1, V_2$  volumes 1 and 2 to be mixed  
 $c_1, c_2$  concentrations of the tracer in the volumes 1 and 2  
 $c_{mix}$  mixing concentration

Radioactive decay is calculated using the half time  $t_{1/2}$ , which is converted into a decay constant depending on the model time step. Thus the radioactive decay is computed by:

$$c_i = c_{i-1} \cdot e^{-\Delta t / t_{1/2} \cdot \ln 2} \quad (136)$$

with  $c_i$  concentration of the radioactive tracer after decay  
 $c_{i-1}$  concentration of the radioactive tracer before decay (from the last time step)  
 $\Delta t$  time step [days]  
 $t_{1/2}$  half time [days]

There can be considered at maximum 9 tracers at the same time. The tracers are modeled absolutely independent of each other even if the concentrations are very high. This is a limitation as well as the inconsideration of the fact that the suctions and conductivities of salty solutions differ from that of pure water. Also the effects of density on the fluxes are not considered. So the model should not be applied to systems where such effects are expected to be important for the water fluxes.

## 2 Overview of required input data, parameters and data flow charts

### 2.1 Input data requirements for some model setups

WaSiM-ETH allows various model configurations depending on the aim of the application and on the amount and quality of input data. It is possible to combine various submodel components and to run the model in various spatial and temporal discretizations.

#### *minimum requirements*

The modules for interception, snow, infiltration (model version 1) and discharge routing may be disabled during the model run. Also the irrigation and the substance transport can be disabled.. Thus, a minimal configuration for a meaningful water balance model would be a combination of data interpolation for precipitation and temperature, evaporation and runoff generation (soil model). If only a single flood event has to be modeled (using WaSiM-ETH version 1 with the TOPMODEL-approach), then even the evaporation module may be disabled and no temperature is needed also. Then only precipitation data and the digital elevation model, land use and soil type data has to be read in. This minimal configuration does not work if there is much snow, but an extension by the snow model does mean only that the temperature will be needed in addition to the precipitation. If the evaporation approaches after HAMON, WENDLING or HAUDE should be applied, the model can be run only in a daily time step or longer.

#### *requirements for an optimal simulation*

For a long term simulation in a high resolution all components which were described in the first part of this documentation should be enabled (except irrigation and substance transport, if this is not important). All of these components should be run in a sufficiently high spatial and temporal resolution. Compared to the minimum configuration there are considerably more input data required. Also the parameterization and the calibration is more complex. Table 3 contains a short overview for three different applications:

Table 3: *required submodels and model-input data for different model objectives*

	flood simulation (only events)	long term water balance simulation (daily time step)	continual simulation (including floods)
<i>resolution</i>			
• temporal	1 min ... 1 h (max 1 d)	1 d	≤ 1 h (max. 1 d)
• spatial (as grid)	dependent on the basin, e.g. 10 m for basins < 1 km <sup>2</sup> 10,000 km <sup>2</sup>		... 5 km for basins ≥ 10,000 km <sup>2</sup>
<i>sub-modules (components)</i>			
• precipitation correction	<b>required</b>	<b>required</b>	<b>required</b>
• input data interpolation	<b>required</b>	<b>required</b>	<b>required</b>
• radiation correc- tion/temperature modification	not required	not required	recommended
• evaporation model	not required	<b>required</b> , WENDLING, HAMON or MONTEITH	<b>required</b> , if possible after PENMAN-MONTEITH
• snow and glacier model	required only in the win- ter or in mountainous basins	<b>required</b>	<b>required</b>
• interception model	recommended	<b>required</b>	<b>required</b>
• infiltration model	recommended	not required	recommended
• soil model	<b>required</b>	<b>Required</b>	<b>required</b>
(both model versions)			
• groundwater model (vers. 2)	not required	recommended	recommended
• discharge routing	<b>Required</b>	<b>required</b> , for large or subdivided	<b>required</b>

	flood simulation (only events)	long term water balance simulation (daily time step)	continual simulation (including floods)
<ul style="list-style-type: none"><li>substance transport (only version 2)</li></ul>	if required (but not recommended for events)	basins if required	if required
<i>spatial distributed data (grids)</i>			
<ul style="list-style-type: none"><li>digital elevation model</li><li>aspect (°)</li></ul>	<b>Required</b> not required	<b>required</b> <b>required</b> (if required <sup>1</sup> )	<b>required</b> <b>required</b> (if required <sup>1</sup> )
<ul style="list-style-type: none"><li>slope angle (°)</li></ul>	not required	<b>required</b> (if required <sup>1</sup> )	<b>required</b> (if required <sup>1</sup> )
<ul style="list-style-type: none"><li>topographic index <math>\ln(a \cdot (T_0 \tan \beta)^{-1})</math></li><li>firm and ice (glacier grid)</li><li>zones for subdivision</li><li>land use</li><li>soil types</li><li>vertical hydraulic conductivity (<math>K_s</math>-value in <math>\text{m} \cdot \text{s}^{-1}</math>, version 1)</li><li>water content at field capacity [mm] (version 1)</li></ul>	<b>required for model-version 1</b> <b>only required and allowed if glaciers are modeled</b> <b>required</b> <sup>2</sup> <b>required</b> <sup>3</sup> <b>required</b> <sup>3</sup> may be estimated from soil data, its also possible to read in separate grids with this data may be estimated from soil data, its also possible to read in separate grids with this data	<b>required for model-version 1</b> <b>required</b> <sup>2</sup> <b>required</b> <sup>3</sup> <b>required</b> <sup>3</sup>	<b>required for model-version 1</b> <b>required</b> <sup>2</sup> <b>required</b> <sup>3</sup> <b>required</b> <sup>3</sup>
<i>groundwater model</i>			
	The use of the groundwater module is recommended for low land catchments with huge sediment layers or if the groundwater is very important for the hydrologic problem. It can be disabled in mountainous regions. (only available in model version 2)		
<ul style="list-style-type: none"><li><math>K_S</math>-value in x-direction for each aquifer [m/s]</li><li><math>K_S</math>-value in y-direction for each aquifer [m/s]</li><li>aquifer thickness for each aquifer [m]</li><li>storage coefficient for each aquifer [<math>\text{m}^3/\text{m}</math>]</li><li>leakage factor for each aquifer to the next lower aquifer [<math>\text{s}^{-1}</math>]</li><li>boundary condition <math>h=\text{const}</math> for each aquifer [m]</li><li>boundary condition <math>q=\text{const}</math> for each aquifer [m]</li></ul>	not required not required not required not required not required not required not required	recommended recommended recommended recommended recommended recommended recommended	recommended recommended recommended recommended recommended recommended recommended
<i>meteorological data (station data)</i>			
<ul style="list-style-type: none"><li>precipitation (mm)</li><li>air temperature (°C)</li><li>air humidity (1/1 or mbar) <sup>5</sup></li><li>global radiation (<math>\text{Wh} \cdot \text{m}^{-2}</math>)</li><li>rel. sunshine duration (1/1)</li><li>wind speed (<math>\text{m} \cdot \text{s}^{-1}</math>)</li></ul>	<b>required</b> <b>required</b> <sup>4</sup> not required not required not required not required	<b>required</b> <b>required</b> not required <b>required</b> at ET after WENDLING <sup>6</sup> <b>required</b> at ET after WENDLING <sup>6</sup> not required	<b>required</b> <b>required</b> <b>required</b> <sup>5</sup> <b>required</b> <sup>6</sup> <b>required</b> <sup>6</sup> <b>required</b>
<i>hydrologic data (discharge data from gauging stations at rivers)</i>			
<ul style="list-style-type: none"><li>subbasin or basin runoff as specific runoffs [mm]</li></ul>	recommended or <b>required</b> <sup>7</sup>	recommended or <b>required</b> <sup>7</sup>	recommended or <b>required</b> <sup>7</sup>
<i>other data</i>			
<ul style="list-style-type: none"><li>land use parameters (table)</li><li>soil parameters (table)</li><li>table with tracer properties</li></ul>	<b>required</b> <b>required</b> if required (not recom-	<b>required</b> <b>required</b> if required, only in	<b>required</b> <b>required</b> if required, only in

	flood simulation (only events)	long term water balance simulation (daily time step)	continual simulation (including floods)
	mended), only in WaSiM-Version 2 with RICHARDS-equation	WaSiM-Version 2 with RICHARDS-equation	WaSiM-Version 2 with RICHARDS- equation

- <sup>1</sup> This data sets are required if using the radiation correction or temperature modification. They can also be derived from the elevation model from within the model
- <sup>2</sup> A zone grid can contain zones determined by any specific property like subbasins, altitude belts, aspects a.s.o. The minimum would be a grid with unique values (i.e. all cells would have the same value), then there is only one zone, else: per zone a integer code >0;
- It's possible to use two zone grids, one for the submodels of interpolation, interception, evaporation and snow and another for the soil- and groundwater model, irrigation and routing. For the first one the properties may be selected from the upper list, for the second one the zones must be hydrologic subbasins or at least closed regions with hydraulic interconnections by flow-channels because for these submodels a hydrologic subdivision is required.
- <sup>3</sup> The minimum would be a unique code for all grid cells, this would mean a constant soil or land use all over the basin. There can be as many soil types and land uses as required. For each code in these grids there must be a matching entry in the soil table and in the land use table, respectively, in the control file with the proper parameters
- <sup>4</sup> required only, if the snow model is enabled
- <sup>5</sup> only one of the variables vapor pressure and relative air humidity is really required
- <sup>6</sup> sunshine duration and global radiation may be derived from one another (see chapter 1.4.1), so one of the variables would be sufficient (with advantage the global radiation), but for a better estimation of the long wave radiation balance observed sunshine duration would be better
- <sup>7</sup> To allow a calibration at observed runoff data there should be runoff data for at least a subset of the model time. The observed runoff data are needed only for computing the model efficiencies

## 2.2 Overview of the most important model parameters

Table 4 gives an overview about the free model parameters. Many of the parameters can be taken from the literature. A sensitivity analysis of the most important parameters is contained in chapter 3.6 of this documentation. The free model parameters are those which have only a low physical background or which can not be easily obtained by measurements. Examples for free parameters are the weighting  $p$  of the distances for the inverse distance interpolation, the re-infiltration parameter  $x_f$  in the infiltration model and the parameters  $m$  and  $T_{korr}$  (but also some others) of the soil model of model version 1 (TOPMODEL version). Parameters which describe typical properties of soils and vegetation should not be calibrated, like the parameters describing the  $k(\Theta)$ - and  $\psi(\Theta)$ -functions or the root depth, leaf area index and resistances of given crop types. These parameters should be seen as “derived internal properties” of an observable parameter like soil type or crop type.

Table 4: Parameters of the submodels

submodel	parameter	unit	comment
precipitation correction	$a_l$	-	
	$b_l$	mm/(m·s <sup>-1</sup> )	after equation (1), from the literature, calibration if required
	$a_s$	-	
	$b_s$	mm/(m·s <sup>-1</sup> )	
	$T_{R/S}$	°C	calibrating between 0 °C ... 2 °C
interpolation of meteorological input data	$d_{max}$	km	max. distance to the next meteorol. station (e.g. 100 km)
after equation (2) to (4)	$p$	-	power of the distance weighting for IDW-interpolation (literature: 2 ... 3)
	$igo, igu$	m	upper and lower inversion layers, dependent on the basin (Thur basin: 800 resp. 1400 m a.s.l.)
modification of temperature after equation (16)	$c_T$	K	scaling factor after equation (16), e.g. 5 K, calibration recommended

submodel	parameter	unit	comment
land use table for evaporation and interception model and ETR-extraction from the soil (for each crop type an entry in the land use table, parameter should <i>not</i> be calibrated)	$r_c$	$\text{s}\cdot\text{m}^{-1}$	resistances: 12 monthly values, literature,
	$LAI$	-	leaf area index: literature, measurements
	$v (= 1-A)$	-	vegetation coverage degree: literature
	$z_0$	m	effective crop height: literature, measure
	$\alpha$	-	Albedo: Literature, measure
	$z_w$	m	root depth: literature, measure
	$d_{1,400} - d_{4,400}$	Jul. Day	phenologic course: literature, observations
	<i>in addition for</i> <u>RICHARDS:</u>		
	$\rho$	-	root density distribution, literature, measurements
	$\Psi_g$	m	minimum suction for reducing <i>ETR</i> compared to <i>ETP</i>
snow model after equations (44) to (49)	$T_{R/S}$	$^{\circ}\text{C}$	transition temperature snow/rain: literature
	$T_{trans}$	K	
	$T_0$	$^{\circ}\text{C}$	transition range snow/rain: literature
			threshold temperature melt, literature,
	$c_0$	$\text{mm}\cdot^{\circ}\text{C}^{-1}\cdot\text{d}^{-1}$	measure, calibrate
glacier model (as an integral component of the snow model)	$DDF_{ice}$	$\text{mm}\cdot^{\circ}\text{C}^{-1}\cdot\text{d}^{-1}$	degree-day-factor: calibrate
	$DDF_{firm}$	$\text{mm}\cdot^{\circ}\text{C}^{-1}\cdot\text{d}^{-1}$	degree-day-factor for ice (T-index-meth.)
	$DDF_{snow}$	$\text{mm}\cdot^{\circ}\text{C}^{-1}\cdot\text{d}^{-1}$	degree-day-factor for firm
	$MF$	$\text{mm}\cdot^{\circ}\text{C}^{-1}\cdot\text{d}^{-1}$	degree-day-factor for snow
			melt-factor for ice/snow/firm (unique)
	$\alpha_{ice}$		radiation coefficient for ice
	$\alpha_{firm}$		radiation coefficient for firm
	$\alpha_{snow}$		radiation coefficient for snow
	$k_{ice}$	h	recession parameter single linear stor. ice
	$k_{firm}$	h	recession parameter firm
interception model after equation (50) and (51) infiltration model after equations (52) to (54) soil model after equations (55) to (67) in WaSiM-ETH version with TOPMODEL-approach	$k_{snow}$	h	recession parameter snow
	$h_{SH}$	mm	maximum water layer thickness, calibr.
			$v$ and $LAI$ from land use table
	$x_f$	-	fraction of re-infiltrating water, calibrate,
			soil properties $K_s$ and $\psi_f$ from soil table
	$m$	m	recession parameter, from observed hydrographs
	$T_{korr}$	-	transmissivity-correction: calibrate
	$K_{korr}$	-	$K_s$ -correction: calibrate
	$k_D$	h	storage coefficient surface runoff: from a hydrograph analysis
	$SH$	mm	maximum content interflow storage: calibrate
soil model starting from equation (79) after RICHARDS-equation	$k_H$	h	storage coefficient interflow: from a hydrograph analysis
	$P_{grenz}$	mm	max. precipitation intensity for matrix infiltration: calibrate, literature
	$r_k$	-	limitation of capillary rise: calibrate (0 ... 1)
	$QD_{Snow}$	-	fraction of surface runoff on snow melt: calibrate (0 ... 1)
	$k_D$	h	storage coefficient surface runoff
	$k_H$	h	storage coefficient interflow ( $k_H$ here should consider only the storage effects of the surface channels like for surface runoff: recommended is $k_D = k_H$ )
	$Q_0$	mm/h	scaling factor for base flow in eq. (122)
			storage coefficient for base flow ( $Q_0$ and $k_B$ are used only if the groundwater model is disabled)
	$k_B$	m	

submodel	parameter	unit	comment
groundwater model (Gauss-Seidel-algorithm)	$d_r$	$m^{-1}$	drainage density for interflow: linear scaling of interflow ( $d_r > 0$ )
	$QD_{Snow}$	-	fraction of surface runoff on snow melt: calibrate (0 ... 1)
	$n_{max}$	-	maximum number of iterations per time step and layer
	$\varepsilon_{iter}$	m	maximum iteration error between two iteration steps (is multiplied with a factor of 50 at confined conditions)
	$\alpha_s$	-	weighting of the head of the time step end (degree of implicitness of the solution), 0 = fully explicit, 1=fully implicit
Soil table (for each soil type an entry exists in the soil table, these parameters should <i>not</i> be calibrated, exclusion: $c_k$ at larger time steps and $k_{rec}$ )	<u>TOPMODEL</u>		
	$FC$	Vol.-%	available field capacity, only TOPMODEL
	$mSB$	Vol.-%	max. available soil water content
	$\psi$	mm	suction at the wetting front after (52)
	$K_s$	m/s	saturated hydraulic conductivity, measure, literature values.
	<u>RICHARDS</u>		
	$\Theta_{sat}$	-	soil specific, measure or from the literature
	$\Theta_{wp}$	-	
	$K_s$	m/s	sat. hydraul. conductivity, measure, liter.
	$\alpha$	$m^{-1}$	van Genuchten parameter, literature
	$n$	-	van Genuchten parameter, literature
	$k_{rec}$	-	$K_s$ -recession $K_s(t)=K_{s,t=0} \cdot (k_{rec})^t$ , $t$ : depth
	$l_v$	-	number of soil layers
	$d_z$	m	layer thickness
	$c_k$	-	limitation of the $K_s$ -relation between two soil layers, useful for large time steps
discharge routing after equations (68) to (76) hydraulic parameters have to be given for each channel and for each external inflow;	$B_h, B_v$	m	width of mean channel and flood plains
	$T_h$	m	channel depth,
	$M_h, M_v$	$m^{1/3} \cdot s^{-1}$	roughness values for mean channel and flood plains, channel slope,
	$I$	$m \cdot m^{-1}$	channel length
	$L$	m	channel length
	$A_E$	$km^2$	catchment area
	$k_h, k_v$	h	reservoir constants for storage effects for mean channel and flood plains
threshold parameter for internal/external abstractions	$Q_{min}$	$m^3/s$	threshold for extractions
	$Q_{rel}$	$m^3/s$	relative fraction of abstracted water on $Q - Q_{min}$
initial concentrations and reservoir contents for reservoirs	$Q_{max}$	$m^3/s$	maximum capacity of the abstraction
	$V_0$	$m^3$	reservoir content at model start
	$C_{0,1} \dots C_{0,9}$	kg/kg	initialization concentrations of all possible 9 tracers within the reservoirs at model start (also if no substance transport is considered, also in WaSiM-version 1)
substance transport	$t_{1/2}$	d	half time (for radioactive tracers)
	$c_{min}$	kg/kg mg/l	minimum and maximum tracer concentrations (if useable, else -9999)
	$c_{max}$	kg/kg mg/l	
irrigation table	$\psi_{dry}$	m	threshold suction for starting irrigation
	$\psi_{wet}$	m	target suction value for stopping irrigation



## 2.3 The internal data flow

### 2.3.1 Spatially distributed data (Grids)

There are two main types of data – spatially distributed data as grids and time series of meteorological input data and of model output data. Figure 2 shows the input and output grids for WaSiM-ETH version 1 (TOPMODEL-approach) as well as the most important internal grids. The abbreviations are explained in table 5 as well as in figure 2 itself (e.g. USE stands for land use, SLIQ for the liquid fraction of the snow cover in mm a.s.o.). Also the following data flow charts in figures 4 to 6 use the abbreviations of figures 2 and 3.

The grids used in WaSiM-ETH can be subdivided into 3 groups:

1. *Input-grids with temporally invariant data.* These are data describing the basin like the digital elevation model, the zone grids, land use and soil data and derived data (like slope and aspect). The absolute minimum amount of data is specified by the first 6 data sets in figure 2 (for WaSiM-version 1). In WaSiM-version 2 the ATB-grid is not needed. It is recommended for some grids like the slope angle (SLP), the flow travel times (FZS), and the topographic index (ATB), to generate them from high resolution grids by resampling to the actual grid size. The flow travel time grid does not necessarily have to be read in, only if translation effects for larger basins should be considered. If this grid is not present, only a single travel time zone is assumed for the entire subbasin. If a glacier grid with the codes 1 for ice and 2 for snow is read, the glacier model is activated automatically (see chapter 9). It is necessary that glaciers appear in the zone grids as separate subbasins otherwise the model stops with an error message.
2. *internally generated parameter grids.* These grids are updated after each model day according to the parameters in the land use table and in the soil table, respectively. They are whether read in nor written to the disk. They are for internal use only. In WaSiM-ETH version 2 some internal grids for the soil moisture dependent irrigation are generated in order to avoid a time consuming conversion of suctions into water contents in every time step.

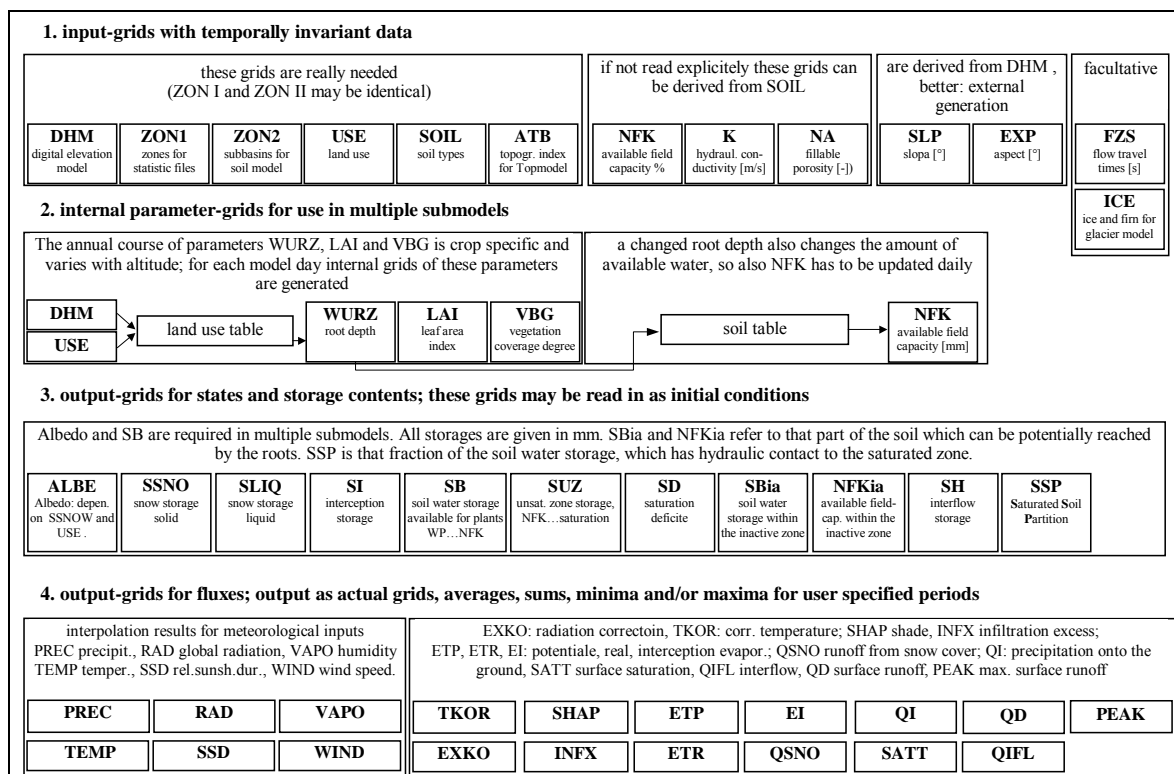


figure 2: input and output grids for WaSiM-ETH version 1 (TOPMODEL-approach)

3. *Output grids for reservoirs/storages, fluxes and system states.* The albedo and all storage states can be read in at the model initialization. This is very useful if e.g. observed values should be used for the model initialization or if a model run should use the final states of a previous model run as initialization conditions. The output grids for interpolated meteorological data are corresponding to the sets of input data, so if only precipitation, temperature and global radiation are interpolated, there are also only these three grids in the output. For model version 2 (Richards-equation, figure 3) the number of output grids for tracer concentrations depends on the number of modeled tracers.

In analogy to figure 2 figure 3 shows the input-output-scheme for WaSiM-ETH version 2. Corresponding to the optional possibilities of the model some additional grids are required (e.g. grids describing drainage, irrigation areas, clay layers, river geometry a.s.o.). There is also a higher number of internal grids. Some grids are in fact 3-D-grids or stacks of 2-D-grids, like the THET, HHYD and QBOT-grids (THET: water content in the soil layers, HHYD: hydraulic heads in all soil layers, QBOT: fluxes between the soil layers). In addition to the state and flux grids in WaSiM-ETH version 2 there are also grids and stacks describing tracer concentrations.

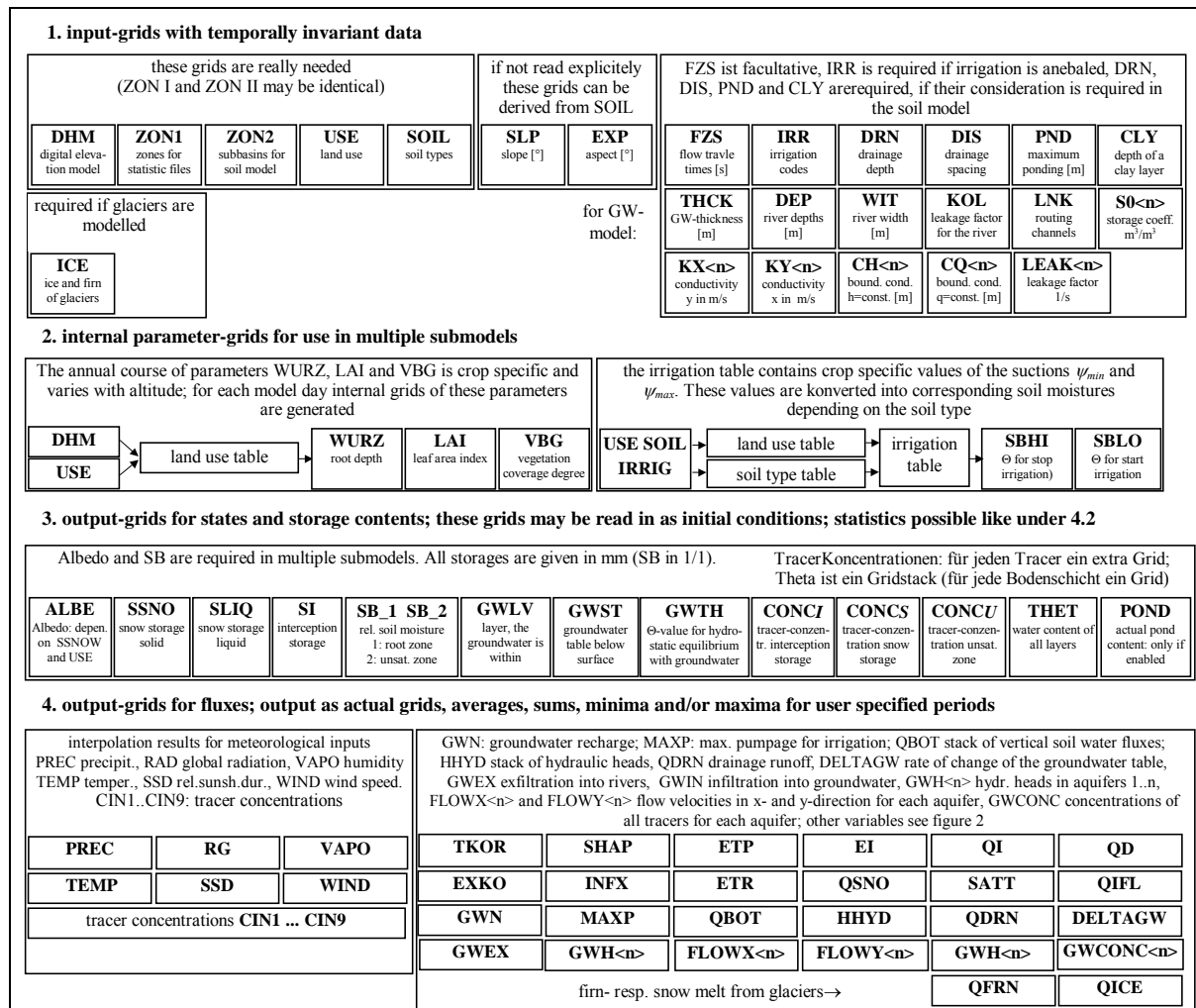


figure 3: input and output grids for WaSiM-ETH version 1 (RICHARDS-equation)

### 2.3.2 Time series

Time series are the meteorological station data or the preprocessed altitudinal gradients as well as the input concentrations of modeled tracers. If the input concentrations of tracer are constant in time, then it is also possible to read this concentration as a invariant grid like any other describing grid. After the interpolation these data can be written to the disk as grids and/or as time series of spatially averaged results. For

each variable it is possible to specify the temporal interval of storing the grid as well as the type of accumulation to be used (averages or sums). Also it must be specified if the output should be written for each subbasin or only for a subset given in a output list or if the output should be written only as a total average for the entire basin.

In addition to this possibilities WaSiM-ETH version 2 allows to write the detailed results of the unsaturated zone model of a single grid cell. Using this possibility there is a chance to check the model results at least for this single grid cell for the discrete layers. The model writes single point files for the water content values (THET), the fluxes between the layers (QBOT), the hydraulic heads (HHYD) and for the tracer concentrations (CONC1..CONC9) for each discrete layer of the soil at this point. Similarly, the groundwater model allows the storage of detailed results for a single grid cell (not necessarily the same as for the unsaturated zone).

### 2.3.3 Internal data flow

The following figures 4, 5 and 6 use different formattings for different data types. Input and output of time series is symbolized by *italic* fonts, output time series are additionally marked by a “Ø”-symbol, whereas point-output files are marked by a ●-symbol. Grids are symbolized by **bold** fonts, output grids are additionally marked by a “❖”-symbol. Grid-stacks are marked by a ☐-symbol. The abbreviations are explained in figures 2 and 3 and in table 5. Figure 4 shows the data flow for the maximum configuration of model version 1 using PENMAN-MONTEITH evaporation and with all submodels enabled. If any submodels are disabled the data flow skips these submodels. A flow chart for a minimum configuration for a continuity simulation is shown in figure 5. Snow model and interception model are disabled, the evaporation is estimated after HAMON.

The input grids required for the submodels are drawn at the left side of the chart. At the right side the possible output time series are shown (prefixed with a “Ø”). In the center column, the flow through the submodels is sketched. The arrows determine the direction of data flow or the data delivery.

*example:* evaporation scheme after PENMAN-MONTEITH

<i>parameter-grids (inputs):</i>	digital elevation model DHM, zone grid ZON1, radiation correction factors EXKO, leaf area index LAI, land use USE, vegetation coverage degree VBG, albedo ALBE
<i>meteorological input:</i>	temperature TKOR, wind speed WIND, vapor pressure VAPO global radiation RAD, relative sunshine duration SSD
<i>output (statistics):</i>	potential evaporation <i>ETP</i> , corrected radiation <i>RGEX</i>
<i>output (grids):</i>	potential evaporation (is input for snow model, interception model and soil model for estimating the real evaporation and the interception evaporation)

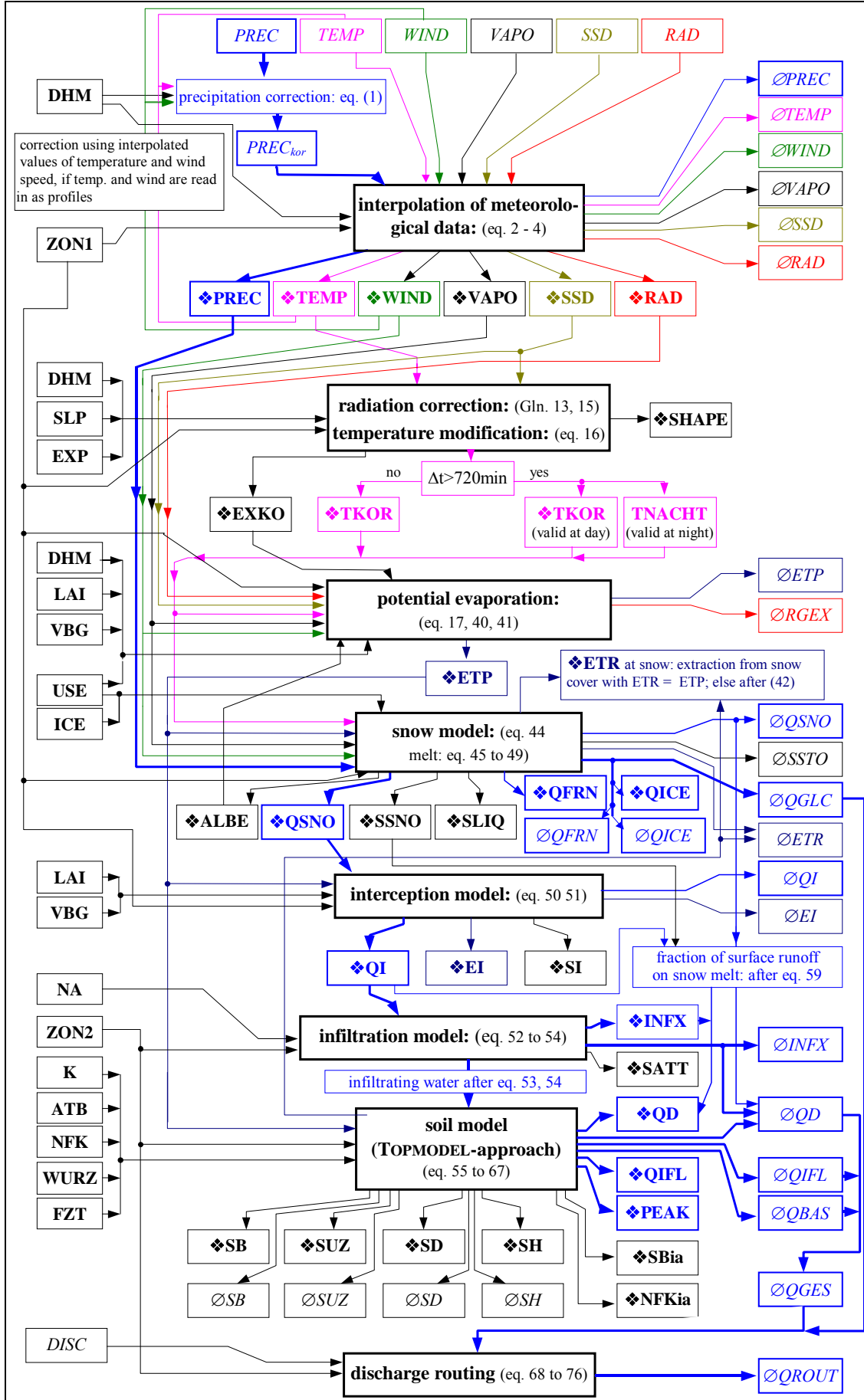


figure. 4: data flow chart for WaSiM-ETH version 1 (TOPMODEL-approach), symbol explanation see fig 2

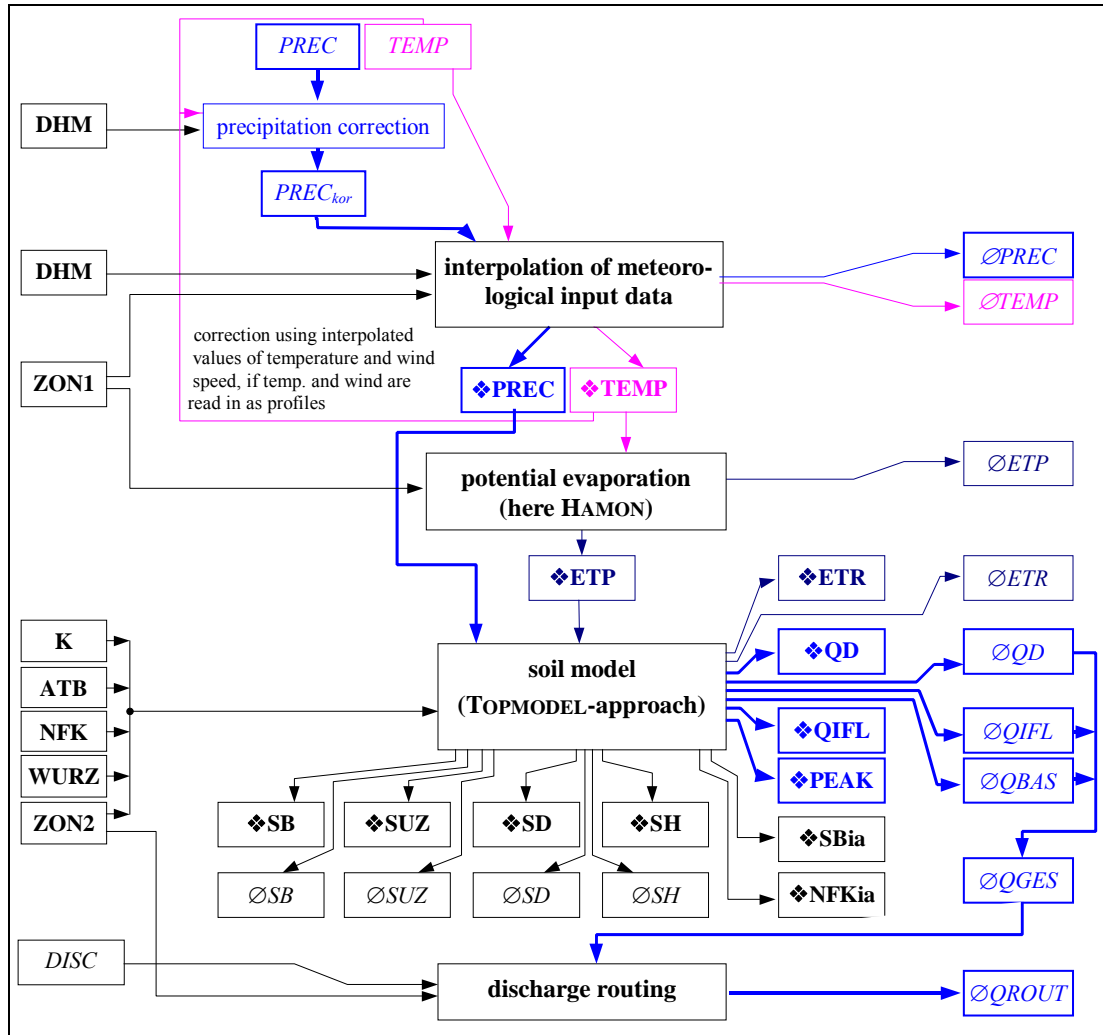


figure. 5: data flow chart for WaSiM-ETH Version 1 for a minimum model configuration

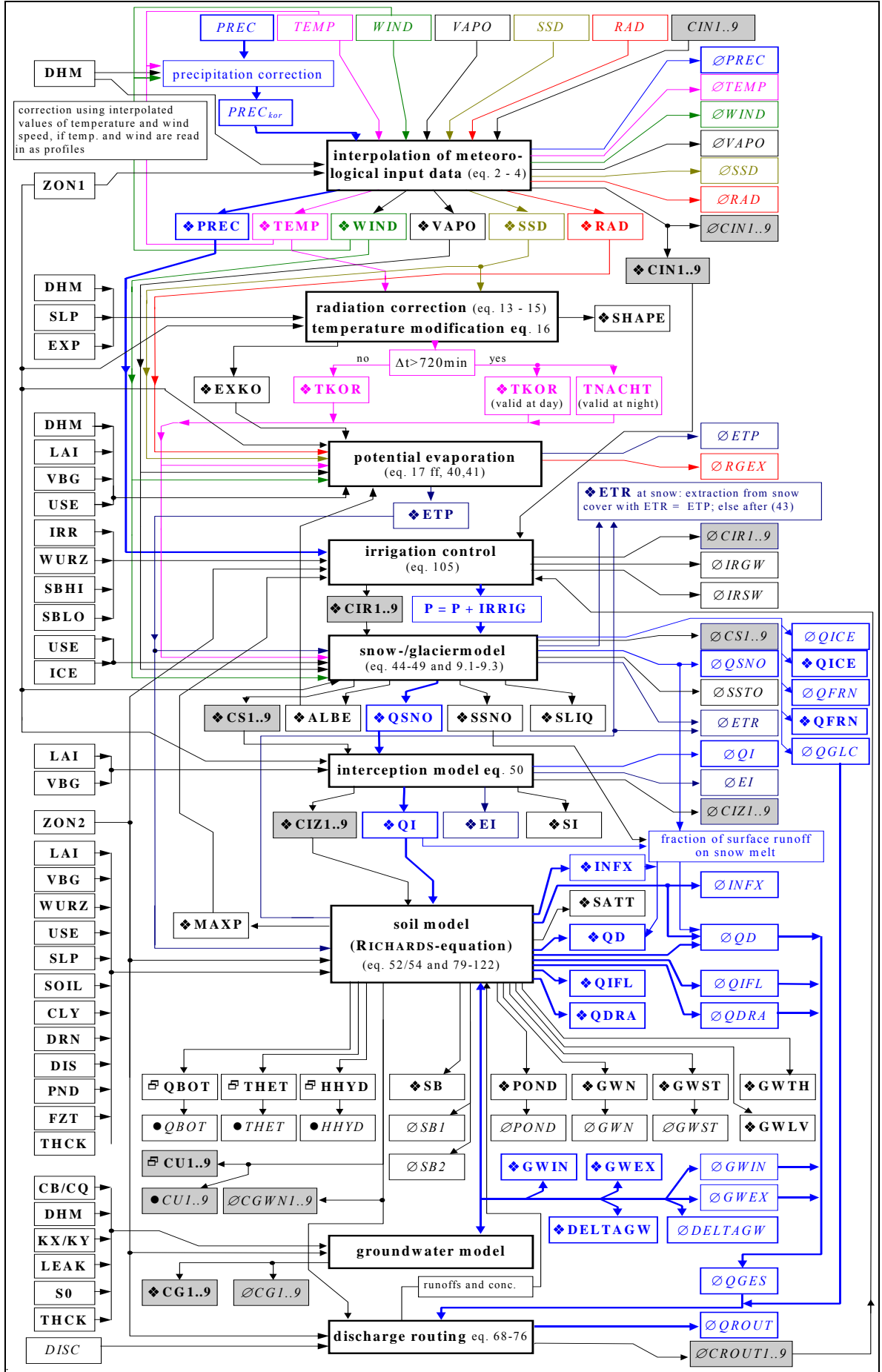


figure. 6: data flow chart for WaSiM-ETH version 2 (RICHARDS-equation), symbols see fig. 3 and table 5


Table 5: description of the symbols in figures 2 to 6

Sym.	data name	description
	<b>grids</b> (❖)	<b>bold font</b> in figures 2 to 6, output grids are marked with a ❖, parameter grids have no prefix
$c, \gamma$	<b>ATB</b> <sup>1</sup>	topographic index $\ln(a/\tan\beta)$
-	<b>CLY</b> <sup>2</sup>	depth of a clay layer in m below surface, if no clay layer: -9999 or 0
-	<b>CH&lt;n&gt;</b>	constant head boundary (groundwater model) one grid for each aquifer [m]
-	<b>CQ&lt;n&gt;</b>	constant boundary flux (groundwater model), in m/s perpendicular to the cells surface (recharge or extraction by pumping in m/s); one grid for each aquifer
$T_H$	<b>DEP</b> <sup>2</sup>	river depths [m] (for exfiltration from groundwater into rivers), only those grid cells which have a river on it have valid values, the other: -9999 or 0
-	<b>DHM</b>	digital elevation model
-	<b>DIS</b> <sup>2</sup>	horizontal spacing between drainage tiles in m (no drainage: -9999 or 0)
-	<b>DRN</b> <sup>2</sup>	depth of the drainage tiles in m below surface (no drainage: -9999 or 0)
$\hat{\Omega}$	<b>EXP</b>	aspect of the grid cell: 0..360°, north=0, east=90, south=180, west=270
-	<b>FZT</b>	flow travel times for surface runoff to the subbasin outlet in seconds
-	<b>ICE</b> <sup>2</sup>	glacier grid: code 1 for ice, 2 for firn, all other cells: nodata (-9999)
-	<b>IRR</b> <sup>2</sup>	codes for irrigation control (like land use or soil type codes), no irrigation: -9999 or 0
$K_S$	<b>K</b> <sup>1</sup>	hydraulic conductivities (generated internally or externally) in m/s
-	<b>KOL</b> <sup>2</sup>	colmation resistance of the river [ $s^{-1}$ ](for exfiltration from groundwater into rivers and vice versa), only those grid cells which have a river on it have valid values, the other: -9999 or 0
$K_X$	<b>KX&lt;n&gt;</b> <sup>2</sup>	horizontal saturated conductivity in m/s for each aquifer in x-direction in m/s
$K_Y$	<b>KY&lt;n&gt;</b> <sup>2</sup>	horizontal saturated conductivity in m/s for each aquifer in y-direction in m/s
-	<b>LAI</b>	leaf area index, interpolated from land use table entries, the actual data and the geodetic altitude (internally generated)
-	<b>LEAK&lt;n&gt;</b> <sup>2</sup>	leakage-factors for leakage between aquifers in 1/s
-	<b>LNK</b> <sup>2</sup>	routing channel links of the river network as used in the model
$n_a$	<b>NA</b> <sup>1</sup>	fillable porosity (internally generated) in 1/1
$nFK$	<b>NFK</b> <sup>1</sup>	available field capacity (generated internally or externally) in mm
-	<b>PND</b> <sup>2</sup>	maximum capacity of the pond storage in mm
$S_0$	<b>S0&lt;n&gt;</b> <sup>2</sup>	specific storage coefficient in $m^3/m^3$ for each aquifer 1..n
-	<b>SBHI</b> <sup>2</sup>	soil moisture threshold for start irrigation (internally generated) in 1/1
-	<b>SBLO</b> <sup>2</sup>	soil moisture threshold for stop irrigation (internally generated) in 1/1
$\beta_t$	<b>SLP</b>	slope angle in grad (0..90)
-	<b>SOIL</b> <sup>2</sup>	soil type, corresponding to the soil table (control file)
-	<b>THCK&lt;n&gt;</b> <sup>2</sup>	aquifer thickness 1..n in m
-	<b>USE</b>	land use codes, corresponding to the land use table in the control file
-	<b>VBG</b>	vegetation coverage degree, interpolated from land use table entries, the actual data and the geodetic altitude (internally generated)
$B_h$	<b>WIT</b> <sup>2</sup>	river widths [m] (for exfiltration from groundwater into rivers), only those grid cells which have a river on it have valid values, the other: -9999 or 0
$z_w$	<b>WURZ</b>	root depth, interpolated from land use table entries, the actual data and the geodetic altitude (internally generated)
-	<b>ZON1</b>	zone grid for interpolation, radiation correction, evaporation, interception, and snow model
-	<b>ZON2</b>	zone grid for soil model/infiltration, irrigation, groundwater, discharge routing
$\alpha$	❖ <b>ALBE</b>	albedo
-	❖ <b>CG1..9</b> <sup>2</sup>	tracer concentrations in the groundwater
-	❖ <b>CIN1..9</b> <sup>2</sup>	interpolated input tracer concentrations (for up to 9 tracers at a time)
-	❖ <b>CIR1..9</b> <sup>2</sup>	tracer concentrations in the irrigation water (for up to 9 tracers at a time)
-	❖ <b>CIZ1..9</b> <sup>2</sup>	tracer concentrations in the precipitation on the soil (for up to 9 tracers at a time)
-	❖ <b>CS1..9</b> <sup>2</sup>	concentrations in the snow melt

<i>Sym.</i>	data name	description
<i>EI</i>	❖ <b>EI</b>	interception evaporation in mm/time step
<i>ETP</i>	❖ <b>ETP</b>	potential evapo-transpiration in mm/time step
<i>ETR</i>	❖ <b>ETR</b>	real evapo-transpiration in mm/time step
<i>f<sub>d</sub></i>	❖ <b>EXKO</b>	result grid radiation correction factors
-	❖ <b>GWLV</b> <sup>2</sup>	index of the discretization layer the groundwater is located within
-	❖ <b>GWN</b> <sup>2</sup>	groundwater recharge in mm/time step
-	❖ <b>GWEX</b> <sup>2</sup>	exfiltration from groundwater into surface water in mm/ time step
-	❖ <b>GWIN</b> <sup>2</sup>	infiltration from routing channels into groundwater or into the unsaturated zone in mm/time step
-	❖ <b>GWST</b> <sup>2</sup>	groundwater table in m below surface (counts negative)
-	❖ <b>GWTH</b> <sup>2</sup>	mean water content of the discretization layer the groundwater is located within
<i>Q<sub>D,I</sub></i>	❖ <b>INF</b>	infiltration excess (after GREEN-AMPT) in mm/time step
-	❖ <b>MAXP</b> <sup>2</sup>	maximum pumpage amount from a grid cell for irrigation in mm/time step
-	❖ <b>NFKia</b> <sup>1</sup>	available field capacity in the inactive fraction of the soil (not rooted)
-	❖ <b>PEAK</b> <sup>1</sup>	surface peak flow in mm/time step
-	❖ <b>POND</b> <sup>2</sup>	content of the pond-storage in mm
<i>P</i>	❖ <b>PREC</b>	interpolated precipitation in mm/time step
<i>Q<sub>B</sub></i>	❖ <b>QBAS</b>	base flow in mm/time step
<i>Q<sub>D</sub></i>	❖ <b>QD</b>	surface runoff in mm/time step
<i>q<sub>drain</sub></i>	❖ <b>QDRA</b> <sup>2</sup>	drainage discharge in mm/time step
<i>Q<sub>FRN</sub></i>	❖ <b>QFRN</b>	melt of firn (glacier model, only if a ICE grid is used)
-	❖ <b>QI</b>	precipitation onto the soil from the interception storage in mm/time step
<i>Q<sub>ICE</sub></i>	❖ <b>QICE</b>	melt of ice (glacier model, only if a ICE grid is used)
<i>Q<sub>I</sub></i>	❖ <b>QIFL</b>	interflow in mm/time step
<i>M</i>	❖ <b>QSNO</b>	snow melt or runoff from the snow cover (or precipitation, if snow is melted away) in mm/time step
<i>R<sub>G</sub></i>	❖ <b>RAD</b>	interpolated global radiation in Wh/m <sup>2</sup>
-	❖ <b>SATT</b>	saturated areas after applying GREEN-AMPT
-	❖ <b>SB</b>	relative soil moisture in 1/1 (in version 1: root zone, in version 2: unsaturated zone)
-	❖ <b>SBia</b> <sup>1</sup>	soil moisture in the inactive soil fraction (WP<nFK but not in the root zone)
<i>SD</i>	❖ <b>SD</b> <sup>1</sup>	saturation deficit in mm
<i>SH</i>	❖ <b>SH</b> <sup>1</sup>	content of the interflow storage in mm
-	❖ <b>SHAPE</b>	result grid shadow
<i>SI</i>	❖ <b>SI</b>	content of the interception storage in mm
-	❖ <b>SLIQ</b>	water content of the snow storage (fraction of liquid water) in mm
<i>SSD</i>	❖ <b>SSD</b>	interpolated relative sunshine duration in 1/1
-	❖ <b>SSNO</b>	snow storage solid (fraction of frozen water) in mm
<i>SUZ</i>	❖ <b>SUZ</b> <sup>1</sup>	content of the unsaturated zone (pore volume > nFK)
<i>T</i>	❖ <b>TEMP</b>	interpolated temperature in °C
<i>T<sub>korr</sub></i>	❖ <b>TKOR</b>	corrected temperature (after radiation correction)
<i>T<sub>Night</sub></i>	❖ <b>TNIGHT</b>	Night temperature (at Δt > 720 min), like the uncorrected temperature
<i>e</i>	❖ <b>VAPO</b>	interpolated vapor pressure in hPa (or relative air humidity in 1/1)
<i>u</i>	❖ <b>WIND</b>	interpolated wind speed in m/s
<i>hydro-meteorological input data</i>		<i>italic font</i> in figures 4 to 6 without any prefixes (but in different colors)
-	<i>CINI..9</i> <sup>2</sup>	input-concentrations for modeled tracers (max 9, for each tracer one file) as station data (or, if they are constant in time, as a invariant grid)
-	<i>DISC</i>	observed discharge rates in mm/time step
<i>P</i>	<i>PREC</i>	station data of precipitation in mm/time step
<i>RG</i>	<i>RAD</i>	global radiation in Wh/m <sup>2</sup> as sum over the time step
<i>SSD</i>	<i>SSD</i>	relative sunshine duration in 1/1
<i>T</i>	<i>TEMP</i>	temperature in °C
<i>e</i>	<i>VAPO</i>	vapor pressure in mbar or hPa resp. relative air humidity



<i>Sym.</i>	<i>data name</i>	<i>description</i>
<i>u</i>	<i>WIND</i>	wind speed in m/s
	<i>statistic files</i> ( $\emptyset$ )	<i>italic font</i> in figures 4 to 6 and prefixed with a $\emptyset$ -symbol. These files contain spatially averaged results for separate zones and, if requested, for the entire model domain. Temporally accumulation can be done by summation or by averaging for a given number of time steps.
-	$\emptyset CGI..9^2$	tracer concentrations in the groundwater
-	$\emptyset CGWN1..9^2$	tracer concentrations in the groundwater recharge
-	$\emptyset CINI..9^2$	input concentrations for each tracer
-	$\emptyset CIR1..9^2$	tracer concentrations in irrigation water
-	$\emptyset CIZ1..9^2$	tracer concentrations in soil precipitation (outflow from the interception storage)
-	$\emptyset CROUT1..9^2$	tracer concentrations in the river network
-	$\emptyset CSI..9^2$	tracer concentrations in snow melt (or outflow from the snow cover resp. rain)
<i>EI</i>	$\emptyset EI$	interception evaporation in mm/time step
<i>ETP</i>	$\emptyset ETP$	potential evaporation in mm/time step
<i>ETR</i>	$\emptyset ETR$	real evaporation (without interception evaporation, but including snow evaporation)
$Q_{exf}$	$\emptyset GWEX^2$	exfiltration from groundwater into surface water in mm/time step
$Q_{inf}$	$\emptyset GWIN^2$	infiltration from surface water into the groundwater in mm/time step
<i>GWN</i>	$\emptyset GWN^2$	groundwater recharge in mm/time step
$h_{GW}$	$\emptyset GWST^2$	groundwater table in m below surface
$Q_{D,I}$	$\emptyset INFX$	infiltration excess in mm/time step
$IR_{GW}$	$\emptyset IRGW^2$	irrigation water taken from groundwater in mm/time step
$IR_{SW}$	$\emptyset IRSW^2$	irrigation water taken from surface water
$S_P$	$\emptyset POND^2$	content in the ponds in mm
$P$	$\emptyset PREC$	precipitation in mm/time step
$Q_B$	$\emptyset QBAS$	base flow in mm/time step
$Q_D$	$\emptyset QD$	surface runoff in mm/time step
$q_{drain}$	$\emptyset QDRA^2$	drainage runoff in mm/time step
$Q_{FRN}$	$\emptyset QFRN$	melt of firn (if glaciers are modeled → ICE-grid)
$Q_G$	$\emptyset QGES$	total runoff in mm/time step
$Q_{GLC}$	$\emptyset QGLC$	total melt from glaciers (if glaciers are modeled → ICE-grid)
-	$\emptyset QI$	outflow from interception storage = input into the soil model in mm/time step
$Q_{ICE}$	$\emptyset QICE$	melt of ice (if glaciers are modeled → ICE-grid)
$Q_I$	$\emptyset QIFL$	interflow in mm/time step
$Q_{out}$	$\emptyset QROUT$	routed runoff in mm/time step
$M$	$\emptyset QSNO$	outflow from the snow cover resp. rain (if snow storage is 0) in mm/time step
$RG$	$\emptyset RAD$	global radiation in Wh/m <sup>2</sup>
$RG_{eff}$	$\emptyset RGEX$	corrected global radiation in Wh/m <sup>2</sup>
$SB$	$\emptyset SB^1$	soil moisture in 1/1
$SB_1$	$\emptyset SB1^2$	soil moisture in the root zone in 1/1
$SB_2$	$\emptyset SB2^2$	soil moisture in the entire unsaturated zone in 1/1
$SD$	$\emptyset SD^1$	saturation deficit in mm
$SH$	$\emptyset SH^1$	interflow storage in mm
$SSD$	$\emptyset SSD$	relative sunshine duration in 1/1
$S_{snow}$	$\emptyset SSO$	snow storage in mm
$S_{UZ}$	$\emptyset SUZ^1$	storage content of the unsaturated zone
$T$	$\emptyset TEMP$	temperature in °C
$e$	$\emptyset VAPO$	vapor pressure in mbar or hPa (or: relative air humidity)
$u$	$\emptyset WIND$	wind speed in m/s
<b>Stacks (<math>\boxplus</math>)</b>		<b>bold font</b> in figure 6 (for WaSiM-ETH version 2 only), prefixed with a $\boxplus$ -Symbol
	$\boxplus CU1..9^2$	concentrations of all modeled tracers in all discretization layers
	$\boxplus HHYD^2$	hydraulic heads in all discretization layers
	$\boxplus QBOT^2$	fluxes between the discretization layers

<i>Sym.</i>	data name	description
	 <b>THET</b> <sup>2</sup>	water content in all discretization layers
	<i>point outputs</i> ( • )	ASCII-output files for state variables and fluxes in a single grid cell but for each soil-discretization layer
	<ul style="list-style-type: none"> <li>• <i>CUI..9</i> <sup>2</sup></li> <li>• <i>HHYD</i> <sup>2</sup></li> <li>• <i>QBOT</i> <sup>2</sup></li> <li>• <i>THET</i> <sup>2</sup></li> </ul>	concentrations of all modeled tracers in all discretization layers of the control point hydraulic Heads in all discretization layers of the control point fluxes between all discretization layers of the control point water content in all discretization layers of the control point

<sup>1</sup> only in WaSiM-ETH version 1 (TOPMODEL-approach)

<sup>2</sup> only in WaSiM-ETH version 2 (RICHARDS-approach)

### 3 Using WaSiM-ETH

This chapter describes how to use the Water Balance Simulation Model WaSiM-ETH. It deals with the possibilities in subdividing the catchment, with formats of input and output data and with the structure of the control file. WaSiM-ETH is available in German and in English, for each language there is one version using the TOPMODEL-approach (program name “wasim” or “wasimvc”) and one version using the RICHARDS-equation (program name “wasimuzr” or “wasimvcz”). The German version will not be supported anymore, so the preferred version should be the English one. It is nevertheless still possible to use the German version, because the only differences between the English and the German versions are the paragraph-headers in the control file and the messages during the program run. The German version can be generated using the same source codes simply by undefining a compiler symbol.

