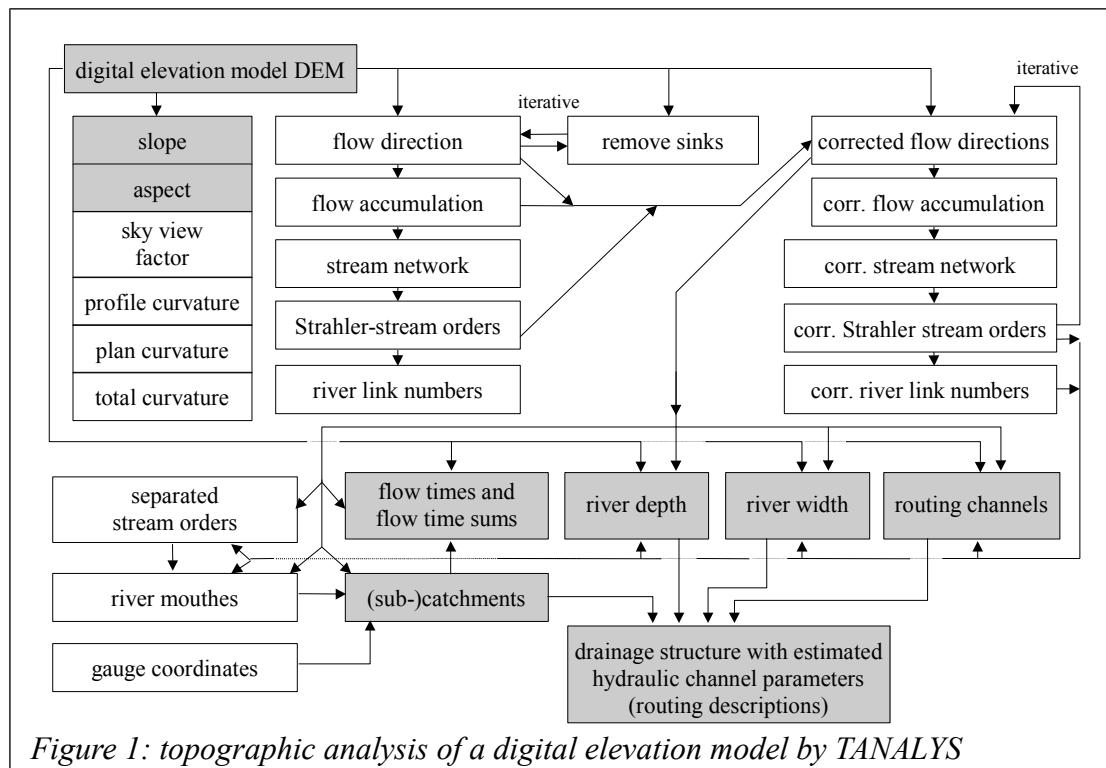


## TANALYS

One of the most important data sets for using the hydrologic model WaSiM 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 information can be determined by using these derived information. 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 1 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.



Only the shaded data sets are really needed by WaSiM. 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 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 (5.1.1) holds:

$$z = Ax^2 y^2 + Bx^2 y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I \quad (5.1.1)$$

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:

$$\begin{aligned}
 I &= z_{2,2} \\
 H &= (z_{2,1} - z_{2,3})/(2L) \\
 G &= (z_{3,2} - z_{1,2})/(2L) \\
 F &= (-z_{1,1} + z_{3,1} + z_{1,3} - z_{3,3})/(4L^2) \\
 E &= [(z_{2,1} + z_{2,3})/2 - z_{2,2}]/L^2 \\
 D &= [(z_{1,2} + z_{3,2})/2 - z_{2,2}]/L^2 \\
 C &= [(-z_{1,1} - z_{1,3} + z_{3,1} + z_{3,3})/4 + (z_{1,2} - z_{3,2})/2]/L^3 \\
 B &= [(z_{1,1} + z_{3,1} - z_{1,3} - z_{3,3})/4 - (z_{2,1} - z_{2,3})/2]/L^3 \\
 A &= [(z_{1,1} + z_{1,3} + z_{3,1} + z_{3,3})/4 - (z_{1,2} + z_{2,1} + z_{2,3} + z_{3,2})/2 + z_{2,2}]/L^4
 \end{aligned}
 \quad (5.1.2)$$

	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 these parameters by:

$$\text{slope angle} \quad \hat{\beta} = \arctan(\sqrt{G^2 + H^2}) \quad (5.1.3)$$

$$\text{aspect angle} \quad \hat{\Omega} = 180 - \arctan(H/G) + 90(G/|G|) \quad (5.1.4)$$

$$\text{profile curvature} \quad \phi = -2(DG^2 + EH^2 + FGH)/(G^2 + H^2) \quad (5.1.5)$$

$$\text{plan curvature} \quad \omega = 2(DH^2 + EG^2 - FGH)/(G^2 + H^2) \quad (5.1.6)$$

$$\text{total curvature} \quad \chi = \omega - \phi = 2E + 2D \quad (5.1.7)$$

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.  $10^\circ$  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  $1 - \sin\beta_h$ :

$$\psi_{sky} = \sum_{i=1}^n \cos^2 \beta_{h,i} \quad (5.1.8)$$

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:

$$R_K = \frac{R_{sun} \cdot \cos \hat{\Theta}}{\cos Z} + D \cdot \psi_{sky} + RG(1 - \psi_{sky}) \cdot \alpha \quad (5.1.9)$$

with  $D$  diffuse shortwave radiation from the sky [ $\text{Wh/m}^2$ ]  
 $R_{sun}, RG$  direct sun radiation resp. global radiation (direct+diffuse) [ $\text{Wh/m}^2$ ]  
 $\alpha$  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 (5.1.8) should be reformulated, using the formula for the surface of a half sphere  $A = 2\pi r^2(1-\sin\beta_h)$ :

$$A_s = 1 - \sum_{i=1}^n \sin \beta_{h,i} \quad (5.1.10)$$

The difference between  $\psi_{sky}$  and  $A_s$  may be considerable, especially for small and medium horizon overhead angles. This is because equation (5.1.10) does not consider LAMBERT's law of the decrease of the irradiation with an decreasing incoming angle. Because of the squared cosine in equation (5.1.8) 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 2 shows these relations. WaSiM 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.