Because of the physical basis of many WaSiM-ETH components the model can generally applied to various basins in a wide range of environmental conditions all over the world. It is recommended to use at least observed runoff data for the model calibration. In addition, internal data like soil moisture, groundwater tables or snow water equivalents would be of advantage for the calibration process. The practical application should be done in a series of steps – in a first step the calibration should be carried out for the most important parameters for well observed subbasins. The most important parameters are usually the parameters for the soil model. Some parameters can be neglected or set to values of former model applications in similar conditions (like the parameters for the interception model, some snow melt parameters, macro pore and capillary rise parameters in the model version 1). Doing so, the number of parameters is reduced to a reasonable amount. The next step would be the calibration of these less important parameters. After a successful calibration of the observed subbasin, a regionalization of the parameters can be carried out using the same or similar parameter sets also for unobserved subbasins.

#### 3.1 Subdividing the basin horizontally

##### 3.1.1 Basic subdivision into a regular raster

The basic concept of the spatial distribution used in WaSiM-ETH is the subdivision of the model domain into a regularly spaced grid. This is a very effective subdivision for computational purposes and it offers easy opportunities for future model extensions. Also the development and the application of such a model is relatively easy because of the broadly available data bases in gridded formats like DEM's. Compared to other methods, e.g. a subdivision into triangles, a disadvantage of a regular grid is the inflexibility in following small but important landscape features like river beds, valleys or ridges. This is usually compensated by using effective parameters or by choosing a finer spatial resolution, which results often in a much more time consuming model run and in much more memory occupancy. However, both aspects will become more and more unimportant in the future considering the rapid development of the average computer performance also for desktop systems.

WaSiM-ETH requires a set of gridded input data. Besides a digital elevation model there are also land use data and soil type data needed. Most of the other data sets can be derived from these grids during the pre-processing or during the model initialization itself, like the data sets for aspect and slope angle. For a full functionality WaSiM-ETH needs at least the three mentioned data sets and in addition a grid containing the topographic index for the model version 1. For using the groundwater module in model version 2 additional grids describing the aquifer(s) are needed. For both model versions two zone grids are needed. These grids can be derived from the elevation model by using the topographical analysis offered by the program TANALYS.

For example, the topographic index used in model version 1 can be generated the following way:

- step 1: calculating the slope angles (data set 2) using the digital elevation model (data set 1);
- step 2: determining the flow directions for each grid cell (data set 3)

step 3: generating the flow accumulation grid (data set 4) using the flow directions

step 4: calculating the topographic index (data set 7) using the hydraulic conductivities (data set 5) and the soil thickness (data set 6)

This example points out, that the various grids are depending on another and cannot be generated independently. If for each of the 3 basis data sets a specific spatial resolution would be used, the data sets could be combined only after a resampling of all data. This should be done using a geographical information system GIS during the preprocessing. For WaSiM-ETH it is imperative that all grids are in the same format (same number of columns and rows, same coordinates, same cell spacing, same nodata value). The spatial resolution of the model grids must be chosen depending on the modeled basin. Usually mountainous basins need a finer resolution than low land basins. The resolution depends also on the computers capacity of installed memory and of processor performance

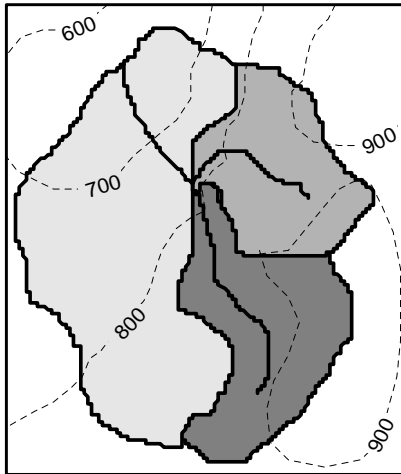
### **3.1.2 Delineating of the basin**

For modeling the water balance of a closed hydrologic basin it is recommendable to mark all cells outside of the basin with a nodata value. This delineation of the basin can be done by using digitized watershed data or by using standard GIS-functionality, also “Tanalys” is able to delineate watersheds from digital elevation models. The delineated watershed (or multiple watersheds, if using subbasins) are contained in the zone grid for the soil model.

### **3.1.3 Zonal statistics**

The spatial subdivision into grid cells is the first subdivision level. The second level is the subdivision into subbasins. This is done by grouping together all cells which are within the same subbasin. Each subbasin is marked by a unique code. The codes and therefore the subbasins are given in the zone grid. This subdivision level is interesting for getting balances and averaged values for subbasins as time series. All statistic output files use the second subdivision level as basis for their statistics.

It is possible to use two different zone grids. One zone grid is used for all submodels except for the submodels for soil, groundwater, irrigation, and discharge routing. The other zone grid is used for these 4 exceptions. Both zone grids may be but do not have to be identical. The first zone grid can contain zones of any shape, also unconnected cells with the same code can be a zone (e.g. elevation belts, land uses, soil types). The second zone grid is limited to zones which are subbasin-like (closed zones, linked by channels). This is because of soil model and groundwater model include lateral water transport effects and thus they depend more or less on a subbasin-like structure of the zone grid. To differentiate between both zone grids, the first zone grid is called zone grid whereas the second zone grid is referred to as sub-catchment grid.



a) Topographische Karte

Ausgehend von der topographischen Karte kann das Einzugsgebiet nach verschiedenen Kriterien unterteilt werden:

- nach Teileinzugsgebieten (Abb. 2.2 a/b)
- nach Höhenzonen (Abb. 2.2 c)
- nach Bodenarten (nicht dargestellt)
- nach Landnutzung (nicht dargestellt) usw.

x	x	x	x	x	x	x	x	x	x	x	x
x	x	x	x	1	1	x	x	x	x	x	x
x	x	1	1	1	1	2	2	x	x	x	x
x	x	1	1	1	1	2	2	2	x	x	x
x	1	1	1	1	2	2	2	2	x	x	x
1	1	1	1	1	3	2	2	2	2	x	x
1	1	1	1	1	3	2	2	2	2	x	x
1	1	1	1	1	3	3	3	3	x	x	x
x	1	1	1	1	3	3	3	3	3	x	x
x	x	1	1	1	1	3	3	3	x	x	x
x	x	1	1	1	1	3	3	3	x	x	x
x	x	1	1	1	3	3	3	x	x	x	x
x	x	x	x	x	3	3	x	x	x	x	x

Teileinzugsgebiet 1: 44 von 83 Zellen, Anteil: 0.530  
 Teileinzugsgebiet 2: 17 von 83 Zellen, Anteil: 0.205  
 Teileinzugsgebiet 3: 22 von 83 Zellen, Anteil: 0.265

eine typische Ausgabedatei mit den Teilgebietsmittelwerten z.B. des Basisabflusses sieht etwa so aus:

gebildeter Basisabfluss in mm je Zone (Bodenmodell)											
YY	MM	DD	HH	1.00	2.00	3.00	g.Mittel				
--	--	--	--	0.530	0.205	0.265	1.000				
84	1	1	1	0.042	0.039	0.040	0.0409				
84	1	1	2	0.039	0.037	0.038	0.0383				
84	1	1	3	0.037	0.035	0.037	0.0366				
84	1	1	4	0.036	0.034	0.035	0.0353				
84	1	1	5	0.034	0.032	0.033	0.0333				
.	.	.	.	.	.	.	.				
.	.	.	.	.	.	.	.				

Bsp.: Teilgebiet 1, Anteil 53%

b) Zoneneinteilung nach Teilgebieten

x	x	x	x	x	x	x	x	x	x	x	x
x	x	x	x	6	7	x	x	x	x	x	x
x	x	6	6	6	7	7	8	x	x	x	x
x	x	6	6	7	7	7	8	9	x	x	x
x	6	6	7	7	7	7	8	8	x	x	x
7	7	7	7	7	8	8	8	8	9	x	x
7	7	7	7	7	8	8	8	9	9	x	x
7	7	7	7	8	8	8	8	9	9	x	x
x	7	7	7	8	8	8	8	9	9	x	x
x	x	7	8	8	8	8	8	9	9	x	x
x	x	8	8	8	8	8	9	9	x	x	x
x	x	8	8	8	8	8	9	x	x	x	x
x	x	x	x	x	8	8	x	x	x	x	x

Höhenzone 6 (600...700m): 8 von 83 Zellen, Anteil: 0.096  
 Höhenzone 7 (700...800m): 29 von 83 Zellen, Anteil: 0.349  
 Höhenzone 8 (800...900m): 34 von 83 Zellen, Anteil: 0.410  
 Höhenzone 9 (900...1000m): 12 von 83 Zellen, Anteil: 0.145

Wird eine Einteilung nach Höhenzonen gewählt, sieht z.B. die Ergebnisdatei für den Schneespeicher so aus:

Schneespeicher in mm im Schneemodell											
YY	MM	DD	HH	6.00	7.00	8.00	9.00	Mittel			
--	--	--	--	0.096	0.349	0.410	0.145	1.000			
84	1	1	1	28.00	34.20	56.50	120.33	55.24			
84	1	1	2	19.90	35.40	75.00	130.34	63.91			
84	1	1	3	16.00	32.50	75.00	130.34	62.53			
84	1	1	4	17.00	38.00	85.40	144.20	70.82			
84	1	1	5	22.50	45.70	96.32	155.20	80.10			
.	.	.	.	.	.	.	.	.			
.	.	.	.	.	.	.	.	.			

Bsp.: Höhenstufe 9, Anteil 14.5%

c) Zoneneinteilung nach Höhenstufen

figure 7: different possibilities of subdividing a grid into zones

The maximum number of zones is limited to 8000, the zone codes may range between 1 and 32767. During the model run, for each internal state and for each flux statistic files can be written dependent on a control parameter in the control file.

Figure 7 shows the principle of the different subdivision levels. The statistic outputs can be averaged e.g. for elevation zones (fig. 7 c) or for subbasins (fig. 7 b). The codes for separate zones doesn't have to be sorted in ascent order without gaps. Only the uniqueness of each code is required (each code is an integer number). The codes in figure 7 b could also be 23, 646 and 101 instead of 1, 2 and 3, respectively. Only the column headers in the output files would change. The model sorts the codes internally in ascending order and it fills gaps by renumbering the zones internally in order to save memory and to reduce errors.

Figure 7 c shows the possibility to use another zone grid for the submodels of interpolation, evaporation, interception and snow. The results are averaged for each elevation belt and a statistic file is written containing these results in ordered format from lower to higher elevations. This could be of advantage for a comparison between observed and modeled snow water equivalents.

Another output possibility is the output of grids. Grids can be written for all modeled storages and fluxes. The disadvantage is the enormous requirement of disk space. Therefore there is the possibility to write temporally accumulated or averaged grids instead of writing all grids for all time steps. This may balance the information requirement against the available disk space.

The most important application of writing grids is the saving of all storage grids at the model end. The saved grids can serve as initialization conditions for another model run. Furthermore it is possible to save also minimum, maximum, mean and summed values of selected grids.

## 3.2 Input data (Preprocessing)

To run WaSiM-ETH, various spatial distributed data (grids), time series of meteorological and hydrological data and initial conditions are needed. The following chapters describe these requirements in detail.

### 3.2.1 Geographical Data

#### 3.2.1.1 Data requirements

Geographical data are temporally usually constant, spatial distributed data describing the properties of the basin. Table 3 gives an overview over the minimum data requirements.

Beside the data describing the groundwater, most of the spatial data can be derived from three basis data sets:

- the digital elevation model
- the land use data
- the soil type data

Usually the digital elevation model and also land use data are relatively exact and high resolution data whereas the soil types with their related soil properties and the aquifer data (conductivities, thickness, storage coefficients, leakage factors and salinity) are only more or less rough estimates.

Some data sets can be derived from other basis data. The slope angle and the aspect can be derived from the elevation model using any GIS or the topographical analysis software TANALYS. It's also possible to derive these data within WaSiM-ETH during initialization. This is done automatically if the required data sets are not specified within the control file. However, in some cases it may be better to avoid this internal derivation by specifying the names of the data sets in the control file, for example if the resolution is too coarse to get realistic slopes. It would then be better to use externally generated grids which were first generated using a much finer resolution and then were resampled to the required model resolution. Also some soil properties can either be put into the model as externally generated grids or as internally derived grids, e.g. the fillable porosity, the saturated conductivity and the available field capacity. However, this

works only for model version 1. In version 2 all soil properties are generated internally using the soil table and it's van Genuchten parameters for the matching codes from the soil type grid.

### 3.2.1.2 File formats

In WaSiM-ETH grids can be used in binary or in ASCII-format. But there are a number of tools, e.g. the program TANALYS and also all grid-utilities, which only can use the binary format. In order to exchange grids between different computer platforms (DOS  $\longleftrightarrow$  UNIX) or to exchange grids with other software, e.g. with Arc/Info, an ASCII-format is required:

rows 1..6: grid header (number of columns and rows, coordinates of the lower left corner, cell size, nodata value)

the following rows will be the grid data from top left to down right like in a book:

ncols	7					
nrows	12					
xllcorner	680500					
yllcorner	222200					
cellsize	2000					
nodata value	-9999					
-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	586	559	595	601	585
584	-9999	-9999	-9999	-9999	-9999	-9999
-9999	449	-9999	-9999	454	511	551
-9999	561	529	509	498	487	499
521	523	523	534	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	345	234
567	453	456	478	789	576	482
123	-9999	1252	1211	876	564	825
-9999	-9999	234	1246	-9999	-9999	-9999

The binary format is structured similar to the ASCII-format. All values are stored in single precision (4 bytes in most computer systems, 6..7 digits precision). Records 1 to 6 are the same data like in the ASCII-Format. Then 6 additional records describing the grid statistics follow:

Records 1..6: like in the ASCII-format

Records 7..12:

- count of valid cells (without nodata-values)
- minimum value of all valid grid cells
- maximum value of all valid grid cells
- sum of all valid grid cells
- mean value of all valid grid cells
- standard derivation of all valid grid cells

After this header all cells of the grid are following in the same order like in the ASCII-format, i.e. from the top left cell to the lower right cell in a row by row order. For converting the formats one into the other there are the programs ASCIGRID and GRIDASCII. The described formats are the same for all system platforms. However, there are internal differences in storing binary numbers dependent on the processor layout. Also ASCII-data are stored in different ways on different systems, but ASCII-formats can be exchanged between different systems using e.g. ftp-programs with an automatic conversion of carriage returns/line feeds. To exchange binary data, they first have to be converted into ASCII-data, then the exchange can be done and thereafter a re-converting on the target platform should be done.

### 3.2.2 Meteorological data

Meteorological data as station data are stored in text files. The first 5 rows contain describing data like station coordinates and altitudes and station names. The station files are organized by columns, i.e. each station is represented by a column in the file. The first 4 data columns contain the date and time of the data. The columns appear in the order year – month – day – hour. The hour may either be the number of

the actual hour, then e.g. „1984 1 2 5“ is the time step from 4:00 to 5:00 at the 2<sup>nd</sup> of January in 1984, or the hour may be the start of the hour, then „1984 1 2 5“ would be the time step from 5:00 to 6:00 at the 2<sup>nd</sup> of January in 1984. For daily time steps the hour can also be set to either 0 or 24. All station files must share the same hour range. The type of the hour range is coded in the control file as fourth parameter in the [output\_interval]-section. The parameter must be zero, if the range is 1...24 (or 24 for daily time steps and longer) and it must be the duration of a time step in minutes, if the hour range is 0...23 (or 0 for daily time steps and longer), e.g. 60 for hourly time steps and 1440 for daily time steps. As delimiters between the columns the tab stops are recommended. Also spaces are allowed. Multiple spaces and tabs are interpreted as a single delimiter. The year can be written in the format YYYY or in the format YY, which is assumed to be valid for the 20<sup>th</sup> century only, so YY is internally extended to 19YY.

description of meteorological/hydrological input data:

Row 1: comment

Row 2: after „yy mm dd hh“: altitudes for each station (int or float ), basin area for hydrologic data

Row 3: after „yy mm dd hh“: x-coordinates of the stations (integer or floating point values)

Row 4: after „yy mm dd hh“: y-coordinates of the stations (integer or floating point values)

Row 5: after „yy mm dd hh“: short identifier for each station e.g. 6-chars

beginning with Row 6: actual date (e.g. 1984 01 01 24), then for each station one value (real or integer) separated by at least one space or tab stop.

For run WaSiM-ETH in the optimum configuration, the following data sets are needed:

- air temperature [°C]
- precipitation [mm/time step]
- wind speed [m/s]
- global radiation [Wh/m<sup>2</sup>]
- vapor pressure [mbar] or relative air humidity [1/1]
- relative sunshine duration [1/1]

The units given above are the units the data are expected by WaSiM-ETH, however it is possible to apply a correction factor in order to scale the input data (see also the example below and the description of the control file).

Example of a file containing meteorological station data (temperatures of ANETZ-station for 1984):

temperatures (*0.1C)														
YY	MM	DD	HH	437	440	463	515	536	750	779	1407	1590	2490	2690
YY	MM	DD	HH	688700	738430	693770	723750	710500	718500	747940	638130	783580	744100	780600
YY	MM	DD	HH	282800	273950	230780	210580	259820	248000	254600	205970	187480	234900	189630
YY	MM	DD	HH	Schaff	Guetti	Waeden	Glarus	Taenik	Rietho	St.Gal	Napf	Davos	Saenti	Weissf
84	1	1	1	17	6	25	28	37	49	39	33	-13	-31	-34
84	1	1	2	13	1	26	25	42	51	45	31	-10	-29	-27
84	1	1	3	8	-5	22	23	49	60	47	32	-5	-25	-25
84	1	1	4	8	-5	14	27	41	36	47	42	-2	-23	-18
84	1	1	5	6	-8	10	22	21	13	38	53	1	-17	-20

Meteorological input data may also be interpolated by altitude dependent regression. This is done during the preprocessing using the programs “regress” (a graphical DOS-program) or “regr” (a text based version of “regress”). The program “regress” generates ASCII-output which is also directly useable by WaSiM-ETH. The model recognizes the format by analyzing the header. If the first characters are “jr mo tg st” (separated by single spaces!), then an ASCII-format is assumed, otherwise a binary format is assumed. Both formats have the same structure except that the binary format does not have a header. The binary file contains all data as single precision values (4 byte per value), the first four data columns for date and time are stored as long integers (4 byte). An example of such a regression file is given below:



jr	mo	tg	st	a[1]	b[1]	igu	a[2]	b[2]	igo	a[3]	b[3]	af	bf[1]	bf[2]
84	1	1	1	-17.954	0.0000	0.0	-17.954	0.0833	969.2	117.001	-0.05591	51.126	-7.21913E-05	-7.45598E-05
84	1	1	2	-29.724	0.0000	0.0	-29.724	0.1048	872.6	105.243	-0.04981	39.8687	-6.95074E-05	-8.48521E-05
84	1	1	3	-46.493	0.0000	0.0	-46.493	0.1350	822.3	104.321	-0.04835	30.1048	-8.14217E-05	-7.85187E-05
84	1	1	4	-34.818	0.0000	0.0	-34.818	0.1050	970.4	117.607	-0.05205	13.8404	-3.43135E-05	-0.000102529
84	1	1	5	-23.550	0.0000	0.0	-23.550	0.0680	1275.7	140.102	-0.06021	11.6198	-1.80593E-05	-9.44962E-05
84	1	1	6	-44.244	0.0000	0.0	-44.244	0.1083	1103.7	140.419	-0.05898	-26.0965	-6.67409E-07	-7.49243E-05
84	1	1	7	-25.346	0.0602	820.0	-17.291	0.0504	1400.0	125.643	-0.05163	-7.7026	-1.50661E-05	-2.84531E-05
84	1	1	8	-17.163	0.0387	820.0	-40.929	0.0677	1400.0	122.876	-0.04930	-17.3485	2.76033E-06	-7.57734E-06
84	1	1	9	-28.146	0.0677	820.0	-7.093	0.0420	1400.0	114.150	-0.04457	-7.1713	-2.59317E-05	-9.54698E-06
84	1	1	10	-14.794	0.0514	820.0	-6.893	0.0418	1400.0	106.073	-0.03888	14.4881	-3.8284E-05	-7.03115E-06
84	1	1	11	-22.906	0.0934	820.0	32.876	0.0253	1400.0	138.656	-0.05017	-15.7421	-1.69895E-05	2.13564E-05
84	1	1	12	-18.494	0.1048	820.0	49.093	0.0224	1400.0	163.018	-0.05894	-5.4302	-2.60689E-05	2.40711E-05

description:

jr, mo, tg, st: this rows contain date and hour, for which the following gradients are valid (each a 4 byte long integer). separated each by **only one space**, hours must be given like in station data files as 0...23 or 1...24 consistent to the station files which are used at the same time

a[1], a[2], a[3]: constants of the linear equation  $y = a + bx$  for the lower, the middle and the upper line.

igu: upper validity limit of the lower regression line

igo: upper validity limit of the middle regression line and lower validity limit of the upper regression line.

af, bf[1], bf[2] regression parameter of the areal regression of the residuals in  $z = a + bf[1] \cdot x + bf[2] \cdot y$

### 3.2.3 Hydrological Data

Hydrological data are time series of observed discharges at river gauges. These data are required in order to calibrate the model and to estimate the model efficiency. The format is identical with the format for meteorological station data, except for the second row which does not contains the altitude but the catchment area of a gauging station. This is important if the discharges (in m<sup>3</sup>/s) are converted into specific discharges (in mm/time step) using the program QTOSPEND. The unit of the discharge file must be mm/time step.

### 3.2.4 Initial conditions (storage contents)

Initial conditions may be very important for the model results, especially if applying the model to a short time period or to an arid or semi arid region. Therefore there is the possibility in WaSiM-ETH to read storage or reservoir content values as initialization grids. Because these grids can also be written at the end of a model run, they can be used as initialization for following model runs. If no initialization grids are available, the internal states are initialized using constant values taken from the control file. Initialization grids and result grids (actual states and reservoir contents) must have the same names and they must be located in the same directory. The initialization grids will be overwritten by the result grids. Grids which can be used for initialization are (in brackets: filenames as used in the sample control file):

grids for multiple submodels

- soil moisture storage (SB) [1/1] (only for model version 1)
- albedo (ALBE) [1/1]

soil model (version 1 with TOPMODEL-approach)

- saturation deficit (SD) [mm]
- storage content of the unsaturated soil zone (SUZ) [mm]
- interflow storage (SIF) [mm]
- soil moisture in the inactive soil storage (SBia) [1/1]
- available field capacity in the inactive soil storage (nFKia) [mm]
- areas which are actually saturated by infiltration after GREEN and AMPT (SATT) [-]
- fraction of the soil moisture storage which is in hydraulic contact to the groundwater (SSP) [-]

soil model and groundwater model (version 2 with RICHARDS-approach)

- areas which are actually saturated by infiltration after GREEN and AMPT (SATT) [-]
- water content off all discretization layers (THET → Stack) [1/1]
- hydraulic heads (potential) of all discretization layers (HHYD → Stack) [m a.s.l.]
- water content in ponds (POND) [mm]
- groundwater table (GWST) [m below surface]
- mean water content of the layer, the groundwater is located within (GWTH) [1/1]
- index of the layer, the groundwater is located within (GWLX) [-]
- concentrations of modeled tracers for the unsaturated zone (e.g. NACUNSAT → Stacks) [1/1]
- groundwater heads for all aquifers (GWH1..GWHn) [m a.s.l.]
- concentrations of modeled tracers for the groundwater (e.g. NACGROU1...NACGROU3)

interception model

- content of the interception storages (SI) [mm]
- concentrations of modeled tracers for the interception storage (e.g. NACINTER, only in version 2)

snow model

- snow fraction in the water equivalent (SSNO) [mm]
- liquid fraction in the water equivalent (SLIQ) [mm]
- concentrations of modeled tracers for the snow storage (e.g. NACSNOW\_, only in version 2)

If no grids are read in, the storage contents are set to initial values. For snow and interception storage this values are zero. The storage content values of the unsaturated zone and of the saturation deficit can be specified as subbasin specific values in the control file (only version 1). The soil storage is initialized to 1.0 (100 % soil moisture). Using model version 2, the soil moisture is initialized for each discretization layer with a water content corresponding to an hydraulic equilibrium with the groundwater (fluxes are zero). The groundwater table is assumed to be in a depth of 20 % of the soil column (specified by the number of layers and layer thickness for each soil type).

For the unsaturated zone it is also possible to read in only the grid containing the groundwater table. Using this grid the initial values for the hydraulic heads in the unsaturated zone are estimated using the hydraulic equilibrium (no flux) condition. This also determines the water content values and the layer index and the mean water content of the layer, the groundwater is located in. All other initialization grids are set to default values (tracer concentrations, pond storage, saturated areas a.s.o.).

### 3.3 Output data

During the model run a number of output files are created controlled by the specifications in the control file. Possible outputs are either grids describing the spatial distribution of fluxes or states accumulated/averaged over a given time period or statistical output files containing spatially averaged values of fluxes, storage contents or states as time series.

#### 3.3.1 Grids

If and how often and in which accumulation a grid is stored to the disk is specified in the control file for each possible output grid. There is a write parameter for each grid containing of 3 digits. The first digit (most significant digit MSD) controls the output of minimum and maximum grids, the second digit controls the output of accumulated or averaged grids and the last digit (lowest significant digit LSD) controls the output of actual storage or flux grids.

The names of the output grids are constructed by taking the first 4 characters of the original name and appending the next characters depending on the type of output. For example, minimum or maximum grids are stored using the same name as the original grid but replacing the extension by “.min” or “.max”.

Possible values for the first of the three digits are:

- 0 or no first digit at all: neither minimum nor maximum grid are written
- 1 a minimum grid will be written when the model finishes the run (for each grid cell the minimum value for this grid cell of all time steps of the model time is stored)
- 2 a maximum grid will be written when the model finishes the run (for each grid cell the maximum value for this grid cell of all time steps of the model time is stored)
- 3 minimum and maximum grid are stored

The code for the second digit of the grid write code can be as follows. The name of the resulting grid is generated from the first four characters of the original grid name followed by 4 digits for year and month or month and day if using codes 2, 3, 6, and 7 or 4 and 8, respectively.

- 0 or no second digit (write code has only 1 digit): no sum and/or average grid is written
- 1 a sum grid with accumulated values over the entire model time is written at the end of the run
- 2 sum grids with accumulated values are stored for each model year at the end of the year
- 3 sum grids with accumulated values are stored for each model month at the end of the month
- 4 sum grids with accumulated values are stored for each model day at the end of the day
- 5 a grid with averaged values over the entire model time is written at the end of the run
- 6 grids with temporally averaged values are stored for each model year at the end of the year
- 7 grids with temporally averaged values are stored for each model month at the end of the month
- 8 grids with temporally averaged values are stored for each model day at the end of the day

The last digit of the grid write code which is responsible for the output of actual grids can have one of 6 possible values. If the grid code consists only of one digit, this digit is the parameter which controls the output of actual grids and no minimum, maximum, sum or average grids are written at all. Possible values are:

- 0 no output of actual grids
- 1 the grid is written in each time step, it always gets the same name, old grids are overwritten
- 2 the grid is stored with unique names for each time step. The grid name is generated using the original grid name and the actual model date (e.g. the precipitation for the 14<sup>th</sup> of January, 7:00 o'clock will get the name "prec0114.007" if the original grid name (from the control file) is e.g. "precm500.grd")
- 3 only the last grid of the model run will be stored. This is the way to get initialization grids for following model runs. The grid name will be the same as the original grid name in the control file
- 4 a new grid is written after a the end of a model day. The grid has always the same name. This is similar to code 1, in fact if using a time step of 1 day it is the same, but if the time step is shorter, e.g. 1 hour, this reduces write access to the disk
- 5 like 4, but the grids are stored using unique names like for write code 2 (but only one grid per day)

If the write code would be 353, the following grids would be written to the disk:

- a minimum grid for the entire model run, e.g. "temppm500.min", annual minimum temperature
- a maximum grid for the entire model run, e.g. "temppm500.max", annual maximum temperature
- a grid containing temporally averaged values for the entire model period, e.g. "temppm500.mit", annual mean air temperature
- a grid containing the last actual values, e.g. "temppm500.grd", the actual value of the last model time step (e.g. of 31<sup>st</sup> of December if the model run stopped at the end of the year)

If the write code would be 352 instead of 353, the actual grids would be stored at each time step. The grid names would range from "temp0101.001" to "temp1231.024". The disk space requirements are enormous, so this writecode is recommended only for short periods or when looking for errors in the data.

### 3.3.2 Zonal averages

Figures 4 and 6 give an overview about the data sets which can be stored as statistic files. Generally most of the data which can be stored as grids also can be stored as statistic files. The statistic files are very useful for calibrating and validating the model. They can easily be imported into any graphics software to draw time series of modeled fluxes and states. The file format is similar to the format of the meteorological input data. Columns are separated by tab stops. The first row contains the zone number the column is valid for, the second row contains a data description, and the third row contains the relative fractions of each subbasin/zone on the entire watershed area. Depending on the write code for the statistic file there will be also an additional last column which contains the average values for the entire model domain. Using the programs RESAGG, RESAGGR, RESMEAN and RESEMANI the statistic files may be aggregated to in order to get balances for month's and years (e.g. aggregated sum of evaporation, runoff and precipitation). In combination with the initial and final storage content values it is possible to check the balance of the model.

example of a statistic result file:

temperature interpolated using regression from temper84.out, zones from m500.ezg																
YY	MM	DD	HH	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	tot average
--	--	--	--	0.238	0.079	0.042	0.185	0.075	0.035	0.043	0.009	0.186	0.002	0.053	0.047	1.0000
84	1	1	1	1.993	2.766	3.274	3.154	4.934	5.010	4.140	4.849	4.669	4.748	5.138	3.442	3.516
84	1	1	2	1.832	2.794	3.422	3.298	5.056	4.750	3.951	5.326	4.738	5.282	5.142	3.198	3.512
84	1	1	3	1.650	2.862	3.620	3.474	5.320	4.818	4.047	5.744	5.007	5.834	5.340	3.280	3.611
84	1	1	4	1.278	2.252	2.906	2.851	5.215	5.550	4.768	5.022	4.898	4.778	5.484	4.178	3.398
84	1	1	5	0.632	1.286	1.727	1.699	3.461	4.729	4.410	3.131	3.673	2.963	4.027	4.526	2.414
84	1	1	6	0.604	1.577	2.241	2.242	4.966	6.215	5.557	4.475	4.859	4.153	5.519	5.274	3.121
84	1	1	7	0.325	0.857	1.214	1.189	2.622	3.700	3.623	2.388	2.819	2.256	3.068	3.936	1.809

Which results for what subbasin are written in which temporal accumulation is defined by a write code following the file name in the control file. The write code has 2 parts. The first digit controls the type of aggregation and the selection of considered zones. The second part defines the temporal aggregation.

explanation of the codes:

0...1000 no output

1<nnn> spatial average *only for the entire basin*, temporally averaged over <nnn> time steps

2<nnn> spatial average for all zones *and* for the entire basin, temporally averaged over <nnn> time steps

3<nnn> spatial average *only for the entire basin*, temporally summed up for <nnn> time steps

4<nnn> spatial average for all zones *and* for the entire basin, temporally summed up for <nnn> time steps

5<nnn> spatial average only for the zones listed in the output list section of the control file and for the entire basin, temporally averaged over <nnn> time steps

6<nnn> spatial average only for the zones listed in the output list section of the control file and for the entire basin, temporally summed up over <nnn> time steps

examples:

2001 one output value (spatially averaged value) per time step for all zones and for the entire model domain,

2004 spatially averaged outputs for all zones and for the entire model domain, temporally averaged over 4 model time steps (e.g. output at hours 4, 8, 12 a.s.o. if running in hourly time step)

4024 spatially averaged outputs for all zones and for the entire model domain, temporally summed up over 24 time steps (e.g. daily evaporation if running in an hourly time step)

5012 spatially averaged output only for the zones listed in the output list section of the control file and for the entire model domain, temporally averaged over 12 time steps

3120 spatially averaged output only for the entire basin, temporally summed up over 120 time steps

Especially if there are many zones or subbasins coded in the zone grid the amount of the output data would be too large for usually available hard disks. If in a model run with 100 zones all files would be

written using the code 2001 for a model year of 8760 time steps (hourly resolution), an amount of some hundred Megabytes would be stored to the disk! Therefore it may be better to store only those results in such high resolutions which are really important for the postprocessing. Also the selection of a reasonable output list (using e.g. only 20 of the 100 zones) will reduce the amount of data considerably.

### 3.4 Temporal scheme

#### 3.4.1 specifying the time step

The model uses a constant time step for all modules and for the entire model run. The modules must be informed about the duration of a time step. This is done by specifying the time step duration in the control file for each submodel. To avoid errors due to different time steps in the same model run (the model would break with an error message), the time step should be declared as a variable in the control file. The time step depends usually on the availability of the meteorological input data. The time step must be identical for all meteorological input data sets.

WaSiM-ETH uses the date and time of the first meteorological data set to be interpolated for comparison with all other data sets. If, for instance, the first data set has the date and time “1984 01 01 2” and the second data set reads “1984 01 01 02”, the model will cancel the run with an error message.

#### 3.4.2 Organization of the space/time/submodel-loops

WaSiM-ETH has to manage the call of various modules for a large number of cells for a series of time steps, so there are at least 3 loops to coordinate: the time loop (running time step after time step), the loop in space (running the model for each grid cell) and the module loop (applying each module).

Because WaSiM-ETH should be able to model the discharge continuously it is reasonable to let the time loop be the loop which embraces all the other loops. Thus the model is applied time step by time step to all grid cells. The module loop is located in-between the time loop and the space loop. This organization is especially important if lateral connections between the cells, like in the groundwater module, have to be considered, so that it is imperative to have the space loop as the inner loop. The user does not have to be concerned about this organization, but it may be of interest at this point.

#### 3.4.3 Modeling over very long times

Although there is no limitation of the model time it may be reasonable to split the simulation time into a series of shorter model runs. The initial conditions for each simulation are stored as final states of the previous run. For each model run, a separate control file is needed. WaSiM-ETH can then be called by typing:

```
wasim <control file 1> [<control file 2>] [<control file 3>] ...
```

The second simulation starts at the state where the first simulation stopped, similarly the third run starts there where the second run stopped and so on. It is required that the names of grids which are transferred from one run to the next run must be identical in all control files. Another possibility would be to call all model runs separately:

```
wasim <control file1>  
wasim <control file2>  
wasim <control file3> a.s.o.
```

In opposition to the first call version the second version needs additional checks for successful model runs, because an error in one of the model runs should result in not running the following runs. This can be done by checking the return code of the model, which will be zero if no errors occurred during the model run. On the other hand, the second call variant offers the possibility to copy or store or archive the result files (also the grids, which will be overwritten by the next model run) before starting the next run.

Both versions allow the mixing of model runs using different resolutions in time and space and even different basins. It may be necessary to run the model in a time step of e.g. one day until a given date is reached and to restart the model using a much shorter time step, e.g. for modeling a flood event.

### 3.5 Controlling the model run by control file

#### 3.5.1 structure of the control file

The control file contains all information required for the model run. There are three types of information:

1. parameters controlling the model run (grid write codes, statistic file write codes, output lists a.s.o.)
2. file names and path names for the input and output streams
3. hydrologic model parameters, property tables (for land use, soil types, tracers), static model parameters

The three parameter types are usually mixed in the control file, because it is organized in a thematic way. The control file is subdivided into separate sections, each section responsible for a submodel or for a separate theme, like for an interpolation parameterization or for the land use table. The syntax of the control file is shown in the following example:

```
# comment (optional)

[first section]
<first Entry>    # comment (optional)
<second Entry>   # comment  --- " ---
<third Entry>    # comment  --- " ---

# comment (optional)
# comment  --- " ---

[second section]
<first Entry>    # comment (optional)
<second Entry>   # comment  --- " ---
# comment (comments are removed in a first interpretation step)
<third Entry>    # comment (optional)
<fourth Entry>   # comment  --- " ---

[third section]
<first Entry>    # comment  --- " ---
<second Entry>   # comment  --- " ---
.
.
```

*the syntax of the control file:*

Sections start with a section header consisting of key words and embraced by brackets “[...]”. The model is able to identify a section by the section header only. Although the sections may appear at any position in the control file it is recommended to organize the order of the sections following e.g. the order of the submodels. Within the sections the order of the entries is fixed. Between entries no empty rows are allowed but there may be comment rows, which must start with a “#”-character. Each row consists of one entry which may consist itself of one or more parameters, file names or combinations of both. Following the parameters and/or file names of an entry, a comment may follow which doesn’t necessarily have to start with a “#”. The comment has to be separated by the last parameter by a space or by a tab stop.

Between sections, comments may appear in any number. Such comments should also be started using the “#”-character. Only within sections comments must be prefixed with a “#”. Comments which start with a “#” are removed from the control file during the model initialization, so also comment rows within sections are removed.

Because some parameters or parts of file names may appear very often in the control file it is possible to declare up to 200 symbols. These symbols will be replaced by their content during the translation of the control file. The syntax of a symbol declaration is:

```
$set $symbol = symbol_value
```

The declaration starts with a “\$set” at the start of a row (without preceding spaces or tabs). The symbol itself starts also with a Dollar-sign “\$”. The symbol name is followed by an equal sign which is followed by the symbol value which is always interpreted as a character string. Each of the four elements of such a declaration must be separated by the others by at least one space or tab stop. This symbol may then be used instead of the symbol value itself at any location in the control file after the declaration. The symbol value may contain also symbols, which are replaced by their value if the symbol which contains the other symbol is declared.

A symbol in the control file must be separated from the preceding and trailing text by spaces or tabs. If it is required that the symbol values of two or more symbols are interpreted as parts of a longer entry, e.g. a path, a file name and a file extension, this would result in a string including some spaces which should not be there. Therefore it is possible to link the symbol values using the concatenation operator “//” which is used instead of a separator.

Example for the replacement of symbols in the control file:

```
# 1st declaration for the path of the input data
$set $path = c:\wasim\input\

# 2nd declaration
$set $grid = m500

# 3rd declaration
$set $elevationmodel = $grid//.dhm
.
.
# somewhere in the control file there is a section containing only
# the name of the name of the elevation model

[elevation_model]
$path//$elevationmodel # name of the digital elevation model
```

The value of the symbol \$elevationmodel is m500.dhm, because after declaring \$elevationmodel the symbol “\$grid” is replaced by its value “m500” and linked to the extension “.dhm” because of the “//”-operator. If a “\$”-character is found in the control file without a “\$set” command at the start of the row, the application of a symbol is expected (this means also, that no other “\$”-characters are allowed in the control file except for declaring or applying symbols). If the symbol is not listed in a symbol table which is generated in a first scan of the file, the model stops with an error message.

Parsing the section [elevation\_model] the program finds the text \$path//\$elevationmodel. The operator “//” marks the end of a first symbol “\$path”. This symbol is replaced by its value. Afterwards the row looks like this (without the removed comment):

```
c:\wasim\input\//$HoeHENmodell1
```

A second scan of the row gives the result that there is another symbol \$HoeHENmodell1 used. Replacing this symbol by its value and linking the value to the preceding text, the complete row would be:

```
c:\wasim\input\m500.dhm
```

This row does not contain any further symbol. This replacement scheme is applied to all rows of the control file before starting the model initialization. The translated control file is stored in a file named like the control file but extended by “\$\$\$”. This file contains no symbols and no comments (only comments starting with a “#” were removed). The translated control file is the one which is used for model initialization. Using the English version of WaSiM-ETH also the sections in the control file are named in English whereas the German version uses German section headers.

*sections in the control file:*

A typical control file contains the following sections (names listed here are for the English version only):

common sections:

```
[output_list]
[output_interval]
[coordinates]
[elevation_model]
[zone_grid]
[standard_grids]
[variable_grids]
[model_time]
[meteo_data_count]
[meteo_names]
```

names of the section headers for interpolations like defined in the section [meteo\_names]:

```
[temperature]
[wind_speed]
[precipitation]
[sunshine_duration]
[global_radiation]
[air_humidity]
[vapor_pressure]
[tracer_input_1]
.
.
[tracer_input_9]
```

now the names of the submodels:

```
[precipitation_correction]
[radiation_correction]
[evapotranspiration]
[snow_model]
[ice_firn]
[interception_model]
[infiltration_model] (required only in WaSiM-Version 1)
[soil_model]         (required only in WaSiM-Version 1)
[unsatzon_model]     (required only in WaSiM-Version 2)
[irrigation]         (required only in WaSiM-Version 2)
[groundwater_flow]  (required only in WaSiM-Version 2)
[routing_model]
```

If the routing module uses reservoirs, for each reservoir a section with an abstraction rule must be present (x stands for the number of the reservoir and should not appear as “x” in the real control file):

```
[abstraction_rule_reservoir_1]
.
.
[abstraction_rule_reservoir_x]
```

and finally the sections containing land use dependent and soil type dependent properties:

```
[landuse_table]
[soil_table]
[substance_transport] (required only in WaSiM-Version 2)
[irrigation_table]    (required only in WaSiM-Version 2)
```

The following description of the sections uses the syntax **<entry>** to express, that instead of **<entry>** the real value of **entry** should appear in the control file. Instead of **<latitude>** the control file should contain e.g. 48.4 if the basin is located at this northern latitude.

section [output\_list]

```
<number x of subbasins, an output should be generated>
<code of the first one of the subbasins to be considered in the output files>
.
.
<code of the x-th subbasin of the output list>
```



section [output\_interval]

<number <n> of time steps; the output to the screen is done every <n> time steps>  
 <1=warn if no station is within search radius for IDW-interpolation >  
 <output of the routed discharge : 0=in mm/time step, 1=in m<sup>3</sup>/s>  
 <time shift between the notation of the hour and the end of the hour, 0 if using 1..24 for hourly time steps, number of minutes of a time step if using 0..23>

If the time step is e.g. 24 hours and the hour should be given as 0, then the time shift will be 1440 (minutes). If the hour in daily time steps is given as 24, then the last parameter must be 0.

section [coordinates]

<geographic latitude>  
 <geographic longitude>  
 <meridian, to which the local time is referring: east: 0..+180; west: 0..-180>  
 <time shift of meteo data against the local time>

The parameter for the time shift considers a shift of the true mean local time against the time which is connected to the meteorological data. For example, a basin at 7.5° eastern longitude has a time shift of – 0.5 hours against the official local time, thus the true mean local time can be determined by subtracting 0.5 hours from the official local time. This time shift parameter is also intended to be used for correcting a different notation for the time of the meteorological data, e.g. if the meteorological data refer to UTC (0° longitude). Then, a basin at 7.5° eastern longitude would have a time shift of +0.5 hours against the notation of the time of the meteorological data, so if the meteo data would have the time 12:00, they are valid for 12:30 of official local time. In addition it happens that the notation of the meteo data refers to a shifted time period, e.g. if the notation is for 12:00, then the data are valid for 11:40 to 12:40. Using the above example this would mean, that the notation 12:00 is valid for the time between 12:10 to 13:10 of the mean true local time (11:40 UTC is 12:40 local official time which is 12:10 of mean true local time). Thus, a time shift factor of 1.16, rounded down to 1.0, would be appropriate here.

section [elevation\_model]

<name of the grid containing the **digital elevation model**>

section [zone\_grid]

<name of the grid containing the **zone grid**>

This zone grid is valid for all modules or submodels except for the soil module, the infiltration module and the routing module in model version 1 respectively the irrigation module, the soil module, the groundwater module and the routing module in model version 2. The zone grid for these exceptions will be defined in the section [standard\_grids], there called subbasin-grid. All grids read in during the initialization are checked on the basis of the zone grid if the check-parameter is set to 1 (in section [standard\_grids] and [variable\_grids]): All cells which are nodata in the zone grid are also set to nodata in the checked grids. Then it is checked if there are nodata values in the other grids where are valid values in the zone grids. In such cases this nodata value is replaced by the next valid value of the checked grid (where the corresponding value of the zone grid is also no nodata value!). This nearest neighbor must be within a distance of 10 cells around the invalid cell, if not, the model gives an error messages and stops its execution. All replacements are logged in a file “modell.log”. If there are very much replacements, this file growth rapidly and it should be deleted from time to time in order to not waste disk space (the file is not newly created when the model starts but appended if it exists already).

section [standard\_grids]

<count 'n' of following grids>  
 <1. **standard grid**> <identification (meaning) in plain text, e.g. slope> <fill code>  
 <2. **standard grid**> <identification (meaning) in plain text> <fill code>  
 .  
 .

```
<n. standardgrid> <identification meaning in plain text> <fill code>
```

Standard grids are e.g. the slope angle (SLP), the aspect angle (EXP), the land use (USE), the soil types (SOIL), the available field capacity (NFK, only version 1), the topographic index (ATB, model version 1), the zone grid for the soil model (ZON2), the depth's of a clay layer (CLY, version 2), the depth's and the horizontal spacing of drainage tiles (DRN and DIS, only model version 2), the irrigation codes (IRR, version 2), the flow travel times (FZT) a.s.o. All of these grids are in the format described in chapter 3.2.1. They must have the same number of rows and columns, the same coordinates of the lower left corner and the same cell size as the zone grid (ZON1), otherwise the model stops its execution. Grids which are not needed by the model do not have to be listed here. If there are any not needed grids, they are read in and nothing is done with them, they are only occupying memory. If required, some grids can be derived internally (like slope, aspect, field capacity, conductivity, fillable porosity a.s.o.). The identification (meaning) using plain text is very important for the communication between the submodels. The names of the example control file are not allowed to change, otherwise the model would not find the right grids. The fill code controls the cross-checking of grid values against the zone grid. If the fill code is one, the check is performed, if the code is 0, no check is done. This is required for grids which contain only some valid cells, like the grids containing river depth (DEP) and river width (WIT), river leakage factors (KOL), routing links (LNK) but also for the boundary condition grids in the groundwater module (BH<n>, BQ<n>; n=1..number of aquifers). If all these grids would be checked, there would be rivers at all grid cells in the groundwater module all grid cells would have constant heads and constant fluxes as boundary conditions.

#### section [variable\_grids]

```
<count 'n' of variable grids (soil moisture, albedo)>
<1st variable grid> <identification (meaning) in plain text> <fill code>
<write code for 1st Grid>
<read parameter for 1st Grid>
<2nd variable Grid> <identification (meaning) in plain text> <fill code>
<write code for the 2nd Grid>
<read parameter for the 2nd Grid>
```

The write codes for the grids are described in chapter 3.3.1. The read parameter is 0, if the grid should not be read from the disk but should be internally generated from e.g. land use or soil type. For instance, the albedo may be generated from the land use (albedo values are defined for each land use in the land use table) and the field capacity or the conductivities may be derived from the soil types (each soil type is listed together with its properties in the soil table). The explanations of the write code and the read parameter apply also to all grids in the following submodel sections.

#### section [model\_time]

```
<start hour 1...24>
<start day 1..last day of a month>
<start month 1...12>
<start year 1900 ... >
<end hour 1...24>
<end day 1..last day of a month>
<end month 1...12>
<end year 1900...>
```

The start time is looked for in all meteorological input files. If this time can not be found in one of the input files, the model stops and gives an error message. The start time must be a time before the end time, otherwise the model would run to eternity. If the end time is found in one of the meteorological input files or if one of these files has reached eof, the model stops its execution and writes all buffers and grids to the hard disk.

#### section [meteo\_data\_count]

```
<number 'x' of meteorologic data sets to be interpolated>
```

The number of meteorological inputs specified here must be represented by a matching number of sections for interpolations as well as by a matching number of meteo names in the next section.

#### section [meteo\_names]

```
<1-st header: header of the 1st section for interpolation parameters>
.
.
.
<x-th header: header of the x-th section for interpolation parameters>
```

Each of the first <x> listed headers (<x> is the number of meteo files defined in the section [meteo\_count]) must be matched by a section header for interpolation parameters. This means that the headers could be named in any way as long as the header list matches the headers of the separate sections. But in fact there are some meteo names which have to be written absolutely in the same way, the models expects them: precipitation, temperature and wind\_speed are looked for explicitly in the precipitation correction module. So it would be wise to leave the section headers of the interpolators like they are in the sample control file. The interpolation sections are described here for the temperature. All other sections for interpolations are identically structured.

section [temperature] (here as an example only for temperature, would be similarly for other meteorological data)

```
<interpolation method 1 idw, 2 regress, 3 idw+regress, 4 Thiessen >
<name of the file with station-data>
<name of the file with regression parameters>
<name of the grid containing results of the interpolation>
<write code for the Grid (see chapter 3.3.1)>
<scaling parameter for matching the required units>
<statistic file for subbasin averaged time series>      <write parameter>
<error threshold for input data: -threshold-1 < valid values < +trheshold+1>
<weighting power of the inverse distance using idw-interpolation>
<weighting of the idw-interpolation on the result if method = 3>
<maximum distance of a station to an interpolation location for idw-interpolation>
<lower limit of the interpolation results>
<replacement value for results below the lower limit>
<upper limit of the interpolation results>
<replacement value for results above the upper limit>
<scenario use: 1 = use scenario data, 0 = do not use>
<type of scenario application, 1 = add, 2 = multiply, 3 = percentile change>
<number of scenario cells n>
<1-st Scenario cell: x-coordinate y-coordinate 12 monthly values>   e.g.:
        699000 235000  5.3  5.8  4.8  3.7  3.5  3.2  3.2  4.8  5.0  4.3  2.7  4.0
<2-nd Scenario cell>
.
.
.
<n-th Scenario cell>
```

If no scenarios should be used, the value of “**scenario use**” should be set to “0”, the following rows are then skipped.

#### section [precipitation\_correction]

```
<run the module 1 = yes, 0 = no>
<snow-rain-threshold temperature for corrections>
<b1 in: Pcorr = P(a1u + b1) for rain>
<a1 in: Pcorr = P(a1u + b1) for rain>
<bs in: Pcorr = P(asu + bs) for snow>
<as in: Pcorr = P(asu + bs) for snow>
```

#### section [radiation\_correction]

```
<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
```

```

<method: 1=only correction factors for radiation, 2 = also modify temperature>
<write code for the grid containing corrected temperatures>
<scaling factor for temperature modification x * -1.6 ... +1.6, e.g. 5>
<result grid with correction factors for direct shortwave radiation>
<write code for the correction factor grid>
<result grid for shapes; code 1 for shape, 0 for no shape (if sun is shining)>
<write code for shape grid>
<interval count, temporal spacing for generating new shape grids: 1 = each time step, 3 =
every third time step a.s.o.>
<splitting of the time step, e.g. at time step=24 hours, a split value if e.g. 24 means,
shapes and correction factors are calculated for each hour and then the weighted average
is calculated>

```

#### section [evapotranspiration]

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<method: 1=Penman-Monteith, 2=Hamon, 3=Wendling, 4=Haude (2, 3 and 4 only daily values)>
<12 correction factors for Hamon-evaporation (monthly values)>
<12 correction factors for Haude-evaporation (monthly values)>
<"coast"-factor for Wendling-evaporation>
<result grid for pot. evapotranspiration in mm/dt>
<write code for the grid of pot. evaporation>
<statistic file of the pot. evapotranspiration> <write parameter>
<result grid for real evapotranspiration in mm/dt>
<write code for the grid of the real evaporation>
<statistic file for real evapotranspiration> <write parameter>
<4 coefficients "cr" of a 3rd-order polynom for modeling the global radiation
by using sunshine duration data>
<4 coefficients "cs" of a 3rd-order polynom for modeling the sunshine duration
by using global radiation data>
<extinction coefficient for shortwave radiation> <variation during the annual course>
<recession constant of a e-function describing the altitude-dependence of the
temperature differences between mean day and mean night temperatures>
<12 monthly values of maximum temperature differences (clear sky) between mean day and
mean night temperatures, valid at sea level>
<fraction of the temperature difference between day and night to be added to the 24-hour
mean temperature in order to get the temperature for the bright day>
<variation of this fraction during the annual course, winter +, summer - >

```

#### section [snow model]

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<method 1=t-index, 2=t-u-index, 3=Anderson, 4=Anderson extended>
<transition zone for mixed rain/snow around TOR ± <transition zone> in Kelvin>
<TOR threshold temperature rain/snow (each 50 % probability) in grad Celsius>
<T0 threshold temperature for melt>
<CWH storage capacity of snow for water relative fraction, e.g. 0.1>
<CRFR coefficient for refreezing used in methods 3 and 4 >
<C0 degree-day-factor mm/d/C used in method 1>
<C1 wind independent melt factor in mm/d/C, used in method 2>
<C2 wind dependent melt factor in mm/(d C m/s) for method 2>
<z0 roughness length in cm for energy balance methods, not used>
<RMFMIN minimum radiation melt factor in mm/d/C for combination methods 3 or 4>
<RMFMAX maximum radiation melt factor in mm/d/C for combination methods 3 or 4>
<albedo albedo for fresh snow -> new since January 15, 1999>
<result grid with runoff of the snow cover, is the input for the following module>
<write code for this grid>
<statistic file snow runoff in mm/dt> <write parameter>
<result grid for snow storage solid in mm >
<write code for this grid>
<result grid for snow storage liquid in mm>
<write code for this grid>
<statistic file total snow storage> <write parameter>
<read parameter for snow grids: 1 = read snow storage grids solid/liquid from disk,
0 = generate newly and initialize with 0>

```

section [ice\_firn]

```

<method 1=t-index, 2=t-index with radiation correction after Hock(1998)>
<T_ice degree-day-factor ice in method 1 in mm/°C/day>
<T_firn degree-day-factor firn in method 1 in mm/°C/day>
<T_snow degree-day-factor snow in method 1 in mm/°C/day>
<MF melt factor in method 2 in mm/°C/day>
<a_ice radiation coefficient of ice in method 2>
<a_snow radiation coefficient of snow and firn in method 2>
<k_ice storage parameter for ice melt for internal glacier-routing in h>
<k_firn storage parameter for firn melt for internal glacier-routing in h>
<k_snow storage parameter for snow melt for internal glacier-routing in h>
<Q_ice initial values of runoff from the ice-Single Linear Reservoir SLR in mm/dt>
<Q_firn initial values of runoff from the firn-SLR in mm/dt>
<Q_snow initial values of runoff from the snow-SLR in mm/dt>
<result grid : firn melt>
<write code for this grid>
<statistic file firn melt> <write parameter>
<result grid : ice melt>
<write code for this grid>
<statistic file ice melt> <write parameter>
<statistic file total routed melt firn+ice+snow> <write parameter>

```

section [interception\_model]

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<result grid : outflow out of the interception storage = input into the soil model>
<write code for this grid>
<statistic file outflow (soil precipitation)> <write parameter>
<result grid interception evaporation>
<write code for this grid>
<statistic file interception evaporation> <write parameter>
<result grid storage content of the interception storage>
<write code for this grid>
<layer thickness of the water on the leaves, multiplied with LAI -> SImax>
<read parameter interception storage: 1 = read from disk, 0 = generate
internally and initialize with 0 (empty storage at model start)>

```

section [infiltration\_model]

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<result grid with infiltration excess in mm>
<write code for this grid>
<statistic file for infiltration excess> <write parameter>
<result grid surface saturation with code 1 = saturation at the end of the time step,
0 no saturation>
<write code for this grid>
<fraction of re-infiltrating water on the infiltration excess>

```

section [soil\_model] (for WaSiM-ETH version 1 with TOPMODEL-approach)

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<method: 1 without delayed base flow, 2 with delayed base flow, -> never use method 2!!>
<result grid Saturation deficit SD>
<write code for this grid>
<result grid storage for unsaturated zone SUZ, dynamic limit: saturation deficit>
<write code for this grid>
<result grid storage for interflow SIF, SD_QI_lim is the upper limit, see parameters>
<write code for this grid>
<result grid soil moisture in the inactive soil storage SBia>
<write code for this grid>
<result grid available field capacity in the inactive soil storage nFKia>
<write code for this grid>

```

```

<result grid, saturated soil partition SSP, fraction of soil which is in hydraulic
    contact to the groundwater>
<write code for this grid>
<result grid surface runoff QD>
<write code for this grid>
<result grid interflow QI>
<write code for this grid>
<result grid peak flow (maximum surface runoff for the entire modeled time) PEAK>
<statistic file surface runoff in mm/dt> <write parameter>
<statistic file interflow in mm/dt> <write parameter>
<statistic file base flow in mm/dt> <write parameter>
<statistic file delayed base flow in mm/dt> <write parameter> (if method = 2)
<statistic file total runoff in mm/dt> <write parameter>
<statistic file soil storage in 1/l> <write parameter>
<statistic file drain storage in mm> <write parameter>
<statistic file interflow storage> <write parameter>
<statistic file saturation deficit in mm> <write parameter>
<subbasin Codes e.g.: 1 2 3 4 5 6 7 8 9 10 11 12>
<recession parameter m in meter; per subbasin>
<correction factor for transmissivities  $T_{\text{kor}}$  one per subbasin>
<correction factor for  $K_s$ -value  $K_{\text{kor}}$  (vertical drainage) per subbasin>
<SLR-recession constant Surface runoff kD in h, per subbasin>
<maximum interflow storage  $SH_{\text{max}}$ , corresponds to saturation deficit>
<SLR-recession constant interflow kH in h, per subbasin>
<SLR-recession constant delayed base flow  $k_{\text{RLS, QBB}}$  in h, per subbasin, only in method 2>
<maximum deep percolation in saturated soils mm/h per subbasin, used only in method 2>
<initial value delayed base flow QBB in mm/dt per subbasin, used only in method 2>
<initial value content of the unsaturated zone in mm, per subbasin>
<initial value saturation deficit in  $n \cdot nFK$ , important for base flow! per subbasin>
<threshold precipitation for macro pore runoff Pgrenz, precipitation above this
    threshold goes directly into the drain storage! per subbasin>
<scaling factor for capillary rise rk, per subbasin>
<fraction on effective snow melt QDsnow which will be surface runoff, per subbasin>
<read parameter 1 = read storage grids from disk, 0 = generate internally and initialize
    with 0 (SUZ-Storage, SSP saturated soil partition); saturation deficit will be
    initialized with  $nFK$ >

```

#### section [unsatzon\_modell] (only for WaSiM-ETH-version 2 with RICHARDS-approach)

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<method: 1 simple, do not use, 2 with finite-difference-method → strongly recommended>
<controlling surface interaction: 0 = no, 1 = only exfiltration, 2 = in/exfiltration>
<controlling surface storage in ponds: 0 = no ponds, 1 = using ponds>
<controlling artificial drainage: 0 = no artificial drainage 1 = using drainage>
<controlling clay layer: 0 = no clay layer, 1 = assuming a clay layer>
<sat. hydraulic conductivity of the clay layer (is used for the clay layer only)>
<statistic file drainage discharge in mm per zone> <write parameter>
<statistic file groundwater depth> <write parameter>
<statistic file mean groundwater recharge per zone> <write parameter>
<statistic file rel. soil moisture 0..0.5 m per zone> <write parameter>
<statistic file rel. soil moisture 0..1 m per zone> <write parameter>
<statistic file infiltration excess> <write parameter>
<statistic file ponding water storage content> <write parameter>
<statistic file surface runoff> <write parameter>
<statistic file interflow> <write parameter>
<statistic file baseflow (if no gw-module is on)> <write parameter>
<statistic file total discharge> <write parameter>
<statistic file infiltration from rivers, only if gw-module enabled> <write parameter>
<statistic file exfiltration into rivers, only if gw-module enabled> <write parameter>
<result stack name, actual soil water content for all soil levels>
<write code for this stack>
<result stack name, hydraulic heads>
<write code for this stack>
<result stack name, geodetic altitudes of the soil levels (lower boundaries)>
<write code for this stack>

```

```

<result stack name, outflows from the soil levels>
<write code for this stack>
<result grid, groundwater depth>
<write code for this grid>
<result grid, theta in GWLEVEL>
<write code for this grid>
<result grid, groundwater recharge>
<write code for this grid>
<result grid, level index of groundwater surface (index of the layer)>
<write code for this grid>
<result grid, drainage flows>
<write code for this grid>
<result grid, code 1=saturation at interval start, 0 no sat.>
<write code for this grid>
<result grid, infiltration excess in mm (surface discharge)>
<write code for this grid>
<result grid, surface runoff>
<write code for this grid>
<result grid, Interflow>
<write code for this grid>
<result grid, baseflow> (equal to DELDAYW, if no gw-module is on it is baseflow)
<write code for this grid>
<result grid, groundwater infiltration from rivers (only if gw-module is on)>
<write code for this grid>
<result grid, groundwater exfiltration into rivers (only if gw-module is on)>
<write code for this grid>
<result grid, content of ponding storage>
<write code for this grid>
<row-index of a control cell> <column-index of a control cell>
<name of a file containing the flows between the layers of the control point>
<name of a file for soil moisture as theta values of the layers of the control point>
<name of a file for the hydraulic heads of the layers of the control point>
<range for subbasin codes>
<storage coefficient for surface flow>
<storage coefficient for interflow>
<drainage density>
<k in qb = Q0 * exp(-k/z) (only valid, if no groundwater flow is calculated)>
<Q0 in the above formula (only valid, if no groundwater flow is calculated)>
<fraction of surface runoff on snow melt>
<read parameter soil model: 2 read only groundwater table, 1 = read all storage grids
from disk, 0 = generate internally>

```

#### section [irrigation] (only for WaSiM-ETH version 2 with RICHARDS-approach)

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<statistic file irrigation water from groundwater> <write parameter>
<statistic file irrigation water from surface water> <write parameter>

```

#### section [groundwater\_flow] (only for WaSiM-ETH version 2 with RICHARDS-approach)

```

<run the module 1 = yes, 0 = no>
<length of a time step in minutes>
<solving method: 1=Gauss-Seidel-iteration, 2=PCG (not yet implemented)>
<max.number of iterations for iterative solving method 1>
<max. changes between two iterations for iterative solving method (1)>
<Alpha for estimation of central differences 0.5 = Crank-Nicholson Method, 0 = fully
explicit, 1 = fully implicit>
<factor for accelerating the iteration if using iterative method (successive
over[/under] relaxation SOR) negative number: automatic estimation of SOR>
<read parameter groundwater model: 1=read all grids from disk, 0=generate internally>
<number of aquifers>
<x y coordinates of a control point for all fluxes and for each aquifers>
<filename of a file containing the flows between the aquifer of the control point>
<filename for a grid for hydraulic heads for aquifer 1>
<output-parameter for this grid>
<filename for a grid for flow velocity in x-direction for aquifer 1>

```

```
<output-parameter for this grid>
<filename for a grid for flow velocity in y-direction for aquifer 1>
<output-parameter for this grid>
```

. a.s.o. for each aquifer three file names and write codes

#### section [routing\_model]

```
<run the module 0 = no, 1=yes, using modeled discharges, 2=yes, using observed
    discharges as inflows into a channel link (better for calibration)>
<length of a time step in minutes>
<min. specific runoff> <max. specific runoff> <log. partitioning of runoffs> <splitting
of the time step> the first three parameters are for generating a discharge table
<statistic file with routed discharges> <write parameter>
<file name with observed runoff data>
<number x of observed runoff time series in the file used for comparing with
    modeled data>
<code of the 1-st considered subbasin> <matching column in the runoff file>
<code of the 2-nd considered subbasin> <matching column in the runoff file>
<code of the 3-rd considered subbasin> <matching column in the runoff file>
.
.
<code of the x-th considered subbasin> <matching column in the runoff file>
<time offset in time steps the efficiency calculation waits at model start>
<1-st routing description>
<2-nd routing description>
.
.
<n-th routing description>
```

Routing descriptions are explained in detail in chapter 3.5.2. The first empty line following the “time offset” parameter is recognized by WaSiM-ETH as the end of all routing descriptions. So if no routing should be done, this can be reached by simply inserting a line feed (and under Windows a carriage return) after the time offset parameter.

#### section [landuse\_table]

```
<number of different land uses described in the following table>
<code> <name> <albedo  $\alpha$ > <monthly values surface resistances  $r_c$  in s/m> <4 Julian days
describing the annual course of following parameters> <leaf area indices LAI at these
days> <eff. heights  $z_0$  at these days> <vegetation coverage VBG at these 4 days> <root
depth  $z_w$  at these 4 days> <parameter  $\rho$  for root density distribution> <suction for ETP-
reduction>
example.:
3 Wald 0.15 90 90 85 75 60 60 60 60 60 80 90 90 110 150 250 280 2 10 10 2 3 10 10 3 0.8 0.9 0.9 0.8 1.5 3.45
(one row per land use, see also sample control file)
```

#### section [soil\_table]

```
<number of soil types described in the following table>
<Code> <Name> <nFK Vol.%> <mSB Vol.%> <kS-value m/s> <suction  $\psi$  at wetting front> <read
parameter for the following parameters: 1=van-Genuchten, 2=look-up-table> < $\Theta_{sat}$ > < $\Theta_{res}$ >
< $\alpha$ > < $n$ > <number of discretization layers  $lv$ > <layer thickness  $dz$ > <maxratio  $k_0/k_u$ > <re-
cession of saturated conductivity with depth  $ck$ >
example:
```

```
5 Loam 12.9 35.2 2.89E-6 352 1 .43 .078 3.60 1.56 31 .3333 90 .4
```

for WaSiM-ETH version 1 (TOPMODEL) only the first 6 parameters are required:

```
5 Loam 12.9 35.2 2.89E-6 352
```

(one row per soil type, see sample control file)

#### section [irrigation\_table] (only for WaSiM-ETH-version 2 with RICHARDS-approach)



<number of irrigation codes>

<Code> <name> <method> 0 no irrigation., 1=after table, 2=irrigation series, 3=after demand> <origin of the water> 1=GW, 2=river> < $\psi$ start for method 3> < $\psi$ stop for method 3>

if method=1, the following table follows in the same row like the other parameters:

<number x of irrigation events> <month\_1> <day\_1> <amount\_1> <month\_2> <day\_2>  
<amount\_2> ... <month\_x> <day\_x> <amount\_x>

example:

19 horticulture 1 1 3 0.3 5 5 15 80 6 1 80 6 15 80 7 1 80 7 15 80 8 1 80

Only the first 5 events will be applied in the above example, because the number of events is set to 5. The water will be taken from the groundwater, because the origin-parameter is set to 1.

If method=2, the following series description follows in the same row like the other parameters:

starting from <start\_month> <start\_day> with <start\_amount> mm to <end\_month> <end\_day>  
with <end\_amount> mm every <step> days; <other series may follow in the same format,  
separated from each other by ";">

<start\_month> and <start\_day> are the starting date, the irrigation starts with <start\_amount> mm on the first day. Then, every <step> days, the irrigation is applied with an amount interpolated between <start\_amount> and <end\_amount>, depending on the actual date. If <end\_month> and <end\_day> are reached, the irrigation stops. There may be multiple series described for subsequent periods, which are separated by a semi-colon.

example:

30 rice00 2 2 3 0.3 starting from 9 20 with 50 mm to 3 9 with 40 mm every 5 days;

The above example is used in a case study for an Australian basin, where rice is irrigated in the period from September to March. The water will be taken from surface water (origin parameter is set to 2).

For method 3 (irrigation after demand) there are no parameters considered after the  $\psi$ start and the  $\psi$ stop parameter. So a simple example for method 3 would look like this:

30 rice00 3 2 3 0.3

If no irrigation should be applied for a coded irrigation land use (e.g. for a given scenario), the method 1 should be applied with a number-of-irrigation-events parameter set to 0, followed by no further dates or amounts, like this:

19 horticulture 1 1 3 0.3 0

section [substance\_transport] (only for WaSiM-ETH version 2 with RICHARDS-approach)

<number of modeled tracers> maximum 9 tracers time can be considered at the same  
<name> <non\_radioactive/radioactive> half\_time = <nnnn> d <evaporating/non\_evaporating>  
min\_conc = <xxxx> max\_conc = <yyyy> kg/kg soilini = <zzzz> gwini = <vvvv> statcode =  
<statcode> gridcode = <gridcode> path = <path> statext = <stat-extension> gridext =  
<grid-extension>

example:

NACL non\_radioactive half\_time = -9999 d non\_evaporating min\_conc = 0 max\_conc =  
350000 mg/l soilini = 1000 gwini = 10000 statcode = \$hour\_mean gridcode = 63  
path = \$outpath statext = \$code//\$year gridext = \$suffix

Of course, the symbols \$hourmean, \$outpath, \$code, \$year, and \$suffix have to be defined already.

### 3.5.2 coding of routing descriptions in WaSiM-ETH

Beside the usual routing of modeled discharges WaSiM-ETH offers also the possibility to consider external inflows as well as artificial (or natural) abstractions. A combination of an abstraction with an inflow is then an internal abstraction/inflow called a bypass. The impact of reservoir retention can be considered by applying an abstraction rule (a volume-runoff-table for each reservoir) or by applying a single linear storage approach to uncontrolled reservoirs.

inflows, abstractions, bypasses: Inflows and abstractions may be internal or external.

*External abstractions* will be subtracted from the modeled discharge, they are “losses” from the sight of the model, e.g. cooling water, irrigation water for external areas, abstractions for drinking water supply, but also losses by karst- phenomenon. Extractions are defined as part of a routing description for a sub-basin (see below). For each abstraction a file is written containing the abstracted amount in units of  $\text{m}^3/\text{s}$  as well as the tracer concentrations of all actually modeled tracers (up to 9 tracers at the same time), each value in a column.

*External inflows*, on the other hand, are discharges which were not generated within the model itself, but which are nonetheless present in the reality, like waste water disposals or, more important, like natural inflows, which are not part of the model. This be happen, if only the lower part of basin should be modeled. Then, the discharges of the upper basin part have to be considered by an external inflow (read in from an external file together with all tracer concentrations, organized in columns).

*Bypasses*, which are combinations of (internal) abstractions and (internal) inflows, describe the artificial or natural transfer of water within the model domain outside of the routing channel system. An example are karst-phenomenons (losses in one subbasin and additional sources in another subbasin). The difference between such bypasses and external inflows/abstractions is, that bypasses will not be written into or read from external files. A bypass can also not be constructed by a combination of external inflows and external abstractions, because the model connects only these inflows/abstractions which are marked with the keyword “intern”. However, it is possible during subsequent model runs to define in the first model run an external abstraction in the first model run which serves as an external inflow for another subbasin in the second model run. During the second model run the external abstraction should be defined, too (because of water balance in the lower basin areas), but it’s important to use a different file name in order to avoid overriding of the abstraction file of the first model run. The advantage of such an approach is, that the inflow is well defined in the second model run and does not depend on any model parameter. Thus, it’s also possible to use observed bypass-data.

reservoirs: If reservoirs have to be considered it is recommended to let them each be a separate small sub-basin (also in the zone grid). A routing description can deal with any number of storages, which are handled as a series of storages, but it is better to subdivide such basins into series of small subbasins. Abstractions will be taken from a reservoir, if there is one, also if there are multiple abstractions, they will be taken from the last (lowest) reservoir of that subbasin. Inflows are flowing into the uppermost (first) reservoir, if there are more than one reservoirs within the subbasin. Weirs or ground bolts should not be handled by reservoirs but by calibrating the hydraulic parameters of the channel, e.g. by calibrating single linear reservoir recession parameters for mean channel and flood plains.

Routing descriptions: For computing the discharge routing, hydraulic parameters of all channels as well as information about the drainage structure of the basin are needed. It is assumed, that the rivers are flowing into each other like in a tree-structure from the smallest branches to the trunk without branching in flow direction and without natural bypasses. This makes it possible to define an identifiable drainage structure for the basin, which could be computed subsequently link by link. However, internal bypasses would destroy this scheme, so a compromise had to be found: the abstraction parts of internal bypasses are considered in the actual time step, but the inflow parts are considered in the next time step. This scheme avoids feed backs within the same time step. It is also physically reasonable to delay the inflow by one time step, because the physical realization of the bypass also needs a certain time. The drainage structure of the basin can be edited by hand using any common ASCII-editor. It is also possible to use the program TANALYS. This program generates a routing structure which is defined by the digital elevation model and by given pour-points or automatically extracted river mouths. However, TANALYS cannot handle abstractions and inflows, whether natural nor artificial ones, and it is also not able to consider reservoirs. These features has to be added by hand after the generation of the drainage structure. If the drainage structure does not match the reality then this may lead to unexpected results.

The routing can be done either by routing each tributary through a separate channel to the outlet where all routed discharges are summed up or by summing up all tributary discharges at the begin of the routing and routing them through a single channel to the outlet. The first method is more appropriate if the basin subdivided according to a artificial gauge network, whereas the second method should be applied if the basin was subdivided following the natural river mouths, because the tributaries are united at the beginning of the routing channel. “Tanalys” can handle both situations. A routing description may contain any number of routing channels of both types (also mixed). All routed discharges and the runoff from the subbasin area itself are superposed at the outlet of the routing channels weighted by their relative areas on the actual subbasin total area (in-between-area of the actual subbasin plus areas of all tributary rivers which have to be routed through the actual subbasin). Each routing description may consist of any number of tributaries, external and internal inflows and abstractions, and reservoirs. The structure of the routing description is explained in the following example:

```
TG 9 (AE= 484.0, AErel=1.0)
from OL 10 (kh=0.4, kv=0.4, Bh=3.5, Bv=20.0, Th=0.5, Mh=25.0, Mv=15.0, I=0.0128, L=10408.3, AE=3.75 )
and OL 11 (kh=0.4, kv=0.4, Bh=7.0, Bv=50.0, Th=1.0, Mh=25.0, Mv=15.0, I=0.0066, L=10838.5, AE=90.75 )
and OL 12 (kh=0.4, kv=0.4, Bh=10.0, Bv=60.0, Th=1.4, Mh=27.0, Mv=15.0, I=0.0084, L=36339.6, AE=81.5 )
TG 5 (AE= 262.1, AErel=1.0)
from SUMTRIB 6&7 (kh=0.4, kv=0.4, Bh=6.0, Bv=30.0, Th=1.2, Mh=25.0, Mv=15.0, I=0.0195, L=10101.2, AE=133.75)
TG 4 (AE=1086.1, AErel=1.0)
from OL 5 (kh=0.3, kv=0.4, Bh=14.0, Bv=40.0, Th=2.5, Mh=30.0, Mv=20.0, I=0.0046, L=27005.3, AE=262.1 )
and OL 8 (kh=0.4, kv=0.4, Bh=6.0, Bv=50.0, Th=1.0, Mh=30.0, Mv=15.0, I=0.0090, L=26206.5, AE=16.5 )
and OL 9 (kh=0.3, kv=0.4, Bh=15.0, Bv=60.0, Th=2.5, Mh=30.0, Mv=20.0, I=0.0037, L=26673.4, AE=488.1 )
TG 2 (AE= 208.8, AErel=1.0)
from OL 3 (kh=0.4, kv=0.4, Bh=7.0, Bv=30.0, Th=0.9, Mh=25.0, Mv=15.0, I=0.0060, L=11952.7, AE=75.25 )
TG 13 (AE=1586.7, AErel=1.0)
from OL 2 (kh=0.3, kv=0.4, Bh=14.6, Bv=30.0, Th=2.0, Mh=40.0, Mv=15.0, I=0.0024, L=841.4, AE=208.8 )
and OL 4 (kh=0.3, kv=1.4, Bh=14.0, Bv=40.0, Th=3.0, Mh=45.0, Mv=15.0, I=0.0019, L=35000.0, AE=1086.1)
TG 1 (AE=1703.0, AErel=1.0)
from OL 13 (kh=0.3, kv=0.7, Bh=22.0, Bv=50.0, Th=4.5, Mh=45.0, Mv=15.0, I=0.0011, L=20289.9, AE=1586.7)
```

No inflows, abstractions, bypasses and reservoirs are contained in the above example (this is shown later). The first routing description (starting with the keyword “TG”) is defines the routing of the subbasins 10, 11 and 12 into the subbasin 9, where the separately routed discharges are superpose with the runoff from the subbasin 9 itself. Then, the routing is done for the subbasins 6 and 7, which are superposed already at the beginning of the routing channel (SUMTRIB = sum of tributaries). The routed sum of subbasins 6 and 7 is superposed with the subbasin-runoff of subbasin 5. Because the subbasins 5, 6 and 7 respectively 9, 10, 11 and 12 are independent of each other, the first routing description could have been also the second and vice versa. This is true also for the routing description of subbasin 3 into subbasin 2, which could appear anywhere before the subbasin 2 is routed itself. All these descriptions are responsible for the routing of head-water watersheds (STRAHLER-order 1) into larger (sub-)catchments of Strahler-order 2. The third description in the above example routes the discharges of the already routed subbasins 5 and 9 to the outlet of subbasin 4 and superposes them with the also routed discharge of subbasin 8 and with the internal runoff of subbasin 4. Applying this scheme, the routing is done according to the tree-structure of the catchment until the outlet of the entire basin is reached. If a model domain contains multiple basins, then its also possible to rout each basin separate using the above described commands.

#### Explanation of the key words in routing descriptions

- TG (German “Teilgebiet”) subbasin; the subbasin for which the tributaries are routed and superposed at the subbasins outlet
- AE = xxxx real subbasin area, the real area includes the subbasin itself and all tributaries regardless if they are included in the model or not (see AErel)
- AErel=xxx relative subbasin area; Normally, the modeled area should be the entire catchment. But if a model application only considers the lower part of a basin, e.g. the lower Ganges river or the lower Mississippi, then the model will get the inflows from the upper basin parts as an external inflow. To remain consistent with the units of the modeled runoff it’s required to tell the model, how large this upper area is (because runoff is routed as specific discharge). This is done by the relative fraction of the modeled basin parts of the total basin area.

Example:

```
TG 9 (AE= 484.0, ARel=0.8264)
from OL 10 (kh=0.4, kv=0.4, Bh=3.5, Bv=20.0, Th=0.5, Mh=25.0, Mv=15.0, I=0.0128, L=10408.3, AE=3.75 )
and OL 11 (kh=0.4, kv=0.4, Bh=7.0, Bv=50.0, Th=1.0, Mh=25.0, Mv=15.0, I=0.0066, L=10838.5, AE=90.75 )
and ZL 1 (modus = extern geb12.dat 4 5, kh=0.4, kv=0.4, Bh=10.0, Bv=60.0, Th=1.4, Mh=27.0, Mv=15.0,
I=0.0084, L=36339.6, AE=84.0 )
```

If the subbasin 12 in the above example would not be included into the model domain, then the real area of subbasin 9 remains at 484 km<sup>2</sup>, but the modeled area for subbasin 9 is only 400 km<sup>2</sup>. So the relative fraction of the modeled on the total basin area is 0.8264. The routed specific discharges has to be scaled by this factor in order to be comparable to observed runoffs for subbasin 9. The inflow from subbasin 12 must be read in as an external inflow. These external inflows are given in m<sup>3</sup>/s and they need the same parameters than the regular tributaries, because they may be natural inflows (like in the example) which are routed through real channels. The Subbasin area of such external inflows must be given only for calculating an internal runoff table.

- OL xx      Zone code of the tributary to be routed (according to the zone grid for the soil model)
- SUMTRIB a&b&c... Codes of tributaries a, b, c a.s.o. which are connected by “&” (no external or internal inflows!); the discharges of all listed tributaries are superposed at the beginning of the routing channel and routed in a single channel. For each routing description (i.e. for each “TG”) any number of OL’s, SUMTRIB’s and ZL’s (see below) may be defined.
- ZL xx      external or internal inflows (explanations see below)
- kh, kv      Storage coefficients for single linear reservoir considering retention in a channel, units in hours, kh for the mean channel, kv for the flood plains
- Bh, Bv      width of the mean channel (Bh) and the flood plains (Bv) [m]
- Th      depth of the mean channel [m]; the depth of the flood plain is theoretically unlimited
- Mh, Mv      Manning-Strickler-roughness parameters for mean channel (Mh) and flood plains [m<sup>1/3</sup>/s]
- I      mean slope angle along the routing channel [1/1]
- L      length of the routing channel [m]
- AE      (real) subbasin area if the tributary [km<sup>2</sup>]

The input of the subbasin area AE in the first row of a routing description is required in order to be able to convert inflows and outflows as well as reservoir extractions from m<sup>3</sup>/s into mm/time step and vice versa. It’s also important to make sure that the weighted superposition of the tributaries discharges works correctly. On the other hand, the input of the subbasin area of the tributaries is only of importance for the generation of discharge-flowtime-tables at the beginning of the model run. These areas should be in such a range that the expected discharges (in mm/h) are within the discharge-flowtime-tables range as given in the control file. If these areas are much too small, the flow times for floods will be too large, because the runoff-flowtime-table will have no entries for such high specific discharges following from too small basins. The same reason is true for the input of a subbasin area for external or internal inflows. The area is needed only for generating the discharge-flowtime-table. For modeled real tributaries WaSiM checks the given areas with the areas taken from the zone grid and changes the values to the latter, if differences occur. This is not possible for inflows, so here a realistic input is required. If a inflow is an observed runoff of a subbasin which is not included in the model, this area can easily be get from the DEM or from the literature. For artificial inflows the “area” should be in a reasonable relation to the other hydraulic parameters of the channel. If, for instance, the channel has a width of 3.5 m, a depth of 0.5 m, a slope of 0.01 and Manning-Strickler-value of 25 m<sup>1/3</sup>/s, a flow velocity of 1.332 m/s would be valid for a full channel according to a discharge of 2.33 m<sup>3</sup>/s. If the expected inflows vary between e.g. 0.2 and 2 m<sup>3</sup>/s, the Area could be chosen between 5 and 30 km<sup>2</sup>, thus resulting in specific discharges between 6.67 and 66.7 l/s/km<sup>2</sup> (at 30 km<sup>2</sup>) respectively between 40 and 400 l/s/km<sup>2</sup> (at 5 km<sup>2</sup>). If the range for the discharge-flowtime-table is given as e.g. 5 l/s/km<sup>2</sup> for the minimum and 1200 l/s/km<sup>2</sup> for the maximum considered specific discharge, then all possible inflows are routed with a velocity which can be found within the table (what area is given is not important as long as the range of resulting specific discharges is in-

between the minimum and maximum values, the flow times are identical for all areas within the proper range because the table entries are only shifted what is compensated by the conversion of discharge from  $\text{m}^3/\text{s}$  into  $\text{l/s/km}^2$  using different areas).

#### Routing using inflows, abstractions and reservoirs:

The following example shows routing descriptions for the Thur basin with some fictive inflows, abstractions and reservoirs. In subbasin 13 the discharged of subbasins 2 and 4 are routed. In addition there is an internal abstraction AL 1 which flows into subbasin 1 as internal inflow, so this is a bypass caused e.g. by a power station, by drinking water supply or by natural karst-phenomenons. The program recognizes this connection as a bypass by finding the keywords “intern” for both, the inflow and the abstraction and by comparing the numbering of the inflow and the abstraction. An internal abstraction 1 must have a matching internal inflow 1 and vice versa. This way, multiple bypasses can be managed between any subbasins.

```
TG 13 (AE=1586.7, AErel=1.0)
from OL 2 (kh=0.3, kv=0.4, Bh=14.6, Bv=30.0, Th=2.0, Mh=40.0, Mv=15.0, I=0.0024, L=841.4, AE=210.0 )
and OL 4 (kh=0.3, kv=1.4, Bh=14.0, Bv=40.0, Th=3.0, Mh=45.0, Mv=15.0, I=0.0019, L=35000.0, AE=1220.0)
and AL 1 (modus = intern 0.1 0.8 0.7 )
TG 1 (AE=1703.0, AErel=1.0)
from OL 13 (kh=0.3, kv=0.7, Bh=22.0, Bv=50.0, Th=4.5, Mh=45.0, Mv=15.0, I=0.0011, L=20289.9, AE=1650.0)
and ZL 1 (modus = intern, kh=0.4, kv=0.4, Bh=10.0, Bv=60.0, Th=1.4, Mh=27.0, Mv=15.0, I=.0084, L=3633, AE=20
)
and SP 1 (file = spv__01.84 , V0 = 1E8 , C0 = 1.0 0.1 3.0 0.0 0.0 0.0 0.0 0.0 0.0 )
and AL 2 (modus = extern abstraction2.dat 0 1 12 m3/s )
```

The internal abstraction is parameterized by 3 parameters (same for external parameters): starting with 0.1 mm/time step discharge in the routing channel there will be abstracted 80 % of the exceeding discharge until the total amount of abstracted water reaches the maximum capacity of 0.7 mm/time step. The parameters are a threshold for beginning the abstraction, the fraction of abstracted water and the maximum capacity of the abstraction. However, the units mm/time step is not recommended because it's not independent on the time step and on the subbasin area. There is also the possibility to specify the parameters 1 and 3 in  $\text{m}^3/\text{s}$  (the subbasin area is  $1586.7 \text{ km}^2$ ):

```
TG 13 (...)
from ...
and ...
and AL 1 ( modus = intern, 44.1 0.8 308 m3/s )
```

In this example the threshold of  $44.1 \text{ m}^3/\text{s}$  is equal to  $0.1 \text{ mm/h}$  and  $308 \text{ m}^3/\text{s}$  are  $0.7 \text{ mm/h}$ . The second parameter, the fraction of abstracted water, remains constant. If an abstraction is external, a file name must be specified. The name appears directly after the “modus=extern” keywords (see abstraction AL 2 in the above example).

If the inflow ZL 1 into subbasin 1 would not have been an internal but an external inflow, a file name and 2 parameters specifying the start row and start column would be required (see example below):

```
and ZL 1 (modus = extern geb12.dat 4 5, kh=0.4, kv=0.4, Bh=10.0, Bv=60.0, Th=1.4, Mh=27.0, Mv=15.0, I=0.0084,
L=36339.6, AE=20.0 )
```

generally: ZL x (modus = extern <file name> <start row> <data col> ....other parameters...

<file name> specifies a file the inflows in units of  $\text{m}^3/\text{s}$  are read from, <data col> specifies the number of the column, the data will be found in and <start row> is the row the input starts at. In the above example the external inflow data are read from a file named “geb12.dat” starting with row 4 and reading the data from column 5.

As a last feature in the example there is also a reservoir, which has an initial content of  $10^8 \text{ m}^3$ . The actual contents are written into a file named “spv\_\_01.84”. The control file contains also the initial concentrations of all 9 possible tracers which could be modeled together with the water fluxes: the first tracer would have an initial concentration of  $1.0 \text{ kg/kg}$ , the second of  $0.1 \text{ kg/kg}$ , the third of  $3 \text{ kg/kg}$  (all unrealistic values), all other tracers have initial concentrations of 0. For each storage an abstraction rule has to be specified in a separate section following the routing descriptions. Such a rule may be look like this:

```
[abstraction_rule_reservoir_1]
```

9		# number of following points
1e4	1.0	
1e5	1.0	
1.0001e5	10.0	
1e6	10.0	
1.0001e6	50.0	
1e7	50.0	
1.0001e7	100.0	
1e8	100.0	
1.0001e8	500.0	

For each point of the abstraction rule, which represents a linear volume-discharge-relation between each 2 of the given points, the first entry specifies a reservoir content in  $\text{m}^3$ , the second entry specifies the corresponding discharge. Between this fixed points the model interpolates linearly. If a step-like abstraction rule should be applied, then some points should be very close to another in their volumes but with large differences in the corresponding discharge, like shown in the above example.

There may be any number of reservoirs in a subbasin but it is recommended to limit the number to only one reservoir per subbasin. Abstractions are taken out of the (last) reservoir instead of out of the river if reservoirs exists. Also irrigation water will be taken out of the reservoirs. If there are more then one reservoir in a subbasin, the inflows are routed into the uppermost reservoir. The outflow of this reservoir (defined in an abstraction rule like the example above) is then the inflow into the next reservoir of the same subbasin a.s.o.

### 3.6 Sensitivity analysis

#### 3.6.1 Introduction

This section deals with a sensitivity analysis of only the most important model parameters. Only those parameters are considered which have a large possible value range, which are not or only difficulty observable, and which are empirical parameters. Mainly the parameters of the soil model of model version 1 will be looked on. The sensitivity of the interpolation algorithms will not be investigated, there are a number of papers dealing with this issue, e.g. MUSTER (1994) and BARDOSSY (1994). The parameters for precipitation correction, which have more or less a linear impact on the results are not considered. The radiation correction does not use empirical parameters whereas the temperature modification does not impact the runoffs of larger basins. Therefore both modules are also not examined. Further, the relations between sunshine duration and radiation can be fitted very exactly using measurements, so these parameters are also no subject to a sensitivity analysis. The routing parameters are in principal observable and they are relatively insensitive compared to the soil model parameters. Therefore, those routing parameters are also not considered here.

If possible and reasonable, the sensitivity of the model to the investigated parameters is expressed using the model efficiency criterions. The examples are taken from the Thur-basin in Switzerland and from the Wernersbach-basin in Germany (Saxonia). In chapter 3.7 the calibration of the model is described using also the model efficiency and showing some examples for the sensitivity of other parameters, e.g. for the unsaturated zone model.

#### 3.6.2 Parameters of the evaporation model

The potential evaporation is usually calculated using the PENMAN-MONTEITH-approach (MONTEITH, 1975). The simplified methods after HAMON (FEDERER AND LASH, 1983) resp. WENDLING (1975) are not considered here, also the parameters for modifying temperatures of day and night after chapters 1.3.2 and 1.4.1. The most difficult parameters of equation is the surface resistances  $r_s$ . Table 6 shows the differences in the evaporation components when varying the resistances between 25 % and 200 % of the optimal value, which was obtained by calibrating the results on the observed water balance (precipitation  $P = 1523 \text{ mm}$ ). The results are taken from model runs for the Rietholzbach-basin for 1984.

Table 6: impact of the minimum stomata resistance  $r_s$  on evaporation and discharge

%-value of optimum $r_{sc} \rightarrow$	25 %	50 %	75 %	<b>100 %</b>	125 %	150 %	175 %	200 %
$ETP$ (pot. evap. [mm])	688	612	557	<b>515</b>	481	453	430	409
$ETR$ (real evap. [mm])	674	609	556	<b>515</b>	481	453	429	409
$EI$ (interception evap. [mm])	143	139	136	<b>133</b>	130	128	126	124
$Q$ (runoff [mm])	844	909	961	<b>1003</b>	1037	1066	1088	1108
$R^2$ (runoff observ. vs. model)	0.764	0.784	0.794	<b>0.795</b>	0.788	0.777	0.762	0.747

If the resistances are set to 50 %, the real evaporation rises by around 19 % ( $ETR_{100\%} = 515$  mm,  $ETR_{50\%} = 556$  mm), whereas an increase of  $r_s$  by 50 % leads to a decrease in evaporation by app. 12 % ( $ETR_{150\%} = 453$  mm). A doubling of  $r_s$  leads even to a decrease by 20 % ( $ETR_{200\%} = 409$  mm).

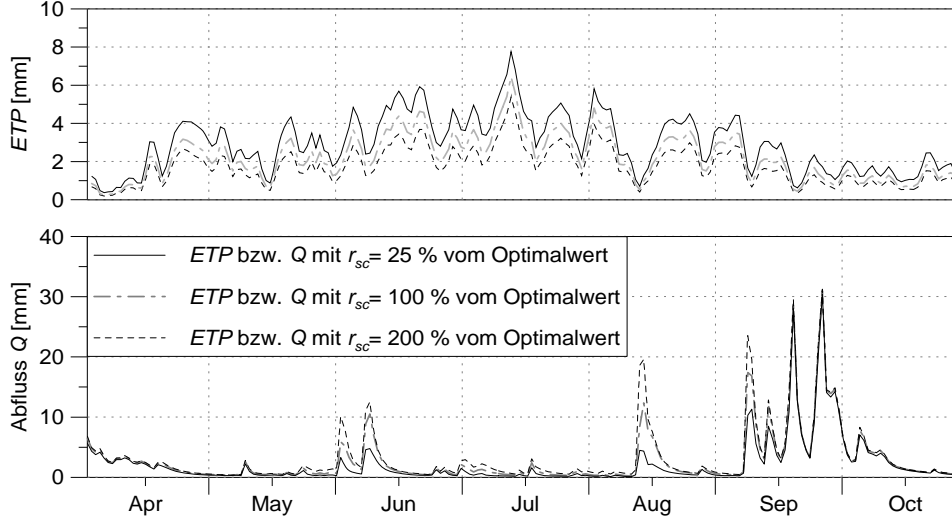


figure 8: model sensitivity on changes in the surface resistances  $r_s$ , using results from the Rietholzbach basin for 1984; units of ETP and discharge are in mm/day

The distribution of the  $R^2$ -values in table 6 shows similarly good results for resistances with 50 % to 125 % of the “optimum” 100 %-values. Comparing the values of observed and modeled discharge it is obvious that resistances with 75 % of the “optimum” values would give a better water balance, but with a slightly lesser  $R^2$ . This example demonstrates the importance of looking also to balances and time series (e.g. modeled versus observed hydrographs) in order to validate the parameters got by a  $R^2$ -optimized calibration.

Figure 8 shows the evaporation and the modeled total discharges as results of 25 %-, 100 %- and 200 %-  $r_s$ -values, all graphs printed as 3-day-moving averages. The very small resistances of the 25 %-variant leads to more soil water extraction resulting in much smaller flood events following the precipitation events (June, August, first September event, solid line). Only when the soil is saturated after the first September event, the flood peaks are much more similar. Using higher values for the surface resistances, less water evaporates and precipitation events will generate much higher floods, like the event in mid August.

Figure 8 and table 6 show, that the surface resistances are very important for the total amount of evaporation. If these parameters can not be calibrated e.g. by comparisons with lysimeter observations or by Bowen-ratio-measurements, they must be calibrated very carefully.

### 3.6.3 Parameters of the interception model

Interception occurs on leaf surfaces as well as on the vegetation litter layer. Also storage on the soil surface in hollows or puddles should be considered by this approach (in WaSiM-version 2 an additional possibility for considering storage in hollows is given by using a pond-grid which defines a maximum surface water storage capacity for each grid cell). For the interception storage the bucket approach is used. The capacity of this storage depends on the vegetation coverage degree  $v$ , on the leaf area index  $LAI$ , and on the maximum thickness of the interception water layer  $h_{SI}$ . Vegetation coverage degree and leaf area

index are in principle observable variables, but  $h_{SI}$  is an “effective” parameter which has to be calibrated because its only an approximation to think of the interception as a storage which is filled and emptied uniformly all over the area with the same rate.

table 7: dependency of evaporation components on the interception storage capacity  $h_{SI}$  ( $h_{100\%} = 0.35$  mm, data from model runs for the Rietholzbach-basin, year 1984; ETR: real evaporation and transpiration taken out of the soil, EI: interception loss, ETP potential evaporation)

$h_{SI}$ as %-age of $h_{opt}$		25 %	50 %	75 %	<b>100 %</b>	125 %	150 %	175 %	200 %
ETR	[mm]	515.3	515.2	515.1	<b>515.0</b>	514.9	514.9	514.9	514.8
ETR - EI	[mm]	468.9	433.3	404.6	<b>381.7</b>	362.4	345.4	330.4	318.0
EI	[mm]	45.8	81.5	110.1	<b>132.9</b>	152.3	169.2	184.2	196.6
EI/ETR	[%]	9 %	16 %	21 %	<b>26 %</b>	30 %	33 %	36 %	38 %

Also the emptying of the interception storage differs between model and reality. The model evaporates with a uniformly potential rate all over the area, but in reality the interception storage consists of separate drops which even may evaporate with higher than the potential rate because of the higher saturation vapor pressure over curved surfaces compared to plain surfaces. However, under humid climates the value of  $h_{SI}$  is only of minor importance for the long term water balance but initial losses for flood generation may be considerably even there. Table 7 shows the results for the evaporation components as annual sums for different maximum storage capacities (Rietholzbach-basin, 1984). It is obvious that the different capacities affect only the ratio of interception evaporation (EI) and transpiration (ETR), the total amount of evaporation remains more or less unchanged at 515 mm. Using a parameter value of 0.35 ... 0.4 mm for  $h_{SI}$ , the interception evaporation gets a realistic fraction of around 25 % ... 30 % on the total evaporation leading to a storage capacity for pine forest of around 4 mm.

### 3.6.4 Parameters of the snow model

The snow model uses 4 effective parameters if using the temperature index approach:

- the threshold temperature for snow melt  $T_{0,m}$
- the temperature  $T_{R/S}$ , at which 50 % of the precipitation are falling as snow and 50 % as rain
- the temperature range for the transition from snow to rain  $2 \cdot T_{trans}$
- the degree-day-factor  $TGF$

These parameters partially affect the models reaction in opposite directions or they depend on another, like the threshold-temperature for snow melt  $T_{0,m}$  and the degree-day-factor  $TGF$ . A higher value for the threshold temperature would also result in higher degree-day-factors to get the same snow melt rates.

the temperature range for the transition from snow to rain  $T_{trans}$  and the central value of this range, the “equilibrium” temperature  $T_{R/S}$ :

These parameters are especially important, if the temperature in the entire model domain is within the range of  $T_{R/S} - T_{trans} \leq T \leq T_{R/S} + T_{trans}$ . This is improbable for mountainous regions but it may more frequently happen in low land regions. There, a large value of  $T_{trans}$  has the effect, that even if the mean temperature is clearly above or below the melt threshold, there are still solid and liquid fractions at the same time, thus avoiding sharp transitions from snow to rain in space as well as in time. This may help in avoiding model errors due to erroneous temperature measurements or interpolations. However, if the temperatures are everywhere in the model domain above  $T_{R/S} + T_{trans}$  or everywhere below  $T_{R/S} - T_{trans}$  the parameter  $T_{trans}$  is meaningless.



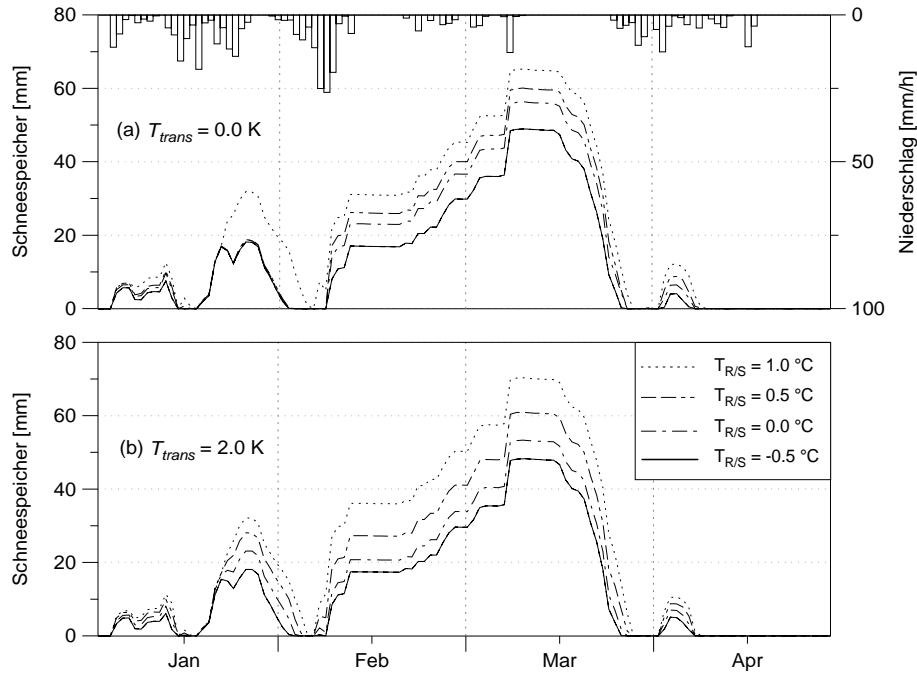


figure 9: Snow accumulation at various threshold temperatures  $T_{R/S}$  (snow/rain)  
 (a)  $T_{trans} = 0.0$  K; (b)  $T_{trans} = 2.0$  K, Rietholzbach catchment, 1984  
 “Schneespeicher” means snow water equivalent; “Niederschlag” means precipitation

Figure 9 shows a comparison of the temporally course of the snow water equivalent, once modeled using a 2 K transition zone from snow to rain (b) and once without this effect (a). The period from January, 20<sup>th</sup> shows the impact of the transition zone on the spatial and temporal distribution of snow: In case (a), with the transition zone  $T_{trans} = 0$ , either it melts and no snow at all is accumulated for temperatures above app.  $0.5 + ^\circ\text{C}$  ( $T_{R/S} < T$ ), or all precipitation is accumulated as snow for temperatures below  $0.5 ^\circ\text{C}$  ( $T_{R/S} > T$ ). On the other hand, case (b) shows a smooth transition from accumulating to melting conditions using a transition zone of 2 K. If the temperatures are below the transition zone, like in figure 9 for the period of mid February to mid March, the parameter  $T_{trans}$  has no effect. It’s also apparent from figure 9 that the value of  $T_{R/S}$  affects also the mean snow water equivalent due to different snow fractions. The optimum values for the Thur-Basin are  $T_{R/S} = 0.6 ^\circ\text{C}$  and  $T_{trans} = \pm 1$  K.

snow melt threshold temperature  $T_{0,m}$  and degree day factor TGF:

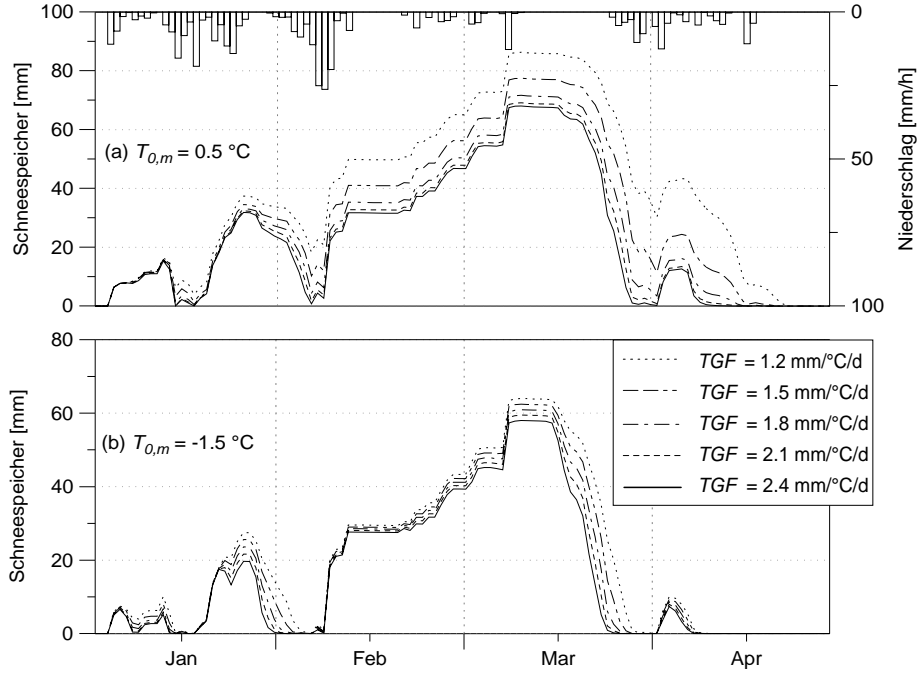


figure 10: temporal course of snow water equivalent for different degree day factors: (a) melt threshold temperature  $T_{0,m} = +0.5\text{ °C}$ , (b)  $T_{0,m} = -1.5\text{ °C}$ , Rietholzbach basin, 1984; “Schneespeicher” means snow water equivalent, “Niederschlag” means precipitation

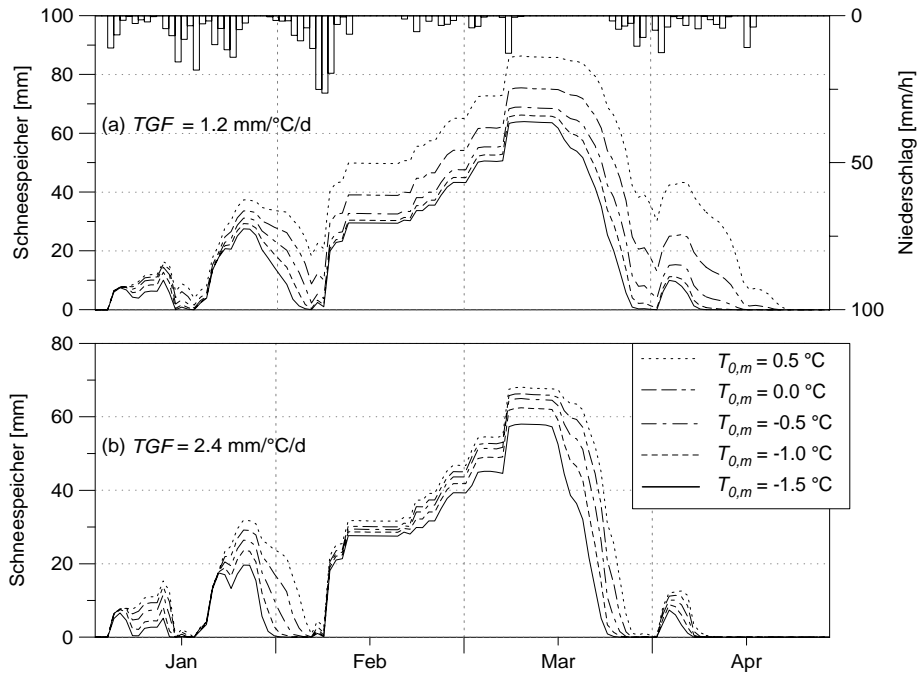


figure 11: temporal course of snow water equivalent for different melt threshold temperatures  $T_{0,m}$  at (a) degree day factor  $TGF = 1.2\text{ mm} \cdot \text{°C}^{-1} \cdot \text{d}^{-1}$ , (b)  $TGF = 2.4\text{ mm} \cdot \text{°C}^{-1} \cdot \text{d}^{-1}$ , Rietholzbach basin, 1984; “schneespeicher” means snow water equivalent, “niederschlag” means precipitation

The melt parameters used in the temperature index approach are mainly the melt threshold temperature  $T_{0,m}$  and the degree day factor  $TGF$ , which must be cross-calibrated because of their impacts on each other. Figures 10 and 11 shows these effects. Figure 10 shows the impact of the degree day factor on the snow melt for a threshold temperature of  $T_{0,m} = +0.5\text{ °C}$  (a) and for a threshold temperature of  $T_{0,m} = -1.5\text{ °C}$  (b), respectively. Particularly at the end of the melting period the differences between small and large  $TGF$ -values are obvious, resulting in a two week difference of the melt periods end if comparing  $TGF = 1.2\text{ mm} \cdot \text{°C}^{-1} \cdot \text{d}^{-1}$  and  $TGF = 2.4\text{ mm} \cdot \text{°C}^{-1} \cdot \text{d}^{-1}$  for case (a). On the other hand, a lower threshold value of  $T_{0,m} -1.5\text{ °C}$  results in a much more independent course of the snow melt.

Also figure 11 shows the impact of the melt threshold  $T_{0,m}$  on the course of the snow water equivalent. The optimum parameter values for the Thur basin were found to be  $TGF = 1.8 \text{ mm} \cdot ^\circ\text{C}^{-1} \cdot \text{d}^{-1}$  and a threshold temperature  $T_{0,m} = -0.5 \text{ }^\circ\text{C}$ . Compared to the literature, e.g. Braun (1985) who found 4 to  $6 \text{ mm} \cdot ^\circ\text{C}^{-1} \cdot \text{d}^{-1}$  to be optimal, the value of  $TGF$  is rather small, but this is also due to the low threshold value as well as due to the temporal resolution of one hour for the calibration runs, so the diurnal course of the temperature is more effective for melt than using a daily temperature average.

### 3.6.5 Parameters of the soil model for model version 1 (Topmodel-approach)

The soil model of model version 1 (without infiltration submodel) is controlled by 9 parameters and 2 initial conditions:

- $m$  recession parameter for base flow [m]
- $T_{korr}$  correction factor for the transmissivity of the soil [-]
- $K_{korr}$  correction factor for vertical percolation [-]
- $k_D$  single reservoir recession constant for surface runoff [h]
- $SH_{max}$  maximum storage capacity of the interflow storage [mm]
- $k_H$  single reservoir recession constant for interflow [h]
- $P_{grenz}^1$  precipitation intensity threshold for generating preferential flow into the saturated zone [ $\text{mm} \cdot \text{h}^{-1}$ ]
- $r_k$  scaling of the capillary rise/refilling of soil storage from interflow [0...1]
- $c_{melt}$  fraction on snowmelt which is surface runoff [0...1]

The initial conditions are the content of the interflow storage and the initial saturation deficit. The recession constants for surface runoff and interflow may be estimated using observed hydrographs. If no interflow is considered ( $SH_{max} = 0$ ) this is true also for the TOPMODEL-recession parameter  $m$ . But if interflow is used, then  $m$  must be calibrated, too, because then  $m$  is not derivable from observed hydrographs anymore. The percolation scaling factor  $K_{korr}$  makes sense only in areas with deep soils with a deep groundwater table. In such basins, often a first flood peak is followed by a second flood which is usually much slower rising and falling but which may be even higher than the first peak.. Because WaSiM-ETH was not applied yet to such basins, a sensitivity analysis using observed runoff data was not processed. In most basins, this effect may be neglected and there  $K_{korr}$  should be set to a sufficient large value to avoid water logging or even an hydraulic disconnection to the saturated zone (e.g. by setting  $K_{korr}$  to 1000).

The following examples cover the impact of the most important parameters of the soil model: the recession parameter  $m$ , the correction factor for the transmissivities  $T_{korr}$ , the “refilling” and capillary rise scaling factor  $r_k$ , and the threshold precipitation capacity for generating macro pore runoff  $P_{grenz}$ . Some of these parameters are not independent from others, so they usually should be cross-calibrated. For example, the recession parameter  $m$  and the scaling parameter  $T_{korr}$  have strong impacts on each other. Therefore it is important to use not only observed discharges for the calibration but also, if available, internal state variables like groundwater table depth’s and/or soil moistures.

#### *recession parameter $m$ and transmissivity correction $T_{korr}$*

Although the recession parameter  $m$  may be estimated by analyzing observed hydrographs (see eq. 66) this parameter is used here for the sensitivity analysis, also because of the estimation of  $m$  is sometimes not even possible due to too much impact of frost or evaporation on the discharge or because of interflow is considered. Also it often depends on the modeler how to define recession periods which are the basis for the estimation of  $m$ . The more clear and long recession periods, which have to be unaffected by frost, evaporation and snow melt, can be analyzed, the more confidential is the value of  $m$ .

This becomes even more complex in basins where the interflow cannot be neglected. Here, also no interflow should be present during the recession periods for the estimation of  $m$ . Recessions during the summer are bad candidates because their corruption by evaporation, whereas wintry recession periods often

are influenced by snow melt or frost. From fall to spring also the impact of interflow is usually significant or there are only too less or too short recession periods. In the end this leads to a calibration of  $m$ , using the estimation after equation (66) as a first minimum estimation – usually the use of interflow requires at least a doubling of  $m$ .

The effect of  $m$  is as follows: The smaller  $m$  (and therefore also the tangent of the inverted discharges), the more water leaves the soil, leading to a fast decreasing of the “groundwater table” and thus to a fast increasing of the saturation deficit. But, on the other hand, a larger saturation deficit decreases the outflow from the saturated zone. In conjunction with higher recharge rates in the winter and higher evaporation losses in the summer this leads to a regime with high base flow rates in the winter and low base flow rates in the summer. Or, in other words, there is only a small long term storage effect of the underground and the baseflow has a large dynamic. Larger  $m$ -values will result in considerably more temporal storage of water in the saturated zone by transferring water from the winter into the summer. Figure 12 shows the effect of a too small parameter  $m$ : The winter precipitations generate too much discharge in the winter. This water is missing in the summer, when too less base flow is generated. This is also obvious from the saturation deficit which remains large from begin of May. The same effect can be observed if using different  $T_{korr}$ -values varied over a wide range.

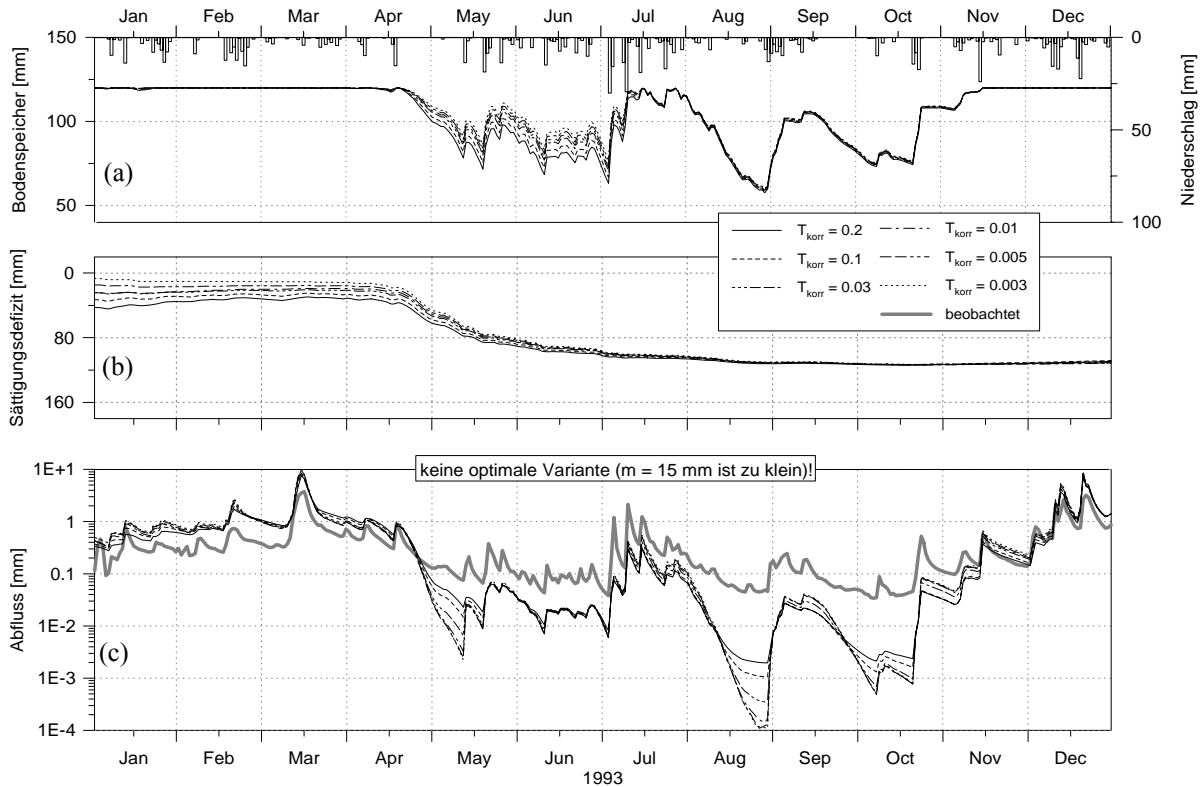


figure 12: model sensitivity on variations in  $T_{korr}$  if using a too small recession parameter  $m$  (15 mm), showed for (a) soil moisture, (b) saturation deficit and (c) discharge; Wernersbach, Saxonia, 4.6 km<sup>2</sup>, 365 to 465 m a.s.l., hourly values, 1993; Abfluss=discharge, Sättigungsdefizit = saturation deficit, Bodenspeicher=soil moisture, beobachtet=observed

A comparison between figures 12 and 13 shows the impact of a variation of the recession parameter  $m$ . Figure 13 shows a temporally much more balanced saturation deficit than figure 12, which is nonetheless more intense affected by the scaling parameter  $T_{korr}$ .

Following equation (65) the maximum base flow  $Q_0 = T_{korr} \cdot e^{-\gamma}$  depends on the mean topographic index  $\gamma$ . From the definition of the topographic index (eq. 55) follows, that both, the topography as well as the transmissivity of the soil affect the maximum base flow of the soil. Because of the resolution of the digital terrain model has an important impact of the distribution function of the topographic index, usually a shift of this function is required to reach reasonable base flow rates after equation (65). Also the impact of the

transmissivity which is usually not exactly measured must be scaled. Both effects can be considered by the scaling factor  $T_{korr}$  which affects the base flow generation linearly but the location of the topographic index distribution function logarithmically. Thus, the possible range of values for  $T_{korr}$  is between approximately  $10^{-5} \leq T_{korr} \leq 10^{+5}$ .

The parameters  $m$  and  $T_{korr}$  depends on another, so they must be calibrated at the same time (so called cross-calibration). Because of the wide range  $T_{korr}$  may be within, both parameters should be estimated very carefully.

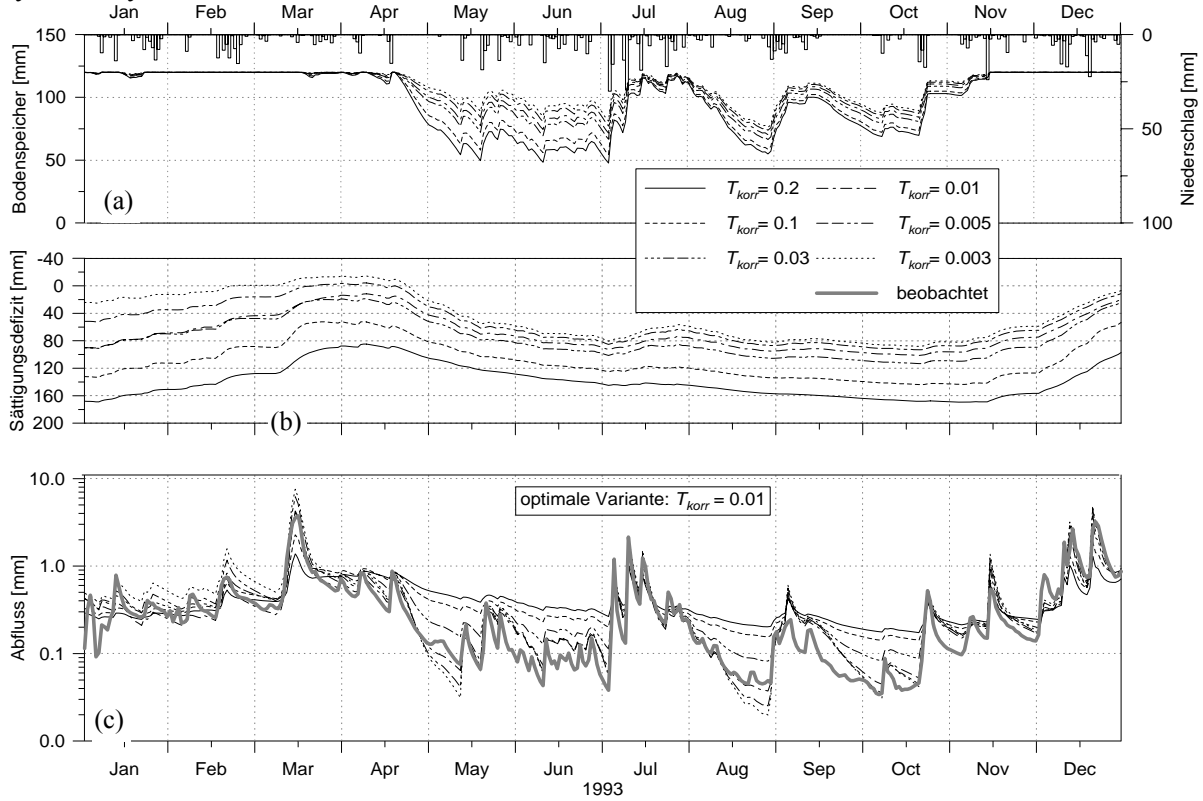


figure 13: model sensitivity on variations of  $T_{korr}$  at a optimum recession parameter  $m$  (55 mm), showed for (a) soil moisture, (b) saturation deficit and (c) discharge; Wernersbach, Saxonia, 4.6 km<sup>2</sup>, 365 to 465 m a.s.l., hourly values, 1993, Abfluss=discharge, Sättigungsdefizit = saturation deficit, Bodenspeicher=soil moisture, beobachtet=observed

A large transmissivity of the soil leads to a temporally more evenly distributed regime than a small transmissivity because even at low groundwater tables there can flow out considerably amounts of base flow. On the other side, this leads to a high dynamic of the groundwater table (or the saturated zone), resulting also in high recharge values after heavy precipitation events and thus in relatively small floods. This can be shown for the graph of  $T_{korr} = 0.2$  in figure 13. Since the depth of groundwater (or the saturation deficit) is an important factor for modeling the capillary rise from the groundwater into the soil storage, both parameters  $m$  and  $T_{korr}$  affect the average soil moisture and thus the real evaporation in cases of dry periods. This effect can also be observed by comparing figures 12a and 13a

Using the model efficiencies (linear as well as logarithmic, explained variances as well as  $R^2$ ) an optimum can be found for both parameters. A series of simulations should be run with various values for  $m$  and  $T_{korr}$ . A result of such a series is shown in figure 14. The model efficiencies are interpolated by a smooth surface, the optimum parameter set for the Wernersbach-basin could be found at  $T_{korr} = 0.018$  and  $m = 0.054$  resulting in a model efficiency (linear  $R^2$ ) of around 0.95.

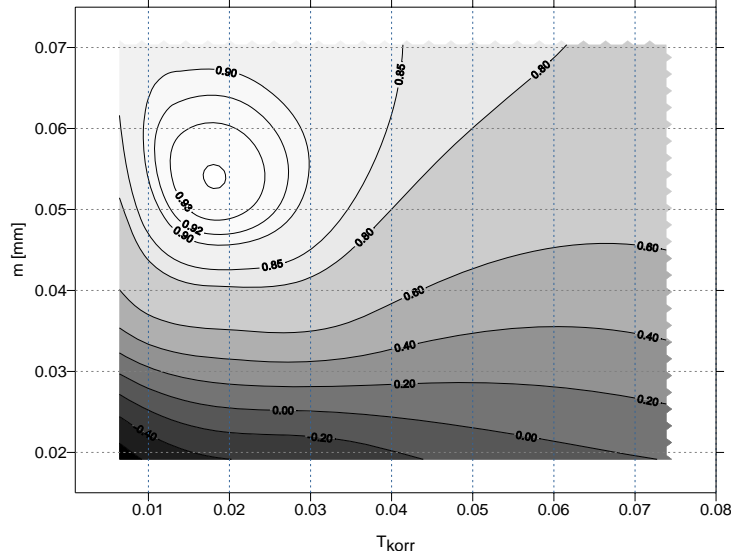


figure 14: distribution of model efficiencies ( $R^2$ ) as function of  $T_{korr}$  and  $m$ ; Wernersbach, Saxonia, 4.6 km<sup>2</sup>, 365 to 465 m a.s.l., daily time step, 1993

precipitation intensity threshold  $P_{grenz}$  for generating macro pore percolation and scaling factor for capillary rise  $r_k$

Both parameters,  $P_{grenz}$  as well as  $r_k$  influence the filling and emptying of the plant available soil water storage, the saturated zone and the interflow storage.  $P_{grenz}$  is responsible for the generation of macro pore runoff, which is routed directly into the saturated zone. Even if the soil is only partly saturated, a fraction of the precipitation (dependent on the precipitation intensity) can be used to fill both the saturated zone storage and the interflow storage. Thus it's possible to explain rising interflow and base flow rates even if the soil storage is still not saturated after a heavy rain event. This concept is an extension of the infiltration model as well as of the TOPMODEL, which presume homogenous soils without macro pores. The water infiltrated by the infiltration model is thus only partially stored in the soil storage.

During the summer, often a decrease in base flow can be observed for small watersheds which is stronger than the usual decrease by base flow and interflow recession. This effect can be explained by the additional extraction of water from the unsaturated zone as well as from the interflow storage by plant roots at shallow groundwater tables. WaSiM-ETH version 1 models this effect in a conceptual way whereas WaSiM-ETH version 2 can consider this effect implicitly by applying the RICHARDS equation. The variable saturation approach of the TOPMODEL version allows a temporally and spatially distributed modeling of shallow groundwater regions which are in contact with the soil water storage. Using the local saturation deficit, the local depth of the saturated zone is compared to the depth of the root zone for each grid cell in each time step. When there is an intensive contact between the soil water storage and the saturated zone, a high rate of capillary rise and reflow from the interflow storage into the soil moisture will be possible. Thus, a moist basin will allow high reflow and capillary rise rates whereas a dry basin will virtually not allow any recharge at all. Because of the conceptual scheme of the TOPMODEL the rate of capillary rise must be scaled using the parameter  $r_k$  which is a calibration parameter.

The parameters  $r_k$  and  $P_{grenz}$  affect the model's reaction in opposite directions. So both parameters have to be investigated together. The impact of the "capillary rise" on the total water balance rises with increasing fractions of evaporation on the entire water balance. For regions with small evaporation fractions the soils are usually not sufficiently dry to allow much capillary rise. There, both parameters are relatively

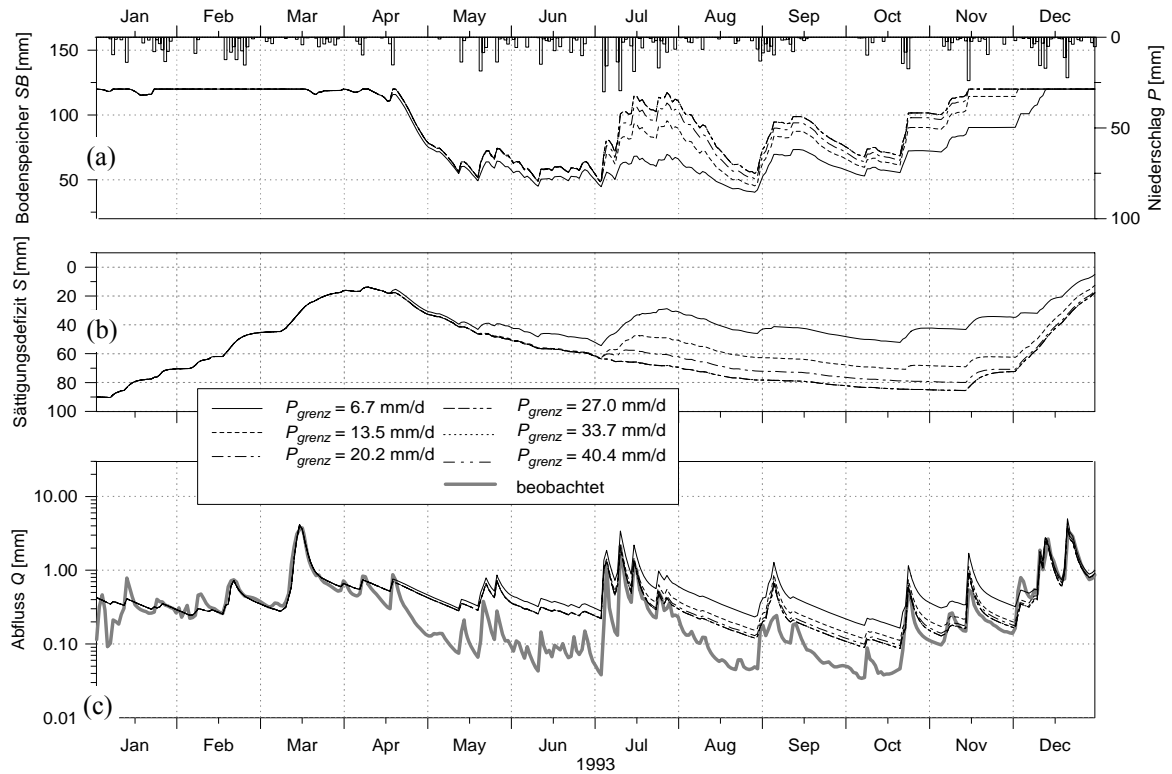


figure 15: Impact of the threshold precipitation intensity  $P_{\text{grenz}}$  for generating macro pore drainage on (a) soil moisture, (b) saturation deficit and (c) runoff; without capillary rise/reflow from interflow into soil storage ( $r_k = 0.0$ ); Wernersbach, Saxonia, 4.6 km<sup>2</sup>, 365 to 465 m ü.M., daily time steps for 1993; “Abfluss”=discharge, “Sättigungsdefizit”=saturation deficit, “Bodenspeicher”=soil storage, “beobachtet”=observed

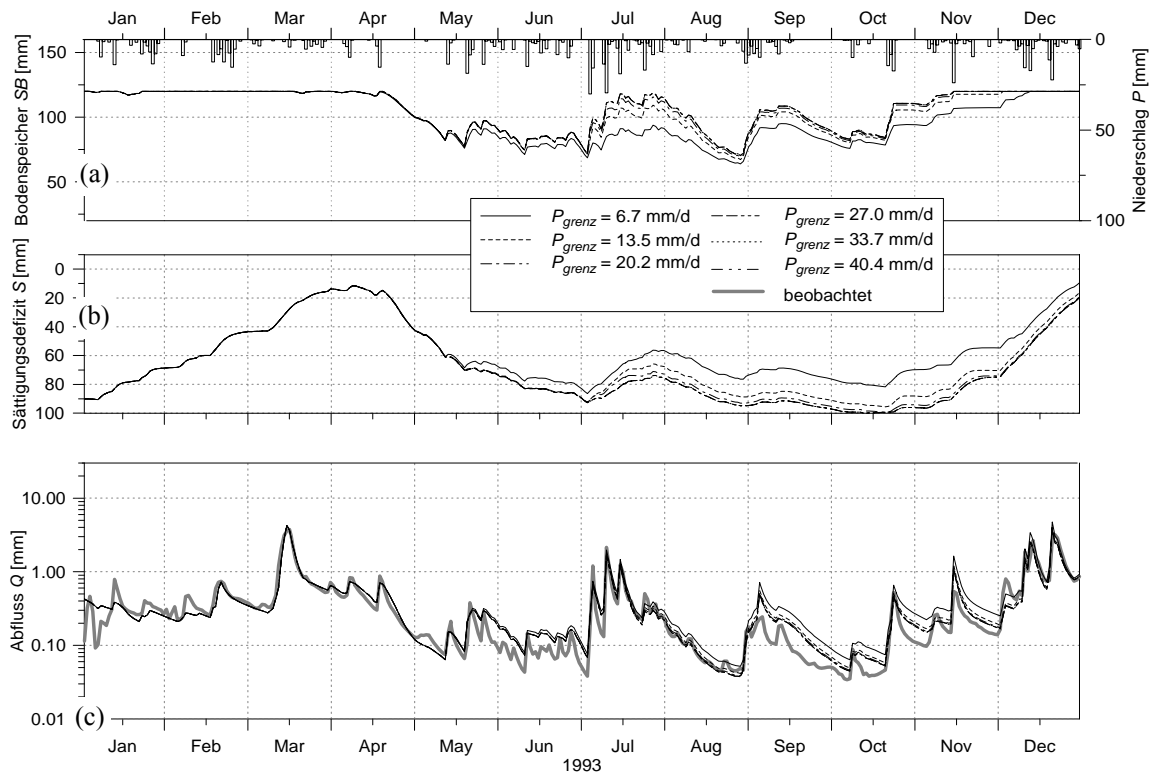


figure 16: Impact of the threshold precipitation intensity  $P_{\text{grenz}}$  for generating macro pore drainage on (a) soil moisture, (b) saturation deficit and (c) runoff; with maximum capillary rise/reflow from interflow into soil storage ( $r_k = 0.0$ ); Wernersbach, Saxonia, 4.6 km<sup>2</sup>, 365 to 465 m ü.M., daily time steps for 1993; “Abfluss”=discharge, “Sättigungsdefizit”=saturation deficit, “Bodenspeicher”=soil storage, “beobachtet”=observed

unimportant. However, the following example of the Wernersbach shows, that capillary rise may well be important for both, total evaporation and runoff.

Figure 15 shows the impact of the precipitation intensity threshold  $P_{grenz}$  on soil moisture, saturation deficit and runoff. All model runs were carried out without capillary rise and reflow from interception storage ( $r_k = 0$ ). The effect are much too high summery discharge rates because of not considering the uptake-processes which are important in this basin. This affects also the soil moisture which decreased dramatically, regardless of the value of  $P_{grenz}$ . Figure 15 makes it clear how the parameter  $P_{grenz}$  affects the separate storages: The smaller  $P_{grenz}$ , the less water can infiltrate in the soil matrix and the less water can be extracted by evaporation. At the same time the saturation deficit is decreasing, the groundwater table rises, leading to higher base flows and also to higher interflow rates. It's also apparent from figure 15 that there will be a characteristic maximum value for  $P_{grenz}$  valid for a given precipitation regime, because larger values of  $P_{grenz}$  will not change the model reaction anymore. In the example of figure 15 this is a value of  $27 \text{ mm} \cdot \text{d}^{-1}$ . Higher precipitation intensities were not found for 1993 in this watershed.

Comparing the courses of soil moisture, saturation deficit, and discharge in figures 15 and 16 it becomes clear how important the processes of capillary rise resp. reflow from saturated zone and interflow storage into the soil storage may be. Compared to the graphs without these effects, the soil moisture in figure 16 is much higher leading to much less days with reduced evaporation conditions. At the same time the saturation deficit is larger leading to less base flow.

The parameter  $P_{grenz}$  has similar impacts in figures 15 and 16. Soil water storage and groundwater table can be affected but the absolute effect is damped considerably by the capillary rise effect. This means that high intensity precipitation which flows directly into the groundwater may return into the soil storage due to the risen groundwater table and thus due to higher capillary rise rates. In the above example  $r_k$  is set to 1.0, the maximum value. The reflow from the interflow storage is calculated after the capillary rise is considered if there are still unsatisfied amounts of evaporation losses which have to be filled up. The potential reflow from the interflow storage is scaled down according to the relative content of the interflow storage itself and according to the parameter  $r_k$ . The scheme of calculating capillary rise and interflow storage reflow is explained by equations (63) and (64). The vertical component, the capillary rise, is only considered if there is a hydraulic connection between the saturated zone and the soil water storage. This criterion is checked by comparing the actual saturation deficit against the threshold saturation deficit, which is determined by the product of the scaling parameter  $r_k$ , the drainable porosity  $n_e$  and the root depth  $z_w$ .

### 3.6.6 Parameters of the soil model for model version 2 (Richards-equation)

Because of its more physical base there are much less sensitive calibration parameters for model version 2 using the RICHARDS-equation than for model version 1 using the TOPMODEL-approach. The soil properties, in particular the porosities, the  $k$ - $\Theta$ - and the  $\psi$ - $\Theta$ -relations should be understand as fix parameters which should not be calibrated at all (may be they could be replaced by measurement results). Finally there are only 3 parameters which may be calibrated:

- the recession constant  $k_{rec}$  for the saturated hydraulic conductivity  $K_s$  with depth after equation (85)
- the interflow drainage density  $d_r$  (see equation 89)
- mainly for larger time steps and larger layer thickness': the maximum relation of the relative hydraulic conductivities of neighboring layers  $c_k$  after equation (87)
- if the groundwater model is disabled, the base flow parameters  $Q_0$  and  $k_{ELS,QB}$  must be calibrated; this is not considered here because the application of the groundwater module makes this obsolete

The recession constant  $k_{rec}$  considers the decreasing hydraulic conductivity with increasing depth. The conductivities are reduced down to 2 m depth, below 2 m the value remains constant and is taken from the 2 m level (2 m are a fix depth fixed in the model internally). If the soil parameterization is not done



using the VAN GENUCHTEN parameters  $n$ ,  $\alpha$ ,  $K_s$ ,  $\Theta_r$ , and  $\Theta_{sat}$  look-up-tables for the saturated conductivities of all layers as well as look-up-tables for the  $k$ - $\Theta$ - and  $\psi$ - $\Theta$ -relations must be applied. Then, the parameter  $k_{rec}$  is not used, but the conductivity profile must be known.

The interflow drainage density  $d_r$  considers the “river density” in a grid cell as well as the difference between horizontal and vertical hydraulic conductivity. It is an effective parameter which linearly affects the amount of interflow (see equation 89). A model presumption is, that for each grid cell where interflow can be generated (slope > 0) there is at least one drainage channel. This limits a physically realistic model application to grid cell sizes larger than the natural or artificial drainage density. But since this is a rather theoretical limit, the model can also be applied to smaller cell sizes, considering interflow but no lateral interconnections via water flow between neighboring grid cells.

The maximum relation of the relative hydraulic conductivities of neighboring layers  $c_k$  was introduced into the model in order to compensate or even avoid numerical problems which arise from the vertical and temporal discretization of the RICHARDS-equation. Unless in other models, WaSiM-ETH uses constant time steps of e.g. 1 hour or 1 day and relatively thick layers of 0.1 to 0.5 m, so the discretization may be too coarse. The parameter  $c_k$  limits the effective  $k_s$ -value used for the flux calculation between two layers up to a minimum value in order to avoid in dry soils a permanent water logging. Without this parameter this could be the result, if a heavy rain would fall onto a dry soil. The dry second layer would have a much too small relative conductivity, so the water would fill up the first layer and then surface runoff would be generated. Since this effect may also occur in the reality, the parameter  $c_k$  is a calibration parameter which should be chosen according to the region, the precipitation pattern and other environmental conditions. It's value depends on the vertical discretization of the soil and on the temporal discretization. It ranges between <50 (Thur-basin, time step 5 days, 33.3 cm soil layers) up to >100 (Thur-basin, time step 1 hour, 33.3 cm) but may be even smaller or larger for other regions of the world.

Chapter 3.7.3 also shows an example of the model sensitivity to this parameter.

### 3.6.7 Spatial resolution

The spatial resolution to use for a given project depends mainly on the spatial structure of the model domain. A measure of the required spatial resolution may be the characteristic morphologic length, also called the macroscopic length or the typical slope length. The altitude-dependence of most of the input variables (like temperature, vapor pressure, wind speed a.s.o.) leads also to a resolution which is adequate to consider these dependencies.

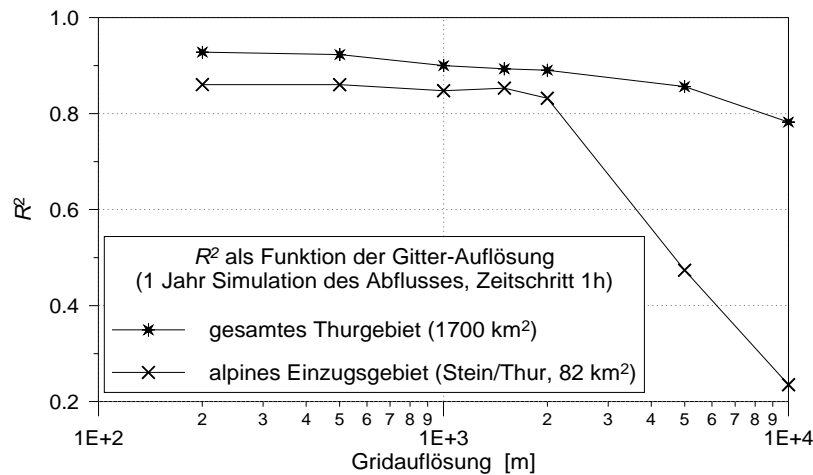


figure 17: Impact of the spatial resolution on the model efficiency, resolution varied between 200 m and 10'000 m, 1 year simulation of discharge, time step 1 hour, the upper graph for the entire Thur basin, the lower graph for the more alpine upper Thur basin at Stein/Thur.

The most efficient resolution (balance between model efficiency (accuracy) and computer run time) may be found by a series of model runs using different spatial resolutions. Figure 17 shows the effects of different spatial resolutions on the model efficiencies  $R^2$ . It clearly suggests, that the maximum grid cell size in alpine regions should be below 2000 m (better: below 1000 m), whereas the resolutions for flatter areas may be up to 2000 m or 5000 m. Often, a too coarse resolution results in difficulties in parameterization of the model, so it may be better to use e.g. a 500 m resolution instead of 1000 m in order to consider the variations in surface or soil properties.

### 3.6.8 Conclusion

The following parameters are the most sensitive parameters with respect to the modeled discharges:

- the surface resistances  $r_{sc}$  for the vegetation if they are much higher or much lesser than the optimum value
- the threshold temperature rain/snow  $T_{R/S}$
- the degree day factor  $TGF$
- the threshold temperature for snow melt  $T_{0,m}$

*soil model of Version 1 (TOPMODEL-approach)*

- the recession parameter  $m$
- the correction factor for transmissivities  $T_{korr}$
- the scaling factor for capillary rise resp. for reflow from the interflow storage into the soil storage  $r_k$

*soil model of model version 2 (RICHARDS-equation)*

- scaling of interflow by a drainage density  $d_r$
- maximum allowed relation of relative conductivities for neighboring layers  $c_k$
- recession constant  $k_{rec}$  for the saturated hydraulic conductivities (recession with depth)

Not too important for the discharge, but important for partitioning the precipitation water into water balance components, the following parameters are:

- the maximum capacity of the interception storage  $h_{SI}$  (model version 1)
- the temperature transition range from snow to rain  $T_{trans}$
- the threshold precipitation intensity for generating macro pore percolation  $P_{grenz}$  (model version 1)

The spatial resolution is important especially for mountainous basins. With increasing cell sizes there is a certain basin dependent threshold the results will become increasingly inaccurate. These thresholds are at around 1000 to 2000 m for alpine catchments and at around 2000 to 5000 m for hilly regions.

## 3.7 Calibrating the model

### 3.7.1 Introduction

The process of the model calibration is not a trivial problem which requires hydrologic expertise as well as a sufficient knowledge of the model structure and the model reactions. The following descriptions may be used as a “calibration guide” for inexperienced WaSiM-ETH users. Based on the parameter sensitivity analysis of chapter 3.6 a ranking for calibrating parameters is suggested including practical hints in doing the calibration.

If WaSiM-ETH is calibrated for a new basin it is generally recommended to use the parameter values of already calibrated basins for the first calibration step, especially for those parameters which are insensitive. Only those parameters which are sensitive or which depends strongly on basin properties should be calibrated then. As showed in the previous sub-chapters, the most important parameters are the soil model parameters for model version 1 (TOPMODEL-approach). In model version 2 (RICHARDS-approach) also the

soil model parameters are sensitive. Therefore, the calibration is shown in two examples for the soil model parameters, once for model version 1 and once for model version 2.

All the other parameters of other modules are less important and they can be taken without large errors from other model applications in similar areas (like evaporation or snow melt parameters). Only the routing parameters must be newly estimated for each model application. This is usually be done during the preprocessing using the topographic analyzing tool TANALYS (see chapter 4.1).

### 3.7.2 Calibrating the soil model for model version 1 (Topmodel-approach)

The soil model of model version 1 is controlled 9 parameters which have to be specified in the control file for each subbasin. Not all of these parameters are equally important, the most sensitive parameters are the recession parameter  $m$  and the scaling factor for the topographic indices  $T_{korr}$ . These two parameters will now be used for a first calibration step.

#### first step of the calibration (soil model, model version 1 - TOPMODEL)

- *parameter identification by hydrograph analysis*

Using observed hydrographs, the estimation of recession constants for surface runoff and interflow is relatively easy. If the original TOPMODEL-approach is used (WaSiM without interflow  $\rightarrow SH_{max} = 0$ ), then this is also true for the recession parameter  $m$ . The estimation of the single reservoir recession constants for  $k_D$  and  $k_H$  using linear regression fits in logarithmic transformations is a well known practice, so here the focus is laid on the estimation of  $m$ .

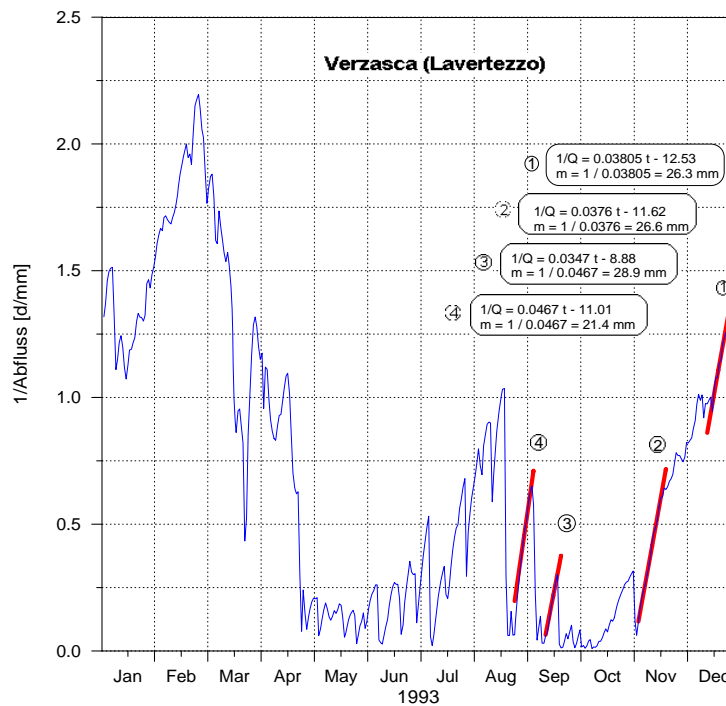


figure 18: Estimation of the recession parameter  $m$  of the river Verzasca (Switzerland) for 1993

Like shown in equation (66) and in sub-chapter 3.6 the parameter  $m$  can be estimated as the tangent of the slope of invertedly plotted discharge recession periods. These recession periods should not be affected by too much evaporation (because the recessions in hot seasons are much faster due to the evaporation from shallow groundwater areas near rivers). Also impacts by snow melt have to be avoided as well as periods with frozen soils. It is recommended to look for as many of useable recession periods as possible in order to get a parameter value which is as confident as possible. The time step of the observed hydrograph does not significantly influence the result, thus discharges in mm/h or mm/day are equally usable. The examples are shown for the alpine Verzasca-catchment (Ticino, Switzerland). Figure 18 shows the inverted

hydrograph for a one-year-period (daily time step). The average value of the tangents of all linear fits is the parameter  $m$  (for use in WaSiM-ETH: convert this result which is given in mm into meter).

Table 8: recession constant  $m$  [m] for the river Verzasca (Switzerland) ;  
 $m = 0.027$  m (average value for 13 recessions between years 1993 and 1996)

1993	1994	1995	1996
0.0266	0.0357	0.0277	0.0287
0.0214	0.0281	0.0217	0.0278
0.0263	0.0235	0.0267	0.0256
0.0289			

• **estimation of  $T_{korr}$**

If the recession constant  $m$  is estimated as a first approximation (later,  $m$  must be varied, again), the scaling factor for the topographic indices has to be determined. There are two possibilities:

- a) parameter estimation using specific basin information's
- b) parameter estimation by optimizing ("trial and error")

parameter estimation using specific basin information's

If  $T_{korr}$  should be estimated in this way, some basin data are required. These data are the mean saturation deficit  $S$  for the subbasin and the matching observed base flow. To get  $S$ , which is not measurable, the mean groundwater table  $GW$  and the mean drainable porosity  $n_e$  have to be known in order to calculate  $S$  by  $S = GW \cdot n_e$ . In addition, the parameter  $m$  (which should now be known as first approximation) and the average topographic index  $\gamma$  should be known.  $\gamma$  can be determined by:

$$\gamma = \frac{1}{n} \sum_{i=1}^n \ln \frac{a}{T_0 \tan \beta} \quad (137)$$

with  $\gamma$  average topographic index [-]  
 $n$  number of grid cells for the subbasin [-]  
 $a$  local specific catchment area ( $a=A/\text{cell size}$ ) [m]  
 $T_0$  hydraulic transmissivity [ $\text{m}^2/\text{s}$ ]  
 $\beta$  local slope [ $^\circ$ , rad]

Base flow is calculated in the model by:

$$Q_B = Q_0 \cdot e^{-S/m} \quad (138)$$

with  $Q_B$  base flow [mm/time step]  
 $Q_0$  maximum base flow at full soil saturation [mm/time step]  
 $S$  average saturation deficit of the subbasin [m]  
 $m$  recession constant [m]

with  $Q_0$  expressed by:

$$Q_0 = e^{-\gamma_{korr}} \quad (139)$$

$$\text{and } \gamma_{korr} = \ln(f \cdot T_{korr}) - \gamma \quad (140)$$

with  $\gamma_{korr}$  corrected average topographic index  
 $f$  unit scale factor for consideration of the unit of discharge and for conversion of the transmissivity units from  $\text{m}^2/\text{s}$  into  $\text{mm}^2/\text{time step}$ .  
if time step = 1 hour:  $f = 3.6 \cdot 10^9$ , if time step = 1 day:  $f = 8.64 \cdot 10^{10}$

Equations (140) and (139) can be integrated into equation (138). This results in the equation for determining the scaling factor  $T_{korr}$ :

$$T_{korr} = \frac{Q_B}{f \cdot e^{-\gamma - S/m}} \quad (141)$$

example: Verzasca (Switzerland)

A baseflow of  $Q_B = 1.3 \text{ m}^3/\text{s}$  was observed for a  $186 \text{ km}^2$  area (this is an equivalent of  $0.6 \text{ mm/day}$ ). The average topographic index is  $\gamma = 21.97$ , the recession parameter was estimated to  $m = 0.027$  (see table 8). The average saturation deficit was estimated to be  $S = 0.06 \text{ m}$ , as given by an estimated mean groundwater table of  $1.5 \text{ m}$  below the surface and a drainable porosity of  $0.04$ . The scaling parameter  $T_{korr}$  is then:

$$T_{korr} = 0.6 / 8.64 \cdot 10^{10} / e^{-21.97} / e^{-0.06/0.027} = 0.22$$

The value of  $T_{korr}$  depends approximately linear on the average groundwater table below the surface. After the first estimation of  $T_{korr}$  by equation (141) it usually must be varied and optimized. However, virtually always the required data for determining  $T_{korr}$  by specific basin properties and states are not available. In such cases, the data may be estimated or  $T_{korr}$  must be determined by an trial and error approach.

#### parameter optimizing

The optimization is done in a first step by varying  $T_{korr}$  in a series of runoff simulations. All other parameters are constant for all optimization runs. To give an orientation table 9 shows preliminary parameter values, except for  $m$  and  $T_{korr}$ .

Table 9: possible initial parameter values, example for a Verzasca-subbasin (Switzerland)

parameter	value	comment
$m \text{ [m]}$	(0.027)	estimation by hydrograph analysis, see fig. 18; usually also $m$ must be varied, especially if the recessions are not unique or if interflow is considered
$K_{korr} \text{ [-]}$	1000	The correction factor scaling the drainage from the unsaturated into the saturated zone should be sufficiently large in order to avoid the breakdown of the hydraulic interconnection between unsaturated and saturated zone. If $K_{korr}$ would be too small and $T_{korr}$ too large, the saturation deficit becomes larger and larger whereas the percolation from the unsaturated zone becomes very, very small due to the exponential recession of the soil conductivities with increasing saturation deficit. In such cases the water will fill up the soil in the unsaturated zone and all rain will become surface runoff. Another reason that $K_{korr}$ should be rather large is the fact that percolation uses also macro pores and other preferential flow paths, but the hydraulic conductivity of the soil is given for vertical matrix flow only.
$K_D \text{ [h]}$	5	from hydrograph analysis or taken from similar catchments
$K_H \text{ [h]}$	50	from hydrograph analysis or taken from similar catchments, at $SH = 0$ this parameter does not make any effects, because no interflow is modeled
$SH_{max} \text{ [mm]}$	0	interflow is not used here, so it must be set to 0; later this will change
$P_{grenz} \text{ [mm} \cdot \text{h}^{-1}]$	10	large precipitation threshold value, in order to avoid any fast macro pore drainage (all precipitation infiltrates into the root zone soil storage)
$r_k \text{ [0...1]}$	0	no consideration of capillary rise and reflow from the interflow storage into the soil storage
$c_{melt} \text{ [0...1]}$	0	no consideration of surface runoff from snow melt
$SUZ_0 \text{ [mm]}$	0	initial content of the unsaturated zone storage (large pores above field capacity)
$SD_0 \text{ [n} \cdot \text{nFK]}$	1.5	initial saturation deficit: affects the initial base flow; with 0 as initial value very much base flow is generated until the model is in equilibrium. Its better to use a small value then a large value because too large values may cause the model to simulate a hydraulic disconnection (like described for the $K_{korr}$ -parameter). If this happens, $SD_0$ must be reduced.

The possible range of the scaling factor  $T_{korr}$  is between approximately  $10^{-5}$  and  $10^{+5}$ . Because the parameter impacts the distribution function of the topographic indices logarithmic, the shift of the distribution function along the x-axis may be in the range of app.  $-9$  to  $+9$ . Experiences in using WaSiM-ETH show a range of  $10^{-3} \leq T_{korr} \leq 10^{+3}$  (logarithmic between  $-6.9 \dots +6.9$ ). If no a-priori information about  $T_{korr}$  are

available (e.g. from estimations using average groundwater table, see above), the range of variation of  $T_{korr}$  has to be very large. The model efficiencies ( $R^2$ ,  $EV$ ) are used to estimate the parameter quality. Because the number of required simulation runs may be high it may be better to use daily time steps instead of hourly time steps. Figure 19 shows the results for the optimizing process for various  $T_{korr}$ -values. Obviously, an optimum for  $T_{korr}$  should be looked for between 0.1 and 1. In a second optimizing step, the search can be refined to get a better estimate for the optimum value, see figure 20.

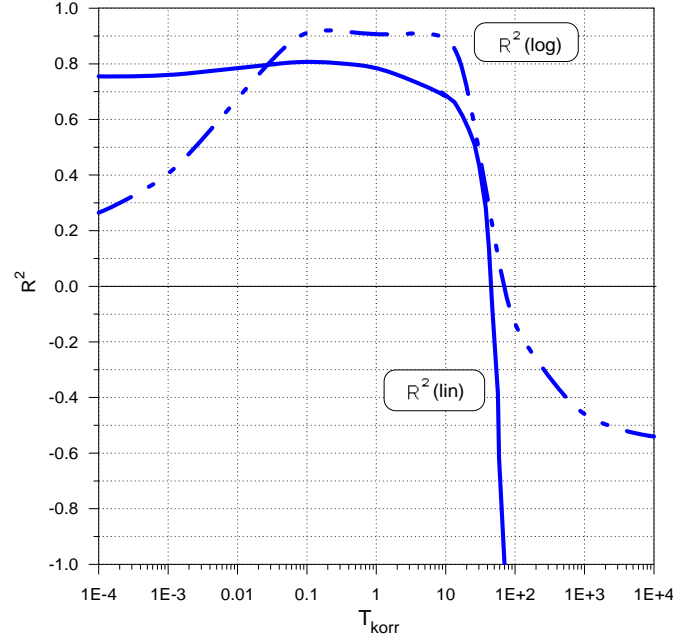


figure 19: 1<sup>st</sup> optimizing step: distribution of the model efficiency  $R^2$  (linear and logarithmic) as reaction an variations in  $T_{korr}$ ; Verzasca, Simulation in daily time steps for 1993

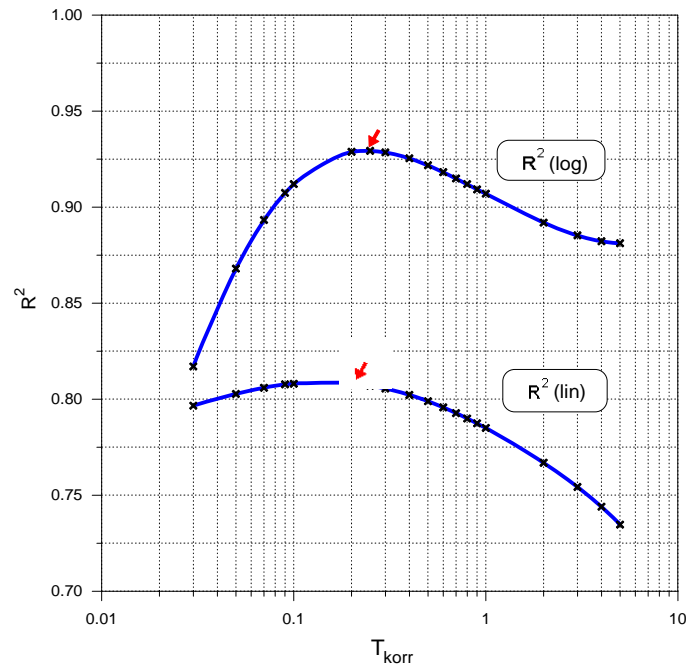


figure 20: 2<sup>nd</sup> optimizing step: distribution of the model efficiency  $R^2$  (linear and logarithmic) as reaction an variations in  $T_{korr}$ ; optimum for  $T_{korr}$  at around 0.25 for  $R^2$ (log); Verzasca, Simulation in daily time steps for 1993

Figure 21 shows the effects of the parameter  $T_{korr}$  on the modeled discharge and on internal states (compare also figures 12 and 13). This underlines the importance of a serious  $T_{korr}$ -estimation.

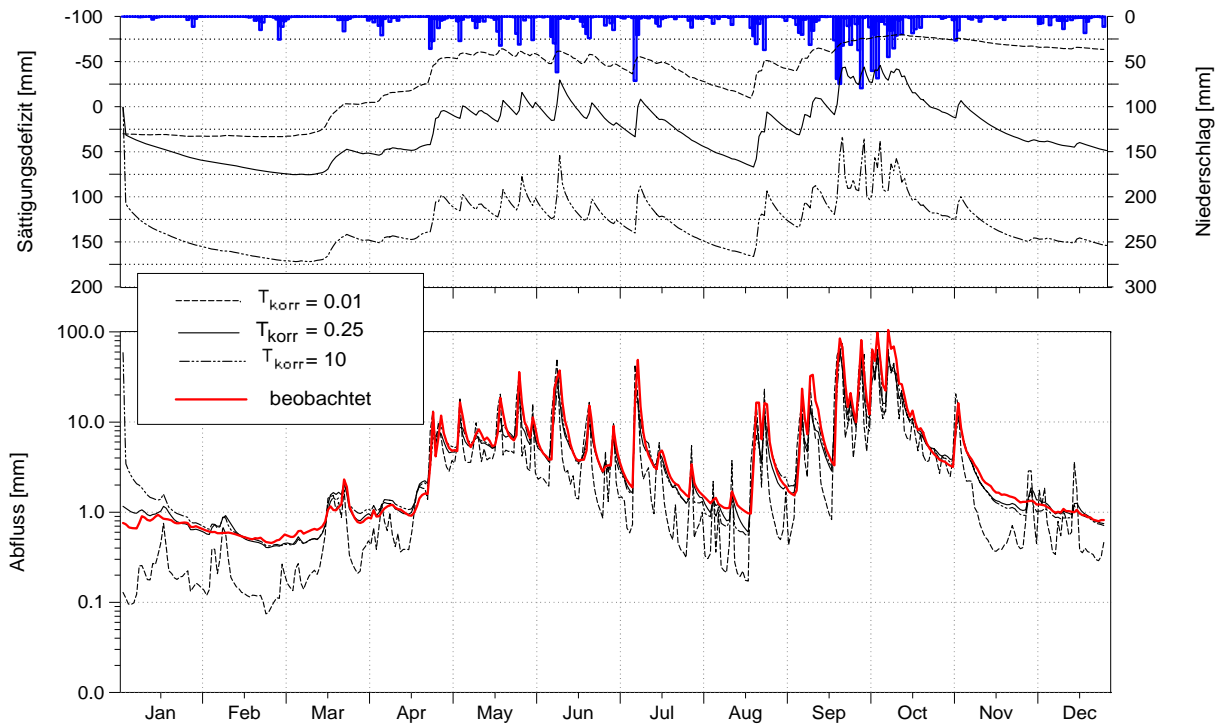


figure 21: model sensitivity on variations in  $T_{korr}$ ; Verzasca, daily time step for 1993; “Abfluss”=discharge, “Sättigungsdefizit”=saturation deficit, “Niederschlag”=precipitation

If a first optimum value for  $T_{korr}$  is found and validated by analyzing the runoff components and other internal state variables, the second calibration step may follow.

**Note:** In opposition to the recession constant  $m$ , which should be determined for as many subbasins as possible by analyzing observed hydrographs, the first-approximation- $T_{korr}$  can also be used for other, similar subbasins (if they are similar in geology, topography, soils and climate). On the other hand, a further calibration like in the second calibration step should also be done for those subbasins.

**Note:** In order to avoid impacts of (badly) modeled discharges of first order subbasins on lower subbasins due to the routing, the routing should be done using the option for considering observed discharges. Therefore the first parameter in the [routing\_model]-section of the WaSiM-ETH control file, the so called “ignorance parameter” must be set to a value of 2, see also chapters 1.10 and 3.5.1.

## second step of calibration (soil model, model version 1 - TOPMODEL)

### • adding interflow

If the first calibration step does not gave satisfactory results or if the modeler knows, that there must be an interflow component, the interflow should be activated by setting the parameter  $SH_{max}$  to values greater than zero. The value of  $SH_{max}$  could either be estimated by analyzing observed hydrographs or by taking values from similar subbasins or even by estimating a value considering only the personal experience of the modeler. Current model applications show, that an interflow storage of 10 to 40 mm may be appropriate, so an initial value could be  $SH_{max} = 20$  mm.

Using interflow means that there are now three runoff components instead of only two. The parameter  $m$  affects now only the base flow, which now is much less dynamic than the mixed interflow/baseflow controlled by  $m$  was before. Because  $m$  and  $T_{korr}$  depend now on another, a re-calibration is required. Again, this is done by a series of simulations using various values for both,  $m$  and  $T_{korr}$ . The results are evaluated using the model efficiencies. An optimum can be found usually for different parameter sets as compared to the parameter set without interflow. A result of such an optimization is shown in figure 22 (see also figure 14). However, it is highly recommended to visualize as much of the results as possible, in particu-

lar the modeled runoff components but also modeled soil moisture, evaporation, snow cover a.s.o. for both, the time series of subbasin averages and the temporally averaged or aggregated result grids.

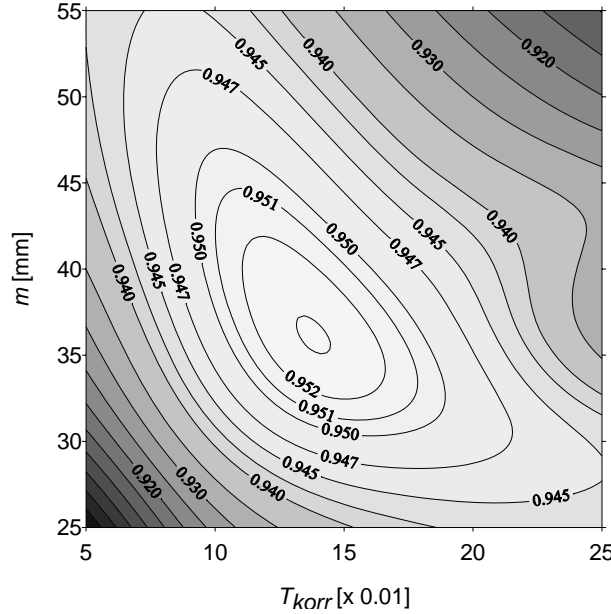


figure 22: distribution of model efficiencies ( $R^2$ ) following variations in  $m$  and  $T_{korr}$ ; optimum values at app.  $T_{korr} = 0.14$ ,  $m = 0.036$  m; Verzasca, 1993

If the fraction of interflow on the modeled total flow is unsatisfactory, then variations of the maximum interflow capacity  $SH_{max}$  will help to balance the components. A greater  $SH_{max}$  usually will lead to increased interflow, whereas a smaller  $SH_{max}$  will result in less interflow. However, any changes made to  $SH_{max}$  will result in the necessity of re-calibrating the recession parameter  $m$  and the scaling parameter  $T_{korr}$ . If  $SH_{max}$  is changed only in small steps, then this can be reached easily. On the other hand, if peak flow discharges or recession periods are modeled incorrect, then an increase or decrease of the responsible recession constants  $k_D$  and  $k_H$  may increase the model efficiency.

If required – and usually it is required – this calibration step should include the optimizing of the initial saturation deficit  $SD_0$ . This is relatively easy, since each change can immediately be evaluated after only some model time steps by looking at the modeled runoff components and comparing it to the observed runoff. Ideally, the model period starts at a time when the observed runoff consists only of slow subsurface runoff (baseflow), since then the observed runoff can be compared directly with then modeled baseflow which is controlled by the initial saturation deficit  $SD_0$ . A well fitted  $SD_0$  increases the total model efficiency  $R^2$  considerably. Another possibility to find a reasonable initial saturation deficit would be a sufficient long time offset from the beginning of the model run until the efficiency criterions are started to estimate. Then the first period is used for a initial stabilization of the model. This can also be reached by running the model twice, the first time with given initial conditions (no grids are read) and written output grids and the second time with read input grids, which are the output grids of the first run.

- **calibration of the remaining parameters of the soil model**

After calibrating the most sensitive model parameters  $m$  and  $T_{korr}$ , the remaining parameters should be calibrated. The parameters  $r_k$  and  $P_{grenz}$  should be calibrated together, because they have partly contrary effects on the model reaction, see chapter 3.6.5. These parameters are most sensitive, if the model is applied to a rather dry catchment with much higher evaporation than runoff. Thus if working on such basins, the calibration of  $r_k$  and  $P_{grenz}$  may be especially important. The last parameter to be calibrated is the surface runoff fraction on snow melt  $c_{melt}$ . It affects in the first way the modeled discharge in winter and spring, especially the peaks of melt floods. A large  $c_{melt}$  value means high surface runoff fractions on snow melt and thus large peak flows in the melt season, but it means also a smaller storage effect of melt water in the soil. Thus,  $c_{melt}$  may also be useful to influence the annual storage behavior. The optimum



value for  $c_{melt}$  must be between 0 and 1, often it can be set to 0.1...0.2 in flat regions or to 0.2...0.35 in mountainous regions.

### 3.7.3 Calibrating the soil model for model version 2 (Richards-equation)

Compared to WaSiM-ETH version 1, WaSiM-ETH version 2 uses a much more physically based soil model. The total number of free parameters is not smaller, but most parameters like the hydraulic properties of the soil (e.g. van Genuchten parameters for  $k-\Theta$  and  $\psi-\Theta$ -relations) are principally observable or derivable from soil type maps. These parameters will not be calibrated here. The calibration parameters, which are empirical parameters, are:

- the scaling parameter for interflow  $d_r$  (drainage density)
- the recession constant  $k_{rec}$  for the saturated hydraulic conductivity with increasing soil depth
- the maximum relation of relative conductivities between neighboring soil layers  $c_k$

The parameter  $c_k$  is relatively insensitive and so it was set to 100 for all calibration runs because it depends mainly on the model resolution in space (soil layer thickness) and time. In addition, the recession parameters for surface runoff and interflow  $k_D$  and  $k_H$  may be calibrated, but both parameters are relatively insensitive if using a flow time travel grid which makes these parameters even scale independent.

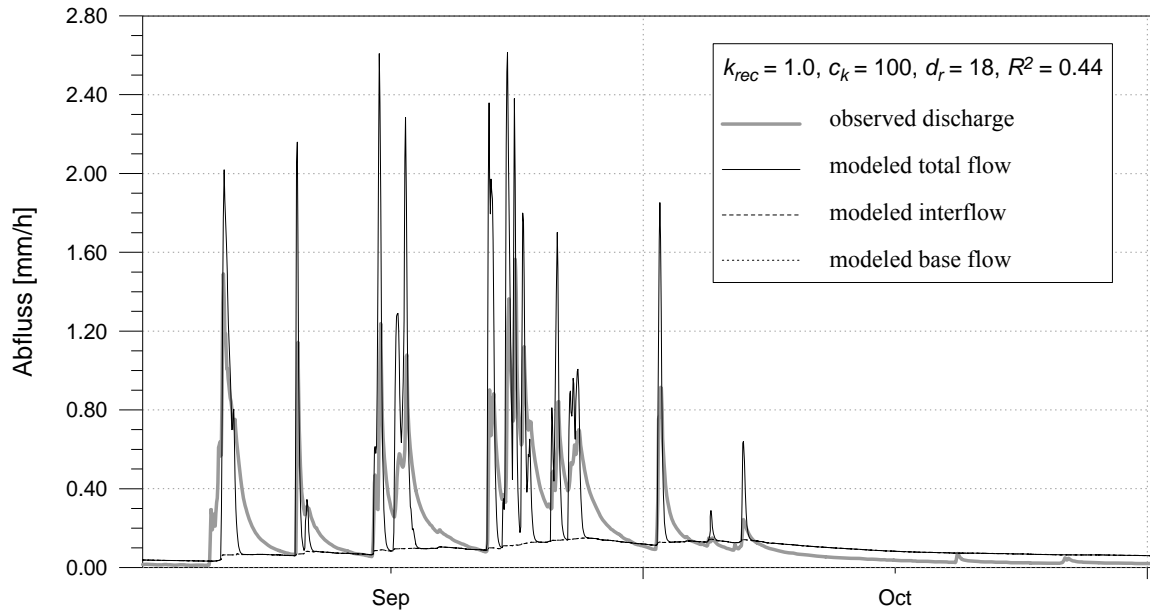


figure 23: Modeled runoff using model version 2 for the Rietholzbach catchment, without interflow

The following example shows the calibration of the soil model for the 3.3 km<sup>2</sup> Rietholzbach catchment, a subbasin of the river Thur. All examples were modeled in a spatial resolution of 500 x 500 m and in a temporal resolution of one hour, so the catchment is represented by 14 cells à 0.25 km<sup>2</sup>. The calibration was done modeling the years 1983 and 1984, but evaluating only 1984, so the initial conditions were taken from the last time step of the first model year. The model efficiency criterions are valid for the entire year 1984, not only for the plotted parts.

The first step was a model run without interflow. This can be achieved either by setting  $d_r = 0$  or by setting  $k_{rec} = 1.0$ . The first parameter  $d_r$  is multiplied with the potential interflow which depends on the local slope, the water content of the soil and the conductivity. If  $k_{rec} = 0$ , then there is no conductivity decrease with depth and no lateral runoff components can be generated. The result of this first approximation is shown in figure 23. The dynamic of the runoff is not met, the base flow is increasing too much and the flood peaks are modeled to large. The next step includes the modeling of interflow, which is usually the main runoff component in most northern pre alpine catchments. The interflow scaling parameter is set to  $d_r = 18$  as taken from similar catchments. The  $k_s$ -recession constant is set to 0.9. All other parameters

remain unchanged. The result is shown in figure 2. Compared to fig. 24 the dynamics of the modeled runoff was improved considerably, as can be seen by the  $R^2$  which has increased from 0.44 to 0.8.

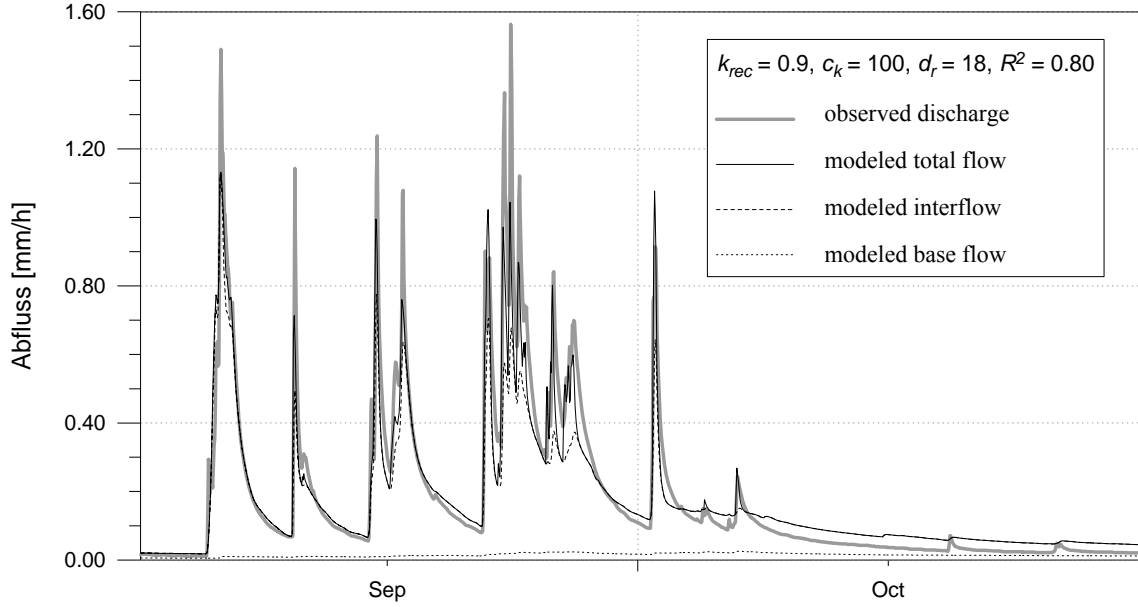


figure 24: Modeled runoff using model version 2 for the Rietholzbach catchment, with interflow,  $k_{rec} = 0.9$

The flood peaks, which were too high in figure 24, are now even too small. The interflow is the major runoff component, whereas the base flow virtually disappeared. The interflow (between base flow and total flow) is too high in October. In order to reduce this flow, now the parameter  $k_{rec}$  was decreased down to 0.1. Figures 25 and 26 show the model results with values of  $k_{rec} = 0.3$  and  $k_{rec} = 0.1$ , respectively. All other parameters remained constant.

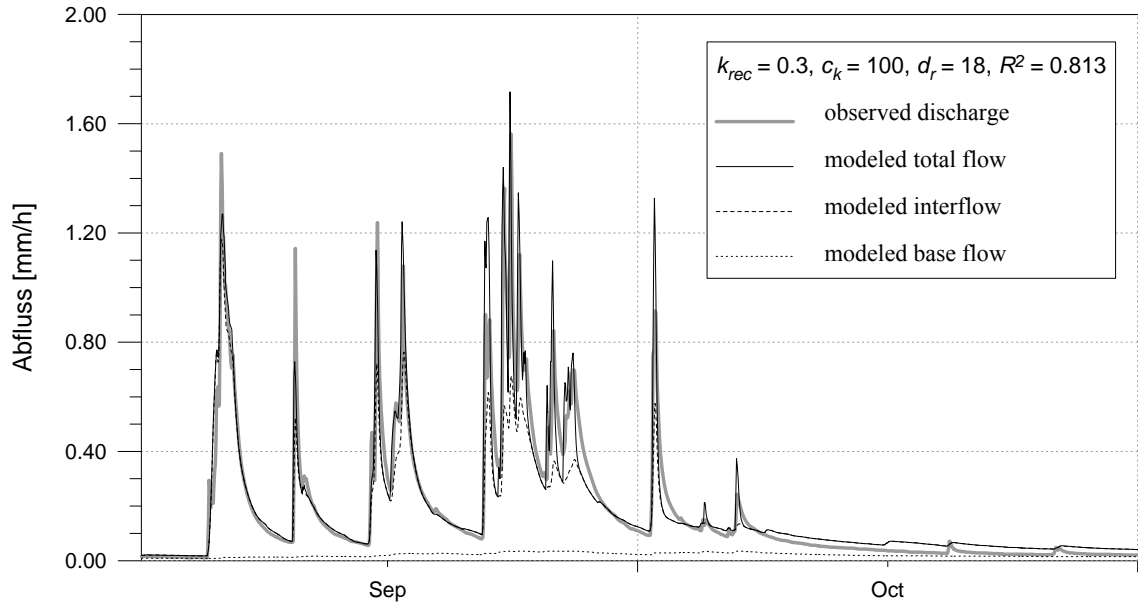


figure 25: Modeled runoff using model version 2 for the Rietholzbach catchment, with interflow,  $k_{rec} = 0.3$

As can be seen in the figures 24 to 26, the overall shape of the modeled runoff hydrograph does not significantly change. However, it is remarkable that the flood peaks show a tendency to higher values with decreasing  $k_{rec}$ -values. It is also obvious that the recession period in October was modeled much more realistic with smaller  $k_{rec}$ -values. But the interflow fraction on the total flow is relatively small in late September, leaving the surface runoff a fraction of partly more than 50 %.

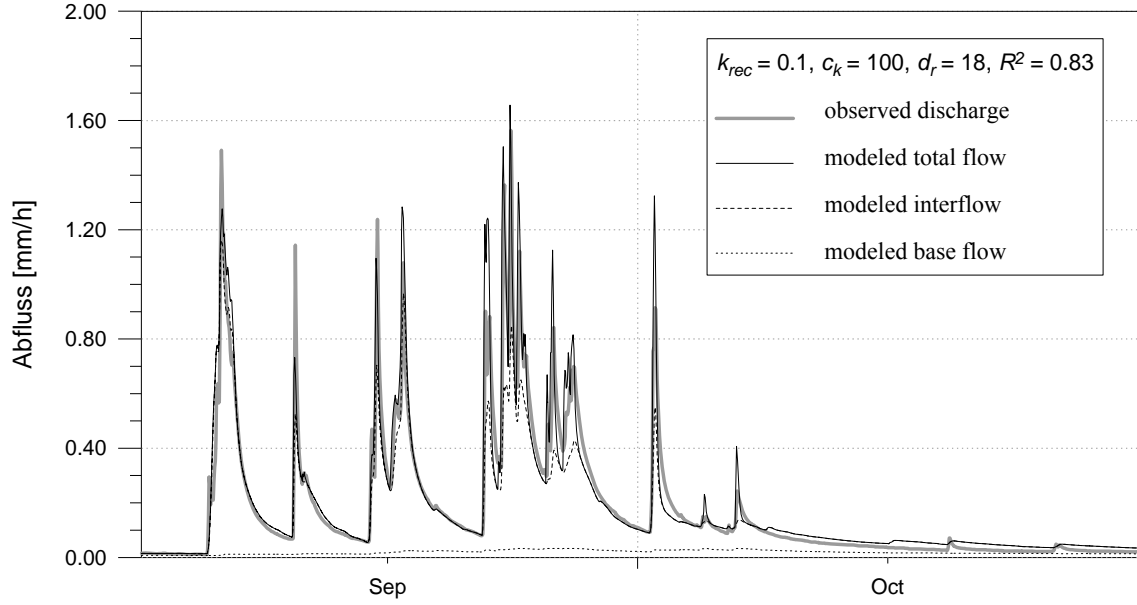


figure 26: Modeled runoff using model version 2 for the Rietholzbach catchment, with interflow,  $k_{rec} = 0.1$

Consequently, the next calibration step was the calibration of the interflow scaling parameter  $d_r$ . The initial value of 18 was varied between 12 and 30. Figures 27 and 28 show the results with both extremes of the investigated  $d_r$ -range.

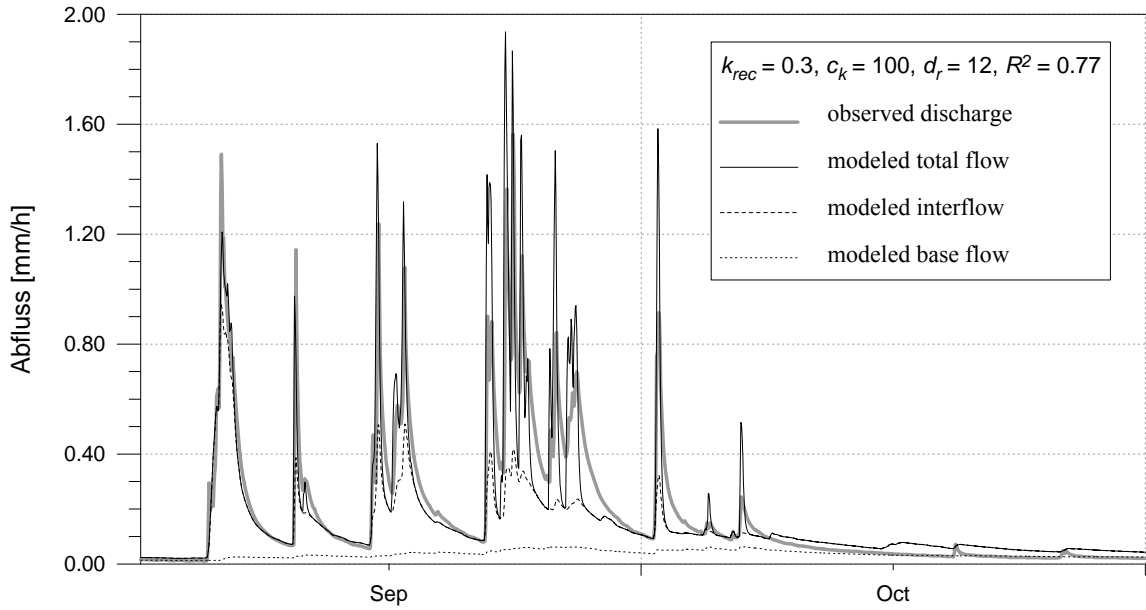


figure 27: Modeled runoff using model version 2 for the Rietholzbach catchment,  $k_{rec} = 0.3$ ,  $d_r = 12$

Figure 27 shows an decreasing model efficiency ( $R^2 = 0.77$ ) compared to the former runs due to decreasing  $d_r$  from 18 to 12. Not only that the decreased interflow fraction leads to more surface runoff and higher flood peaks, also the base flow in October is increasing again because more water could percolate down to the groundwater. Only an increased drainage density factor  $d_r$  leads to the wanted effect of higher interflow fractions on the total runoff and at the same time to smaller runoff values during the recession period. The quality of this parameter set is also underlined by the till now best  $R^2$ -values of  $R^2_{log} = 0.85$  and  $R^2_{log} = 0.89$ . The achieved quality of fit is sufficient, so the parameter set can be seen as optimized. However, further small improvements may be possible, but they will be minor compared to the large effect of the above calibrated parameters  $d_r$  and  $k_{rec}$ . The recession constant  $k_{rec} = 0.1$  could also be validated for local soils, which show a recession of the saturated hydraulic conductivity by two orders of magnitude down to two meters depth.

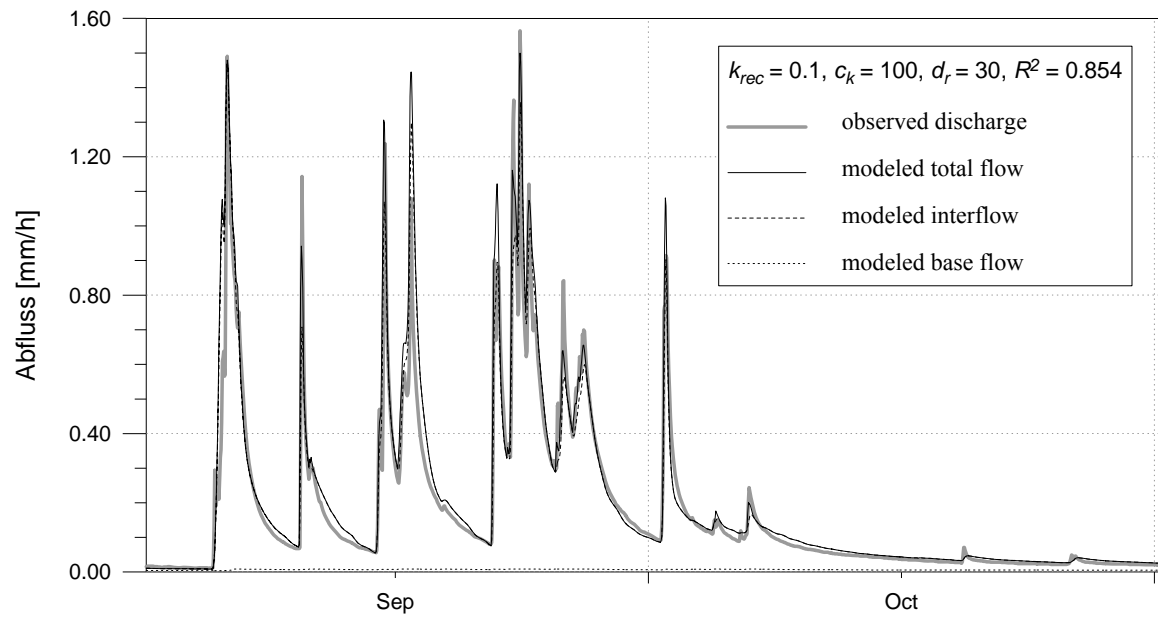


figure 28: Modeled runoff using model version 2 for the Rietholzbach catchment,  $k_{rec} = 0.1$ ,  $d_r = 30$

## 4 Software for pre- and postprocessing

### 4.1 Working with spatially distributed data (grids)

#### 4.1.1 ASCIGRID

Converting ASCII grids into binary grids

command: `ascigrid <ascii-grid> <binary-grid>`

During the conversion a statistic of all valid cell values is calculated and stored in the records 7 to 12 of the binary grid. The statistic parameters are number, minimum, maximum, sum, average, and standard deviation of all valid cells. Nodata values does not count for the statistics. **Note:** The maximum size of a grid depends on the memory of the computer as well as on the data itself. Because the statistics needs an internal sum of all squared values, an arithmetic overflow may happen if the values are very large. This should happen extremely seldom, because the statistic registers are able to deal with numbers up to  $\pm 1.0E+4300$  (Intel PC).

see also: GRIDASCII, GRIDSURF, SURFGRID, MF2WASIM, GRIDCOLM

#### 4.1.2 FIELDGEN

Generating (log-)normal distributed correlated random fields in ASCII-Grid-file format.

Command: `fieldgen <outfile> <ncols> <nrows> <xll> <yll> <cellsize> <nodata-value>  
<average> <std.dev.> <corr-length-x> <corr-length-y>  
[init_value=<init_value>] [<cm_log>=0|1]`

The ASCII formatted output grid is specified by its name <outfile>, its dimensions <ncols> and <nrows> (number of columns and rows), the coordinates of the lower left corner <xll> and <yll>, the <cellsize> and the nodata-value. The grid values are generated randomly according to the given parameters <average> and <standard deviation> of the probability distribution. A correlation length relative to the cellsize have to be specified for each direction. The range for the correlation length is within >0 to 1. In order to get well defined reproducible results, the random number generator can be initialized by the option `init_value=<init_value>`, with `init_value` as any number. Each run which uses the same `init_value` will deliver identical grids. The results are usually normally distributed. However, the option `cm_log=1` forces the program to generate a log-normal distribution (LN3). The generated random values are then interpreted to be exponents for the parameters <average> and <standard deviation> to the base 10, so the result grid will contain the powers of the random numbers to the base 10. The lower limit is 0 (third parameter of a 3 parameter log-normal distribution). The statistic shown with GRIDSTAT will therefore not match the given parameters for <average> and <std.dev.>, because it does not refer to the exponents but to the plain values. FIELDGEN can be used e.g. for generating  $K_f$ -values with a spatial correlation and anisotropy, e.g. for the WaSiM-ETH groundwater module. If the correlation length' are very small, the generated field is spatially virtually uncorrelated and normal (or log-normal) distributed. However, because of the used generation methodology it is better to use the program GRIDGAUS for generating uncorrelated fields, because correlation lengths of 0 are not supported in FIELDGEN. An equal distribution may be achieved by a very large standard deviation, but, again, this should be done with another program, this time the program GRIDRAND, which generates uncorrelated, equally distributed random numbers (e.g. for generating land use distributions).

see also: GRIDRAND, GRIDGAUS, GRIDSTAT, MAKEGRID, ASCIGRID

#### 4.1.3 FOCLMEAN

Low band filtering of grid values using a defined window-size in terms of grid cells

Command: `foclmean <ingrid> <outgrid> <window-size>`

For each grid cell a replacing value is generated as average value of all cells within the window centered at the actual cell. The window is moved row by row down the grid. The window size is an odd integer number in terms of grid cells, the smallest window size of 3 (a 3x3 window).

#### 4.1.4 GRIDADD

Adds two grids to a resulting grid.

Command: `gridadd <ingrid1> <ingrid2> <outgrid>`

see also: GRIDMULT, GRIDQUOT, GRIDGRID, GRIDDIFF

#### 4.1.5 GRIDASCII

Converts binary grids into ASCII-formatted grids. The default precision is the optimum precision chosen by the system. However, its possible to specify a precision parameter as last parameter of the program. It may range between 0 and 9 with 9 indicating the optimum precision like the program would generate without precision option. **Note:** A precision of 0 may lead to large errors duo to rounding!

The output is formatted as shown in the example in chapter 3.2.1. The grid values are written row by row downwards like in a table. Separators are tab stops between grid cells and a line feed at the row end. If such files should be transferred between different systems (UNIX ↔ DOS/WINDOWS) the transfer should be done using e.g. ftp or programs which convert line feeds correctly (e.g. unix2dos, dos2unix).

Command: `gridascii <binary-grid> <ASCII-grid> [<significant digits>]`

see also: ASCIGRID, GRIDSURF, SURFGRID, MF2WASIM

#### 4.1.6 GRIDCOLM

Converts a binary grid into a x-y-z formatted ASCII file. The ASCII-file contains three columns for x- and y-coordinates and for the z-values, respectively. Each row contains one grid cell triple (x,y,z).

Command: `griddiff <binary-grid> <ASCII-grid> [<significant digits>]`

see also: GRIDASCII, ASCIGRID, GRIDSURF, SURFGRID, MF2WASIM

#### 4.1.7 GRIDDIFF

Subtracts the second grid from the first grid of the command line parameters.

Command: `griddiff <ingrid1> <ingrid2> <outgrid>`

see also: GRIDASCII, ASCIGRID, GRIDSURF, SURFGRID, MF2WASIM

#### 4.1.8 GRIDEDIT

A basic tool for editing single grid cells. The coordinates of the grid cell has to be entered as row and cell indices. The edited grid overrides the old version after the user was asked for confirmation.

Command: `gridedit <grid>`

#### 4.1.9 GRIDGAUS

Generating normal distributed, uncorrelated random number fields

Command: `gridgaus <outfile> <ncols> <nrows> <xll> <yll> <cellsize> <nodata-value> <average> <std.dev.> <step> [<init_value>]`

The ASCII formatted output grid is specified by its name <outfile>, its dimensions <ncols> and <nrows> (number of columns and rows), the coordinates of the lower left corner <xll> and <yll>, the <cellsize> and the nodata-value. The grid values are generated randomly in space according to the specified command line parameters <average> and <standard deviation> of the normal probability distribution. The values are spatially uncorrelated. In order to get reproducible results, the random number generator may

be initialized using the option `init_value=<init_value>` with `<init_value>` as any real number. The parameter `<step>` can be used if the results should be integer values. The program generates only integer multiples of `<step>`. Continuous values will be generated if `<step>` is set to -1 or no `<step>` parameter is given (in this case, also `<init_value>` has **not** to be specified!). Integer cell values may be needed e.g. for discrete, normal distributed values.

see also: GRIDRAND, FIELDGEN, MAKEGRID, ASCIGRID

#### 4.1.10 GRIDGRID

Multiplying two grids on cell by cell basis. If one cell in one or both of the inputs grids is nodata, then the matching cell in the result grid will be also nodata.

Command: `gridgrid <ingrid1> <ingrid2> <outgrid>`

see also: GRIDADD, GRIDDIFF, GRIDMULT, GRIDQUOT

#### 4.1.11 GRIDMASK

A mask grid is used to mask an input grid. Only those grid cells are copied into the output grid which have valid matching grid cells in the mask grid (similar to the “setwindow” command in Arc/Info). The cell sizes of the input grid and the mask grid must be identical. The coordinates of the lower left corner must be identical or shifted by integer multiples of the grid cell size. The program can be used to generate the required matching grids for WaSiM-ETH from different data sources.

Command: `gridmask <ingrid> <mask-grid> <outgrid>`

see also: RESIZE, REMAP, RESAMPLE, REFINER

#### 4.1.12 GRIDMULT

Multiplies all cell values of a grid with a constant value. The constant is typed in interactively during the program run. nodata values in the input grid remain nodata values in the output grid.

Command: `gridmult <ingrid> <outgrid>`

see also: GRIDADD, GRIDQUOT, GRIDDIFF, GRIDGRID

#### 4.1.13 GRIDQUOT

Divides all cells of the first grid by the corresponding values of the second grid if both cells are valid. If the second grid contains a cell with the value 0, the operation is not performed there and a nodata value is written to the result grid.

Command: `gridquot <ingrid1> <ingrid2> <outgrid>`

see also: GRIDADD, GRIDQUOT, GRIDDIFF, GRIDGRID

#### 4.1.14 GRIDRAND

Generating equally distributed uncorrelated random fields.

Command: `gridgaus <outfile> <ncols> <nrows> <xll> <yll> <cellsize> <nodata-value> <minimum> <maximum> <step> [<init_value>]`

The ASCII formatted output grid is specified by its name `<outfile>`, its dimensions `<ncols>` and `<nrows>` (number of columns and rows), the coordinates of the lower left corner `<xll>` and `<yll>`, the `<cellsize>` and the `<nodata-value>`. The randomly generated grid values are equally distributed between the parameters `<minimum>` and `<maximum>`. The values are spatially uncorrelated. In order to get reproducible results, the random number generator may be initialized using the option `init_value=<init_value>` with `<init_value>` as any real number. The parameter `<step>` can be used if the results should be integer values. The program generates only integer multiples of `<step>`. Continuous values will be generated if `<step>` is set to -1 or no `<step>` parameter is given (in this case, also `<init_value>` has **not** to be specified!). Integer cell values may be needed e.g. for discrete values like land use classes.

see also: GRIDGAUS, FIELDGEN, MAKEGRID, ASCIGRID

#### 4.1.15 GRIDSTAT

Prints the data contained in the 12 records of the grid header to the screen: number of rows, number of columns, x- and y-coordinates of the lower left grid corner, cell size, nodata value, and the statistic parameters, which are the number, sum, minimum, maximum, average and standard deviation of all valid cells within the grid. The option “full” forces the program to actually recalculate the statistics.

Command: `gridstat <ingrid> [full]`

#### 4.1.16 GRIDSURF

Converts a binary grid into an ASCII format which can be read by the GS Surfer software. This format uses a reversed order of rows (from bottom to top) and a different header compared to WaSiM and Arc/Info.

Command: `gridsurf <wasim-ingrid> <surfer-outgrid>`

see also: SURFGRID, ASCIGRID, GRIDASCII, MF2WASIM, GRIDCOLM

#### 4.1.17 MAKEGRID

Generating a grid with defined coordinates and structure and initializing all cells with a unique initialization value. The resulting is an ASCII formatted grid which can be converted into a binary grid using e.g. ASCIGRID.

Command: `makegrid <grid name> <ncols> <nrows> <xll> <yll> <cellsize> <nodata-value> <value>`

see also: ASCIGRID, FIELDGEN, GRIDRAND, GRIDGAUS

#### 4.1.18 MF2WASIM

Converting MODFLOW-grids into WaSiM-grids. Since MODFLOW does not store the grid structure, the parameters <xll>, <yll>, <cellsize> and <nodata-value> has to be specified interactively during the program run.

Command: `gridsurf <modflow-ingrid> <wasim-outgrid>`

see also: SURFGRID, ASCIGRID, GRIDASCII, GRIDSURF, GRIDCOLM

#### 4.1.19 RECLASS

Classifies the data of a grid into classes which are written to the output grid. The class number is the integer fraction of the quotient of the value of the input grid minus an offset and the class width. Both parameters, the offset and the class width, are specified interactively by the user. If, for instance, the class width is set to 100 and the offset is set to 0, RECLASS can be used to generate a grid containing elevation belts from the digital elevation model, where the class number is the first digit of the 100 m – elevation belt.

Command: `reclass <ingrid> <outgrid>`

#### 4.1.20 REFINE

REFINE is a powerful tool to change the grid properties like the cellsize and the lower left coordinates, thus the tool can be used to synchronize two or more grids with respect to their coordinates and cell sizes. If any changes in the cellsize and the coordinate origin of the grid are done, an interpolation is required. There are 3 methods for choice, of which each has specific use cases:

1. Nearest-neighbor-method: For getting the value in the output grid, the nearest matching cell of the input grid is looked for and taken as result value. This method should be used if categorized data like land use or soil types should be converted into a finer grid resolution.



2. single bi-cubic interpolation: for each grid cell of the output grid a parabolic surface is constructed using that 3 x 3 window of the input grid which is nearest to the position of the actual output grid cell. The equation for the parabolic surface is given in the description of the program TANALYS (equation 143 and 143). The output value  $z$  is get by putting the actual  $x$ - and  $y$ -coordinates in equation 142. This method is fast and gives smooth surfaces, it can be used for continuous data like elevation models, slopes, aspects a.s.o., but not for categorized data, which are not allowed to interpolate.
3. multiple bi-cubic interpolation: For getting even smoother transitions from cell to cell, not only one but up to four parabolic surfaces are constructed after equation (142). The 3 x 3 windows are centered on the four grid cells which are nearest to the actual output cell. If the output cell is exactly on a link between two input cells, then only two parabolic surfaces are constructed. The results of the four interpolations after (142) are then weighted using the inverse distance weighting interpolation with distances depending on the location on the central cells of the up to four parabolic surfaces relative to the output cell location. This method is usually even more accurate than the single bi-cubic interpolation but like those method it cannot be used for categorized data (e.g. land use).

Command: refine <ingrid> <outgrid> [<method(1, 2 or 3)>] [<xll>] [<yll>]

<method> is one of the above described methods for interpolation. <xll> and <yll> are the new coordinates of the lower left corner of the output grid. The last three parameters are optional, the default values are method 3 and the coordinates of the input grid.

The program asks interactively for the new cell size, which may be any size. The new number of rows and columns is calculated considering also new origin coordinates. If the output grid cell size is much larger then the input grid cell size it is recommended to use the program RESAMPLE or a combination of RESAMPLE and REFINER to get the best results. The method for generating aggregated values used in RESAMPLE gives usually better results when converting a grid into a coarser raster. If, for example, a 50 m grid should be converted into a 70 m grid, it should be converted in a first step into a 35 m grid and the an aggregation using RESAMPLE should be performed to get the 70 m grid.

#### 4.1.21 REMAP

Changes the values of a grid according to a remap (or translation) table. The remap table contains ranges of input values which are replaced by an single output value.

All data of the input grid within the interval ]0,100] (lower limit is not included in the interval) are converted to 1 in the output grid. Similarly, all values within the interval ]100,101] are replaced by the output value 2 a.s.o. Data, which are not included in any of the given intervals in the remap table are copied into the output grid without changes. **Note:** Also nodata-values are handled like normal numbers, so REMAP can also be used to change the nodata code or to blank some regions (e.g. to hide a subbasin).

*example for a remap-table:*

0	100	: 1
100	101	: 2
101	104.5	: 3
110	128	: 7

Command: remap <ingrid> <remap-table> <outgrid>

#### 4.1.22 RESAMPLE

Resamples the ingrid to an outgrid with a larger cell size which has to be an integer multiple of the input cell size (example: a 25 m grid can only be resampled into a 50 m-, 75 m-, 100 m, 125 m-grid a.s.o.). The coordinates of the grid origin remain unchanged, the numbers of rows and columns is changed according to the new cellsize. The user has the choice between 3 methods: the output cell will either contain (1) an arithmetic average of all corresponding input cell (at least 50 % of the resulting grid cell area must be covered by valid input data cells) → recommended for continuous data, or (2) the nearest neighbor in the input grid to the corresponding center of the output cell → recommended for some derived continuous

data like aspect angle and also for categorized data, or (3) the most frequent value of all corresponding input grid cells → recommended for some use cases of categorized data like land use data.

Command: `resample <ingrid> <outgrid>`

#### 4.1.23 RESIZE

RESIZE can be used for cutting out a specified area of the input grid. The new grid has usually different coordinates and row and column numbers than the ingrid. The cutting area is specified interactively.

Command: `resize <ingrid> <outgrid>`

#### 4.1.24 SURFGRID

Converting a SURFER-ASCII-grid into a binary WaSiM grid. Beside the different headers, the SURFER grid format has a reversed order of rows compared to WaSiM-ETH or Arc/Info.

Command: `gridsurf <surfer-ingrid> <WaSiM-outgrid>`

see also: GRIDSURF, ASCIGRID, GRIDASCII, MF2WASIM, GRIDCOLM

#### 4.1.25 TANALYS

One of the most important data sets for using the hydrologic model WaSiM-ETH is a digital elevation model (DEM), especially when applying the model to mountainous regions. The DEM can be used to calculate a number of derived data sets, like local slope, aspect and curvature. But also some important hydrologic informations can be determined by using these derived informations. This are, for example, flow directions, flow accumulations (specific catchment area), the river network and the subbasin structure. Its also possible to calculate topographic shading and sky view factors for parameterizing radiation sensitive models. The program TANALYS performs a complex analysis of the digital elevation model. In a series of steps, the data sets as shown in figure 29 are generated. Arrows are indicators that a data set can only be generated if the arrow source already exists. The topographic analysis is controlled by a control file which uses all the features of the WaSiM control file. Some parameters controlling the extend of the analysis and specifying some threshold values or constants and a number of file names have to be specified in this control file.

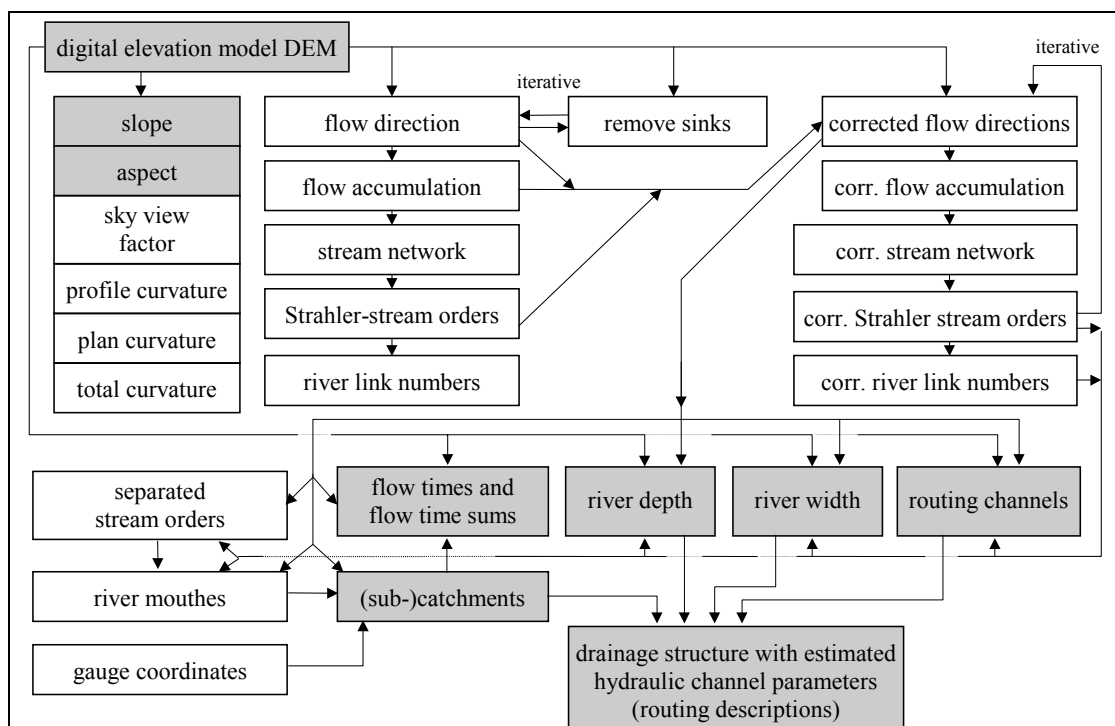


figure 29: topographic analysis of a digital elevation model by TANALYS

Only the shaded data sets are really needed by WaSiM-ETH. The grid containing the (sub-)catchments and the text file containing the routing descriptions are required only if the infiltration- and soil module and the runoff routing should be modeled, aspect and slope are required only for the radiation correction and temperature modification (and for the generation of interflow in model version 2) and the will be generated internally during the WaSiM-ETH initialization if they are not already there. The flow time sums are used for routing surface runoff and interflow, the grid is not absolutely necessary. River width and depth and the routing channel codes are required, if the model version 2 should consider interactions of surface water and groundwater (infiltration and exfiltration).

The basis of the topographic analysis is the digital elevation model (DEM). Slope, aspect and curvatures are determined using the algorithms given by e.g. BINLEY and BEVEN (1993) or TARBOTON et al. (1993). A 3 x 3 moving window is used to construct a 2<sup>nd</sup>-order parabolic surface fitting the 9 points. For each of the 9 points equation (142) holds:

$$z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I \quad (142)$$

If local coordinates are used with 1,1 in the upper left cell and if the distance between the points is normalized and set to  $L=1$  (which is allowed for quadratic grid cells), it is easy to get a solution of the linear equation system (coordinates  $x, y \in \{1, 2, 3\}$ ). The coefficients  $A$  to  $I$  are then given by:

$$\begin{aligned} I &= z_{2,2} \\ H &= (z_{2,1} - z_{2,3}) / (2L) \\ G &= (z_{3,2} - z_{1,2}) / (2L) \\ F &= (-z_{1,1} + z_{3,1} + z_{1,3} - z_{3,3}) / (4L^2) \\ E &= [(z_{2,1} + z_{2,3}) / 2 - z_{2,2}] / L^2 \\ D &= [(z_{1,2} + z_{3,2}) / 2 - z_{2,2}] / L^2 \\ C &= [(-z_{1,1} - z_{1,3} + z_{3,1} + z_{3,3}) / 4 + (z_{1,2} - z_{3,2}) / 2] / L^3 \\ B &= [(z_{1,1} + z_{3,1} - z_{1,3} - z_{3,3}) / 4 - (z_{2,1} - z_{2,3}) / 2] / L^3 \\ A &= [(z_{1,1} + z_{1,3} + z_{3,1} + z_{3,3}) / 4 - (z_{1,2} + z_{2,1} + z_{2,3} + z_{3,2}) / 2 + z_{2,2}] / L^4 \end{aligned} \quad (143)$$

	x=1	x=2	x=3
y=1	$z_{1,1}$	$z_{1,2}$	$z_{1,3}$
y=2	$z_{2,1}$	$z_{2,2}$	$z_{2,3}$
y=3	$z_{3,1}$	$z_{3,2}$	$z_{3,3}$

Some local parameters can be derived directly from this parameters by:

$$\text{slope angle} \quad \hat{\beta} = \arctan(\sqrt{G^2 + H^2}) \quad (144)$$

$$\text{aspect angle} \quad \hat{\Omega} = 180 - \arctan(H / G) + 90(G / |G|) \quad (145)$$

$$\text{profile - curvature} \quad \phi = -2(DG^2 + EH^2 + FGH) / (G^2 + H^2) \quad (146)$$

$$\text{plan - curvature} \quad \omega = 2(DH^2 + EG^2 - FGH) / (G^2 + H^2) \quad (147)$$

$$\text{total curvature} \quad \chi = \omega - \phi = 2E + 2D \quad (148)$$

The sky view factor may be of interest if spatially distributed radiation budgets are required for modeling the influence of topography on hydrological processes. Using the algorithms as shown in Chapter 1.3 for calculating the shading of a DEM, for each grid cell all directions (in steps of e.g. 10° starting with north) are scanned for that sun angle which would lead to shading by surrounding hills or mountains. Slope and aspect of the actual cell are also taken into consideration. For each segment, the result is an horizon overhead angle  $\beta_{h,i}$  which is used to calculate the fraction of diffuse incoming shortwave radiation for this segment  $i$  of the sky relative to the theoretical diffuse incoming shortwave radiation of the same segment if there would be no horizon overhead. After OKE (1987), the sky view factor  $\psi_{sky}$  can be calculated considering both, LAMBERT's law of the intensity dependency of the radiation on its incoming angle as well as the visible fraction of the sky which decreases with increasing horizon overhead after  $1 - \sin\beta_{h,i}$ :

$$\psi_{sky} = \sum_{i=1}^n \cos^2 \beta_{h,i} \quad (149)$$

with  $\beta_{h,i}$  horizon overhead angle for segment  $i$  [rad]  
 $n$  number of segments to build a full circle

The shortwave radiation budget  $R_K$  can be expressed following eq. (13) as follows:

$$R_K = R_{sun} \cdot \frac{\cos \hat{\Theta}}{\cos Z} + D \cdot \psi_{sky} + RG(1 - \psi_{sky}) \cdot \alpha \quad (150)$$

with  $D$  diffuse shortwave radiation from the sky [Wh/m<sup>2</sup>]  
 $R_{sun}, RG$  direct sun radiation resp. global radiation (direct+diffuse) [Wh/m<sup>2</sup>]  
 $\alpha$  mean albedo of the terrain visible from the actual point [-]

The mean value of the sky view factors of all segments is the output value for the sky view factor grid. As mentioned, this includes LAMBERT's law as well as the nonlinear decrease of the visible sky area and is thus valid for units of diffuse radiation only. If on the other hand only the visible fraction  $A_s$  of the sky should be calculated, equation (149) should be reformulated, using the formula for the surface of a half sphere  $A = 2\pi^2(1 - \sin \beta_h)$ :

$$A_s = 1 - \sum_{i=1}^n \sin \beta_{h,i} \quad (151)$$

The difference between  $\psi_{sky}$  and  $A_s$  may be considerable, especially for small and medium horizon overhead angles. This is because equation (151) does not consider LAMBERT's law of the decrease of the irradiation with an decreasing incoming angle. Because of the squared cosine in equation (149) small overhead angles does not make much effect at all. Thus, the sky view factors are above 0.99 for  $\beta_h < 5^\circ$ , whereas at the same time the visible sky fraction decreases down to only 91 %. Figure 30 shows these relations. WaSiM-ETH does not use the sky view factor actually but it is planned for future versions to incorporate the effect of horizon overhead on diffuse radiation.

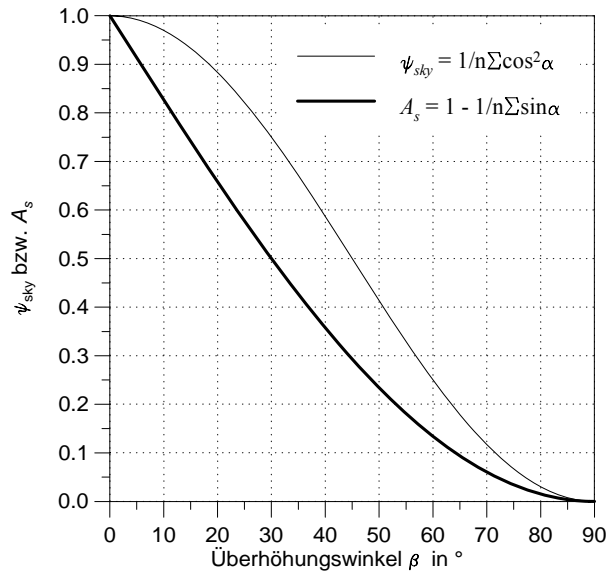


figure 30: Sky-view-factor  $\psi_{sky}$  and fraction of the sky  $A_s$  dependent on the horizon overhead angle  $\beta_h$

Flow directions are determined by the steepest of the slopes to the at maximum 8 neighboring cells. Flow is allowed into only *one* of these cells. Artifacts like sinks or flat areas which may be the result of generating the elevation model, but also real, natural sinks, e.g. in karst regions, are filled iteratively. Sinks are removed by looking for the lowest point of all points outside but connected to the border of the sink

which have a higher elevation than the sink itself. This elevation is then used as replace value for all cells within the sink. If after the filling all boundary cells of the sink, which has grown by at least one cell, still have no gradient to the outside of the sink, the filling is done again, now looking for the next higher elevation of the surrounding cells. This is done iteratively until at least one cell of the (usually now much larger) sink has a flow gradient to the sinks outer side or until the growing sink reaches a nodata value or the boundary of the grid, which both are handled as pour points. Then, the sink has become a “flat region”. Now, the flow directions within the flat regions are directed to the one ore more pour points in an iterative way starting at the pour points and looking for undefined flow directions in their neighborhood.

Profile and plan curvature may be used for determining zones of convergence or divergence. This can be used for generating multiple flow directions by weighting the flow fractions by flow lengths and slope. WaSiM-ETH does not use neither the profile nor the plan curvature.

After calculating the flow directions and filling the sinks, the flow accumulation can be calculated, which is the catchment area for each grid cell in units of grid cells draining directly or indirectly through each cell. The accumulation is done by following the flow directions of each cell until the grid boundary or a nodata value have been reached and summing up the numbers of touched cells. The result value includes the cell itself, so the cells at the catchment boundary have already a flow accumulation value of 1 in order to avoid errors e.g. in calculating the topographic index. For calculating the topographic index, the flow accumulation value should be scaled by the cell size, in order to get grid scale independent results.

By setting a threshold for the flow accumulation, the river network can be extracted as a first approximation. The extraction of river networks is a rather complicated task, see e.g. Tarboton et al., 1993. The river network is used together with the flow direction grid to determine the flow orders after STRAHLER and to identify each river link with a river link number.

If the extracted stream network still shows artifacts like parallel rivers in neighboring grid cells, these artifacts can be removed by applying a flow direction correction algorithm. It is also an iterative task. In a first step rivers of STRAHLER-order 1 are checked (head waters). If they are flowing alongside a river of higher order or alongside a river of the same order but with a larger catchment and if there is at maximum 1 no-river grid cells between the rivers (which must have an elevation less or equal to the lower of the river cells), then the smaller rivers flow direction is redirected by 45° to the larger river. After processing the entire grid, the same procedure is done for rivers of STRAHLER-order 2 and then for rivers of STRAHLER-order 3. Then, the correction is done again for rivers of STRAHLER-order 1 resp. 2 in order to correct new artifacts which may have been introduced by the correction of higher order flow directions. After each single correction step a recalculation of the flow accumulations, the river network and the Strahler-orders has to be performed.

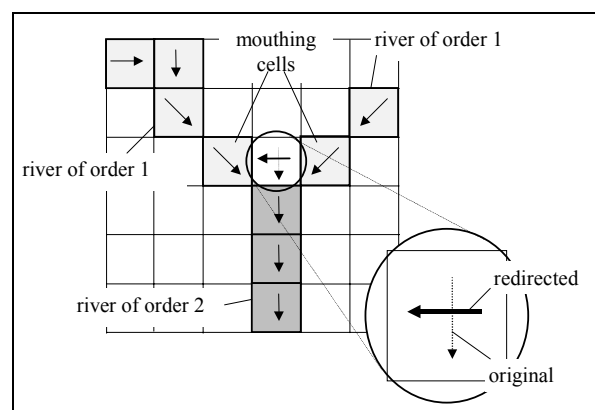


figure 31: flow direction correction at mouths

A further correction may be necessary if grid cells drain between the mouthing points of two rivers directly into the higher order river. Then, a redirection of flow directions has to be performed. Figure 31

shows the principle of this correction. Without this correction, the subbasin for the river of order 2 would extend upstream between the catchments of the mouthing rivers of order 1. This is an artifact and it would stand against all logic and against the reality. Therefore the flow direction of the last in-between-grid-cell is redirected to the last cell of the nearest or, if both mouthing rivers have the same distance to the redirected cell, to the larger river.

By separating rivers of order 2 and higher or order 3 and higher and so on, the stream network can be limited to rivers of a given minimum order (or corresponding catchment area). The separated rivers are newly numbered and then the mouths are determined, where these rivers are flowing in higher order rivers. Mouthing points are the last grid cells of a river when looked on it in flow direction.

For each stream link of the river number grid a flow velocity after MANNING-STRICKLER is estimated. The velocity depends mainly on the mean slope as given by the length and the elevation range of the link.

$$v = M \cdot R_h^{2/3} \cdot I^{1/2} \quad (152)$$

$$\dot{V} = M \cdot A \cdot R_h^{2/3} \cdot I^{1/2} \quad (153)$$

with	$v$	flow velocity	[m/s]
	$M$	roughness parameter after Manning-Strickler (10 ... 40)	[m <sup>1/3</sup> /s]
	$A$	cross section area of the flow (rectangle profile with depth/width = 1/8)	[m <sup>2</sup> ]
	$R_h$	hydraulic radius (= flow cross section area $A$ / channel cross section perimeter $U$ )	[m]
	$I$	average slope of the river link	[m/m]

Beside the roughness parameter  $M$ , which is specified as a global parameter in the TANALYS control file, also the hydraulic radius  $R_h$  in equation (152) is a unknown parameter which is estimated automatically by TANALYS. Since  $R_h$  also depends the absolute flow, another global parameter for the specific discharge  $q$  [liter/(s·km<sup>2</sup>)] has to be specified in the control file. The absolute discharge at a given profile is then the product of the local catchment area  $A_E$  and the specific discharge  $q$ . Then it is assumed that the channels have rectangle profiles with a depth to width ratio of 1:8. The hydraulic radius  $R_H$  is then given by:

$$R_h = \frac{A}{1.25\sqrt{8A}} \quad (154)$$

Since  $A$  depends on the flow velocity, which should be the result of the calculation, an iteration is required. The first assumption is  $v = 1$  m/s. After calculating the first hydraulic radius  $R_H$ , the second estimation of  $v$  is get after equation (152), using the constant parameters  $M$  and  $I$  and the first estimation for  $R_H$ . The iteration converges to some certain values for  $v$  and  $R_H$  and thus for the river depth and width. Convergence is assumed for iteration errors of  $\Delta v < 0.05$  m/s or after 12 iteration steps. The calculated flow velocities are valid only for the specified specific discharge  $q$  and for the roughness parameter  $M$ . The velocity is converted into flow times the water needs to cross each grid cell of the actual river link, see equations (156) and (157). In order to get realistic results for the discharge routing in later WaSiM-ETH applications, the specified specific discharge should be in the range of the specific medium flood discharge. These are the discharges which are most important for the routing algorithm.

Also for grid cells which are not river cells a flow velocity is calculated. This surface runoff velocity is also calculated after equation (152). The flow velocity is converted into the flow time required for crossing the grid cell and summed up along the flow path for each grid cell until the basin outlet is reached (including river cells) in order to generate a flow travel time grid. This grid is used by WaSiM-ETH for routing the surface runoff as well as the interflow within subbasins. As a simplification of the hydraulic calculations, a flow depth of  $R_H = 1$  cm is assumed for surface runoff. Also a constant Manning-roughness parameter of  $M = 10 \text{ m}^{1/3} \cdot \text{s}^{-1}$  is presumed. Then, the flow velocity on land surfaces depends only on the local slope, see equation (155). The flow time  $t$  the water needs for crossing a cell, depends on the effective flow length (diagonal or perpendicular to a cell side):

$$v = 10\text{m}^{1/3}\text{s}^{-1} \cdot (0.01\text{m})^{2/3} \cdot \sqrt{I} \quad (155)$$

$$t = \frac{cs \cdot \sqrt{2}}{v} \quad \text{for flow directions } \nearrow \searrow \swarrow \nwarrow \quad (156)$$

$$t = \frac{cs}{v} \quad \text{for flow directions } \uparrow \rightarrow \downarrow \leftarrow \quad (157)$$

Subcatchments are delineated using the mouthing points or any other pour points given in separate grids, e.g. locations of gauging stations as numbered grid cell codes in a pour point grid. The flow times for crossing the grid cells are now also summed up for each cell until the next pour point is reached. Grid cells which are part of a routing channel are coded with the number of the largest of its tributaries. This will be the so called link-grid, which is used in WaSiM-version 2 for budgeting the re-infiltration rates with the flow in the rivers. River width and depth are also written into separate grids. At the same time, the drainage structure is analyzed and written into a text file which contains also the estimated hydraulic parameters. The structure matches the requirements of the routing descriptions in the section [routing\_model] of the WaSiM-ETH control file. It can simply be inserted into this file.

Figure 32 shows an example for a flow travel time grid. The catchment shown is the Thur basin, subdivided into 12 subcatchments, each of which is observed by a flow gauging station at the outlet. The separate zones are flow times in hours the water needs to reach the next subbasin. Bright areas stand for short times, dark areas means that the water needs much more time to reach the outlet, up to 13 hours in the example. The flow time spectrum depends on the MANNING-roughness parameter as well as on the presumed flow depth for overland flow and on the presumed specific discharge for the channels.

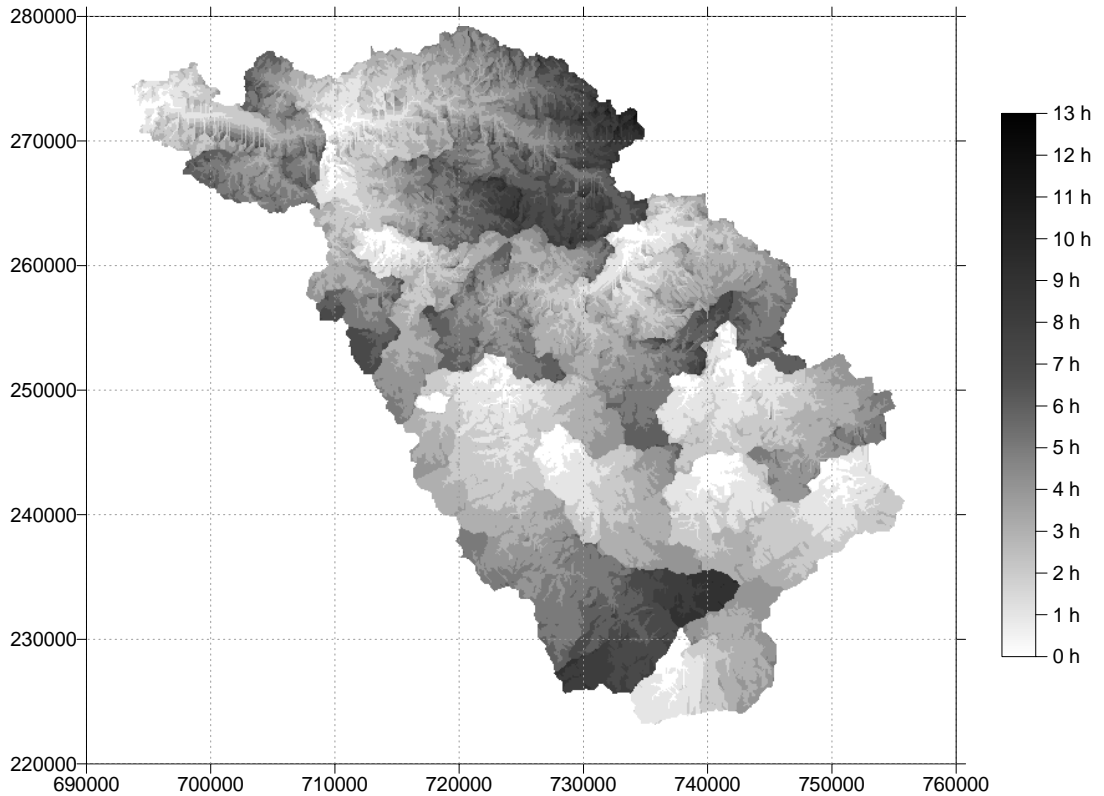


figure 32: flow travel time grid for the river gauge network of the Thur-basin, hour zones

#### 4.1.26 TOPOFACT

Calculates the soil-topographic index  $\ln(A/(T_0 \cdot \tan \beta))$  using the local catchment area  $A$ , the local transmissivity  $T_0$  and the local slope angle  $\beta$ . In opposition to the usual definition of the soil topographic index,  $A$  is the local catchment, not the local specific catchment (this is a program restriction). In order to compare

TOPOFACT's results to the topographic indices of other programs, the value  $\ln(\text{cellsize})$  has to be subtracted from all grid cells. If only the topographic index without the influence of the transmissivity is wanted, then for  $T_0$  a grid with constant cell values of 1.0 should be used.

Command: `topofact <flow accumulation> <transmissivity> <slope> <outgrid>`

#### 4.1.27 ZONESTAT

Calculates the statistics of the values in an input grid separately for each zone of a zone grid. The parameters are: zone ID, zone value, minimum, maximum, sum, average, standard deviation.

Command: `zonestat <ingrid> <zone grid> <statistic file>`

Each zone is coded by an integer value ( $0 < \text{zone value} < 32768$ ) in the tone grid. Zones do not have to cover contiguous areas, e.g. if elevation belts should be used as zones. Such zones can be generated using the programs RECLASS or REMAP.

The output file contains the statistic parameters of the input grid separated after the zones of the zone grid in an ASCII text file.

## 4.2 Working with station data (meteorological time series)

### 4.2.1 IDWP

Performs a temporally and spatially interpolation of precipitation data in order to get daily courses of precipitation data for climate stations which data are given as 12-hour or 24-hour precipitation sums. Required input data are both, the high resolution hourly precipitation data as well as the 12-hour and/or 24 hour low resolution precipitation data of as much stations as available. The precipitation of the high resolution data are interpolated to the locations of the low resolution data. Then, the results are weighted on the total sums of these low resolution data according to the matching period. This process is described in detail in the following paragraphs.

The interpolation is done in two steps. During the first step, the precipitation of the high resolution data is interpolated to the location of the conventional climate stations using inverse distance weighting interpolation (IDW). Some parameters have to be entered by the user, like the power of the inverted distance  $p$  in equation (4) and the maximum search radius for valid station data around the location of interpolation  $d_{max}$ . Furthermore, it is possible to specify fix upper and lower limits which should not be exceeded by the results. If this should happen such unwanted results are replaced by user specified default values, e.g. for precipitation values below  $0.1 \text{ mm}\cdot\text{h}^{-1}$ , which may be replaced by 0 mm in order to avoid too much and too long precipitation events due to the interpolation algorithm.

For each grid cell, all stations within the specified search radius around that cell are used for the interpolation. The weight parameter is used as exponent to calculate the power of the distance, which is then inverted in order to give more far stations a fare less weighting for the interpolation result. The sum of all inverse weighted distances is scaled to 1.0, the resulting scaling factor is then applied to each station weight and finally multiplied by the station data. The sum of all station data is the interpolation result.

After this interpolation of hourly values (7:00 to 7:00 of the next day) for the locations of the conventional climate stations, the 12-hour or 24-hour sums of the interpolated values are scaled to the observed sums, the resulting scaling factor is applied to each interpolated hourly value of the matching 12-hour resp. 24-hour interval.

The output file contains the original (e.g. 1-hour-values) values of the high resolution stations and the interpolated data of the conventional climate stations in the same temporal resolution. It can be used directly as an input file for the interpolation algorithms in WaSiM-ETH. The hourly input data have to be read in IDWP in  $1/10 \text{ mm}$ , the 12-hour and 24-hour data in mm. The result is given in  $1/10 \text{ mm/h}$ . The file names and parameters are specified interactively by the user or by an ASCII-file via redirected input.



### 4.2.2 STRLKORR

Removes all negative and (e.g. if the sun should be below the horizon) also positive global radiation values of the meteo-input file for global radiation. The format of the file is described in section 3.2.2.

Command: `strlkorrr <input file> <output file>`

### 4.2.3 REGRESS

Calculates altitude dependent gradients for input data of any time steps. The regression is done for two separate altitudinal ranges which can be specified by the user. If the regressions does not cross each other in a given altitudinal range, the profile may consist of up to three sections.

If the input data are not only consist of high resolution data (e.g. hourly values) but *also* of data of conventional stations, which may be represented by a number of observations at given times of the day, these data are also included in the regression. This integration is done in a second order temporal interpolation: for the times with valid data of both input types (high resolution *and* conventional observations) two regressions are calculated, one only for the high resolution data, the other for all data including the conventional observations. This is done for each time when all data are available. The deviations between both regressions are then temporally interpolated between the observation times. Using the interpolated deviations, the algorithms estimates “observation” data for the conventional climate stations for the unobserved times. The last step is the re-calculation of the altitudinal regressions using now all data, including the estimated data for the conventional stations in-between the observation times.

The gradients can be viewed on the screen and also be sent to a HP-DeskJet printer (as raw bitmap) or to a HPGL-plotter in HPGL-format. This can be done by typing <p> during the display of the gradients. This HPGL-files can usually also be printed on most Postscript printers.

The parameters for REGRESS are saved in a parameter file. This file is also used by REGR, the non interactive version of REGRESS for use on UNIX workstations if no PC is available. However, it is highly recommended to use REGRESS for at least a part of the input data in order to be sure to specify the right parameters, especially the right inversion elevations. REGRESS generates an ASCII-result file (and some ASCII-files containing efficiency criterions and the original and temporally interpolated input data). The regression file contains for each time step a set of parameters for 3 linear equations for the at maximum 3 valid ranges and 3 parameters for the areal regression of the residuals of the altitudinal regressions (see also description of the regression in chapter 1).

The maximum number of stations to be considered is 200. For each station, a 0/1 code in the last row of the control file (interactively checked in REGRESS after specifying all parameters) specifies the use of the station for the regression.

Command: `regress <parameter_file>`

### 4.2.4 REGR

REGR is the non interactive version of REGRESS for use under UNIX or for use of well parameterized data sets, i.e., the inversion altitudes and other parameters are known, e.g. from former runs of REGRESS. REGR uses the same parameter file like REGRESS but generates a binary output file instead of an ASCII file. Both output file versions can be read by WaSiM-ETH without conversions, but the binary version is smaller and faster to read but cannot be transported onto other platforms. WaSiM-ETH recognizes the format of the regression result file automatically by the first 2 words “jr” and “mo”, separated by only one space or tab stops. The following programs can be used for converting the file formats into another.

Command: `regr <parameter_file>`

#### 4.2.5 REGRASCI

Converts a binary regression as generated by REGR file into an ASCII-regression file as generated by REGRESS. This may be wanted for file transfer between different systems (e.g. DOS/WINDOWS ↔ UNIX) or for looking into the file for data checking. Since WaSiM-ETH recognizes the format of the regression file automatically, a re-converting into the target systems binary format is not necessary but may be performed in order to save hard disk space. The specification of both formats are described in chapter 3.2.2.

Command: `regrasci <binary_in_regression_file> <ASCII_out_regression_file>`

#### 4.2.6 ASCIREGR

The opposite of REGRASCI, converts ASCII-regression files into binary regression files.

Command: `asciregr <ASCII_in_regression_file> <binary_out_regression_file>`

#### 4.2.7 GMDtoTAB

This program should be used to convert so called GMD formatted data into the WaSiM-ETH table format as described in chapter 3.2.2. Data of a number of input files are copied into one output file using parameters as given in a control file like the time period, the station names and codes and scaling factors. The GMD-format allows a discontinuous storing of data, this is not allowed, if GMDTOTAB should be used for conversions, so all data have to be in a strong temporal order without gaps or multiple occurrences.

Command: `gmdtotab <control file>`

The control file is structured as follows:

```

1st row:  number n of following GMD-data files
2nd row:  start time of conversion as      YYYY MM DD hh mm
3rd row:  end time of conversion as      YYYY MM DD hh mm
4th row:  <name of the 1st GMD-file>    <station code> <scaling factor>
5th row:  <name of the 2nd GMD-file>    <station code> <scaling factor>
.
.      (a.s.o. for all GMD-input files)
.
last row:  <name of the WaSiM-ETH output file>
```

#### 4.2.8 QtoSPEND

Converts discharges in m<sup>3</sup>/s into specific discharges in mm/time step.

Command: `qtospend <discharge_file> <specific_discharge> [<header_rows>]  
[<number of data columns>] [<time step in hours>]`

The number of header rows is 5 by default, the number of data columns is determined automatically. If both values are specified explicitly, no automatic check is done. If the time step differs from 1 hour, then the time step should be specified in hours, e.g. in order to get mm/day if using 1-day-resolution input data.

#### 4.2.9 SPENDINV

Converting specific discharges in mm/time step into time steps/mm. This file may be used for fitting regression parameters to discharge recessions in order estimate the recession parameter *m* for WaSiM-ETH version 1 (soil model). The number of header rows should be 5, the number of data columns is determined automatically.

Command: `spendinv <specific discharges> <inverted specific discharges>`

#### 4.2.10 SONNEREL

Converting absolute sunshine duration into relative duration. The parameters for the geographic location (latitude, longitude), for time steps of input and output data and for a time shift (e.g., if the official time does not match the mean local sun time) must be specified interactively. The program calculates the on the basis of these parameters for each time step a theoretical maximum sunshine duration which is used for scaling the absolute sunshine duration in the input file into a relative sunshine duration.

Command: `sonnerel <absolute_sunshine_duration> <relative_sunshine_duration>`

### 4.3 Software for visualization

#### 4.3.1 REGRESS

In opposite to REGR, the program REGRESS is able to print the calculated altitudinal gradients for meteorological input data as graphics on the screen of the computer as well as on HPGL-Plotters or printers. Different colors show the different input file regressions (e.g. for hourly and 6-hourly data). By pressing “p” during the display of a graph, this page can be printed or plotted (into a file) in HP-DeskJet or HPGL-format. For further description see section 4.2 of this documentation.

#### 4.3.2 GRIDSHAD

GRIDSHAD can be used for displaying binary grids on the screen. It can be used on DOS/Window PC’s only. If grids should be displayed on other systems, e.g. UNIX, other packages like Arc/Info, Interactive Data Language IDL, or the program xview (after converting the grid into a TIFF or BMP format) must be used. The IDL program for displaying grids has only 19 rows! An isoline plot can be displayed using Gnuplot or IDL. If grids should be displayed in a more professional way, the grid should be converted e.g. into the GS-Surfer format for further processing with the Surfer-Software or into any other professional formats (TIFF, BMP a.s.o.). Gridshad scales the grid automatically to the display. The options may be given in upper or in lower case.

Command: `gridshad <gridfile> [/M] [/G<mode>] [/L] [/E] [/N] [/P<precision>]  
[ /A<polygonfile>] [/C<polygon_color>] [/H<background_color>]  
[/min=<min> /max=<max>]`

/M            **m**ultiple files are viewed, once per key-stroke (carriage return)

/G<mode>    the graphics **m**ode <mode> is used for the display.

0 =        standard VGA 640x480, 16 colors (if <printscreens> is used under WINDOWS to copy the picture to the clipboard, this mode must be used)

1 =        320x200, 256 colors (only if the display adapter is VESA-compatible)

2 =        640x480, 256 colors (only if the display adapter is VESA-compatible)

4 =        800x600, 16 colors (only if the display adapter is VESA-compatible)

5 =        800x600, 256 colors (only if the display adapter is VESA-compatible)

7 =        1024x768, 16 colors (only if the display adapter is VESA-compatible)

8 =        1024x768, 256 colors (only if the display adapter is VESA-compatible)

/L            **l**ogarithmic scaling of the colors

/E            **M**ultiple grids are displayed using the minimum/maximum values of the first grid for color table scaling. If this option is not given, each grid is displayed using its own minimum/maximum values for scaling the color table.

/N            The Nodata-value cells are drawn with the background color. This is useful if multiple grids are displayed. If the option is not given, the old grid is covered only at the valid cells of the next displayed grid.

/P            **P**recision of the legend. The legend consists of twelve bars with different colors and matching labels. The legend is scaled between minimum and maximum displayed value.

<code>/A&lt;polygonfile&gt;</code>	A polygon may be drawn over the grid using the color defined by <code>/C&lt;polygon_color&gt;</code> . The format of the polygon is a x,y-ASCII-format, each point is described by its x- and y-coordinates separated by a space and finished by a line feed. The first row contains the number of points
<code>/C&lt;polygons_color&gt;</code>	Defines the color index of the color palette to be used for drawing the polygon (and the legend). The range of this integer parameter matches the color depth of the actual graphics mode (e.g. 0..15 for 16-color modes)
<code>/H&lt;backgroundcolor&gt;</code>	Defines the color for the background. Else the same like <code>polygons_color</code>
<code>/min=&lt;min&gt;</code>	defines the minimum to be used for the color scale
<code>/max=&lt;max&gt;</code>	defines the minimum to be used for the color scale (values below <code>&lt;min&gt;</code> or above <code>&lt;max&gt;</code> are not displayed)

example: `gridshad m500.* /M /G5 /P3 /Cthur.pol /C40 /H200 /E /N`

This example displays all grids with names starting with “m500.” The graphics mode is mode 5 using 800 x 600 pixels and 256 colors (possible only at VESA-compatible adapters). The legend has 3 digits precision (after the “.”). The grid should be overlaid by a polygon given in the file “thur.pol”, the color of the polygon is the 40<sup>th</sup> color of the color table, the background has color number 200. All following grids should be scaled using the automatically determined values of the first grid. Nodata values should be drawn in background color.

The Color table of the displayed grids may be changed simply by pressing one of the keys 0 or 1...6. The “-“-key inverts the table. If graphic mode 0 is chosen, then the mouse may be used for getting information about specific grid cells. A left mouse button click leads to a display of the coordinates (row and column number and geographical coordinates) and of the grid value as well as of the displayed color at the specified coordinates. The mouse pointer can be hidden by pressing `<m>`. If a polygon should be digitized, the right mouse button can be used for this. Each time, the right mouse button is pressed, the actual grid coordinates of the mouse pointer are appended to the file “polygon.dat”.

## 4.4 Other programs

### 4.4.1 MAKEGWN

Calculates the brut and net groundwater recharges using the result files of WaSiM-ETH version 1 (TOP-MODEL-approach).

Command: `makegwn <results_SD> <results_QB> <brut_recharge> <net_recharge>`  
`[<header rows>] [<data columns>]`

The input files are the ASCII-result files of a WaSiM-ETH (version 1) run containing the average saturation definite of all subbasins (SD) and the base flow (QB). The result files contain the brutto recharge (positive values and negative values) and the netto recharge (only positive values). The specification of the number of header rows and the number of data columns is optional.

#### 4.4.2 POLYGRID

Converts a closed polygon into a grid. The input file has an ASCII-format with x- and y-coordinates of all points in separate rows. x- and y-coordinate of the points are separated by a space. The number of rows and columns, the lower left coordinates, the cell size and the nodata value of the result grid are specified interactively by the user. POLYGRID runs on DOS/WINDOWS PC's. It uses the screen as a grid matrix and draws the polygon onto the screen. Then a user specified point within the polygon is used as starting point to fill the polygon. The resulting grid is generated by reading the colors of each screen pixel and writing the colors into an ASCII-result grid.

Command: `polygrid <in_polygon_file> <out_grid_file>`

#### 4.4.3 POLYGONE

If multiple polygons has to be converted into a grid, POLYGONE should be used instead of POLYGRID. The polygons has to be ordered in the input file separated by an empty row. The first row for each polygon contains the number of following polygon points. The polygons must be closed in order to avoid the filling of the entire screen, so the last point and the first point should be identical.

Command: `polygone <in_polygon_file> <out_grid_file>`

#### 4.4.4 RESAGGR

Temporal aggregation of hourly- or daily WaSiM-ETH result (or any other files in any WaSiM-table-format). The inputs are summed up to daily and monthly values for each data column of the input file. At the end, a total sum is given. The result files get the same name as the input files except for the first character of the file extension which is replaced by a "t" for daily aggregates and by a "m" for monthly aggregates. The number of header rows and the number of data columns is detected automatically but can also be specified explicitly.

Command: `resaggr <input_file> [<number of header rows>] [<number of data columns>]`

#### 4.4.5 RESAGG

Aggregates the input data for a given number of time steps. The name of the result file and the aggregation base (aggregation over how many time steps?) must be specified in the command line. It is a more general version of RESAGGR. The number of header rows and the number of data columns is detected automatically but can also be specified explicitly.

Command: `resagg <input_file> <output_file> <aggregation_time_steps>  
[<number_of_head_rows>] [<number_of_data_columns>]`

#### 4.4.6 RESMEAN

Averages for each data column the 1-hour or 1-day results of WaSiM to daily and monthly averages. At the end, a total average is given for each zone. The result files get the same names as the input files except for the first character of the file extension which is replaced by a "t" for daily averages and by a "m" for monthly averages. The number of header rows and the number of data columns is detected automatically but can also be specified explicitly.

Command: `resmean <input_file> [<number_of_head_rows>] [<number_of_data_columns>]`

#### 4.4.7 RESMEANI

Averages the input data for any given number of time steps. The name of the result file and the aggregation base (averaging over how many time steps?) must be specified in the command line. It is a more general version of RESMEAN. The number of header rows and the number of data columns is detected automatically but can also be specified explicitly.

Command: `resmeani <input_file> <output_file> <aggregation_time_steps>  
[<number_of_head_rows>] [<number_of_data_columns>]`

#### 4.4.8 QUANTIL

Estimates the percentiles of monthly or daily aggregates of WaSiM-ETH results, e.g. of the aggregation results contained in the RESAGG(R) or RESMEAN(I) results. The data sets may be normal or log-normal distributed (with 2 or 3 parameters, then a lower limit is used).

Command: `quantil <control_file> [NV|LN2|LN3]`

The control file contains the names of all files which have to be evaluated. The result file has the same name like the control file but the extension “.sta”. The optional parameters NV, LN2 or LN3 define the type of distribution function to be used for the parameter estimation. LN2 is the default. If LN3 is chosen, a lower limit has to be specified interactively (using the same units like the input data, e.g. mm/month if input data are monthly aggregated discharge sums). The files are processed in the order as given by the control file. All input files have to be structured identically, i.e., the same number of zones and the same applied aggregation method. For each zone or subbasin, a set of parameters is estimated (average, standard deviation) which are used to calculate the 5%, 50% and 95% percentiles. These percentiles and the minimums and maximums of the input data are written to the output file.

#### 4.4.9 LOWFLOW

Extracts the minimum moving average values from the WaSiM-ETH discharge results.

Command: `lowflow <input_file> <output_file> <moving average window_width>  
<data_column> [/date] <header_rows>`

The input file should be a file with daily discharges in the WaSiM-ETH result format. If the model run uses hourly values, then the results should be aggregated first using RESAGGR. The moving average window width is the number of time steps the moving average is calculated for. For daily discharges, the window width should be 7, 15 or 30. The data column specifies the zone (subbasin) to be processed. The first 4 columns of the input file contain the date and time, they are no data columns, so the 5<sup>th</sup> column of the input file is the 1<sup>st</sup> data column. The option “/date” forces the program to write the date and time also into the output file. The default number of header rows is 3, any other value must be specified explicitly.

#### 4.4.10 FLOODS

Lists all discharges of an discharge file which are above a specified threshold to an output file.

Command: `floods <input_file> <output_file> <threshold> <data_column>  
[/date] <header_rows>`

Instead of the interval number in LOWFLOW, a threshold must be specified here. Of all exceeding discharges the maximums are written to the output file for each exceeding period. These maximums have to be real maximums, thus the maximum have to be preceded **and** succeeded by at least one value which is less than the maximum itself. This may be important at the begin and at the end of the time series, since otherwise e.g. the starting value which may be a value in the midst of a recession could be taken as a maximum instead. At the end of the time series the runoff hydrograph must be below the threshold in order to write the maximum into the output file.

#### 4.4.11 FLOWROUT

FLOWROUT can be used to model the discharge routing independently of the other WaSiM-ETH modules. The same control file is used and the same output is generated. This is especially interesting if the routing-module should be calibrated.

Command: `flowrout <control_file>`

## 5 Example of a control file for WaSiM

The sample control file “control.dat” contains all model parameters, file names and control parameters which are used for the modeling of the Thur-Basin. The file is well commented and should be looked on by using also chapter 3 of this documentation. If WaSiM-ETH is started, the control file is read in. All symbols are replaced, all comments are removed and the resulting file is written to the disk with the extension changed to “.\$\$\$”. Also this file should be consulted if unknown problems occur. Sometimes the reason for problems is a misuse of comments in the control file leaving not allowed lines in the control file. Only the translated control file is read in by each submodel to get the required names, model and control parameters. The rows of the control file are not allowed to be longer than 2000 characters, otherwise WaSiM-ETH may read undefined values.

printout of control.dat (with some changed formattings for a better layout in this documentation):

```
$set $year          = 84

# the year appears in each statistic file name, in each input file name and in the control file section for
# setting the start and end time. Thus a change of this symbol forces the model to model a complete different
# year

#
# comment lines are indicated by an "#". They are allowed after the entries or at the beginning of the lines
#
# paragraphs of the control file:
#
# [output_interval]
# [coordinates]          geogr. coordinates
# [elevation_model]      name of the elevation model
# [zone_grid]            name of the zone grid
# [standardgrids]        name of other static grids like slope angle, slope aspect, topogr. factor
# [variable_grids]       names of albedo and soil storage - used by more than one modules
# [model_time]           start end end-dates of model time
# [meteo_data_count]     number of meteo data to interpolate
# [meteo_names]          names of meteo data to interpolate - each name is later the headline of
#                        a paragraph for interpolation
# [precipitation_correction] paragraph for parameters of the precipitation correction
# [radiation_correction] paragraph with parameters for radiation correction
# [evapotranspiration]   paragraph with parameters for evapotranspiration
# [snow_model]           paragraph with parameters for the snow model
# [interception_model]   paragraph with parameters for the interception model
# [infiltration_model]   paragraph with parameters for the infiltration model
# [soil_model]           paragraph with parameters for the soil model
# [unsatzon_model]       paragraph with parameters for the unsaturated zone model
# [irrigation]           paragraph with parameters for irrigation model
# [groundwater_flow]     paragraph with parameters for groundwater model
# [routing_model]        paragraph with parameters for discharge routing
# [landuse_table]        paragraph with land use (vegetation) parameters
# [soil_table]           paragraph with soil properties
# [substance_transport]  paragraph with tracer properties
#
# symbol definitions starts with the set command
# max. 200 symbols can be defined

$set $outpath       = d:\sim\thur\output\
$set $inpath        = d:\sim\thur\input\

$set $time          = 60.0

$set $grid          = m500
$set $stack         = s500
$set $suffix        = grd
$set $code          = s

# variables for standardgrids
# first section: grids, which differ for different subdivisions of the basin
$set $zone_grid     = $grid//.e13
$set $subcatchments = $grid//.e13
$set $flow_time_grid = $grid//.fzs
$set $river_links_grid = $grid//.lnk

#second section: grids, which doesn't depend on subdivision (only cell-values are of interest)
$set $elevation_model = $grid//.dhk
$set $slope_grid      = $grid//.slp
$set $aspect_grid     = $grid//.exp
$set $land_use_grid   = $grid//.use
$set $ice_firn_grid   = $grid//.ice
$set $field_capacity_grid = $grid//.nfk
$set $ATBgrid         = $grid//.atb
$set $hydr_cond_grid  = $grid//.k
$set $soil_types      = $grid//.art
```

```

$set $sky_view_factor_grid = $grid//.hor
$set $drain_depth_grid    = $grid//.drn
$set $drain_distance_grid = $grid//.dis
$set $irrigationcodes     = $grid//.irr
$set $max_pond_grid       = $grid//.pnd
$set $clay_depth_grid     = $grid//.cly
$set $river_depth_grid    = $grid//.dep
$set $river_width_grid    = $grid//.wit
$set $tracer_1            = $grid//.c1
$set $tracer_2            = $grid//.c2
$set $tracer_3            = $grid//.c3
$set $tracer_4            = $grid//.c4
$set $tracer_5            = $grid//.c5
$set $tracer_6            = $grid//.c6
$set $tracer_7            = $grid//.c7
$set $tracer_8            = $grid//.c8
$set $tracer_9            = $grid//.c9
$set $kolmationsgrid      = $grid//.kol
$set $gw_kx_1_grid        = $grid//.kx1
$set $gw_kx_2_grid        = $grid//.kx2
$set $gw_kx_3_grid        = $grid//.kx3
$set $gw_ky_1_grid        = $grid//.ky1
$set $gw_ky_2_grid        = $grid//.ky2
$set $gw_ky_3_grid        = $grid//.ky3
$set $gw_bound_h_1_grid   = $grid//.bh1
$set $gw_bound_h_2_grid   = $grid//.bh2
$set $gw_bound_h_3_grid   = $grid//.bh3
$set $gw_bound_q_1_grid   = $grid//.bq1
$set $gw_bound_q_2_grid   = $grid//.bq2
$set $gw_bound_q_3_grid   = $grid//.bq3
$set $aquiferthick1       = $grid//.aq1
$set $aquiferthick2       = $grid//.aq2
$set $aquiferthick3       = $grid//.aq3
$set $gw_storage_coeff_1  = $grid//.s01
$set $gw_storage_coeff_2  = $grid//.s02
$set $gw_storage_coeff_3  = $grid//.s03
$set $gw_kolmation_1      = $grid//.gk1
$set $gw_kolmation_2      = $grid//.gk2
$set $gw_kolmation_3      = $grid//.gk3

# grids for surface hydrology modules, smbols are used later in the module sections
$set $albedo_grid         = albe//$grid//.$suffix
$set $soilstoragegrid     = sb_//$grid//.$suffix
$set $troughfall          = qi_//$grid//.$suffix
$set $snowcover_outflow   = qsno//$grid//.$suffix
$set $firn_melt           = qfir//$grid//.$suffix
$set $ice_melt            = qice//$grid//.$suffix
$set $preci_grid          = prec//$grid//.$suffix
$set $irrig_grid          = irri//$grid//.$suffix
$set $tempegid            = temp//$grid//.$suffix
$set $windgrid            = wind//$grid//.$suffix
$set $sunshinegrid        = ssd_//$grid//.$suffix
$set $radiationgrid       = rad_//$grid//.$suffix
$set $humiditygrid        = humi//$grid//.$suffix
$set $vaporgrid           = vapo//$grid//.$suffix
$set $ETPgrid             = etp_//$grid//.$suffix
$set $ETRgrid             = etr_//$grid//.$suffix
$set $SSNOgrid            = ssno//$grid//.$suffix
$set $SLIQgrid            = sliq//$grid//.$suffix
$set $sat_def_grid        = sd_//$grid//.$suffix
$set $SUZgrid             = suz_//$grid//.$suffix
$set $SIFgrid             = sif_//$grid//.$suffix
$set $EIgrid              = ei_//$grid//.$suffix
$set $SIgrid              = si_//$grid//.$suffix
$set $ExpoCorrgrid        = exco//$grid//.$suffix
$set $Tcorrgrid           = tcor//$grid//.$suffix
$set $Shapegrid           = shap//$grid//.$suffix
$set $INFEXgrid           = infx//$grid//.$suffix
$set $SATTgrid            = satt//$grid//.$suffix
$set $Nagrid              = na_//$grid//.$suffix
$set $SSPgrid             = ssp_//$grid//.$suffix
$set $Peakgrid            = peak//$grid//.$suffix
$set $SBIagrid            = sbia//$grid//.$suffix
$set $fcia_grid           = nfki//$grid//.$suffix

# now variables for unsaturated zone model
$set $QDgrid              = qd_//$grid//.$suffix
$set $QIgrid              = qifl//$grid//.$suffix
$set $GWdepthgrid         = gwst//$grid//.$suffix
$set $GWthetagrid         = gwth//$grid//.$suffix
$set $GWNgrid             = gwn_//$grid//.$suffix
$set $GWLEVELgrid         = gwlv//$grid//.$suffix
$set $QDRAINgrid          = qdrn//$grid//.$suffix
$set $QBgrid              = qb_//$grid//.$suffix
$set $GWINgrid            = gwin//$grid//.$suffix
$set $GWEXgrid            = gwex//$grid//.$suffix
$set $act_pond_grid       = pond//$grid//.$suffix

# variables for groundwater modeling

```



```

$set $flowx1grid = gwx1//$grid//.$suffix
$set $flowx2grid = gwx2//$grid//.$suffix
$set $flowx3grid = gwx3//$grid//.$suffix
$set $flowy1grid = gwy1//$grid//.$suffix
$set $flowy2grid = gwy2//$grid//.$suffix
$set $flowy3grid = gwy3//$grid//.$suffix
$set $head1grid = gwh1//$grid//.$suffix
$set $head2grid = gwh2//$grid//.$suffix
$set $head3grid = gwh3//$grid//.$suffix

# result-stacks for unsatzon_model
$set $Thetastack = teth//$stack//.$suffix
$set $hydraulic_heads_stack = hhyd//$stack//.$suffix
$set $geodetic_altitude_stack = hgeo//$stack//.$suffix
$set $flowstack = qu//$stack//.$suffix
$set $conccstack = conc//$stack//.$suffix

# parameters for interpolation of meteorological input data
$set $SzenUse = 0
$set $IDWmaxdist = 100000
$set $IDWweight = 2
$set $Anisoslope = 35.0
$set $Anisotropie = 0.65

# explanation of writegrid and outputcode some lines below
$set $Writegrid = 3
$set $Writestack = 3

#
# Writegrid : max. 3 digits (nnn)
#
# only if writegrid >= 100: 1. digit (1nn, or 2nn or 3nn)
# 0 = no minimum or maximum grid is written
# 1 = minimum grid is written (minimum value for each of the grid cells over the entire model period)
# 2 = maximum grid is written (maximum value for each of the grid cells over the entire model period)
# 1 = both grids are written (minimum and maximum value for each grid cell over the entire model period)
# only if Writegrid >= 10: 2nd digit: sums or means (n1n ... n8n)
# 0 = no sum grid will be written
# 1 = one sum grid will be written at the end of the model run
# 2 = one sum grid per model year
# 3 = one sum grid per model month
# 4 = one sum grid per day (only, if time step < 1 day)
# 5 = one mean value grid at the end of the model run
# 6 = one mean value grid per model year
# 7 = one mean value grid per month
# 8 = one mean value grid per day
# last digit (nn1 .. nn5) (for actual values, not for Sums or means)
# 1 = (over)write each time step into the same grid (for security in case of model crashes)
# 2 = write grids each time step to new files, the name is build from the first 4 letters
# of the regular grid name and then from the number of month, day and hour (hour as file extension).
# example: tempm500.grd will become prec0114.07 for 14.January, 7:00.
# 3 = only the last grid of the model run will be stored
# 4 = the grid from the last hour of each day will be stored (for each day the file will be overwritten)
# 5 = like 4, but each day a new grid file is created (like for code 2)
#

# readgrids : 1 = read storage grids (as SI, SSNOW,SLIQ...) from hard disk, 0=generate and initialize with 0
$set $readgrids = 1

[output_list]
4 # number of following rows indicating each a subbasin for which output should be generated
1 # ascending order is required !
2
10
12

# the following commented lines should be used instead of the then following section, if
# statistic output should be generated only for the subbasins contained in the output list above
# $set $outputcode = 5001
# $set $output_meteo = 5001
# $set $day_sum = 6024
# $set $day_mean = 5024
# $set $hour_mean = 5001
# $set $routing_code = 6001

# if this section is uncommented, then the output list is not active (because the codes, which are used
# to indicate the type of storing, starts with 1 to 4, not with 5 or 6, see explanation below
$set $outputcode = 2001
$set $output_meteo = 2001
$set $day_sum = 4024
$set $day_mean = 2024
$set $hour_mean = 2001
$set $routing_code = 4001

# outputcode (for statistic files for zones or subcatchments)
#
# the Codes behind the names of the statistic files have the meaning of:
# <1000 : no output
# 1<nnn> : spatial mean values for the entire basin, averaged in time over <nnn> time steps

```

```

# 2<nnn> : spatial mean values for all zones and for the entire basin, averaged in time over <nnn> time steps
# 3<nnn> : spatial means for the entire basin, added up in time over <nnn> time steps
# 4<nnn> : spatial means for all zones and for the entire basin, added up in time over <nnn> time steps
# 5<nnn> : spatial means for the entire basin and for the subbasins specified in the output-list, averaged in
#         time over <nnn> time steps
# 6<nnn> : spatial means for the entire basin and for the subbasins specified in the output-list, added up in
#         time over <nnn> time steps
#
# example:
# 2001 = per time step for all subcatchments (and for the entire basin) one (spatially averaged) value,
# 2004 = each 4 time steps one averaged value over the last 4 time steps for all subcatchments and for the
#         entire basin,
# 4024 = Sums of mean subcatchment/entire basin values of the time steps over 24 time steps (e.g. daily rain
#         sums for subcatchments),
# 3120 = averaged values (over 120 time steps!) only for the entire basin (spatially averaged)
# 5012 = averaged values (over 12 time steps) as spatial averages for the entire basin and for each of the
#         subbasins specified in the output-list
#
[output_interval]
4          # increment of time steps until for screen output (24 = each day one output, if time step = 1h)
1          # warning level for interpolation (no station within search radius) 0=no warning, 1=warning
0          # output of the routed discharge: 0=mm/time step, 1=m^3/s
0          # minutes from the hour-entry in the input data files until the end of the time step is reached #
0 if the end of time step is given like "84 01 01 01", $time if the begin is given like in "84 01 01 00"

[coordinates]
47.4       # geogr. latitude (center of the basin -> for radiation calculations)
9.2        # geogr. longitude (center of the basin)
15.0       # meridian according to the official time (middle Europe: 15)
#          # (east: 0 ... +180 degree, west: 0 ... -180 (or 360 ... 180)
1          # time shift of Meteo-data-time with respect to the true local time (mean sun time)
# e.g.: if meteo-data are stored in UTC-time and the time meridian is 15 east (central Europe),
# than the local time is 1 hour later than the time in the meteo-data-file, so 1 hour has to be added to the
# time from this file. This is important for calculation of sunshine duration and radiation

[elevation_model]
$inpath//$elevation_model # grid with the digital elevation data

[zone_grid]
$inpath//$zone_grid       # grid with Zone codes

[standard_grids]
26                        # number of standard grids
# path                    # identification    # fillcode 0=no 1=yes fill missing values with nearest neighbor
$inpath//$land_use_grid   landuse          1 # grid with land use data
$inpath//$ice_firn_grid   ice_firn          0 # grid with firn (code 2) or ice (code 1)
$inpath//$slope_grid      slope_angle       1 # slope angle data
$inpath//$aspect_grid     slope_aspect       1 # aspect angle data
# the ATB grid is used in model version 1 only
$inpath//$ATBgrid         topographic_faktor 1 # soil-topographic-factor ln(A/(T*tanb))
$inpath//$subcatchments   zonegrid_soilmodel 1 # zone grid for the runoff generation model
$inpath//$soil_types       soil_types        1 # soil types as codes for the soil table
# $inpath//$hydr_cond_grid hydraulic_conductivity 1 # hydraulic conductivity of the soil
# $inpath//$field_capacity_grid available_soil_moisture 1 # available soil moisture at field capacity
# a flow time grid may be used but it is not absolutely necessary (if no flow time grid is used, then
# only one flow time zone is assumed consisting of the entire subbasin
$inpath//$flow_time_grid   flow_times        1 # flow times for overland flow to the next outlet
#
# grids for model version 2
# tracer input concentrations should be interpolated if they are time dependent!!!
$inpath//$tracer_1         concflux_tracer_1_input 1
$inpath//$tracer_2         concflux_tracer_2_input 1
$inpath//$tracer_3         concflux_tracer_3_input 1
# $inpath//$tracer_4         concflux_tracer_4_input 1 # at maximum 9 tracers may be modeled
# $inpath//$tracer_5         concflux_tracer_5_input 1 # parallel to the water fluxes
# $inpath//$tracer_6         concflux_tracer_6_input 1
# $inpath//$tracer_7         concflux_tracer_7_input 1
# $inpath//$tracer_8         concflux_tracer_8_input 1
# $inpath//$tracer_9         concflux_tracer_9_input 1
#
# grids for the unsaturated zone model: river depth and width and leakage factors are used for calculating
# infiltration/exfiltration (surface-groundwater interaction), river links are needed to get a balance
# with the actual river flow when calculating infiltration from a river into the groundwater
# surface interaction can be enabled in two steps, see section [unsatzon_model]
$inpath//$river_depth_grid river_depth        0 # depth of streams in the stream network in m
$inpath//$river_width_grid  river_width        0 # width of all streams in m
$inpath//$river_links_grid  river_links        0 # codes of tributaries for real routing channels
$inpath//$kolmationsgrid    kolmation          0 # leakage factor for river cells
#
# if drainage is used (see section [unsatzon_model]), this grids are needed:
$inpath//$drain_depth_grid  drainage_depth     1 # grid with depth of drainage pipes in the soil
$inpath//$drain_distance_grid drainage_distance 1 # distances of drainage pipes from each other
#
# if a clay layer should be considered, the clay depth is needed
$inpath//$clay_depth_grid   clay_depth         1 # depth of impermeable layer (0 or nodata if no)
#
# if ponding may occur (small dams around the fields, flooded by irrigation or rain water)
$inpath//$max_pond_grid     max_ponding_storage 1 # maximum ponding storage in mm
#

```

```

# if irrigation is considered, the irrigated areas have to be coded here
$inpath//irrigationcodes      irrigation_codes      1 # irrigation codes
#
# for each aquifer, a number of grids has to be read in like thickness, storage coefficients,
# conductivities, leakage factors, and boundary conditions
$inpath//aquiferthick1      aquifer_thickness 1      1 # thickness of first aquifer
$inpath//gw_storage_coeff_1 gw_storage_coeff 1      1 # storage coefficients for 1. aquifer
$inpath//gw_bound_h_1_grid  gw_boundary_fix_h_1      0 # boundary conditions 1 constant head for layer 1
$inpath//gw_bound_q_1_grid  gw_boundary_fix_q_1      0 # boundary conditions 2 constant flux for layer 1
$inpath//gw_kx_1_grid       gw_k_x_1      1 # hydraulic conduct. for aquifer 1 in x direction
$inpath//gw_ky_1_grid       gw_k_y_1      1 # hydraulic conduct. for aquifer 1 in y direction
$inpath//gw_kolmation_1     gw_kolmation_1      1 # leakage factor between 1st and 2nd aquifer
#
# only one aquifer is considered here. If multiple aquifers should be used, each aquifer needs
# it's own grids for thickness, storage coefficients, conductivities, leakage factors, and boundary conditions
# $inpath//aquiferthick2      aquifer_thickness 2      1 # thickness of aquifer 2
# $inpath//gw_storage_coeff_2 gw_storage_coeff 2      1 # storage coefficients for aquifer 2
# $inpath//gw_bound_h_2_grid  gw_boundary_fix_h_2      0 # boundary conditions 1 constant head for layer 2
# $inpath//gw_bound_q_2_grid  gw_boundary_fix_q_2      0 # boundary conditions 2 constant flux for layer 2
# $inpath//gw_kx_2_grid       gw_k_x_2      1 # hydraulic conduct. for aquifer 2 in x direction
# $inpath//gw_ky_2_grid       gw_k_y_2      1 # hydraulic conduct. for aquifer 2 in y direction
# $inpath//gw_kolmation_2     gw_kolmation_2      1 # leakage factor between aquifers 2 and 3
# $inpath//aquiferthick3      aquifer_thickness 3      1 # thickness of aquifer 3
# $inpath//gw_storage_coeff_3 gw_storage_coeff 3      1 # storage coefficients for aquifer 3
# $inpath//gw_bound_h_3_grid  gw_boundary_fix_h_3      0 # boundary conditions 1 constant head for layer 3
# $inpath//gw_bound_q_3_grid  gw_boundary_fix_q_3      0 # boundary conditions 2 constant flux for layer 3
# $inpath//gw_kx_3_grid       gw_k_x_3      1 # hydraulic conduct. for aquifer 3 in x direction
# $inpath//gw_ky_3_grid       gw_k_y_3      1 # hydraulic conduct. for aquifer 3 in y direction
# $inpath//gw_kolmation_3     gw_kolmation_3      1 # leakage factor between aquifers 3 and 4

# variable grids are used by more than one module or can be changed (like albedo and soil storage)

[variable_grids]
2                                # Number of variable grids to read
# path                          # identification # fillcode 0=no 1=yes fill missing values with nearest neighbor
$outpath//albedo_grid          albedo      1      # albedo; for time without snow derived from land use data
$writegrid                    # Writegrid for albedo_grid
$readgrids                    # 0, if albedo is derived from land use, 1 if read from file
$outpath//soilstoragegrid      soil_storage 1      # soil water storage
$writegrid                    # Writegrid for this grid
$readgrids                    # 0: soil_storage is derived from soil types, 1: read from file

[model_time]
1                                # start hour
1                                # start day
1                                # start month
19//$year                      # start year
24                              # end hour
31                              # end day
12                              # end month
19//$year                      # end year

[meteo_data_count]
6

[meteo_names]
precipitation
temperature
vapor_pressure
global_radiation
wind_speed
sunshine_duration
air_humidity # since the number of meteorological inputs is set to 6, the humidity is not processed (No. 7)

[temperature]
2                                # Method 1=idw, 2=regress, 3=idw+regress, 4=Thiessen
$inpath//tempe//$year//a.dat    # file name with station data (if method = 1, 3 or 4, else ignored)
$inpath//temper//$year//.out    # file name with regression data (if method = 2 or 3)
$outpath//stempegrid           # output grid, used for deriving names of sums or averages for days, months aso.)
5//$writegrid                  # 0, if no grid-output is needed, else one of the codes described above
0.1                            # correction factor for results
$outpath//temp//$grid//.//$code//$year $hour_mean # file name for the statistic output of averages per zone
998                            # error value: data greater than or lesser the negative value are nodata
$IDWweight                     # weighting of the reciprocal distance for IDW
0.1                            # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist                    # max. distance of stations to the actual interpolation cell
$Anisoslope                    # slope of main axis of the anisotropy-ellipsis, -90 to +90 degr, math. pos.
$Anisotropie                   # ratio of the short to the long axis of the anisotropy-ellipsis
-40                            # lower limit of interpolation results
-40                            # replace value for results below the lower limit
40                              # upper limit for interpolation results
40                              # replace value for results with larger values than the upper limit
$SzenUse                       # 1=use scenario data for correction, 0=dont use scenarios
1                               # 1=add scenarios, 2=multiply scenarios, 3=percentual change
0                               # number of scenario cells

[wind_speed]
2                                # method: 1=idw 2=regress 3=idw+regress 4=thiessen
$inpath//wind//$year//a.dat    # file name with station data (if method = 1, 3 or 4, else ignored)

```

```

$inpath//wind//$year//.out # file name with regression data (if method = 2 or 3)
$outpath//windgrid # output grid, used for deriving names of sums or averages for days, months aso.)
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
0.1 # correction factor for results
$outpath//wind//$grid//.//$code//$year $hour_mean # file name for the statistic output of averages per zone
998 # error value: data greater than or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.3 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of main axis of the anisotropy-ellipsis, -90 to +90 degr, math. pos.
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0 # lower limit of interpolation results
0 # replace value for results below the lower limit
90 # upper limit for interpolation results
90 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios
3 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
0 # number of scenario cells

[precipitation]
3 # method: 1=idw 2=regress 3=idw+regress 4=thiessen
$inpath//regen//$year//.dat # file name with station data (if method = 1, 3 or 4, else ignored)
$outpath//regen//$year//.out # file name with regression data (if method = 2 or 3)
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
1//$Writegrid # correction factor for results
$outpath//prec//$grid//.//$code//$year $hour_mean # file name for the statistic output of averages per zone
998 # error value: data greater than or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.75 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of main axis of the anisotropy-ellipsis, -90 to +90 degr, math. pos.
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0.1 # lower limit of interpolation results
0 # replace value for results below the lower limit
900 # upper limit for interpolation results
900 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios
2 # 3 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
1 # 4 # number of scenario cells
699000 235000 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 # koordinates of the cells, then one value for
# each month of a year

[sunshine_duration]
1 # method: 1=idw 2=regress 3=idw+regress 4=thiessen
$inpath//sonne//$year//a.rel # file name with station data (if method = 1, 3 or 4, else ignored)
$outpath//sonne//$year//.out # file name with regression data (if method = 2 or 3)
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
1.0 # correction factor for results
$outpath//ssd//$grid//.//$code//$year $hour_mean # file name for the statistic output of averages per zone
998 # error value: data greater than or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.5 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of main axis of the anisotropy-ellipsis, -90 to +90 degr, math. pos.
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0 # lower limit of interpolation results
0 # replace value for results below the lower limit
1.0 # upper limit for interpolation results
1.0 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios
3 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
0 # number of scenario cells

[global_radiation]
2 # method: 1=idw 2=regress 3=idw+regress 4=thiessen
$inpath//Kglob//$year//a.dat # file name with station data (if method = 1, 3 or 4, else ignored)
$outpath//global//$year//.out # file name with regression data (if method = 2 or 3)
$Writegrid # 0, if no grid-output is needed, else one of the codes described above
1.0 # correction factor for results
$outpath//rad//$grid//.//$code//$year $hour_mean # file name for the statistic output of averages per zone
1400 # error value: data greater than or lesser the negative value are nodata
$IDWweight # weighting of the reciprocal distance for IDW
0.5 # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist # max. distance of stations to the actual interpolation cell
$Anisoslope # slope of main axis of the anisotropy-ellipsis, -90 to +90 degr, math. pos.
$Anisotropie # ratio of the short to the long axis of the anisotropy-ellipsis
0 # lower limit of interpolation results
0 # replace value for results below the lower limit
1367 # upper limit for interpolation results
1367 # replace value for results with larger values than the upper limit
$SzenUse # 1=use scenario data for correction, 0=dont use scenarios
1 # 1=add scenarios, 2=multiply scenarios, 3=percentual change
0 # number of scenario cells

# humidity is listed here but not processed, because there are only 6 variables to be interpolated as
# specified in the sections [meteo_data_count] and [meteo_names]

```

```

[air_humidity]
2                                # method: 1=idw 2=regress 3=idw+regress 4=thiessen
$inpath//feuch//$year//a.dat    # file name with station data (if method = 1, 3 or 4, else ignored)
$inpath//feucht//$year//.out    # file name with regression data (if method = 2 or 3)
$outpath//$humiditygrid         # output grid, used for deriving names of sums or averages for days, months aso.)
$Writegrid                      # 0, if no grid-output is needed, else one of the codes described above
0.001                           # correction factor for results
$outpath//humi//$grid//.//$code//$year $hour_mean # file name for the statistic output of averages per zone
9998                            # error value: data greater than or lesser the negative value are nodata
$IDWweight                      # weighting of the reciprocal distance for IDW
0.5                             # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist                     # max. distance of stations to the actual interpolation cell
$Anisoslope                     # slope of main axis of the anisotropy-ellipses, -90 to +90 degr, math. pos.
$Anisotropie                    # ratio of the short to the long axis of the anisotropy-ellipses
0.01                            # lower limit of interpolation results
0.01                            # replace value for results below the lower limit
1.0                             # upper limit for interpolation results
1.0                             # replace value for results with larger values than the upper limit
$SzenUse                        # 1=use scenario data for correction, 0=dont use scenarios
3                               # 1=add scenarios, 2=multiply scenarios, 3=percentual change
1                               # number of scenario cells
699000 235000 0 0 0 0 0 0 0 0 0 0 0 0
# here an example for a scenario without effect is given

[vapor_pressure]
2                                # method: 1=idw 2=regress 3=idw+regress 4=thiessen
$inpath//dampf//$year//a.dat    # file name with station data (if method = 1, 3 or 4, else ignored)
$inpath//dampf//$year//.out    # file name with regression data (if method = 2 or 3)
$outpath//$vaporgrid           # output grid, used for deriving names of sums or averages for days, months aso.)
$Writegrid                      # 0, if no grid-output is needed, else one of the codes described above
0.1                             # correction factor for results
$outpath//vapo//$grid//.//$code//$year $hour_mean # file name for the statistic output of averages per zone
998                             # error value: data greater than or lesser the negative value are nodata
$IDWweight                      # weighting of the reciprocal distance for IDW
0.5                             # for interpolation method 3: relative weight of IDW-interpolation in the result
$IDWmaxdist                     # max. distance of stations to the actual interpolation cell
$Anisoslope                     # slope of main axis of the anisotropy-ellipses, -90 to +90 degr, math. pos.
$Anisotropie                    # ratio of the short to the long axis of the anisotropy-ellipses
0                               # lower limit of interpolation results
0                               # replace value for results below the lower limit
90                              # upper limit for interpolation results
90                              # replace value for results with larger values than the upper limit
$SzenUse                        # 1=use scenario data for correction, 0=dont use scenarios
1                               # 1=add scenarios, 2=multiply scenarios, 3=percentual change
4                               # number of scenario cells
699000 235000 0.994 1.187 1.021 1.035 1.201 1.021 .635 .566 .538 1.021 .800 1.007
699000 290000 1.021 1.201 1.035 1.049 1.201 1.035 .649 .566 .538 1.035 .787 1.021
737000 235000 0.980 1.173 1.035 1.076 1.173 1.021 .621 .635 .593 1.035 .800 1.007
737000 290000 1.007 1.187 1.049 1.090 1.173 1.035 .649 .649 .607 1.049 .800 1.007
# this was an example for vapor pressure scenarios using 4 scenario cells. They are used only, if
# the symbol $SzenUse is set to 1!

#
# ----- now the parameters for model components -----
#

# for precipitation correction the paragraphs "[precipitation]" "[temperature]" and
# "[wind_speed]" are searched in the memory. If they are not there (e.g. due to missing definition of interpo-
# lators in the control file for precipitation, wind or temperature),
# the precipitation correction will not be performed. If only precipitation and wind are found, the correction
# is temperature independent.

[precipitation_correction]
1                                # 0=ignore this module, 1 = run the module
0.5                             # Snow-rain-temperature
1.01                            # liquid: b in: y = p(ax + b)
0.01                            # liquid: a in: y = p(ax + b) = 1% more per m/s + 0.5% constant
1.10                            # Snow: b in: y = p(ax + b)
0.13                           # Snow: a in: y = p(ax + b) = 15% more per m/s + 45% constant

# correction factors for direct radiation are calculated
# if the cell is in the shadow of another cell, or if a cell is not in the sun (slope angle!)
# then the factor is 0.
# control_parameter: 1 = radiation correction WITH shadow WITHOUT temperature correction
#                   2 = radiation correction WITH shadow WITH temperature correction
#                   3 = radiation correction WITHOUT shadow WITHOUT temperature correction,
#                   4 = radiation correction WITHOUT shadow WITH temperature

[radiation_correction]
1                                # 0=ignore this module, 1 = run the module
$time                           # duration of a time step in minutes
2                               # control parameter for radiation correction (see above)
$outpath//$Tcorrgrid            # name of the grids with the corrected temperatures
5//$Writegrid                   # Writegrid for corrected temperatures
5                               # factor x for temperature correction x * (-1.6 .... +1.6)
$outpath//$ExpoCorrgrid         # name of the grids with the correction factors for the direct radiation
$Writegrid                      # Writegrid
$outpath//$Shapegrid            # grids with codes 1 for theor. shadow, 0 for theor. no shadow (assumed: SSD=1.0)
$Writegrid                      # Writegrid

```

```

1      # time step counter, after reaching this value, a new correction is calculated here: every time step
1      # Spitting of the interval, useful for time step=24 hours (then: split=24, ->
# each hour one correction calculation)

[evapotranspiration]
1      # 0=ignore this module, 1 = run the module
$stime      # duration of a time step in minutes
1      # Method: 1=Penman-Monteith, 2=Hamon (only daily), 3=Wendling (only daily) 4= Haude (only daily)
0.5 0.6 0.8 1.0 1.1 1.1 1.2 1.1 1.0 0.9 0.7 0.5 # PEC correction factor for HAMON-evapotranspiration
0.20 0.20 0.21 0.29 0.29 0.28 0.26 0.25 0.22 0.22 0.20 0.20 # fh (only method 4) monthly values (Jan ... Dec)
0.5      # fk -> factor for Wendling-evapotranspiration (only for Method = 3)
$outpath//SETPgrid      # result grid for pot. evapotranspiration in mm/dt
1//Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//etp_//$grid//.$code//$year $hour_mean # statistic file for subbasins of pot. evapo-Transpiration
$outpath//SETRgrid      # result grid for real evapotranspiration in mm/dt
1//Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//etr_//$grid//.$code//$year $hour_mean # zonal statistic of the real evapotranspiration
$outpath//rgex_//$grid//.$code//$year $hour_mean # zonal statistic of the corrected radiation
+0.23 +1.77 -2.28 +1.28 # coefficients for Polynom of order 3 RG = c1 + c2*SSD + c3*SSD^2 + c4*SSD^3
+0.072 -0.808 +2.112 -0.239 # coefficients x for Polynom of order 3 SSD = x1 + x2*RG + x3*RG^2 + x4*RG^3
0.88 0.05 # extinction coeff. for RG-modeling (Phi and dPhi) (summer phi=phi-dphi, winter phi=phi+dphi)
1654.0 # recession constant (e-function for recession of the daily temperature amplitude with altitude [m]
3.3 4.4 6.1 7.9 9.4 10.0 9.9 9.0 7.8 6.0 4.2 3.2 # monthly values of the max. daily T-amplitudes
0.62 0.1 # part of the temperature amplitude (dt), that is added to the mean day-temperature
# (followed by the range of changing within a year ddt) to get the mean temperature of light day
# in the night: mean night temperature is mean day temperature minus (1-dt)*(temp. amplitude)

[snow_model]
1      # 0=ignore this module, 1 = run the module
$stime      # duration of a time step in minutes
1      # method 1=T-index, 2=t-u-index, 3=Anderson comb., 4=extended com.
1.0      # transient zone for rain-snow (TOR +- this range)
0.5      # TOR temperature limit for rain (Grad Celsius)
-0.2      # T0 temperature limit snow melt
0.1      # CWH storage capacity of the snow for water (relative part)
1.0      # CRFR coefficient for refreezing
1.9      # C0 degree-day-factor mm/d/C
1.0      # C1 degree-day-factor without wind consideration mm/(d*C)
0.8      # C2 degree-day-factor considering wind mm/(d*C*m/s)
0.07      # z0 roughness length cm for energy balance methods (not used)
1.5      # RMFMIN minimum radiation melt factor mm/d/C comb. method
2.5      # RMFMAX maximum radiation melt factor mm/d/C comb. method
0.75      # Albedo for fresh snow
$outpath//snowcover_outflow # discharge from snow, input (precipitation) for following modules
Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//qsch_//$grid//.$code//$year $hour_mean # melt flow (or rain, if there is no snow cover) in mm/dt
$outpath//SSNOgrid      # name of the grids with the snow storage solid in mm
Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//SSLIQgrid      # name of the grids with the snow storage liquid in mm
Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//ssto_//$grid//.$code//$year $hour_mean # total snow storage, in mm, (liquid and solid fraction)
$readgrids      # 1=read snow storage solid, liquid grids from disk, 0=generate new grids

[ice_firn]
2      # method for glacier melt: 1=classical t-index, 2=t-index with correction by radiation
5      # t-index factor for ice
4      # t-index factor for firn
3      # t-index factor for snow
2      # melt factor
.001 # radiation coefficient for ice (for method 2)
.002 # radiation coefficient for snow (for method 2)
3      # els-constant for ice
300 # els-constant for firn
30 # els-constant for snow
1      # initial reservoir content for ice discharge (single linear storage approach)
1      # initial reservoir content for firn discharge (single linear storage approach)
1      # initial reservoir content for snow discharge (single linear storage approach)
$outpath//$firn_melt # melt from firn
Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//qfir_//$grid//.$code//$year $hour_mean # melt from firn as statistic file
$outpath//$ice_melt # melt from ice
Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//qice_//$grid//.$code//$year $hour_mean # melt from ice as statistic file
$outpath//qglo_//$grid//.$code//$year $hour_mean # melt from ice and firn as statistic file

[interception_model]
1      # 0=ignore this module, 1 = run the module
$stime      # duration of a time step in minutes
$outpath//$troughfall      # result grid : = outflow from the interception storage
Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//qi_//$grid//.$code//$year $hour_mean # statistic file interception storage outflow
$outpath//SEIgrid      # Interception evaporation, grid
1//Writegrid      # 0, if no grid-output is needed, else one of the codes described above
$outpath//ei_//$grid//.$code//$year $hour_mean # zonal statistic
$outpath//SSIgrid      # storage content of the interception storage
Writegrid      # 0, if no grid-output is needed, else one of the codes described above
0.35      # water layer thickness on the leaves (multiplied with LAI -> storage capacity)
$readgrids      # 1=read grids from disk, else generate internal

```

```

[infiltration_model]
1 # 0=ignore this module, 1 = run the module
$stime # duration of a time step in minutes
$outpath//INFEXgrid # grid with infiltration excess in mm (surface runoff)
1//Writegrid # Writegrid for surface discharge (fraction 1)
$outpath//infx//$grid//.$code//$year $hour_mean # statistic file for the infiltration excess
$outpath//SATgrid # grid with code 1=saturation at interval start, 0 =no saturation.
$Writegrid # Writegrid for saturation code grids
0.1 # fraction of re-infiltrating water (of the infiltration excess)

[unsatzon_model]
1 # 0=ignore this module, 1 = run the module
$stime # duration of a time step in minutes
2 # method, 1=simple method, 2 = FDM-Method (strongly recommended)
2 # interaction with surface water: 0 = no interaction, 1 = exfiltration 2 = infiltration and exfiltration
0 # surface storage in ponds: 0 = no ponds, 1 = using ponds (pond depth as standard grid needed)
0 # artificial drainage: 0 = no drainage 1 = using drainage
0 # clay layer: 0 = no clay layer, 1 = assuming a clay layer (clay-grid needed!)
5e-8 # permeability of the clay layer (is used for the clay layer only)
$outpath//qdra//$grid//.$code//$year $hour_mean # result drainage discharge in mm per zone
$outpath//gwst//$grid//.$code//$year $hour_mean # result groundwater depth
$outpath//gwn//$grid//.$code//$year $hour_mean # result mean groundwater recharge per zone
$outpath//sb05//$grid//.$code//$year $hour_mean # result rel. soil moisture 0..0.5 m per zone
$outpath//sb1//$grid//.$code//$year $hour_mean # result rel. soil moisture 0..1 m per zone
$outpath//infx//$grid//.$code//$year $hour_mean # result statistic of the infiltration excess
$outpath//pond//$grid//.$code//$year $hour_mean # result statistic of the ponding water storage content
$outpath//qdir//$grid//.$code//$year $hour_mean # result statistic of the direct discharge
$outpath//qifl//$grid//.$code//$year $hour_mean # result statistic of the interflow
$outpath//qbas//$grid//.$code//$year $hour_mean # result statistic of the baseflow
$outpath//qges//$grid//.$code//$year $hour_mean # result statistic of the total discharge
$outpath//gwin//$grid//.$code//$year $hour_mean # infiltration from surface water into groundwater
$outpath//gwex//$grid//.$code//$year $hour_mean # exfiltration from groundwater into surface water
$outpath//Thetastack # stack, actual soil water content for all soil levels
$Writestack # Writecode for this stack
$outpath//hydraulic_heads_stack # stack, containing hydraulic heads
$Writestack # Writecode for this stack
$outpath//geodetic_altitude_stack # stack, containing geodetic altitudes of the soil levels (lower boundaries)
$Writestack # Writecode for this stack
$outpath//flowstack # stack, containing the outflows from the soil levels
$Writestack # Writecode for this stack
$outpath//GWdepthgrid # grid with groundwaterdepth
$Writegrid # writegrid for this grid
$outpath//GWthetagrid # grid with theta in GWLEVEL
$Writegrid # writegrid for this grid
$outpath//GWNgrid # grid with groundwater recharge
1//Writegrid # writegrid for this grid
$outpath//GWLEVELgrid # grid with level index of groundwater surface (layer index)
$Writegrid # writegrid for this grid
$outpath//QDRAINgrid # grid with the drainage flows
$Writegrid # writegrid for this grid
$outpath//SATgrid # grid with code 1=saturation at interval start, 0 no sat.
$Writegrid # writegrid for this grid
$outpath//INFEXgrid # grid with infiltration excess in mm (surface discharge)
1//Writegrid # writegrid for this grid
$outpath//QDgrid # grid with direct discharge
1//Writegrid # writegrid for this grid
$outpath//QIgrid # grid with Interflow
1//Writegrid # writegrid for this grid
$outpath//QBgrid # grid with baseflow
1//Writegrid # write code for baseflow
$outpath//GWINgrid # grid with infiltration from rivers into the soil (only if GW-module enabled)
1//Writegrid # writegrid for re-infiltration
$outpath//GWEXgrid # grid, exfiltration from groundwater (only generated id GW-module is enabled)
1//Writegrid # writegrid for exfiltration
$outpath//sact_pond_grid # grid with content of ponding storage
$Writegrid # writegrid for pond storage
61 55 # coordinates of a control cell, theta, qu and tracer conc. are written to files
# the following three files will be generated only, if the coordinates are not 0,0
$outpath//qbot//$grid//.$code//$year # file containing the flows between the layers of the control point
$outpath//thet//$grid//.$code//$year # file containing the theta values of the control point layers
$outpath//hhyd//$grid//.$code//$year # file containing the hydraulic head of the layers of the control point
1 2 3 4 5 6 7 8 9 10 11 12 13 # range for subbasin codes
3 5 5 3 3 3 3 3 3 3 5 3 # kelsqd
15 12 10 15 8 8 10 10 8 6 8 12 15 # kelsqi
17 15 15 17 18 30 20 25 15 20 22 17 # drainage density
0.43 0.43 0.43 0.43 0.43 0.43 0.43 0.43 0.43 0.43 0.43 0.43 0.43 # k in qb = Q0 * exp(-k/z)
0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 # Q0 in the above formula
0.2 0.2 0.2 0.2 0.3 0.35 0.35 0.3 0.3 0.4 0.3 0.3 0.2 # fraction of surf. runoff on
# snow melt
$readgrids # 1=read all grids from disk, 2=read only gw-level (m below surface) else (i.e. 0) generate all
# grids internally (setting the groundwater table to that layer, which is in 1/5th of total depth as given by
# the soil table). If the read parameter is set to 2, then only the groundwater table in m below surface is read
# in used for generating all other grids like the theta-stack and the GW-level, GW-Theta a.s.o.

[irrigation]
0 # 0=ignore this module, 1 = run the module
$stime # duration of a time step in minutes
$outpath//irgw//$grid//.$code//$year $hour_mean # statistic of the irrigation water from groundwater
$outpath//irsw//$grid//.$code//$year $hour_mean # statistic of the irrigation water from surface water

```

```

[groundwater_flow]
1 # 0=ignore the module, 1 = run the module
$time # duration of a time step in minutes
1 # solving method: 1=Gauss-Seidel-iteration 2=PCG (not yet implemented)
1000 # if iterative solving method (1): max. number of iterations
0.00001 # if iterative solving method (1): max. changes between two iterations
1.0 # Alpha for estimation of central differences 0.5 = Crank-Nicholson Method,
# 0 = fully explicit, 1 = fully implicit
-1.30 # factor for relaxing the iteration if using the iterative method
# (successive over[under] relaxation); negative values: automatic SOR estimation
$readgrids # 1=read heads from disk, 0=do not read but initialize with gw-level from unsat. zone
1 # number of aquifers
0 0 # coordinates of a control point for all fluxes and for each layer : q0..q4, leakage up and down
# if the control cell coordinates are 0 0, then no output is written to the following file
$outpath//glog//$grid//.$code//$year # name of a file containing the flows between of the control point
$outpath//$head1grid # (new) grid for hydraulic heads for layer 1
26//$Writegrid # writecode for hydraulic heads for layer 1
$outpath//$flowx1grid # (new) grid for fluxes in x direction for layer 1
26//$Writegrid # writecode for flux-x-grid in layer 1
$outpath//$flowy1grid # (new) grid for fluxes in y direction for layer 1
26//$Writegrid # writecode for flux-y-grid in layer 1
#
# if only one aquifer is defined, then the following parameters are skipped
#
$outpath//$head2grid # (new) grid for hydraulic heads for layer 2
26//$Writegrid # writecode for hydraulic heads for layer 2
$outpath//$flowx2grid # (new) grid for fluxes in x direction for layer 2
26//$Writegrid # writecode for flux-x-grid in layer 2
$outpath//$flowy2grid # (new) grid for fluxes in y direction for layer 2
26//$Writegrid # writecode for flux-y-grid in layer 2
$outpath//$head3grid # (new) grid for hydraulic heads for layer 3
26//$Writegrid # writecode for hydraulic heads for layer 3
$outpath//$flowx3grid # (new) grid for fluxes in x direction for layer 3
$Writegrid # writecode for flux-x-grid in layer 3
$outpath//$flowy3grid # (new) grid for fluxes in y direction for layer 3
$Writegrid # writecode for flux-y-grid in layer 3

# this paragraph is not needed for WaSiM-2 but for the WaSiM-version with the variable saturated area approach
(after Topmodel)
[soil_model]
1 # 0=ignore this module, 1 = run the module
$time # duration of a time step in minutes
1 # method, 1 = without slow baseflow, 2 = with slow baseflow (not recommended)
$outpath//$sat_def_grid # (new) saturation deficit-grid (in mm)
$Writegrid # writegrid for this grid
$outpath//$SUZgrid # (new) storage grid for unsat. zone
$Writegrid # writegrid for this grid
$outpath//$SIFgrid # (new) storage grid for interflow storage
$Writegrid # writegrid for this grid
$outpath//$SBIagrid # (new) grid for soil moisture in the inactive soil storage
$Writegrid # Writegrid for inactive soil moisture
$outpath//$fcia_grid # (new) grid for plant available field capacity in the inactive soil storage
$Writegrid # writegrid for this grid
$outpath//$SSPgrid # relative fraction of the soil storages, which is in contact with ground water
$Writegrid # writegrid for this grid
$outpath//$QDgrid # surface runoff
1//$Writegrid # writegrid for this grid
$outpath//$QIgrid # Interflow
1//$Writegrid # writegrid for this grid
$outpath//$Peakgrid # grid for peak flow (maximum peak flow for the entire model time)
$outpath//qdir//$grid//.$code//$year $hour_mean # statistic of the surface discharge
$outpath//qifl//$grid//.$code//$year $hour_mean # statistic of the interflow
$outpath//qbav//$grid//.$code//$year $hour_mean # statistic of the base flow
$outpath//qbav//$grid//.$code//$year $hour_mean # statistic of the slow base flow
$outpath//qges//$grid//.$code//$year $hour_mean # statistic of the total discharge
$outpath//sb_//$grid//.$code//$year $hour_mean # soil storage in mm per zone
$outpath//suz_//$grid//.$code//$year $hour_mean # drainage storage in mm per zone
$outpath//sifl//$grid//.$code//$year $hour_mean # interflow storage in mm per zone
$outpath//sd_//$grid//.$code//$year $hour_mean # saturation deficit per zone in mm
1 2 3 4 5 6 7 8 9 10 11 12 13 # subbasin codes
0.025 0.045 0.042 0.022 0.032 0.052 0.027 0.040 0.031 0.015 0.030 0.013 0.025 # recession parameter m
5.0 5.0 5.0 7.0 3.0 3.0 3.0 3.0 8.0 40.0 3.0 20.0 5.0 # scaling factor Tkorr
2.0 2.0 2.0 2.0 2.0 2.0 1.0 2.0 2.0 8.0 2.0 8.0 2.0 # scaling factor Kkorr
6.0 7.0 7.0 6.0 4.0 4.0 6.0 3.0 6.0 6.0 6.0 8.0 6.0 # recession constant surf. runoff
25.0 25.0 25.0 20.0 15.0 15.0 18.0 15.0 15.0 0.0 15.0 0.0 25.0 # maximum interflow storage
80.0 80.0 80.0 60.0 70.0 40.0 50.0 40.0 60.0 1.0 60.0 1.0 80.0 # recession constant interflow
# attention: please donst use the next three parameters: never use method 2, it is not tested!!
3600 3600 3600 3600 3600 3600 3600 3600 3600 3600 3600 3600 3600 # recession const. slow baseflow
0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 # max. deep percolation
0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 # initial value slow baseflow
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 # init. content unsat. zone
0.75 0.75 0.75 0.6 0.45 0.45 0.45 0.4 0.45 0.45 0.3 0.7 0.75 # init. satur. deficit in n*nFK
3.0 3.0 4.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 5.0 3.0 3.0 # Pgrenz (macro pore flow)
0.9 0.9 0.9 0.9 0.9 0.9 1.0 0.9 0.9 0.9 0.9 0.9 0.9 # scaling of capillary rise
0.1 0.1 0.1 0.4 0.4 0.5 0.4 0.5 0.4 0.4 0.35 0.35 0.1 # fraction on snow melt going
# into surface runoff
$readgrids # 1=read grids from disk, else generate internal

```



```

#
# now the routing descriptions follow
# TG (Teilgebiet) is the code for subbasin, OL (Oberlieger) is the code for a upper subbasin (tributary) ,
# flowing into the actual subbasin TG.
# AE and AErel (in TG (...)) are the area of the subbasin (TG) and the relative fraction of the modeled
# compared to the real subbasin area (normally 1.0, but if inflows have to be considered or only parts of a
# subbasin are modeled, AErel can be smaller)
#
# example:
# TG 9 (AE= 484.0, AErel=0.8125) # TG 11 is external inflow ZL 1:
# from OL 10 (kh=0.4, kv=0.4, Bh=3.5, Bv=20.0, Th=0.5, Mh=25.0, Mv=15.0, I=0.0128, L=10408.3, AE=3.75 )
# and ZL 1 (modus = extern $outpath//abstract11.dat 4 5 , kh=0.4, kv=0.4, Bh=7.0, Bv=50.0, Th=1.0, Mh=25.0,
# Mv=15.0, I=0.0066, L=10838.5, AE=90.75 )
# and OL 12 (kh=0.4, kv=0.4, Bh=10.0, Bv=60.0, Th=1.4, Mh=27.0, Mv=15.0, I=0.0084, L=36339.6, AE=81.5 )
# TG 9 (AE= 484.0, AErel=0.6435)
# from OL 10 (kh=0.4, kv=0.4, Bh=3.5, Bv=20.0, Th=0.5, Mh=25.0, Mv=15.0, I=0.0128, L=10408.3, AE=3.75 )
# TG 9 with external inflow from OL 11 and 12
# and ZL 2 (modus = extern $outpath//abstract11.dat 4 5, kh=0.4, kv=0.4, Bh=7.0, Bv=50.0, Th=1.0, Mh=25.0,
# Mv=15.0, I=0.0066, L=10838.5, AE=90.75 )
# and ZL 1 (modus = extern $outpath//abstract12.dat 4 5, kh=0.4, kv=0.4, Bh=10.0, Bv=60.0, Th=1.4, Mh=27.0,
# Mv=15.0, I=0.0084, L=36339.6, AE=81.5 )
#
# kh, kv are storage coefficients for mean channel and flood plain flow; measure in h
# Mh, Mv are Manning roughness for mean channel (Mh) and flood plains (Mv); measure in m^(1/3)/s
# Bh, Bv are width of mean channel resp. floodplains; measure in m
# Th is the water depth in the mean channel, measure in m
# I is the slope angle in flow direction in m/m, L is flow length in m, AE is the area of the sub-basin in km^2
#
# for abstractions: modus = intern or extern (if extern, a file name must follow),
# then 3 numeric parameters: min. threshold, fraction of abstracted water, max. capacity of abstraction
# channel, then the measure (standard is mm/h, other poss.: m3/s or m^3/s; all other measures are interpreted
# as mm/h)
# example:
# and AL 1 (modus = intern 0.0 1.0 1 m^3/s ) -> there must be an corresponding internal inflow ZL 1 !
# and AL 2 (modus = extern $outpath//abstrac2.dat 0 1 15 m^3/s )
#
# for inflows: like normal routings except that the first parameters are modus = intern / extern,
# if modus = extern, a filename and two integer parameters indicating the start row/start column for the given
# file must follow
# example:
# from ZL 1 (modus = intern , kh=0.4, kv=0.4, Bh=10, Bv=60, Th=1.4, Mh=27, Mv=15.0, I=0.0084, L=10, AE=81.5 )
# or:
# from ZL 1 (modus = extern $outpath//abstrac1.dat 4 5, kh=0.4, kv=0.4, Bh=10.0, Bv=60.0, Th=1.4, Mh=27.0,
# Mv=15.0, I=0.0084, L=36339.6, AE=81.5 )
#
# for reservoirs: a filename for the output of reservoir content/tracer concentrations, an initial filling and
# initial tracer concentrations must be given additionally for each reservoir a paragraph containing the
# abstraction rule has to be found within the control file
# example:
# and SP 1 ( file = $outpath//spv__01.//$code//$year , V0 = 1E8, C0 = 1.0 0.1 3.0 0 0 0 0 0 0 )
# C0: initial concentration for all of max. 9 tracers in the reservoir water
# ..
# [abstraction_rule_reservoir_1]
# 2 # number of following reservoir-content - abstraction points
# 0 20.0 # first value: reservoir content in m^3, second value: outflow at this filling level
# 1e8 20.0
#
#
[routing_model]
1 # 0=ignore, 1=run , 2=run the module with observed inflows (from discharge files)
$time # duration of a time step in minutes
5 1200 90 24 # minimum/maximum specific discharge (l/s/km^2), number of log. fractions of the range,
# splitting of the time step (24= 1 hour-intervals are splitted into 24 Intervals of 2.5 min. duration)
# 5 1200 90 24 means: the flow velocities are calculated before the model start for a range of 5 to 1200
# l/s/km^2 with a logarithmic splitting into 90 flow range intervals. Each time step is also splitted into 24
# time sub-intervals
$outpath//qgko//$grid//.$code//$year $routing_code # name of the statistic file with routed discharges
$inpath//spende//$year # name of the file with observed discharges (l/s/km^2)
13 # number of following column descriptor (which column in the spec. disch. file corresponds to which subbasin
1 1 # first number: subbasin, second: column index
2 2
3 3
4 4
5 5
6 6
7 7
8 8
9 9
10 10
11 11
12 12
13 0 # this is not required. If there is no column in the file for a subbasin, then this is indicated by
# an absent entry for this subbasin or by setting column index to 0
0 # time offset (for r-square calculation. intervals up to this parameter are not evaluated)
TG 12 (AE= 81.5, AErel=1.0)
from AL 1 (modus = extern $outpath//ableit_1.dat 4.5 0.35 7.5 m^3/s )

```

```

TG 2 (AE=210.250, AErel=1.0)
from OL 3 (kh=0.1, kv=0.4, Bh= 9.1, Bv= 36.4, Th= 0.91, Mh=25.0, Mv=10.0, I=0.0080, L=10363.9, AE=75.750)
TG 5 (AE=269.750, AErel=1.0)
from OL 7 (kh=0.1, kv=0.4, Bh= 8.2, Bv= 32.7, Th= 0.93, Mh=25.0, Mv=10.0, I=0.0129, L=13778.1, AE=76.500)
and OL 6 (kh=0.1, kv=0.4, Bh= 6.4, Bv= 25.8, Th= 0.86, Mh=25.0, Mv=10.0, I=0.0178, L=10156.8, AE=66.250)
TG 9 (AE=491.750, AErel=1.0)
from OL 10 (kh=0.1, kv=0.4, Bh= 4.7, Bv= 18.9, Th= 0.55, Mh=25.0, Mv=10.0, I=0.0138, L=8828.4, AE=2.500)
and OL 11 (kh=0.1, kv=0.4, Bh=10.3, Bv= 41.3, Th= 1.03, Mh=25.0, Mv=10.0, I=0.0085, L=8535.5, AE=110.250)
and OL 12 (kh=0.1, kv=0.4, Bh= 9.1, Bv= 36.3, Th= 0.91, Mh=25.0, Mv=10.0, I=0.0099, L=31263.3, AE=77.250)
TG 4 (AE=1086.000, AErel=1.0)
from OL 5 (kh=0.1, kv=0.4, Bh=15.7, Bv= 62.7, Th= 1.57, Mh=25.0, Mv=10.0, I=0.0055, L=22071.0, AE=269.750)
and OL 9 (kh=0.1, kv=0.4, Bh=21.2, Bv= 84.7, Th= 2.12, Mh=25.0, Mv=10.0, I=0.0036, L=22520.7, AE=491.750)
Mv=10.0, I=0.0036, L=22520.7, AE=491.750)
and OL 8 (kh=0.1, kv=0.4, Bh= 4.9, Bv= 19.5, Th= 0.49, Mh=25.0, Mv=10.0, I=0.0097, L=22142.0, AE=15.750)
TG 13 (AE=1592.000, AErel=1.0)
from OL 2 (kh=0.1, kv=0.4, Bh=19.6, Bv= 78.4, Th= 1.96, Mh=25.0, Mv=10.0, I=0.0010, L=1000.0, AE=210.250)
and OL 4 (kh=0.1, kv=0.4, Bh=30.2, Bv=120.7, Th= 3.02, Mh=25.0, Mv=10.0, I=0.0027, L=30263.3, AE=1086.000)
TG 1 (AE=1697.000, AErel=1.0)
from OL 13 (kh=0.1, kv=0.4, Bh=41.9, Bv=167.4, Th= 4.19, Mh=25.0, Mv=10.0, I=0.0010, L=18535.5, AE=1592.000)

```

# in the real file, the landuse table has too long lines to show them here as complete lines.

# The arrows should indicate that fact for this documentation!

[landuse\_table]

# number of following land use codes, per row one use		albe- surface resistances rsc as monthly values												julian day for the param.-sets				
#Co name of the	#de Landuse type	do	1	2	3	4	5	6	7	8	9	10	11	12				
#----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
1	water	0.05	20	20	20	20	20	20	20	20	20	20	20	20	110	150	250	280
2	settlements	0.1	100	100	100	100	100	100	100	100	100	100	100	100	110	150	250	280
3	pine_forest	0.12	80	80	75	65	55	55	55	55	55	75	80	80	110	150	250	280
4	deciduous_forest	0.17	100	100	95	75	65	65	65	65	65	85	100	100	110	150	250	280
5	mixed_forest	0.15	90	90	85	70	60	60	60	60	60	80	90	90	110	150	250	280
6	agriculture	0.25	80	80	75	75	65	65	65	65	65	75	90	90	110	150	250	255
7	grass	0.25	90	90	75	65	50	55	55	55	60	70	90	90	110	150	250	280
8	bushes	0.20	80	80	70	70	50	50	50	55	55	70	80	80	110	150	250	280
15	rock	0.12	250	250	250	250	250	250	250	250	250	250	250	250	110	150	250	280
19	horticulture	0.25	100	100	90	70	60	60	60	60	60	80	100	100	110	150	250	280

# second part of the landuse table

LAI				(eff. veget. height)				Veg.covering				root depth [m]				Param. root distribution.		h-value for start etp-reduction	
1	2	3	4	z01	2	3	4	1	2	3	4	1	2	3	4				
1	1	1	1	.01	.01	.01	.01	.1	.1	.1	.1	0.01	0.01	0.01	0.01	1.0		3.45	
1	1	1	1	10	10	10	10	.5	.5	.5	.5	0.2	0.2	0.2	0.2	1.0		3.45	
8	12	12	8	10	10	10	10	.9	.9	.9	.9	1.2	1.2	1.2	1.2	1.0		3.45	
.5	8	8	.5	.3	10	10	.3	.7	.95	.95	.7	1.4	1.4	1.4	1.4	1.0		3.45	
2	10	10	2	3	10	10	3	.8	.92	.92	.8	1.3	1.3	1.3	1.3	1.0		3.45	
1	5	3	1	.05	.5	.2	.05	.3	.8	.7	.3	0.05	0.4	0.3	0.05	1.0		3.45	
2	4	4	2	.15	.4	.3	.15	.95	.95	.95	.95	0.4	0.4	0.4	0.4	1.0		3.45	
3	5	5	3	1.5	2.5	2.5	1.5	.9	.95	.95	.9	0.5	0.5	0.5	0.5	1.0		3.45	
1	1	1	1	.05	.05	.05	.05	.8	.8	.8	.8	0.1	0.1	0.1	0.1	1.0		0.5	
.5	5	5	.5	.4	3	3	.4	.75	.75	.75	.75	0.8	0.8	0.8	0.8	1.0		3.45	

# like for the landuse table, in the real file the soil table has too long lines to show them here as complete lines. The arrows should indicate that fact for this documentation!

[soil\_table]

# number of following entries		FC(Vol.%) mSB(Vol.%) ksat(m/s) suction. parameter				[mm] 1=par 2=tab	
#Code	name						
#----	----	----	----	----	----	----	----
1	Sand_(S)	6.21	38.5	8.25E-5	385	1	
2	loamy_sand_(LS)	10.91	37.3	4.05E-5	373	1	
3	sandy_loam_(SL)	12.28	34.5	1.23E-5	345	1	
4	silty_loam_(SIL)	22.58	38.3	1.25E-6	383	1	
5	loam_(L)	12.9	35.2	2.89E-6	352	1	
6	sandy_clay_(SC)	19.43	28.0	3.33E-7	280	1	
7	silty_clay_(SIC)	27.65	29.0	5.56E-8	290	1	
8	clay_(C)	29.12	31.2	5.56E-7	312	1	
9	moor_(M)	47.31	75.0	8.25E-5	750	1	
10	settlements_rock_(R)	14.00	15.0	1.00E-9	50	1	
11	clay_loam_(CL)	21.24	31.5	7.22E-7	315	1	
12	silt_(SI)	28.17	42.6	6.94E-7	426	1	
13	silty_clay_loam_(SICL)	28.16	34.1	1.94E-7	341	1	
14	sandy_clay_loam_(SCL)	13.35	29.0	3.64E-6	290	1	

Theta_sat	Theta_res	alpha	n	layer	thick	maxratio	k-recession
1/1	1/1	1/m			[m]	ko_rel/ku_rel	per m ku/ko
.43	.045	14.5	2.68	31	.3333	90	.7
.43	.057	7.00	1.70	31	.3333	90	.7
.41	.065	7.50	1.89	31	.3333	90	.7
.45	.067	2.00	1.41	31	.3333	90	.7
.43	.078	3.60	1.56	31	.3333	90	.7
.38	.100	2.70	1.23	31	.3333	90	.7
.36	.070	0.50	1.09	31	.3333	90	.7
.38	.068	0.80	1.09	31	.3333	90	.7
.80	.200	4.00	1.23	31	.3333	90	.7
.20	.040	8.00	1.80	31	.3333	90	.7

.41	.095	1.90	1.31	31	.3333	90	.7
.46	.034	1.60	1.37	31	.3333	90	.7
.43	.089	1.00	1.23	31	.3333	90	.7
.39	.010	5.90	1.48	31	.3333	90	.7

```

# allowed keywords for substance transport (without "-"chars):
# "radioactive" resp. "non_radioactive"
# "evaporating" resp. "non_evaporating"
# "half_time" with its unit "d"
# "min_conc" and "max_conc"
# measures: "mg/l", "g/l", "kg/kg", "Kg/Kg"; all other units will be interpreted as kg/kg
# (relative concentration)

```

```

# the tracer table consists of long lines which are splitted here in this documentation
# as indicated by the arrows and brackets
#
[substance_transport]
0 # number of tracers to be considered (max. 9)
#
# name radioact. or not half time in days evapor. or not minim. concentr. max.conc. with unit
#3chars if no: -9999 mg/l g/l kg/kg
#-----
180 non_radioactive half_time = -9999 d evaporating min_conc = -9999 max_conc = -9999 kg/kg
NACL non_radioactive half_time = -9999 d non_evaporating min_conc = 0 max_conc = 0.35 kg/kg
3H radioactive half_time = 4493 d evaporating min_conc = 0 max_conc = 3500 kg/kg
#-----
# now the tracer table is continued the first time
#
# initial initial output code writecode output path
# conc. in soil conc. in gr.w statfiles for grids with closing "\"
#-----
soilini = 1.0 gwini = 1.0 statcode = $hour_mean gridcode = $Writegrid path = $outpath
soilini = 0.01 gwini = 0.01 statcode = $hour_mean gridcode = $Writegrid path = $outpath
soilini = 3.0 gwini = 3.0 statcode = $hour_mean gridcode = $Writegrid path = $outpath
#-----
# now the tracer table is continued the second and last time
#
# output extension output extension
# for stat-files for grid files
#-----
statext = $code//$year gridext = $suffix
statext = $code//$year gridext = $suffix
statext = $code//$year gridext = $suffix
#-----

[irrigation_table]
10 # number of following irrigation codes, per row one crop type with its irrigation schedule and parameters
#
#Code name method from control by
# (0=no irr, (1=GW demand: table:
# 1=table, 2=river) psi[m] [mm] [mm]
# 2=series start stop count MM1 DD1 amount1 MM2 DD2 amount2
# 3=demand)
#-----
30 rice00 2 2 3 0.3 starting from 9 20 with 50 mm to 3 9 with 50 mm every 5 days;
31 rice01 2 2 3 0.3 starting from 9 22 with 50 mm to 3 11 with 50 mm every 5 days;
32 rice02 2 2 3 0.3 starting from 9 24 with 50 mm to 3 13 with 50 mm every 5 days;
33 rice03 2 2 3 0.3 starting from 9 26 with 50 mm to 3 15 with 50 mm every 5 days;
34 rice04 2 2 3 0.3 starting from 9 28 with 50 mm to 3 17 with 50 mm every 5 days;
35 grapes 1 2 3 0.3 2 01 01 80 01 15 50
36 pasture 1 2 3 0.3 0
37 barley 1 2 3 0.3 0
38 lucerne 1 2 3 0.3 0
39 corn 3 2 3 0.3 0
#-----
----- end of the WaSiM-control file -----

```

## 6 Example of a control file for Tanalys

Tanalys uses a similarly structured control file like WaSiM-ETH. All informations required for the topographical analysis are contained in this control file. There are sections for each task, enclosed in “[brackets]”. Comments are allowed everywhere if the first character of a row is a “#”. Other comments are allowed behind the parameter entires, but they should also start with a “#”. The command “\$set \$identifier = \$<identifier\_value>” may be used to define at maximum 200 symbols, see also chapter 3.5.1.

The digital elevation model as the origin data source is read in an own section. All other sections require the specifications of the input-grid names. Each section can be disabled by the “ignorance” parameter. If a task is disabled, but it’s results will be needed by another task, the required grids are first looked for at the hard disk. If they are not found, TANALYS stops its execution.

If a new basin should be analyzed by TANALYS it is usually sufficient to change the symbols \$path, \$grid and \$threshold, sometimes also the Manning-roughness parameter \$Manning and the specific discharge for average floods \$specific\_discharge should be changed (section [Flieesszeiten]). Then, all sections should be enabled by setting their ignorance parameters to 1. If TANALYS is started with such a control file, a complete topographical analysis should be performed generating a series of output grids which may be analyzed using GRIDSHAD.

In the section for delineating subbasins ([Einzugsgebiete]), any grids containing pour points may be specified. By default, this are the mouths of rivers of different orders, e.g. of rivers of order 2, 3, 4 and 5. However, if the user would like TANALYS to delineate subbasins for given pour points, e.g. for gauge-coordinates, such grids may also be specified in this section. If all the other grids exists, it is also possible to enable only the section [Einzugsgebiete]. Then, the flow directions and flow times are read from the disk. The pour point grid may also be edited using GRIDEDIT in order to set gauges to well defined grid cells. pour points must be unique and in the range of 1...32767.

TANALYS may require a lot of computer memory, dependent on the size of the grid. At maximum 8 grids are stored in the memory at the same time. If running TANALYS under Windows 95, only 64 MB of main memory and 128 MB Swap-memory can be used. Other systems like UNIX or PC-LINUX have do restrictions, so there should be no theoretical limit for applying TANALYS to digital elevation models of any size.

```
# control file for the topographical analysis of a digital elevation model
# entries staring with a # are comments.
# the file names are looked for internally in a first step before looking on the hard disk

$set $path          = c:\user\schulla\temp\
$set $grid          = r25
$set $threshold     = 64
$set $Manning       = 25
$set $specific_discharge = 200

$set $elevation_model = //$grid//.dhm
$set $stream_network  = //$grid//.lin
$set $Flowdirection   = //$grid//.fld
$set $Flowaccumulation = //$grid//.acc
$set $stream_numbers  = //$grid//.num
$set $stream_orders   = //$grid//.ord

# elevation model is required for almost all modules
[Hoeihenmodell]
1                # ignorance parameter, 0=ignore, 1=read
$path//$elevation_model # file name of the digital elevation model

[Aspect]
1                # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.exp   # result grid aspect

[Gefaelle]
1                # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.slp   # result grid slope angle

[Horizont]
```

```

1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.hor            # result grid horizon overhead angle
12                             # number of sections the circle should be subdivided into to calculate horizon angles

[Profilcurvature]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.prc            # result grid profile curvature

[Plancurvature]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.plc            # result grid plan curvature

[Curvature]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.cur            # result grid total curvature

[Flowdirection]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$Flowdirection          # result grid flow directions
$path//$grid//.sin            # result grid containing the numbered sink areas
$path//$grid//.dhk            # result grid filled elevation model (without sinks)

[Flowaccumulation]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$Flowaccumulation       # result grid flow accumulation
$path//$Flowdirection          # input grid flow direction
$threshold                     # threshold for flow accumulation separate a river

[Flussnetz]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$stream_network         # result grid stream network (without any orders or numbers)
$path//$Flowaccumulation       # input grid flow accumulation
$threshold                     # threshold for flow accumulation separate a river

[Flussordnungen]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$stream_orders          # result grid stream network, separated by Strahler-stream orders
$path//$stream_numbers         # result grid stream network, separated by link identifications (numbers)
$path//$stream_network         # input grid stream network without any orders or link numbers
$path//$Flowdirection          # input grid flow directions

[Fliesskorrektur]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.ork            # result grid, corrected stream orders
$path//$grid//.nuk            # result grid, corrected stream link numbers
$path//$grid//.flk            # result grid, corrected flow directions
$path//$grid//.ack            # result grid, flow accumulation from corrected flow directions
$threshold                     # threshold for flow accumulation separate a river
$path//$elevation_model        # input grid elevation model
$path//$stream_orders          # input grid original (uncorrected) stream orders
$path//$Flowdirection          # input grid original (uncorrected) flow direction
$path//$Flowaccumulation       # input grid original (uncorrected) flow accumulation
$path//$stream_network         # input grid original (uncorrected) stream network
5                               # number of correction steps (min. 2*1st order and 2*2nd order and 1*3rd order)
#                               # stream order for first correction step
2                               # stream order for second correction step
1                               # stream order for third correction step
3                               # and so on until the number of correction steps is reached
1                               # ..

[Fliesszeiten]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.fzt            # result grid flow times (for water crossing single cells)
$path//$grid//.dep            # result grid river depth
$path//$grid//.wit            # result grid river width
$Manning                       # Manning roughness parameter
$specific_discharge            # specific discharge the channels are designed for (by nature!) in l/s/km2
$path//$grid//.dhk            # input grid elevation model
$path//$grid//.slp            # input grid slope grid
$path//$grid//.flk            # input grid flow directions (following water flow paths)
$path//$grid//.ack            # input grid flow accumulation (estimating average catchment area)
$path//$grid//.nuk            # input grid river network (see below also!)

# input grid river network: for generating an enumerated like for river links but containing a table of maxi-
# mum/minimum elevations and subcatchment areas

[Flusseparation]
1                               # ignorance parameter, 0=do not perform, 1=do it
$path//$grid//.m              # result grid mouths, file name is extended by the stream order of the mouths
1                               # minimum stream order subbasin mouths should be extracted of
6                               # maximum stream order subbasin mouths should be extracted of
$path//$grid//.ork            # input grid stream orders (use of corrected orders here)
$path//$grid//.nuk            # input grid stream link numbers (for numbering also the mouths)
$path//$grid//.flk            # input grid flow direction

[Einzugsgebiete]
1                               # ignorance parameter, 0=do not perform, 1=do it
$Manning                       # Manning-roughness parameter in [m1/3]/s
$specific_discharge            # a discharge which is assumed to be the mean 2-year flood (full channels)

```

```

$path// $grid//.dhk      # input grid (filled) elevation model
$path// $grid//.ack      # input grid (corrected) flow accumulations
$path// $grid//.flk      # input grid (corrected) flow directions
$path// $grid//.fzt      # input grid flow times (for single cells)
4                        # number of following pour point grids
$path// $grid//.m02      # pour point grid 1
$path// $grid//.e02      # result grid subbasins for pour point grid 1
$path// $grid//.zs2      # result grid flow time sums for pour point grid 1
$path// $grid//.ln2      # result grid routing channels according to pour point grid 1
$path// $grid//stru.kt2  # drainage structure for pour point grid 1 as text file for (for WaSiM control file)
$path// $grid//.m03      # pour point grid 2
$path// $grid//.e03      # result grid subbasins for pour point grid 2
$path// $grid//.zs3      # result grid flow time sums for pour point grid 2
$path// $grid//.ln3      # result grid routing channels according to pour point grid 2
$path// $grid//stru.kt3  # drainage structure for pour point grid 2 as text file for (for WaSiM control file)
$path// $grid//.m04      # pour point grid 3
$path// $grid//.e04      # result grid subbasins for pour point grid 3
$path// $grid//.zs4      # result grid flow time sums for pour point grid 3
$path// $grid//.ln4      # result grid routing channels according to pour point grid 3
$path// $grid//stru.kt4  # drainage structure for pour point grid 3 as text file for (for WaSiM control file)
$path// $grid//.m05      # pour point grid 4
$path// $grid//.e05      # result grid subbasins for pour point grid 4
$path// $grid//.zs5      # result grid flow time sums for pour point grid 4
$path// $grid//.ln5      # result grid routing channels according to pour point grid 4
$path// $grid//stru.kt5  # drainage structure for pour point grid 4 as text file for (for WaSiM control file)

```





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## 8 Error codes of the model

return codes of WaSiM-ETH version 1 with TOPMODEL-approach resp. version 2 with RICHARDS-equation, if the programs are cancelled by an error or by user break via Cntr-C.

- 1 not enough memory (error allocating memory)
- 2 no control file given
- 3 zone codes too less (<1) or too large (>32768)
- 4 too much zones (>8192)
- 5 error opening log-file
- 6 all cells are nodata in the flow travel time grid
- 7 all cells are nodata in the zone grid
- 8 row index for point-statistic-files is larger than number of rows in the grid
- 9 column index for point-statistic-files is not in the range of valid values
- 10 error reading parameters for unsaturated zone module
- 11 error closing control file
- 12 not enough space for new grids in the "gridinfo"-array
- 13 number of levels in a stack read in from disk doesn't match the number of levels according to the soil table
- 14 theta-value < 0
- 15 error opening a statistics file
- 16 error closing a statistics file
- 17 parameter not found in control file
- 18 write error (writing binary grid)
- 19 read error (reading binary grids)
- 20 memory allocation error (like 1)
- 21 error opening grid
- 22 error reading grid
- 23 error closing grid
- 24 error in grid measures (coordinates of lower left cell or number of rows/columns or cell size)
- 25 too big area with nodata-values within grid, which should not be nodata according to the zone grid
- 26 error opening grid (like 21)
- 27 error closing grid (like 22)
- 28 error opening control file
- 29 error in landuse table
- 30 error in soil table
- 31 wrong land use code
- 32 wrong soil type code
- 33 grid not found in memory (from a module during initialization)
- 34 paragraph not found in control file
- 35 error reading a routing description
- 36 error comparing routing date with date from the external inflow file
- 37 error opening file for reservoir content or external abstraction
- 38 end of control file reached unexpected
- 39 error reading from external inflow file
- 40 string is too long (reading a file)
- 41 wrong subbasin code
- 42 other error in routing module
- 43 discharge not found in memory during initialization of the routing module
- 44 time step too short (e.g. for Hamon-evaporation time step must be larger than 1 day)

- 45 too less correction factors for Hamon-evaporation
- 46 data requirements not satisfied for evapotranspiration
- 47 infiltration module can only be started, if soil model is also active
- 48 error reading scenario data for meteo-inputs
- 49 error opening meteorological input data file
- 50 error closing met. input file
- 51 starting date not found in met. input file
- 52 wrong date in met. input file
- 53 wrong interpolation method given in control file
- 54 wrong interpolation parameters
- 55 floating point error soil model (only in debug-versions)
- 56 error reading tracer parameters
- 57 discharge not initialized (only debug versions)
- 58 more than 9 tracers described in the control file
- 59 two ore more tracers have the same name (first 3 chars)
- 60 no routing is done, but irrigation is active (activate both, irrigation and routing)
- 61 error in flow travel time grid: the first time zone has no cells in one of the subbasins  
(this may happen, if the derivation of the travel flow time grid was based on an different sub-basin grid than the one that is actually used for the modeling)
- 62..97 reserved
- 98 program cancelled by Ctrl-C (option: 2 no writing of buffers and grids)
- 99 program cancelled by Ctrl-C (option: 1, writing all buffers and grids)

## 9 Model extensions and upgrades

This chapter contains the documentation of the latest model extensions. Newly developed model components should be documented here in order to avoid trouble in numbering equations, figures and tables. The original text should only be extended by foot notes pointing to this chapter.

### 9.1 Glacier model

(documented on January 26, 1999 by Jörg Schulla; implemented on January 11)

WaSiM-ETH was extended by a glacier melt model which describes the melt of firn, ice and snow on glaciers as well as the routing of the glacier discharge within the glacier. The module is fully integrated in the snow model and it can be used with both model versions (TOPMODEL and RICHARDS-approach).

To enable the glacier module, an additional standard grid, the so called glacier grid, has to be read in. It codes the cells which are covered by glaciers with the codes 1 for ice and 2 for firn, respectively. Further it is required that glaciers are defined in the subbasin grid as separate subcatchments. Thereby, it is not necessary that each small glacier must be a separate subbasin, it would also be possible to put all glaciers together into one or only a few subbasins (glacier subbasins do not have to be closed areas). However, it is required that the glacier subbasins as defined in the subbasin grid contain no other landuse than firn or ice and that both, firn and ice, are present only in glacier subbasins, thus the glacier subbasins are exclusive for the glacier melt model. This must hold because of the internal model branching since all of the following submodels are skipped for glacierized cells:

- interception
- soil model (RICHARDS-approach or TOPMODEL-approach)
- irrigation control
- real evaporation
- groundwater flow
- solute and tracer transport in all of the above mentioned modules

Only the discharge routing re-unites the data streams again, because discharges of glacier subbasins are routed like any other discharges. A section “[ice\_firn]” was inserted in the control file containing all melt and routing parameters and file names for the glacier model. In addition to the statistic output file and the grid for the snow melt, there will be also grids and statistic files for melt of ice and firn. A fourth statistic file contains the total glacier melt. This last statistic file contains the already internally routed and superposed discharges, whereas the snow, firn and ice melt statistic files contain the areal averaged melt rates for each time steps without reservoir effects. All of these statistic files contain data columns for each subbasins, even if there are no glaciers, in which last case the data are only zero for firn and ice melt.

*melt of firn and ice:*

There are two methods for calculating glacier melt: a classical temperature index method and an extended temperature index method after HOCK (1998) including information on the global radiation during each time step on each grid cell in order to modify the melt. The melt after the classical temperature index approach is calculated by:

$$M = \begin{cases} \frac{1}{n} DDF_{snow / firn / ice} \cdot (T - T_0) & : T > T_0 \\ 0 & : T \leq T_0 \end{cases} \quad (9.1.1)$$

with  $M$  melt [mm/time step]  
 $n$  number of time steps per day [ $\text{day}^{-1}$ ]  
 $DDF$  3 degree-day-factors for snow, firn and ice, respectively [ $\text{mm} \cdot ^\circ\text{C}^{-1} \cdot \text{day}^{-1}$ ]  
 $T$  air temperature in a standard elevation of 2 m [ $^\circ\text{C}$ ]

$T_0$  threshold temperature for melt

The melt is calculated for snow, firn, and ice separately using specific parameters. If a glacier cell, which is recognized by the codes 1 or 2 in the ice\_firn-grid, is covered with snow, the melt calculation is done using the parameters  $DDF_{snow}$  and no firn or ice melt is calculated. If the cell is not covered by snow, then the melt calculation is done using the parameters according to the cell code:  $DDF_{ice}$  for ice cells (code 1) or  $DDF_{firn}$  for firn cells (code 2). Usually the relation  $DDF_{ice} > DDF_{firn} > DDF_{snow}$  holds. All three parameters are constant in space and time for the entire model run. The parameter values are ranging between 2 ... 10 mm·°C<sup>-1</sup>·day<sup>-1</sup>.

Using the extended melt approach after HOCK (1998), the melt of snow, firn, and ice is calculated by:

$$M = \begin{cases} \left( \frac{1}{n} MF + \alpha_{snow/firn/ice} \cdot I_0 \cdot \frac{G_s}{I_s} \right) \cdot (T - T_0) & : T > T_0 \\ 0 & : T \leq T_0 \end{cases} \quad (9.1.2)$$

with	$M$	melt [mm/time step]
	$n$	number of time steps per day [day <sup>-1</sup> ]
	$MF$	melt factor with identical values for snow, firn and ice (around 2 mm·°C <sup>-1</sup> ·day <sup>-1</sup> )
	$\alpha$	empirical coefficients for snow and firn (identical, app. 0.002) and for ice (around 0.001) [mm·Wh <sup>-1</sup> ·m <sup>2</sup> ·°C <sup>-1</sup> ·day <sup>-1</sup> ]
	$I_0$	potential direct incoming shortwave radiation (visible incoming sun radiation) for each grid cell (depends on shading, aspect and slope angle, time and season, but not on cloudiness) [Wh·m <sup>-2</sup> ]
	$I_s$	like $I_0$ , but for the well defined location of a meteorological station [Wh·m <sup>-2</sup> ]
	$G_s$	observed radiation at the same station [Wh·m <sup>-2</sup> ]
	$T$	air temperature in a standard elevation of 2 m [°C]
	$T_0$	threshold temperature for melt

The correction of the melt factor is done using the relation of the observed global radiation at a meteorological station and the theoretical potential global radiation at the same location. This relation represents the effects of cloudiness and topographic shading, multiplied with the potential radiation  $I_0$  on the actual cell this measure represents the local real global radiation. Since WaSiM-ETH uses global radiation interpolated from non-shaded stations and since the WaSiM-ETH performs already a radiation correction considering the local topography as well as shading, the term  $I_0 \cdot G_s / I_s$  is replaced internally by the interpolated global radiation, corrected after equations (13) and (15), respectively. The actual correction is done in the evaporation module. However, for using this melt model approach, it is necessary to enable the radiation correction and to use PENMEN-MONTEITH or WENDLING evaporation in order to get corrected radiation. Also it is recommended not to use net radiation instead of global radiation. If no radiation correction and shading is done, no variations in the melt pattern will be recognizable since only the interpolated radiation is used for scaling the melt. The model stops its execution if no radiation is found during the initialization.

The parameters  $\alpha_{ice}$ ,  $\alpha_{firn}$ , and  $\alpha_{snow}$  are becoming smaller in this order and range between 10<sup>-4</sup> ... 5·10<sup>-3</sup> mm·Wh<sup>-1</sup>·m<sup>2</sup>·°C<sup>-1</sup>·day<sup>-1</sup>. The radiation is given in Wh·m<sup>2</sup> scaling the small  $\alpha$ -values to the order of reasonable degree day factors. Since the product of  $\alpha$  and interpolated global the radiation is added to the melt factor  $MF$ , the last one is smaller than the degree day factors for a classical temperature index approach after equation (9.1.1) and ranges around 2 mm·°C<sup>-1</sup>·day<sup>-1</sup>.

If a glaciated cell is coded as firn but covered with snow, the melt was calculated using the parameters for snow. However, since this snow melt flows directly into the firn layer and since the reservoir effects of firn are so much larger than the reservoir effects of snow, the melt of snow on firn cells is handled like melt of firn.

### *routing of the different melt components through the glacier*

For glacierized subbasins there are three runoff components calculated after equations (9.1.1) and (9.1.2), respectively. These components are now superposed and routed to the subbasin outlet using a set of parallel single linear reservoirs.

The total runoff from a glacier subbasin is given by:

$$Q(t) = \sum_{i=1}^3 \left( Q_i(t-1) \cdot e^{-\frac{1}{k_i}} + R_i(t) \cdot (1 - e^{-\frac{1}{k_i}}) \right) \quad (9.1.3)$$

with  $Q(t)$  total runoff during time step  $t$  [mm/time step]  
 $i$  reservoir index (1 reservoir for snow melt, 1 for firn melt and 1 for ice melt)  
 $Q_i(t-1)$  outflow of reservoir  $i$  during the last time step  $t-1$  [mm/time step]  
 $R_i(t)$  input into reservoir  $i$  in the actual time step  $t$ , this equals the sum of melt and additional rain [mm/time step]  
 $k_i$  storage coefficient (recession constant) for reservoir  $i$

Equation (9.1.3) describes the superposition of three parallel reservoirs 1... $i$  ( $i=3$ ), each of which has specific storage coefficients  $k_i$  and inflow rates  $R_i$ , representing the areal means of the three melt components. The storage coefficients for ice, snow and firn range in this order with values for  $k_{firn}$  of around 100 to 1000, for  $k_{snow}$  of 10 to 100, and for  $k_{ice}$  of 1 to 10 hours.

For the calibration of the model it is important to initialize the three parallel reservoirs with matching initial values. If the calibration starts at a state when the total glacier is frozen, e.g. in January, then only the firn reservoir must be initialized with a small initial outflow, the other two reservoirs may be initialized with zero.

The total runoff from the glacier subbasins is handled in the discharge routing module like the runoff of any other subbasin. Thus, WaSiM-ETH can be applied also to very large basins ranging from glacierized high mountains down to low land regions with important groundwater reservoirs, lakes and irrigation impacts.

The control file must contain a section named [ice\_firn], if an ice\_firn-grid is given as a standard grid:

```
[standard grids]
0          # number of standard grids
# path     # identification # fillcode 0=no, 1=yes (fill with values of nearest neighbor)
$inpath//$ice_firn_grid      ice_firn      0 # grid with firn or ice cells
...
...

[ice_firn]
2          # method for glacier melt: 1=classical t-index, 2=t-index with correction by radiation
5          # t-index factor for ice
4          # t-index factor for firn
3          # t-index factor for snow
2          # melt factor
.001       # radiation coefficient for ice (for method 2)
.002       # radiation coefficient for snow (for method 2)
3          # els-konstante for ice
300        # els-konstante for firn
30         # els-konstante for snow
1          # initial reservoir content for ice discharge (single linear storage approach)
1          # initial reservoir content for firn discharge (single linear storage approach)
1          # initial reservoir content for snow discharge (single linear storage approach)
$outpath//$firn_melt # melt from firn
$writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//qfir//$grid//.$code//year $hour mean # melt from firn as statistic file
$outpath//$ice_melt # melt from ice
$writegrid # 0, if no grid-output is needed, else one of the codes described above
$outpath//qice//$grid//.$code//year $hour mean # melt from ice as statistic file
$outpath//qglc//$grid//.$code//year $hour mean # melt from ice and firn as statistic file
...
```

## 9.2 Extensions for coupling WaSiM-ETH to Climate Models and for modeling large regions

The model extensions described below were documented at March 27, 1999 and implemented between March 19, 1999 and March 26, 1999 by J. Schulla. They are dealing with the capability of WaSiM-ETH to handle climatologically inhomogeneous large to very large regions (e.g. up to some 100.000 km<sup>2</sup> or more) in a single model run by extending the interpolation methods. Also the coupling of WaSiM-ETH with climate model results is now possible as a one-way-coupling by using the newly implemented bilinear interpolation method in conjunction with monthly scaling grids in order to get more spatially detailed downscaling information.

### 9.2.1 Using multiple regression parameter sets for multiple regions

If the model area is too large or, e.g. due to mountain ridges like the Alps within the model domain, meteorologically too inhomogeneous to use only one regression parameter set for each meteorologic variable, the model area may now be subdivided into regions. Actually, up to 30 regions are allowed. This maximum number can be increased simply by changing a compiler constant in the „modconst.h“ header file, but 30 regions should be enough for almost all applications.

The regions are given as a grid according to the same geometry as the zone grid (same numbers of rows and columns, same cellsize, nodata value, lower left x- and y-coordinates). Each region is identified by a unique code. The codes should be integer numbers of any order, no ranking is required, gaps are allowed (e.g. if using codes 4, 1 and 8 following any special notation).

The regions are technically totally independent on the zones, except for the fact, that each valid grid cell of the zone grid must belong to one of the regions. Zones are used for the statistic output of the model results whereas regions are used for selecting the matching regression parameter set. Regions take only effect when regression interpolation methods are used. Near the borders between the regions the model produces a smooth transition by weighing the regression interpolation results of up to three regions dependent on the distances of the actual cell to the respective regions.

If there are multiple regions defined, the model performs the following tasks:

Tasks at initialization:

- Reading the region grid (the identification string for the region grid in the control file has to be „`regression_regions`“ in lower cases without quotes).
- Reading the transition distance, i.e. the maximum distance of a cell to any regions border to be affected also by the neighboring region(s). This parameter is given in meters in the new section [region\_transition\_distance] of the control file.
- Generating a REGION2- and a REGION3-grid. The REGION2 grid contains for each grid cell the region code of the second region the cell is affected by. If the grid cell is not within the maximum transition distance from any region border, then the REGION2 grid contains a zero-value in the matching location. In Analogy to REGION2, the REGION3 grid contains the codes of the third region the cell is affected by, also only if there is a third affecting region at all. The REGION2 and REGION3 grids are written into the directory the region grid was read from with the file extensions „`$r2`“ and „`$r3`“, respectively.
- Generating a WEIGHT1, WEIGHT2 and WEIGHT3-grid containing the weights the respective regions have for the interpolation result. When doing the interpolation, for each grid cell the up to three region grids are checked. If the matching positions contain codes greater than zero, the actual result is scaled with the weight of the according WEIGHT<n> grid. The weights are calculated after the following scheme. If a cell in row  $i$  and column  $j$  is affected by only one region (coded in the grid RE-



GION1), the weights are  $WEIGHT1_{ij} = 1.0$ ,  $WEIGHT2_{ij} = 0$  and  $WEIGHT3_{ij} = 0$  for the regions indexed in the matching grids  $REGION1_{ij}$ ,  $REGION2_{ij}$ , and  $REGION3_{ij}$ , respectively.

*region weights for cells affected by two regions*

Weights for cells affected by two regions are calculated using a linear transition starting with a weight of 1.0 if the cell is at the maximum transition distance from the region border and decreasing to 0.5 if the cell is directly at the border. This weight is stored in  $WEIGHT1_{ij}$ , the weight of the neighboring regions regression result is then simply  $WEIGHT2_{ij} = 1.0 - WEIGHT1_{ij}$ .

$$\begin{aligned} w1_{i,j} &= 0.5 + 0.5 \cdot d / r \\ w2_{i,j} &= 1.0 - w1_{i,j} \end{aligned} \quad \begin{array}{l} \text{(if only 2 regions affect the actual cell)} \\ \end{array} \quad (9.2.1)$$

with  $w1_{i,j}$  weight of the regression result using the parameters for the region the cell belongs to  
 $w2_{i,j}$  weight of the regression result using the parameters for the second region the actual cell is affected by  
 $d$  distance of the actual cell to the region border [m]  
 $r$  maximum distance to be considered for smooth transitions, specified in the control file in the section [region\_transition\_distance], unit [m]

*region weights for cells affected by three or more regions*

If a cell is affected by three or more regions, only the three nearest regions are used for calculating weights. The scetch in figure 9.2.1 illustrates the calculation of weights. The maximum distance from any region border a point must have to be not influenced by another region is the radius  $r$ .

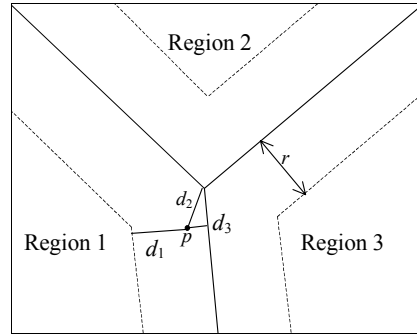


figure 9.2.1: Weighting of multiple regions for a point  $p$  near the regions crossing point

If the interpolation point is only affected by one neighboring region, the above formula (9.2.1) is applied. Only if the crossing point of three regions is within the distance  $r$  around the interpolation point, two neighboring regions are considered for calculating the weights. The weights are calculated by a modified inverse distance weighting scheme. The following constraints must hold:

- (1) Regardless of the shape of the region borders, a point at the crossing point of three regions have to have a weight of  $1/3$ .
- (2) The weight of a region decreases with increasing distance  $d$  of the point to that region until it reaches the value of 0.0 at the distance  $d = r$ .
- (3) The rate of increase of the weights should be linearly related to the decreasing distance to the nearest region in order to match the linear transition of weights between two regions at the outer limit of the three-region-affected area.
- (4) The sum of all three weights must be 1.0.

In a first step the distances  $d_2$  and  $d_3$  are extended by  $r$  in order to satisfy condition (1) resulting in:

$$\begin{aligned}
u_1 &= d_1 \\
u_2 &= r + d_2 \\
u_3 &= r + d_3
\end{aligned} \tag{9.2.2}$$

If  $d_2 = d_3 = 0$ , then  $u_1 = u_2 = u_3 = r$  resulting in equal weights of  $1/3$  for all regions. To satisfy conditions (2) and (3), the inverted distances  $u_1$  to  $u_3$  are modified in the following way:

$$\begin{aligned}
x_1 &= \frac{1}{u_1} - c \cdot \frac{1}{2r} \\
x_2 &= \frac{1}{u_2} - c \cdot \frac{1}{2r} \\
x_3 &= \frac{1}{u_3} - c \cdot \frac{1}{2r}
\end{aligned} \tag{9.2.3}$$

with  $x_1 \dots x_3$  modified inverse distances from the interpolation point to the three regions of interest  
 $u_1 \dots u_3$  distances  $d_1$  to  $d_3$  to the three regions after figure 9.2.1, extended by  $r$  after equation (9.2.2).  
 $r$  maximum distance of the interpolation point to another region to be affected by this region  
 $c$  correction factor for modifying the inverse distances

The correction factor  $c$  depends on the minimum distance of the interpolation point to any regions interior area (usually of region 1) and is responsible for satisfying condition (3). It is estimated after:

$$c = 0.9 - \frac{1}{2} \cdot \cos\left(\frac{\pi}{2} \cdot \frac{\min(u_1, u_2, u_3)}{r}\right) \tag{9.2.4}$$

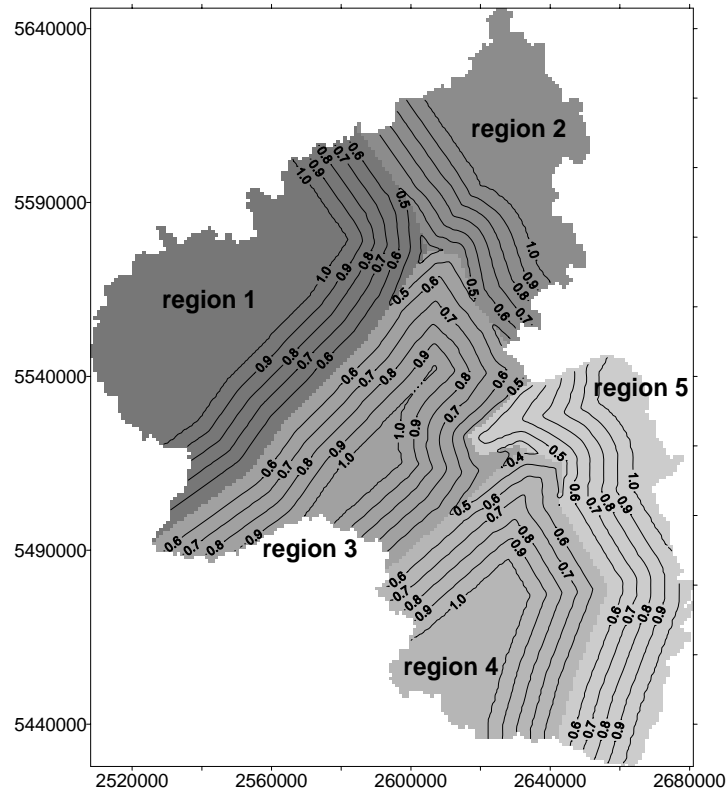


figure 9.2.2: Weighting of the actual region if using multiple regions. Rheinland-Pfalz, Germany, 5 regions, maximum transition distance  $r$  was set to 20 km.

The weights of the regions are then calculated by the usual inverse distance weighting scheme:

$$w_i = \frac{1}{d_i} \cdot \frac{1}{\sum_{i=1}^3 d_i} \quad (i=1..3) \quad (9.2.5)$$

with  $w_i$  weighting of the regions 1...3 for the modified inverse distance interpolation

Figure 9.2.2 shows the weights for the regression parameter sets of the regions 1 to 5 for cells which belong to the respective regions. Such weighting grids are also generated for the second and third region affecting the actual regions. The sum of all three weighting grids is 1.0 for all valid region cells.

Tasks at interpolation:

- Each time the interpolation is done, the region grids REGION1<sub>ij</sub>, REGION2<sub>ij</sub>, and REGION3<sub>ij</sub> are checked for entries unequal to zero for each location *ij*. Region grid REGION1 must contain valid entries for each grid cell which is valid in the zone grid, whereas the other region grids contain only valid entries, if the cell is affected by other regions when its location is within the maximum transition distance between two or more regions *r*.
- calculating the regression results using the parameter sets of the at maximum 3 affecting regions:

$$\begin{aligned} z_1 &= f(z, a_1, b_1, af_1, bf_{x,1}, bf_{y,1}) \\ z_2 &= f(z, a_2, b_2, af_2, bf_{x,2}, bf_{y,2}) \\ z_3 &= f(z, a_3, b_3, af_3, bf_{x,3}, bf_{y,3}) \end{aligned} \quad (9.2.6)$$

with  $z_1...z_3$  regression results using parameter sets for regions 1 to 3  
 $a_i, b_i$  parameters for altitudinal regressions ( $i = 1...3$ ) for regions 1 to 3  
 $af_i, bf_{x,i}, bf_{y,i}$  parameters for areal fit of the residuals ( $i = 1...3$ ) for region 1 to 3

The regressions are done following the descriptions in chapter 1.2, equations (2) and (3).

- combining the results by using the region weights for the actual location:

$$z = w_1 z_1 + w_2 z_2 + w_3 z_3 \quad (9.2.7)$$

with  $z$  weighted result of altitude dependend regression for the actual location  
 $z_1...z_3$  results of the altitude dependend regressions for the three regions affecting the actual location  
 $w_1...w_3$  weights for the three regions after equation (9.2.5)

*Changes in the control file:*

Some changes respectively some new entries have to be made in the control file in order to use the new capabilities of using multiple regions:

- The region grid must be read in as a standard grid, it may have any file name, but the identification string must be *regression\_regions*, the fill parameter must be 1:

```
[standard grids]
...
$inpath//$grid.reg      regression_regions      1      # regression regions
...
```

- The section [region\_transition\_distance] must be created in the control file containing the maximum distance, a cell can be located from any other region to be affected by this other region:

```
[region transition distance]
10000      # maximum transition distance in meter
```

- The sections for the meteorological interpolators MUST contain as many regression parameter file names as there are regions, even if the interpolation method is not 2 or 3:

```
[temperature]
2 # 1=idw, 2=regress, 3=idw+regress, 4=Thiessen 5=bilinear
$inpath//tempe//$year//a.dat # file name with station data (for method 1)
$inpath//temper1.reg # file name with regression data for region 1
$inpath//temper2.reg # file name with regression data for region 2
$inpath//temper3.reg # file name with regression data for region 3
$inpath//temper4.reg # file name with regression data for region 4
$inpath//temper5.reg # file name with regression data for region 5
$outpath//$tempegrid # output grid
$writegrid # writecode for result grids
1.0 # correction faktor for results
$outpath//temp//$grid//.$code//$year $hour mean # statistic output
# error value
...
```

If the number of regions in the region grid is changed or if the region grid is removed from the standard grid section, the number of file names must be changed also. If no region grid is given, then only one regression parameter file name is allowed there!

### 9.2.2 Using bilinear interpolation for one-way-coupling with climate model results

Bilinear interpolation is particularly useful for downscaling meteorological input data which are already gridded, e.g. in case of using outputs of global circulation models (GCM) or weather models to drive WaSiM-ETH. However, the gridded input data are not read in as grids but as usual station data files as described in chapter 3.2.2, representing the GCM grid cells by separate columns which contain the “station” coordinates ( $x, y, z$ ) in the header and one date per row for each model time step. Bilinear interpolation can also be used for usual climate station files, if the station positions are very close to a regular grid.

Whilst usual bilinear interpolation requires the input data in a regular grid with equal spaces between the grid nodes all over the grid covering the entire interpolation area, this constraint was slightly liberated in WaSiM-ETH: At initialization, for each grid cell the next input station is looked for in each of the four quadrants. The station indexes are stored in four internal index-grids to speed up the later interpolation by avoiding wasting time by searching the stations again and again in every time step. By looking for the four nearest stations in the respective quadrants, the stations does not have to be arranged in a grid order at all. However, the bilinear interpolation assumes a more or less regular order, otherwise the interpolation results may show abrupt steps – but in principal it is possible to use any pattern of stations for this interpolation scheme. This liberation is also reasonable since GCM results are usually not given in regular grids but in latitude/longitude resolutions which depend on the geographical location within the grid. If a station does not have four stations for interpolation available, i.e. if there is no station in at least one of the four quadrants or the actual data value is a nodata value, the interpolation method used for this cell is switched automatically to inverse distance weighting interpolation.

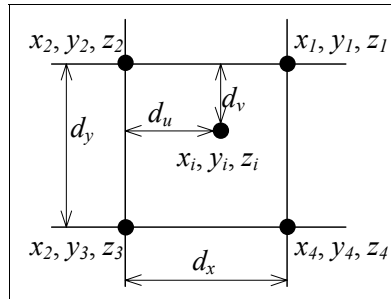


figure 9.2.3: scheme of calculating weights of points 1, 2, 3, and 4 for bilinear interpolation to point  $i,j$

Figure 9.2.3 shows the scheme of calculating the weights for the interpolation location  $i,j$ . The weights are given by:

$$u = \frac{d_u}{d_x} = \frac{x_i - x_2}{x_1 - x_2} \quad \text{and} \quad v = \frac{d_v}{d_y} = \frac{y_i - y_2}{y_3 - y_2} \quad (9.2.8)$$

with  $u$  weight of data of stations 1 and 4 (first and fourth quadrant) in  $x$ -direction  
 $v$  weight of data of stations 3 and 4 (third and fourth quadrant) in  $y$ -direction  
 $d_u$  distance of the interpolation location from  $x_2$  in  $x$ -direction  
 $d_v$  distance of the interpolation location from  $y_2$  in  $y$ -direction  
 $x_1, x_2$   $x$ -coordinates of „stations“ 1 and 2 (in quadrants 1 and 2, resp.)  
 $y_2, y_3$   $y$ -coordinates of „stations“ 2 and 3 (in quadrants 2 and 3, resp.)

The interpolation result is then calculated by:

$$z_{i,j} = u \cdot (1 - v) \cdot z_1 + (1 - u) \cdot (1 - v) \cdot z_2 + (1 - u) \cdot v \cdot z_3 + u \cdot v \cdot z_4 \quad (9.2.9)$$

To tell WaSiM-ETH that bilinear interpolation should be used, simply the interpolation method has to be changed to 5 in the interpolation section of the respective climate variable.

### 9.2.3 Using a linear combination of bilinearly interpolated gradients and residuals

When interpolating e.g. the temperature or other altitude dependent variables, it may be important to consider small scale local variations in the digital elevation model. Therefore, another interpolation was introduced into WaSiM-ETH, the so called **BIGRES**-method (**B**ilinear **I**nterpolation of **G**radients and **R**ESiduals). In fact, it is a linear combination of two independently performed bilinear interpolations, the first one interpolating the gradients, the second one interpolating the residuals. Both input data have to be read in as usual „station“-files, i.e., the gradients and residuals have to be calculated externally.

The results of both interpolations are then linearly combined using the digital elevation model as scaling parameter for the gradients and the residuals as offset:

$$z_{i,j} = z r_{i,j} + h_{i,j} \cdot z g_{i,j} \quad (9.2.10)$$

with  $z_{i,j}$  result of the linear combination  
 $z r_{i,j}$  result of the bilinear interpolation of the residuals (after 9.2.9)  
 $z g_{i,j}$  result of the bilinear interpolation of the gradients (after 9.2.9)  
 $h_{i,j}$  elevation from the digital elevation model [m]

To use this interpolation method, the method parameter in the interpolation section has to be set to 7. The residuals are given as the first file (the usual station file name). Then, and this is important, the 2<sup>nd</sup> filename for the gradients follows as an additional filename. The filename(s) of the regression file(s) must appear as usual! The following example shows a sample sequence from a control file using this interpolation method:

```
[temperature]
7                               # Methode 1=idw, 2=regress, 3=idw+regress, 4=Thiessen
$inpath//t_0_100.asc AdditionalColumns=0 # residuals (if method = 1, 3 or 4, else ignored)
$inpath//grad100.asc AdditionalColumns=0 # gradients (if method !=6: comment it out!!!!)
$inpath//temper//$year//.out # file name with regression data (if method = 2 or 3)
$outpath//$tempegrid # name of the output grid
52 //$Writegrid # 0, if no grid-output is needed,
1 # correction faktor for results
.
.
.
```

### 9.2.4 Bicubic spline interpolation

As an extension to the bilinear interpolation, also bicubic spline interpolation is applicable. The required input data are the same as for bilinear interpolation. The interpolation is done in three steps:

1. The stations are automatically organized in a grid-like structure (like for bilinear interpolation) including a virtual rotation of the domain
2. The north-south-meridians are spline-interpolated to the required density of information
3. An east-west-interpolation is done using the interpolated data of the meridians

To use this interpolation-method, the control file must be manipulated as shown for bilinear interpolation, except that the interpolation code is 7.

It's also possible to use a combination of bicubic-spline-interpolated residuals and gradients, like for bilinear interpolation. The application is also identical like those, except that the interpolation code is 8 instead of 6.

The application of bicubic spline interpolation generally gives smoother surfaces, but it may happen, that unexpected results are shown: Since the interpolation makes a smooth curve ist possible, that minimum or maximum values exceed the value ranges of an entity. In this case the maximum and minimum parameter has to be set to proper values (e.g. for precipitation the minimum has to be set to 0, for humidity the minimum has to be set to 0, the maximum to 1).

### 9.2.5 Applying monthly scenario grids

When WaSiM-ETH is driven by results of GCM's which are interpolated using bilinear interpolation it may be advantageous to consider known small scale variability by scaling the interpolation results by a spatially varying factor. Thus, the known variability of e.g. monthly rainfall, or sunshine duration, or radiation a.s.o. can be layed over the rather smooth interpolation results. Since there was already a possibility in WaSiM-ETH to scale the interpolation results by monthly scenarios for given locations, and since the consideration of scaling grids can be seen as a more detailed way of applying scenarios, the declaration of scenario grids is consequently done in the control file sections for interpolating meteorological data:

```
[temperature]
...
$IDWweight      # weighting of the reciprocal distance for IDW
0.1              # for method 3: relative weight of IDW-on the result
$IDWmaxdist     # max. distance of stations to the actual interpolation cell
$Anisoslope     # slope of main axis of the anisotropy-ellipse...
$Anisotropie    # axis ratio of the anisotropy-ellipse
-40              # lower limit of interpolation results
-40              # replace value for results below the lower limit
40              # upper limit for interpolation results
40              # replace value for results above the upper limit
1               # 1=use scenario data, 0=dont use scenarios
5               # 1=add, 2=multiply, 3=percentual change, 5=monthly scaling grids
$inpath//scalegrd.01 # scaling grid for small scale variability month 1
$inpath//scalegrd.02 # scaling grid for small scale variability month 2
$inpath//scalegrd.03 # scaling grid for small scale variability month 3
$inpath//scalegrd.04 # scaling grid for small scale variability month 4
$inpath//scalegrd.05 # scaling grid for small scale variability month 5
$inpath//scalegrd.06 # scaling grid for small scale variability month 6
$inpath//scalegrd.07 # scaling grid for small scale variability month 7
$inpath//scalegrd.08 # scaling grid for small scale variability month 8
$inpath//scalegrd.09 # scaling grid for small scale variability month 9
$inpath//scalegrd.10 # scaling grid for small scale variability month 10
$inpath//scalegrd.11 # scaling grid for small scale variability month 11
$inpath//scalegrd.12 # scaling grid for small scale variability month 12
0                 # number of scenario cells
```

For each month, a scaling grid has to be specified. The grids are sequentially read in during the model run each time when a new month starts. Until now, there is no temporal interpolation between different grids respectively between different months, so abrupt changes in the scenario grid will cause also abrupt changes in the temporal course of the scaled interpolation results.

### 9.2.6 Using variable cell sizes

- Relative cell area grid **rca** may be given, if not is is generated from **csx** and **csy**. If these grids are not given, too, it is generated containing in all cells the value 1.0
- grid of cellsize in x direction **csx**: It may be given together with the **rca** grid and the **csy** grid. It contains the absolute cell size in x direction in m for each cell. In case of given **csx** and **csy** files, **rca** is

checked - or generated, if not given, using the default cell size given in the zone grid to calculate the relative area by  $csx*csy/cellsz$

- grid of cell size in y direction **csy**: the same like for **csx** but in y-direction.
- grid with x coordinates of cells **cx**: This grid is generated during model initialization. It considers the different cell sizes, using the left and the bottom edge of the grid as orientation (assuming South-North-direction for the left edge and West-East-direction for the bottom edge)
- grid with y coordinates of cells **cy**: See above under **cx**-grid
- generation of these grids -> **rca** and **csx** and **csy**, or **rca** and one of **csx** or **csy**, or only **rca** or only one of **csx** or **csy** or none of these grids (then no variable cell size is assumed): If only one of **csx** or **csy** is read in and no **rca** is given, then the relative cell size is estimated using the standard cell size and the value given in **csx** or **csy**, resp.
- changes in the control file: read in as standard grid: **rca**-grid and/or one of **csx**/**csy** or both.
- using rotated coordinates in meteorological interpolations. All coordinate dependend functions have been updated to use the real coordinates. This is in particular done for the interpolation methods IDW, THIESSEN, Bilinear Interpolation and BIGRES.
- the control file should be changed in the following way (only those grids must appear as standard grids, which are really there, mostly recommended is the **csx** and **csy** - combination

```
[standard grids]
0          # number of standard grids
# path      # identification # fillcode 0=no, 1=yes (fill with values of nearest neighbor)
$inpath//RelCellArea grid      RelCellArea  1 # grid with relative cell area
$inpath//CellSizeX grid        CellSizeX    1 # grid with cellsize in x-direction (in meter)
$inpath//CellSizeY grid        CellSizeY    1 # grid with cellsize in y-direction (in meter)
...
...
```

### 9.2.7 Tolerating additional columns in meteorological input files

Additional columns in the meteorological input files may appear after the four columns for the date (YYYY, MM, DD, HH). The reasons for the existence of such columns may be, that the input file is generated as an output of a GCM. Such additional columns must be specified in the following way. In the control file each input file is specified with its name. If a clause like "AdditionalColumns=2" follows this filename, then two additional columns are expected. There are no spaces or tabs allowed before or after the equal-sign.

Example:

```
[temperature]
2          # Methode 1=idw, 2=regress, 3=idw+regress, 4=Thiessen
$inpath//tempe//$year//a.dat AdditionalColumns=2 # station data and # of add. columns
$inpath//temper//$year//.out # file name with regression data (if method = 2 or 3)
```

The given number of additional columns will be neglected in each row of the input file. They **MUST** appear in each row after the 4 date-columns.

## 9.3 The storage content file

When WaSiM-ETH is applied in a series of model runs which should match exactly together (i.e., the end of e.g. the discharge of the first model run and the start of the discharge of the second model run are fitting smoothly together), then it's important to not only save the grids of soil moisture, groundwater table, snow storage a.s.o., but also the actual contents in the single linear reservoirs and in the different flow

travel time zones which are used to route the runoff to the subbasins outlet. Also the contents of the routing channels has to be saved in such cases.

Therefore, WaSiM-ETH writes a so-called “Storage Content File” containing these data in ASCII-format. The name must be specified as a file name like the other file names without any additional parameters. This name appears as the last most parameter in the sections [soil\_model] and [unsatzonmodel] for model versions 1 and 2, respectively.

When starting a new model run, this file will only be read in, if the \$gridread parameter was set to 1 (or, in case of the [unsatzonmodel], if it is set to 2), otherwise the data in this file is ignored, because the grids are not read in, too. If the parameters of the unsaturated zone or soil model in the new model run differ from the ones stored in the “Storage Content File” or if the basin structure has changed (different codes or number of subbasins, other routing parameters), an error will be generated and WaSiM-ETH stops its execution.

Here is an example of how to change the control file for model version 1 (TOPMODEL-Approach).

```
[soil_model]
1                      # 0=ignore this module, 1 = run the module
$time                 # duration of a time step in minutes
.
.
.
.
.
1      2      3      4      5      6      7      8      9      10     11     12     13 # subbasin codes
0.025 0.045 0.042 0.022 0.032 0.052 0.027 0.040 0.031 0.015 0.030 0.013 0.025 # recession parameter m
5.0   5.0   5.0   7.0   3.0   3.0   3.0   3.0   8.0   40.0  3.0   20.0  5.0   # scaling factor Tkorr
2.0   2.0   2.0   2.0   2.0   2.0   1.0   2.0   2.0   8.0   2.0   8.0   2.0   # scaling factor Kkorr
6.0   7.0   7.0   6.0   4.0   4.0   6.0   3.0   6.0   6.0   6.0   8.0   6.0   # recession constant surf. runoff
25.0  25.0  25.0  20.0  15.0  15.0  18.0  15.0  15.0  0.0   15.0  0.0   25.0  # maximum interflow storage
80.0  80.0  80.0  60.0  70.0  40.0  50.0  40.0  60.0  1.0   60.0  1.0   80.0  # recession constant interflow
# attention: please donst use the next three parameters: never use method 2, it is not tested!!
3600  3600  3600  3600  3600  3600  3600  3600  3600  3600  3600  3600  3600  # recession const. slow baseflow
0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.03  0.03  # max. deep percolation
0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  # initial value slow baseflow
0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   # init. content unsat. zone
0.75  0.75  0.75  0.6   0.45  0.45  0.45  0.45  0.45  0.45  0.3   0.7   0.75  # init. satur. deficit in n*nFK
3.0   3.0   4.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0   5.0   3.0   3.0   # Pgrenz (macro pore flow)
0.9   0.9   0.9   0.9   0.9   0.9   1.0   0.9   0.9   0.9   0.9   0.9   0.9   # scaling of capillary rise
0.1   0.1   0.1   0.4   0.4   0.5   0.4   0.5   0.4   0.4   0.35  0.35  0.1   # fraction on snow melt going
# into surface runoff
$readgrids            # 1=read grids from disk, else generate internal
$outpath//storage_topmodel.ftz # if readgrids = 1, then this file contains the contents of the flow travel
time zones for interflow and surface flow and for the tracers
```

Here is an example of how to change the control file for model version 2 (RICHARDS-Approach).

```
[unsatzon_model]
1                      # 0=ignore this module, 1 = run the module
$time                 # duration of a time step in minutes
2                      # method, 1=simple method, 2 = FDM-Method (strongly recommended)
.
.
.
.
.
$outpath//hhyd//$grid//.$code//$year # file containing the hydraulic head of the layers of the control point
1      2      3      4      5      6      7      8      9      10     11     12     13 # range for subbasin codes
3      5      5      3      3      3      3      3      3      3      5      3      # kelsqd
15     12     10     15     8      8      10     10     8      6      8      12     15 # kelsqi
17     15     15     17     18     30     20     25     15     20     20     22     17 # drainage density
0.43  0.43  0.43  0.43  0.43  0.43  0.43  0.43  0.43  0.43  0.43  0.43  0.43 # k in qb = Q0 * exp(-k/z)
0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01  0.01 # Q0 in the above formula
0.2   0.2   0.2   0.2   0.3   0.35  0.35  0.3   0.3   0.4   0.3   0.3   0.2   # fraction of surf. runoff on
# snow melt
$readgrids            # 1=read all grids from disk, 2=read only gw-level (m below surface) else (i.e. 0) generate all
# grids internally (setting the groundwater table to that layer, which is in 1/5th of total depth as given by
# the soil table). If the read parameter is set to 2, then only the groundwater table in m below surface is
# read
# in used for generating all other grids like the theta-stack and the GW-level, GW-Theta a.s.o.
$outpath//storage_richards.ftz # if readgrids = 1, then this file contains the contents of the flow travel
time zones for interflow and surface flow and for the tracers
```



## 9.4 Considering multi-layered vegetation

Since WaSiM-ETH version 7.x the seasonal evolution of vegetation is controlled by a two-part landuse table. Compared to the old landuse table (cf. Chapters 3.5 and 5) the new parametrization scheme allows the parametrization and simulation of multi-layered vegetation. It consists of two parameter tables: (a) the primary **[landuse\_table]** containing the parameter values for each vegetation type and (b) the **[multilayer\_landuse]** table which links vegetation types provided by the one-layer (primary) **[landuse\_table]** to complex (multi-layered) vegetation structures. The landuse codes within the **[multilayer\_landuse]** table have to correspond to the codes of the landuse grid. The two-part landuse table is not limited with respect to the number of table entries (landuse codes). It is structured as follows:

```
[multilayer_landuse]
4 # count of multilayer landuse codes
1 urban_areas { Landuse_Layers = 7, -9999, -9999; k_extinct = 0.3; LAI_scale = 10; }
2 mixed_forest { Landuse_Layers = 8, 4, 3; k_extinct = 0.3; LAI_scale = 10; }
3 deciduous_forest { Landuse_Layers = 9, 2, 1; k_extinct = 0.3; LAI_scale = 10; }
4 pasture { Landuse_Layers = 1, -9999, -9999; k_extinct = 0.3; LAI_scale = 10; }

[landuse_table]
7 # number of following land-use codes
#co- name of the
#de land-use type
#-- -----
1 grass_low {method = VariableDayCount;
  RootDistr = 1.0;
  TReduWet = 0.95;
  LimitReduWet = 0.5;
  HReduDry = 3.45;
  IntercepCap = 0.75;
  Juldays = 15 46 74 105 135 166 196 227 258 288 319 349;
  Albedo = 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25;
  rsc = 90 90 75 65 50 55 55 55 60 70 90 90;
  rs_interception = 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5;
  rs_evaporation = 130 130 130 130 130 130 130 130 130 130 130 130;
  LAI = 2 2 2 2 3 4 4 4 4 2 2 2;
  z0 = 0.15 0.15 0.15 0.15 0.3 0.4 0.4 0.3 0.3 0.15 0.15 0.15;
  VCF = 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95;
  RootDepth = 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4;
  AltDep = 0.02 0.02 0.02 0.02 0.02 0.02 -0.02 -0.02 -0.02 -0.02 -0.02 -0.02;
2 grass_high {method = VariableDayCount; RootDistr = 1.0; ... ; AltDep = 0.025 ... -0.025;}
3 fern {method = VariableDayCount; RootDistr = 1.0; ... ; AltDep = 0.025 ... -0.025;}
4 shrubbery {method = VariableDayCount; RootDistr = 1.0; ... ; AltDep = 0.025 ... -0.025;}
7 urban_grass {method = VariableDayCount; RootDistr = 1.0; ... ; AltDep = 0.025 ... -0.025;}
8 pine {method = VariableDayCount; RootDistr = 1.0; ... ; AltDep = 0.025 ... -0.025;}
9 birch {method = VariableDayCount; RootDistr = 1.0; ... ; AltDep = 0.025 ... -0.025;}
```

The parameters denote:

k_extinct	: extinction coefficient describing the reduction of radiation in multi-layered vegetation [-]
LAI_scale	: empirical parameter scaling the aerodynamic resistance in multi-layered vegetation [-]
RootDistr	: parameter for root density distribution [-1: konkav, 1: linear, >1: konvex]
TReduWet	: relative theta value for beginning oxygen stress [-]
LimitReduWet	: relative reduction factor of real transpiration for water-saturated soils [-]
HReduDry	: hydraulic head for beginning dryness stress [m]
IntercepCap	: specific thickness of the water layer on the leaves [mm]
Juldays	: Julian days valid for all following rows
Albedo	: albedo (snow free) [0..1]
rsc	: leaf surface resistance [s/m]
rs_interception	: interception surface resistance [s/m]
rs_evaporation	: soil surface resistance (for evaporation only) [s/m]
LAI	: leaf area index [m <sup>2</sup> /m <sup>2</sup> ]
z0	: aerodynamic roughness length [m]
VCF	: vegetation covered fraction [0..1]
RootDepth	: root depth [m]
AltDep	: shift in temporal vegetation development per metre altitude [Julian day]

### 9.4.1 [multilayer\_landuse] table

Each row in the **[multilayer\_landuse]** table begins with an entry for a landuse (grid) code. Then it follows the name of the landuse type and a certain number of parameters within curly brackets. The first entries within the brackets are the vegetation components or landuse layers. They have to be set in particular order. The uppermost layer (or top layer) is the left entry. Then entries to the underlying vegetation com-

ponents are following. For all landuse types it has to be set the same number of vegetation components. Missing components get the ignorance parameter “-9999”. Apart from the layer code settings, two additional parameters,  $k_{extinct}$  and  $LAI\_scale$ , can be defined for each landuse type (cf. COUPMODEL in Jansson und Karlberg, 2001).

$k_{extinct}$  is the light extinction coefficient which reduces the incoming radiation on its way through the layered vegetation (no consideration of diffuse light components). In conformity with the Lambert-Beer-Law the following relations are used:

$$\begin{aligned}
 \text{for } i = 1: \quad R_{use,i} &= VCF_i \cdot R_n \cdot (1 - e^{-k_{extinct} \cdot LAI_i}) \\
 \text{for } i = 2: \quad R_{use,i} &= VCF_i \cdot (R_n - R_{use,i-1}) \cdot (1 - e^{-k_{extinct} \cdot LAI_i}) \\
 \text{for } i = 3: \quad R_{use,i} &= VCF_i \cdot (R_n - R_{use,i-2} - R_{use,i-1}) \cdot (1 - e^{-k_{extinct} \cdot LAI_i}) \\
 &\text{(analogical procedure for } i > 3)
 \end{aligned} \tag{9.4.1}$$

with  $R_{use}$  available net radiation [Wh/m<sup>2</sup>]  
 $i$  vegetation component with  $i=1$  as the top level component (e.g. treetop)  
 $R_n$  available (total) net radiation (measured or simulated) [Wh/m<sup>2</sup>]  
 $VCF$  vegetation covered fraction [-]  
 $LAI$  leaf area index [m<sup>2</sup>/m<sup>2</sup>]

$LAI\_scale$  is an empirical parameter used for the calculation of the aerodynamic resistances  $r_{a,i>1}$  below the treetop (for the vegetation layers 2..n).

$$r_{a,i>1} = r_{a,i=1} + LAI\_scale \cdot LAI_{kum} \tag{9.4.2}$$

with  $r_{a,i=1}$  aerodynamic resistance of the top level vegetation component [s/m]  
 $LAI_{kum}$  cumulated leaf area index above the actual vegetation component [m<sup>2</sup>/m<sup>2</sup>]

Default values for  $k_{extinct}$  and  $LAI\_scale$  are 0.3 and 10, respectively. These values are also used in the case of parameter absence (in the control file). As the parameters  $k_{extinct}$  and  $LAI\_scale$  significantly affect the evapotranspiration of multi-layered vegetation, they should be carefully calibrated. According to values from literature,  $k_{extinct}$  can be between 0.25 and 0.85 (e.g. 0.5 for grass), whereas the values for  $LAI\_scale$  can range from 1 to 30.

JANSSON, P.E., KARLBERG, L. (2001): Coupled heat and mass transfer model for soil-plant-atmosphere system. – Division of Land & Water Resources, Depart. of Civil and Environ. Engineering, Royal Institute of Technology, Stockholm. Web document: <ftp://www.lwr.kth.se/CoupModel/CoupModel.pdf>

#### 9.4.2 [landuse\_table]

The primary [landuse\_table] has been substantially restructured and extended. In contrast to the old landuse table, the new one is no longer limited to a fixed number of “Julian day” entries (so far 4 entries). Now the seasonal evolution of vegetation can be predefined with much higher precision than before. For each “Julian day” entry the [landuse\_table] requires entries for the following parameters: *albedo*, *rsc*, *rs\_interception*, *rs\_evaporation*, *LAI*, *z0*, *VCF*, *RootDepth* and *AltDep*. This list of temporally varying parameters contains two new resistance parameters, one for the evaporation of intercepted water (*rs\_interception*) and the other for the evaporation of water from the soil surface (*rs\_evaporation*). The dependence of plant growth on altitude is controlled by the following approach:

$$Juldays_{i,cor} = Juldays_i + AltDep_i \cdot (h_M - 400) \tag{9.4.3}$$

with  $Juldays_i$  actual “Julian day” entry  
 $cor$  adjusted for altitude  
 $AltDep_i$  shift of the actual parameter *Julday* per meter altitude [Julian days]

$h_M$  altitude above sea level [m]

In addition to the temporally variable parameters, there are also some static parameters which are not linked to the “Julian Day” entries, namely *RootDist*, *TReduWet*, *LimitReduWet*, *HReduDry* and *IntercepCap*.

Apart from the root density distribution function (parameter *RootDist*) and the threshold value for starting dryness stress (*HReduDry*), three new parameters have been added to the [landuse\_table]. Two parameters (*TReduWet*, *LimitReduWet*) are defining the reduction potential of real transpiration due to oxygen stress when soil water content reaches saturation (see also Fig. 9.4.1). The third parameter (*IntercepCap*), which is defining the water storage capacity on leaves, is an optional parameter. If this parameter is omitted here, then it is used the default parameter from the [interception\_model].

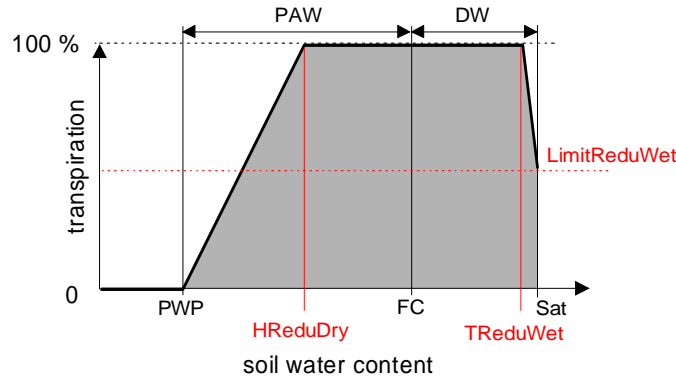


Figure 9.4.1: Interdependence between transpiration and soil water content. PAW: plant-available water, DW: drainable or gravitational water, PWP: permanent wilting point, FC: field capacity, Sat: soil water content at saturation, *HReduDry*: threshold value for starting dryness stress, *TReduWet*: threshold value for starting oxygen stress due to (nearly) water saturated soils, *LimitReduWet*: maximum reduction of transpiration due to oxygen stress

The extended [landuse\_table] allows parameter entries in both (i) multi-line and (ii) single-line formats. Each parameter block (containing all parameter entries of one landuse type) is framed by curly brackets. Parameter groups within one block are separated by semicolons. The method identifier “VariableDay-Count” signaled WaSiM-ETH that an extended landuse entry has to be read in.

The [landuse\_table] can be used in mixed form, i.e. it is possible to use both single-line and multi-line formats within the same table. Moreover, the formats of the old [landuse\_table] are furthermore valid. However, for clarity reasons the authors recommend the use of an uniform format of parametrization.

## 9.5 Upgrading the soil table

The scheme of soil parametrization has been restructured and significantly extended. The new [soil\_table] allows a horizon-dependent parametrization of the vertical soil profile including the consideration of macropore runoff. Similar to the scheme of the new [landuse\_table] (described in the section before), the parametrization of soil profiles can be done in (i) multi-line or/and (ii) single-line formats. Each parameter block (containing all parameter entries of one soil profile) is framed by curly brackets, whereas parameter groups within one block are separated by semicolons. The method identifier “MultipleHorizons” signaled WaSiM-ETH that an extended table entry has to be read in.

The new soil parametrization scheme is characterized by a high level of structural flexibility. The restructured [soil\_table] can generally handle different formats, i.e. individual soil profiles can be defined in both single-line and multi-line formats within the same table. In addition, the compatibility to the format of the older soil table (cf. Chapter 5) is guaranteed.

The extended [soil\_table] is structured as follows:

```
[soil_table]
1          # number of following soil codes
#co- name of the
#de soil profile
#-- -----
1  profile_1 {method = MultipleHorizons;
    PMacroThresh = 5.0;
    MacroCapacity = 4.0;
    CapacityRedu = 1.0;
    MacroDepth = 1.5;
    horizon      = 1      2      3;
    Name         = SL      SC      L;
    ksat         = 1.2e-5  3.3e-7  3.0e-6;
    k_recession  = 0.4      0.4      0.8;
    theta_sat    = 0.41     0.38     0.43;
    theta_res    = 0.065    0.10     0.078;
    alpha        = 7.50     2.70     3.60;
    Par_n        = 1.89     1.23     1.56;
    Par_tau      = 0.5      0.3      0.5;
    thickness    = 0.10     0.20     0.40;
    layers       = 3        2        25; }
```

The parameters denote:

PMacroThresh	: precipitation capacity needed to activate macropore runoff [mm/h]
MacroCapacity	: capacity of the macropores [mm/h]
CapacityRedu	: relative reduction of the macropore capacity per meter depth [0..1]
MacroDepth	: maximum depth of the macropores [m]
Horizon	: soil horizon; coding corresponds with the actual horizon sequence from top to down
Name	: name of the horizon
ksat	: saturated hydraulic conductivity [m/s]
k_recession	: ksat recession with depth [-]
theta_sat	: saturated water content [0.01 Vol. %]
theta_res	: residual water content [0.01 Vol. %]
alpha	: van Genuchten parameter [1/m]
Par_n	: van Genuchten parameter [-]
Par_tau	: Mualem parameter in the van Genuchten Equ. [-] (default: 0.5)
thickness	: layer thickness [m]
layer	: numerical number of soil layers in the actual horizon

### 9.5.1 Macropore runoff

The macropore approach implemented into WaSiM-ETH follows the „bypass-flow-concept” after Jansson und Karlberg (2001). This approach allows the simulation of macropore runoff in layered soil profiles. The approach describes macropores by three parameters: depth of the macropores, capacity of the macropores and reduction of the macropore capacity per meter soil depth. By means of these parameters a maximum possible macropore flow can be calculated for each soil layer (potential macropore runoff). An additional parameter is given by the precipitation threshold value. Only if this predefined precipitation intensity is reached or exceeded, water can infiltrate into the macropores and macropore runoff can be generated. The real amount of macropore infiltration depends on the actual water content of the adjacent soil layers. Water which exceeds the free capacity of these soil layers, can not infiltrate into the macropores.

The infiltrated macropore water is used to fill up the adjacent soil layers from down to top. When an actual soil layer is saturated then the remaining macropore water is trying to infiltrate into the next upper soil layer. Macropore water is not stored from one simulation time step to another but it has to completely infiltrate into the adjacent soil layers within the actual time step. As the macropore infiltration is strongly dependent on the free water capacity of the soil, the actual macropore runoff can be reduced with respect to the potential runoff.

The parametrization of the macropores is optional. Missing entries are automatically replaced by the following values (i.e. deactivation of the macropore system):

- *PMacroThresh* = 1000
- *MacroCapacity* = 0
- *CapacityRedu* = 1.0
- *MacroDepth* = 1.0

### 9.5.2 Horizon-dependent soil parametrization

The user can define individual horizon sequences with specific parametrization. For each soil horizon, it can be specified the following parameter entries: saturated hydraulic conductivity ( $ksat$ ), recession of  $ksat$  with depth ( $k\_recession$ ), van Genuchten parameters for defining the soil-water-retention curve ( $theta\_sat$ ,  $theta\_res$ ,  $alpha$ ,  $Par\_n$ ,  $Par\_tau$ ), horizon *thickness*, and number of soil layers per horizon. For technical reasons all soil profiles must be divided into the same number of layers but the depth of the soil profiles (column) may vary from one grid cell to another due to different thicknesses of soil layers (horizons). In this context, it is important to note that the depth of the soil profile has to be larger than the thickness of the uppermost (first) groundwater aquifer. Otherwise problems can arise during the use of the WaSiM-ETH groundwater model (groundwater table is falling below the deepest soil layer). For  $k\_recession = 1.0$  the parameter  $ksat$  remains constant within the actual soil horizon. In the latter case interflow is only generated at the horizon boundaries (if the actual soil profile uses different horizon-dependent  $ksat$  values).

## 9.6 Coupling WaSiM-ETH to an external model

A new model component allowing the online data exchange to an external groundwater model has been integrated into WaSiM-ETH. At the moment the functionality of the coupling module is limited to the data exchange with the groundwater model PCGEOFIM (Programsystem for Computation of GEOFiltration and geoMigration; see <http://www.ibgw-leipzig.de/>) but it might be relatively simple to adapt this coupling module to other external models. The WaSiM-ETH coupling module can be run with or without activation of the internal groundwater module.

The online data exchange between WaSiM-ETH and the external model can be carried out at the end of each simulation time step or at predefined simulation intervals. The parametrization scheme of the coupling module is shown below (new section in the WaSiM-ETH control file):

```
[ExternalCoupling]
1
$exchngpath//wasim.inf
100
D
1440
1
$exchngpath//gwtable.grd GWTableExtern 1 0
#$exchngpath//bh.grd      gw_boundary_fix_h_1 0 0
2
$exchngpath//gwn.grd groundwater_recharge
$exchngpath//balance.grd Balance SumTotal_MY
#$exchngpath//gwstand.grd groundwater_distance
2
$exchngpath//qdir.tab
$exchngpath//qifl.tab
$exchngpath//geofim.inf
geofim
```

The line-by-line entries denote:

Line	Description
1	activate / deactivate the external coupling module; 0 = no coupling, 1 = coupling
2	path and name of semaphore (or synchronization) file provided by the external model
3	wait interval for scanning the exchange directory for the new semaphore file [ms]
4	Coupling mode: I = each interval, H = each hour, D = each Day, M = each month, Y = each year
5	time interval used by the external model [min]
6	number of grids provided by the external model; the file names must be available once the semaphore file was written. Each following row (1..n) will contain a symbolic name.
7	first parameter: path and file name, second parameter: internal grid name, third parameter: "fillMissing" parameter (0 = no fill, 1 = fill with nearest neighbors value), fourth parameter: re-
8	name(1)/delete(0) parameter here labelled (#) as comment; in general additional files of the external model could be defined here for providing them WaSiM-ETH
9	number of grids provided by WaSiM-ETH before next synchronisation can be done
10	first parameter: path and name of the groundwater recharge grid, second parameter: internal grid name
11	first parameter: path and name of the balance grid (Due to the exchange of groundwater tables WaSiM-ETH has to adapt the internally calculated soil water content to the new condition. The cumulated amount of adaptation water is balanced by the balance grid.), second parameter: internal grid name, third parameter: writecode (D = daily sum grids, M = monthly sum grids, Y = annual sum grids; other options e.g. MY = both monthly and annual sum grids)

```

12 here labelled (#) as comment; in general additional files of WaSiM-ETH could be defined here
13 number of subbasin correlated statistics (mean values) which should be written as table (in ASCII-
14 Format)
14 first parameter: path and name of the file with direct flow per subbasin/zone [mm/Δt]; second parame-
15 ter: internal file name
15 first parameter: path and name of the file with interflow per subbasin/zone [mm/Δt]; second parameter:
16 internal file name
16 path and name of semaphore file provided by WaSiM-ETH after all of the output above was written
17 content of the semaphore file written by WaSiM-ETH

```

The exchange data containing the routed direct runoff and interflow (per subbasin) are provided by WaSiM-ETH as Ascii tables with the following format:

```

direct discharge [mm per Zone] (QD) unsatzon_model; 4 zones
1      0.128897
2      1.3298
3      4.5257
4      2.14858

```

## 9.7 Additional WaSiM-ETH outputs

Since WaSiM-ETH version 7.x the number of possible model outputs has been significantly increased. The actual model version is able to calculate and write out the following additional outputs (cf. Chapters 3.5 and 5):

Flow variables:

- rain (liquid fraction of precipitation) [mm/Δt]
- snow (solid fraction of precipitation) [mm/Δt]
- snow evaporation [mm/Δt]
- snow age [days]
- interception storage outflow for each vegetation component [mm/Δt]
- potential evaporation of intercepted water for each vegetation component [mm/Δt]
- real evaporation of intercepted water for each vegetation component [mm/Δt]
- potential evapotranspiration for each vegetation component [mm/Δt]
- reale transpiration for each vegetation component [mm/Δt]
- infiltration amount into the upper soil layer [mm/Δt]
- potential evaporation from the upper soil layer [mm/Δt]
- real evaporation from the upper soil layer [mm/Δt]
- percolation [mm/Δt]
- capillary rise [mm/Δt]
- withdrawal of soil water due to transpiration for each soil layer [mm/Δt]
- interflow for each soil layer [mm/Δt]
- infiltration amount in macropores [mm/Δt]

Storage variables:

- interception storage for each vegetation component [mm/Δt]
- total snow storage [mm/Δt]
- soil water content over the total soil profil [mm/Δt]
- balance of all changes in soil water content due to coupling with the external model PCGEOFIM (cf. Section 9.6) [mm]

## 9.8 Dynamic calculation of plant development

Phenology is of growing importance for hydrological water balance simulations, especially in the context of impact studies on climate change. Recent studies have shown that phenological phases (i.e. start and length) can significantly change under changing climate conditions. In addition, phenology can also show pronounced year-to-year variations, mainly depending on the seasonal course of air temperature.

Until now plant development was statically simulated by using predefined intra-annual courses of vegetation dynamics. Since WaSiM-ETH 7.8.x this deficiency is remedied. Now temperature-induced variations in the timing of phenological phases can be dynamically calculated. For this purpose, WaSiM-ETH offers

three different phenological models which can only be used if time series of air temperature are available. The applicability of the models is not limited to daily model time steps but also possible in any other time steps. The necessary conversion from non-daily temperature values into daily values is performed internally by WaSiM-ETH.

Table 10: Comparison of phenological models implemented into WaSiM-ETH

Model name in WaSiM-ETH	DynamicPhenology_1 (DP1)	DynamicPhenology_2 (DP2)	DynamicPhenology_3 (DP3)
Model type	„Thermal Time Model“	„Sequential Model“	„Thermal Time Model“
Start of growing period	dynamically simulated	dynamically simulated	dynamically simulated
Next stages of growing	predefined (relatively to the start day)	predefined (relatively to the start day)	dynamically simulated
Landuse type to simulate	trees, groves	trees, groves	grasses, arable crops

### 9.8.1 DynamicPhenology\_1 (DP1)

DP1 represents a simply “thermal time model” and simulates the phenological response of trees to changes in air temperature. The model does not take dormancy into account. It assumes that the release of dormancy is usually reached at the end of the year. Leaf unfolding only starts when plant-specific heat sums (forcing units) have been reached. The “forcing units” are calculated after the logistic function of Sarvas (1974):

$$S_f(t) = \sum_{i=t_1}^t R_f(T_i) \quad S_f(t_2) := F^* \quad (9.8.1)$$

$$R_f(T_i) = 0 \quad \text{for} \quad T_i \leq T_{Bf} \quad (9.8.2)$$

$$R_f(T_i) = \frac{28.4}{1 + \exp(-0.185 \cdot (T_i - T_{Bf} - 18.4))} \quad \text{for} \quad T_i > T_{Bf} \quad (9.8.3)$$

with  $S_f$  state of forcing  
 $R_f$  forcing rates  
 $F^*$  forcing units; heat sum which has to be reached before the phenophase can be started  
 $T_i$  daily mean temperature [°C]  
 $T_{Bf}$  plant-specific base temperature for „forcing“ [°C]  
 $t_1$  end of dormancy; start day for calculating  $F^*$  [JulDays]  
 $t_2$  start of the phenophase (active growth) [JulDays]

From Equations 9.8.1 - 9.8.3 it can be seen that DP1 only requires the optimization of three parameters:  $F^*$ ,  $t_1$  and  $T_{Bf}$  (in the WaSiM-ETH control file these parameters have slightly different names:  $F^*$ ,  $DP1\_t1\_dorm$ ,  $DP1\_T\_Bf$ ).

The DP1 model can be activated by setting the plant-specific method identifier in the primary [landuse\_table] to “DynamicPhenology\_1”. This table entry signalsizes WaSiM-ETH that phenology has to be calculated dynamically and that DP1 parameters have to be read in.

Besides the three above-mentioned parameters WaSiM-ETH needs two additional parameter entries in its [landuse\_table]:

- $JDReset\_TStart$  [JulDays]:  
guaranteed a proper start of a new vegetation period (reset from  $TStart$  to -1 and reset of the „forcing units“ to zero)
- $maxStartJDforDP1$  [JulDays]:  
denotes the last possible starting day for the use of DP1 within the actual calendar year. In the case that the model is started after this date,  $TStart$  is set automatically to:

$$TStart = maxStartJDforDP1 - delta \quad (9.8.4)$$

Here  $TStart$  denotes the start of the phenophase (active growth) and has to be set to -1 in the parameter row  $JulDays$ . During the initialization the model looks for this value and stores the column number for  $TStart$ . The value in the following column is interpreted as delta [JulDays]. It denotes the end of leaf unfolding.

It is worthy to note that the entries for  $JulDays$  before and after these both days ( $TStart$  and  $delta$ ) are fixed (resp. variable with the altitude only) and used as always (cf. method “VariableDayCount”). That means that the course of the phenological development after its (dynamically calculated) start follows the well-known old model scheme and uses statically predefined vegetation curves. For these predefined sections it is possible to consider the influence of altitude on plant development whereas this feature can not be used for the column entries  $TStart$  and  $delta$ . In this case the parameter  $AltDep$  (altitude dependence) has to be set to zero because here the air temperature is already implicitly considered. Furthermore it is not possible to interpolate between parameters which are earlier than  $TStart$ .

SARVAS, R. (1974): Investigations on the annual cycle of development of forest trees II. Autumn dormancy and winter dormancy. *Communicationes Instituti Forestalis Fenniae*, 84 (1), 1-101.

### 9.8.2 DynamicPhenology\_2 (DP2)

DP2 is a „sequential model“ for simulating the timing of phenology for trees and groves. In contrast to DP1 it considers both the dormancy and the following phase of ontogenetic development.

Normally trees require a certain period with chilling temperatures before they can react to higher temperatures, which force the development of buds and induce leaf unfolding and lowering in spring (Chmielewski et al., 2005). That means that the release of dormancy is only possible if the “chilling units” are reached. The DP2 “chilling-forcing” model calculates the plant-specific heat and chilling units as follows:

$$S_c(t) = \sum_{i=t_0}^t R_c(T_i) \quad \text{with} \quad S_c(t_1) := C^* \quad (9.8.5)$$

$$S_f(t) = \sum_{i=t_1}^t R_f(T_i) \quad \text{with} \quad S_f(t_2) := F^* \quad (9.8.6)$$

and  $F^* = a \cdot e^{b \cdot C^*}$

$$R_c(T_i) = 0 \quad \text{for} \quad T_i \leq z_1 \quad \text{or} \quad T_i \geq z_2 \quad (9.8.7)$$

$$R_c(T_i) = \frac{T_i - z_1}{T_{Bc} - z_1} \quad \text{for} \quad z_1 < T_i \leq T_{Bc} \quad (9.8.8)$$

$$R_c(T_i) = \frac{T_i - z_2}{T_{Bc} - z_2} \quad \text{for} \quad T_{Bc} < T_i < z_2 \quad (9.8.9)$$

$$R_f(T_i) = 0 \quad \text{for} \quad T_i \leq T_{Bf} \quad (9.8.10)$$

$$R_f(T_i) = \frac{28.4}{1 + \exp(-0.185 \cdot (T_i - T_{Bf} - 18.4))} \quad \text{for} \quad T_i > T_{Bf} \quad (9.8.11)$$

with  $S_c$  state of chilling  
 $R_c$  chilling rates  
 $C^*$  chilling units; chilling sum which has to be reached before the dormancy can be finished  
 $S_f$  state of forcing



$R_f$	forcing rates
$F^*$	forcing units; heat sum which has to be reached before the phenophase can be started
$a, b$	empirical parameter
$T_i$	daily mean temperature [°C]
$T_{Bc}$	plant-specific base temperature for „chilling“ [°C]
$T_{Bf}$	plant-specific base temperature for „forcing“ [°C]
$z_1$	constant (for forest = -3.4 and for fruit trees = 3.0)
$z_2$	constant (for forest = 10.4 and for fruit trees = 12.0)
$t_o$	start of dormancy; start for calculating $C^*$ [JulDays]
$t_1$	end of dormancy; start for calculating $F^*$ [JulDays]
$t_2$	start of the phenophase (active growth) [JulDays]

Similar to DP1 the phenological model DP2 has to be activated by setting a plant-specific method identifier in the primary [landuse\_table]. In the case of DP2 the table entry is “DynamicPhenology\_2”.

For using DP2 WaSiM-ETH requires the following plant-specific parameter entries (for explanations see above):

```
# extract from the primary landuse table

[landuse_table]
1
5 oak {method = DynamicPhenology_2;
RootDistr      = 1.0;
TReduWet       = 0.95;
LimitReduWet   = 0.5;
HReduDry       = 3.45;
IntercepCap    = 0.35;
StressFactorDynPhen = 1.0;
F*             = 221.2;
DP1_t1_dorm    = 1;
DP1_T_Bf       = 0;
DP2_t0_dorm    = 244;
DP2_t1_dorm    = 60;
DP2_T_Bf       = 0.2;
DP2_T_Bc       = 8.4;
DP2_Par_a      = 231.6;
DP2_Par_b      = 0.0;
DP2_Offset_1   = -3.4;
DP2_Offset_2   = 10.4;
JDReset_TStart = 1;
maxStartJDforDP1 = 150;
JulDays        = 1      -1      +10      258      288      319      349;
#(max) JulDays  = 1      130     200      217      293      319      366;
#ForcingThreshold = -1    334.8   1024.3   -1        1143.3   -1        -1;
...
```

Note that DP2 cannot be used for simulating the phenology of the first model year because at this time WaSiM-ETH does not know the state of chilling ( $S_c$ ). In this case WaSiM-ETH changes automatically the phenological model from DP2 to DP1. This switch setting can only be deactivated if results from previous model runs are available for the initialization of DP2.

CHMIELEWSKI, F.-M., MÜLLER, A., KÜCHLER, W. (2007): Possible impacts of climate change on natural vegetation in Saxony (Germany). Int J Biometeorol, 50: 96-104.

### 9.8.3 DynamicPhenology\_3 (DP3)

The third implemented phenological model is DP3. It is a simple “thermal time model” focusing mainly on the simulation of phenophases for crops. DP3 calculates the forcing rates ( $R_f$ ) very simplified as growing-degree-days (GDD) and not by means of the more complex Sarvas function (cf. DP1).

$$S_f(t) = \sum_{i=t_1}^t R_f(T_i) \quad \text{with} \quad S_f(t_2) := F^* \quad (9.8.12)$$

$$R_f(T_i) = 0 \quad \text{for} \quad T_i \leq T_{Bf} \quad (9.8.13)$$

$$R_f(T_i) = T_i - T_{Bf} \quad \text{for} \quad T_i > T_{Bf} \quad (9.8.14)$$

with	$S_f$	state of forcing
	$R_f$	forcing rates
	$F^*$	forcing units; heat sum which has to be reached before the phenophase can be started
	$T_i$	daily mean temperature
	$T_{Bf}$	plant-specific base temperature for „forcing“
	$t_1$	start for calculating $F^*$
	$t_2$	smallest whole number where $S_f(t_2) \geq F^*$ is valid; start of the phenophase

The phenological model DP3 is activated by setting the plant-specific method identifier in the extended [landuse\_table] to “DynamicPhenology\_3”. Compared to the previous models (DP1 and DP2), DP3 does not only allow to simulate the starting day of active growth but also the timing of the subsequent phenophases.

The practical use of DP3 requires the definition of so-called “Sample-Days” which indicate the “maximum Julian days” where the actual phenophase should be started at the latest. The “Sample-Days” are plant-specific parameters. They have to be given within the parameter row (*max*) *JulDays* in the WaSiM-ETH [landuse\_table].

The “Sample-Day” entries are closely linked to another newly introduced pheno-parameter, namely the “forcing thresholds”. These thresholds (in the WaSiM-ETH control file named as *ForcingThreshold*) have to be defined separately for each “Sample-Day”.

WaSiM-ETH interprets positive “Sample-Day” entries as threshold values which have to be reached by the “forcing rates” ( $R_f$ ). In the case that  $R_f$  reaches the *ForcingThreshold* earlier than the corresponding “Sample-Day”, the actual Julian day is used as start day of the new phenophase. In the other case (the *ForcingThreshold* is not reached earlier than the corresponding “Sample-Day”) the given “Sample-Day” is taken as new start day.

It is important to know that the first and last “Sample-Day” entries cannot be calculated dynamically but have to be fixed to 1 and 366, respectively. In both cases, the corresponding *ForcingThresholds* have to be set to -1.

In general, “Sample-Days” are interpreted as fixed if the corresponding *ForcingThresholds* are set to -1. Then plant growth can only be influenced by its altitude dependency.

WaSiM-ETH linearly interpolates between “Sample-Days”. It can be discriminated between two scenarios:

Scenario 1: The next “Sample-Day” is fixed.

Here the temporal interpolation is done linearly by using the Julian-Day entries of the actual (fixed or dynamic) and next (fixed) “Sample-Days”.

*Example:* The leaf area index (LAI) between day 60 (with LAI = 2) and day 100 (with LAI = 10) is interpolated to 4 at day = 70.

Scenario 2: The next “Sample-Day” is calculated dynamically.

Here the temporal interpolation considers both the reached “forcing rates” of the actual (fixed or dynamic) and the *ForcingThresholds* of the subsequent “Sample-Day”.

*Example:* The LAI between day 60 (with  $S_f = 200$  and LAI = 2) and the next (uncertain) day (with *ForcingThreshold* = 600 and LAI = 10) is interpolated to 4 at  $S_f = 300$ .

WaSiM-ETH does not allow using DP3 without having the parameter entries for DP1 and DP2. The simulated Julian days indicating the start and the end of the phenophases can be controlled by a data stack

which is written at the end of the model run. The stack is labelled as “MultipleStartTimes1\_End” and contains phenological information for each „Sample-Day“. In addition the actual state of forcing ( $S_f$ ) is saved in stack layer 0.

#### 9.8.4 Considering the influence of soil moisture on phenology

A stress factor has been introduced into the [landuse\_table] of WaSiM-ETH in order to simulate the influence of soil moisture on phenological development. The factor is labelled as *StressFactorDynPhen* and can be defined separately for each landuse type. As seen in Equation 9.8.15 the stress factor is used as scaling parameter for the forcing units ( $F^*$ ).

$$F^{*'} = F^* \cdot \text{StressFactorDynPhen} \cdot \left( \frac{\Psi(t) - H\text{ReduDry}}{150 - H\text{ReduDry}} \right) \quad (9.8.15)$$

with  $F^*$  forcing units; heat sum which has to be reached before the actual phenophase can be started  
 $\Psi$  actual hydraulic head (calculated by using the van Genuchten parameters of the upper soil layer and the mean soil water content of the rooted soil zone)  
 $H\text{ReduDry}$  hydraulic head for beginning dryness stress (reduction of transpiration)

The stress factor can influence the plant development in two different ways: a) Stress values larger than 1 will probably accelerate the phenology, whereas a deceleration can be expected for values smaller than 1. No phenological stress occurs in the case of missing or negative stress factor values (the same is valid for *StressFactorDynPhen* = 0). As far as our experience goes an useful range for the stress factor is between 0.5 and 2.

#### 9.8.5 Handling of phenological output data

The results of the phenological simulation can be saved and controlled by using the writegrid options in the section [variable\_grids] of the WaSiM-ETH control file. The model allows creating outputs for the the following variables (outputs for each vegetation layer):

- SumOfForcingUnits (for DP1, DP2 and DP3)
- Pheno\_start (for DP1, DP2 and DP3)
- SumOfChillingUnits (for DP2)
- FStar\_ForcingsThreshold (for DP2 and DP3)

Furthermore, the above-mentioned grid outputs can also be used for the initialization of (serial) model runs (option \$DPreadgrids with: 0 = initialize internally, 1 = read in from grid).

```
# extract from section [variable_grids] for vegetation layer 1
$outpath//$forcingunitsgrid1      SumOfForcingUnits1      0 -1
$Writegrid
$DPreadgrids
$outpath//$TStartPhenoGrid1      Pheno_start1          0 -1
$Writegrid
$DPreadgrids
$outpath//$chillingunitsgrid1     SumOfChillingUnits1    0 -1
$Writegrid
$DPreadgrids
$outpath//$FStargrid1            FStar_ForcingsThreshold1 0 -1
$Writegrid
$DPreadgrids
```

The both codes shown behind the grid names have the following meaning:

The first code indicates if “nodata values” should be replaced automatically by “nearest neighbor values” (0 = no, 1 = yes). The second code informs if a grid should be read in or internally initialized. For the

phenological variables the latter code is set to -1 per default because this signalizes WaSiM-ETH that threshold values have not been reached yet.

### 9.9 Dynamic time step control

The implementation of the dynamic time step controller into the Richards model of WaSiM-ETH allows a more flexible and process-oriented soil parametrization as well as an improved simulation quality of vertical water fluxes in layered soils. Using this controller soil water fluxes can be simulated with a very high level of numerical stability even in cases with extreme parameter setups (e.g. very thin soil layers combined with the pronounced hydraulic conductivity of sandy soils).

The introduced dynamic time step control algorithm (available in WaSiM-ETH since version 7.9) considers explicitly the Courant stability criterion in order to prevent oscillations possibly caused by the discretization scheme of the actual soil profile. The Courant criterion is defined as follows:

$$Co = \left| \frac{\Delta t \cdot v}{\Delta x} \right| \leq 1 \quad (9.9.1)$$

with  $Co$  Courant criterion  
 $\Delta t$  time step [s]  
 $v$  velocity [m/s]  
 $\Delta x$  spatial distance between the nodes [m]

After its transformation the boundary condition for a stabil numerical solution are given by:

$$\Delta x \geq \Delta t \cdot v \quad \text{resp.} \quad \Delta t \leq \frac{\Delta x}{v} \quad (9.9.2)$$

with  $\Delta t$  simulation time step [s]  
 $v$  hydraulic conductivity [m/s]  
 $\Delta x$  thickness of the actual soil layer [m]

In WaSiM-ETH the algorithm of dynamic time step control has been a slightly adapted:

$$\Delta t = \min_{i=1}^k \left( \frac{\Delta z_i}{k(\Theta)_{rel,i} \cdot k_{sat,i}} \right) \quad (9.9.3)$$

with  $\Delta t$  minimum time for flowing of water through the soil layer at the actual water content [s]  
 $i$  layer index (from 1..k)  
 $k$  index of last soil layer above the groundwater level  
 $\Delta z_i$  thickness of the actual soil layer i [m]  
 $k(\Theta)_{rel,i}$  relative moisture-dependent conductivity of layer i  
 $k_{sat,i}$  saturated hydraulic conductivity of layer i [m/s]

If the Courant time interval is shorter than the predefined model time step ( $\Delta t < I$ ) then a certain split factor has to be calculated in order to reduce the length of the original time step:

$$f_{split} = \left\lceil \frac{I}{\Delta t} \right\rceil \quad (9.9.4)$$

with  $f_{split}$  split factor with  $f_{split} \geq 1$

$I$	length of the selected time step interval (as defined in control file) [s]
$\Delta t$	result from Equation (9.9.3) [s]
$\lceil \cdot \rceil$	character for a rounded up integer

The internal reduction of the (original) model time step is done separately for each grid cell. For this purpose the implemented control algorithm checks all soil layers above the groundwater level with regard to the actual Courant criterion. If necessary ( $\Delta t < I$ ) then the (original) model time step is subdivided into a certain number of subintervals ( $f_{split}$ ). In this case, the absolute input data [in mm] for the soil model have to be recalculated for each subinterval whereas data of flow velocity (e.g. descent and ascent rates of the groundwater level or water flows between soil layers) can be used as before (i.e. without subdivision) because of their independence of the length of calculation time interval.

The shortest possible subinterval is one second. That means in effect that a model time step of one hour can be subdivided into up to 3600 subintervals. In order to increase the flexibility of the implemented algorithm, it is possible to define a minimum subinterval length [in s].

The dynamic time step control can be activated by selecting method “3” in the section [unsatzon\_model] of the WaSiM-ETH control file.