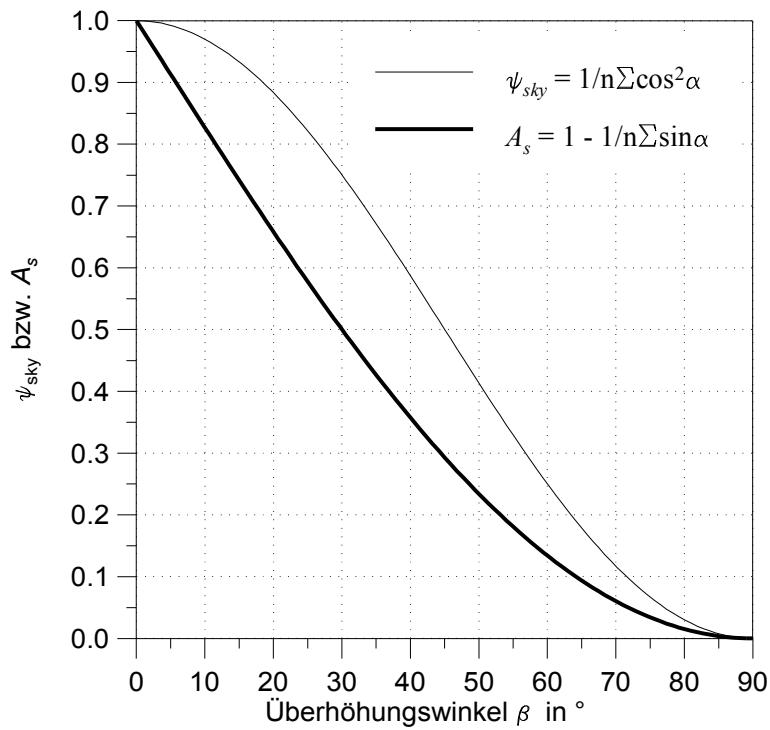


Figure 2: Sky-view-factor  $\psi_{sky}$  and fraction of the sky  $A_s$  dependent on the horizon overhead angle  $\beta_h$

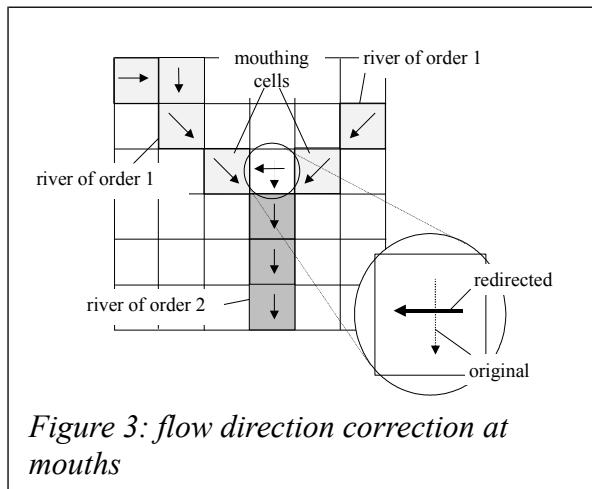
Flow directions are determined by the steepest of the slopes to the at maximum 8 neighboring cells. Flow is allowed into only *one* of these cells. Artifacts like sinks or flat areas which may be the result of generating the elevation model, but also real, natural sinks, e.g. in karst regions, are filled 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 or 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 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  $45^\circ$  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 3: 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 3 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.

$$v = M \cdot R_h^{2/3} \cdot I^{1/2} \quad (5.1.11)$$

$$\dot{V} = M \cdot A \cdot R_h^{2/3} \cdot I^{1/2} \quad (5.1.12)$$

with  $v$  flow velocity [m/s]

$M$  roughness parameter after Manning-Strickler (10 ... 40) [ $m^{1/3}/s$ ]

$A$  cross section area of the flow (rectangle profile with depth/width = 1/8) [ $m^2$ ]

$R_h$  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 (5.1.11) is an 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:

$$R_h = \frac{A}{1.25 \sqrt{8A}} \quad (5.1.13)$$

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 (5.1.11), 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 (5.1.15) and (5.1.16). In order to get realistic results for the discharge routing in later WaSiM 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 (5.1.11). 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 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  $M = 10 m^{1/3} \cdot s^{-1}$  is presumed. Then, the flow velocity on land surfaces depends only on the local slope, see equation (5.1.14). The flow time  $t$  the water needs for crossing a cell, depends on the effective flow length (diagonal or perpendicular to a cell side):

$$v = 10 m^{1/3} s^{-1} \cdot (0.01 m)^{2/3} \cdot \sqrt{I} \quad (5.1.14)$$

$$t = \frac{cs \cdot \sqrt{2}}{v} \quad \text{for flow directions } \uparrow\downarrow\leftarrow\rightarrow \quad (5.1.15)$$

$$t = \frac{cs}{v} \quad \text{for flow directions } \uparrow\rightarrow\downarrow\leftarrow \quad (5.1.16)$$

Sub-catchments are delineated using the mouth 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 control file. It can simply be inserted into this file.

Figure 4 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 mean 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.

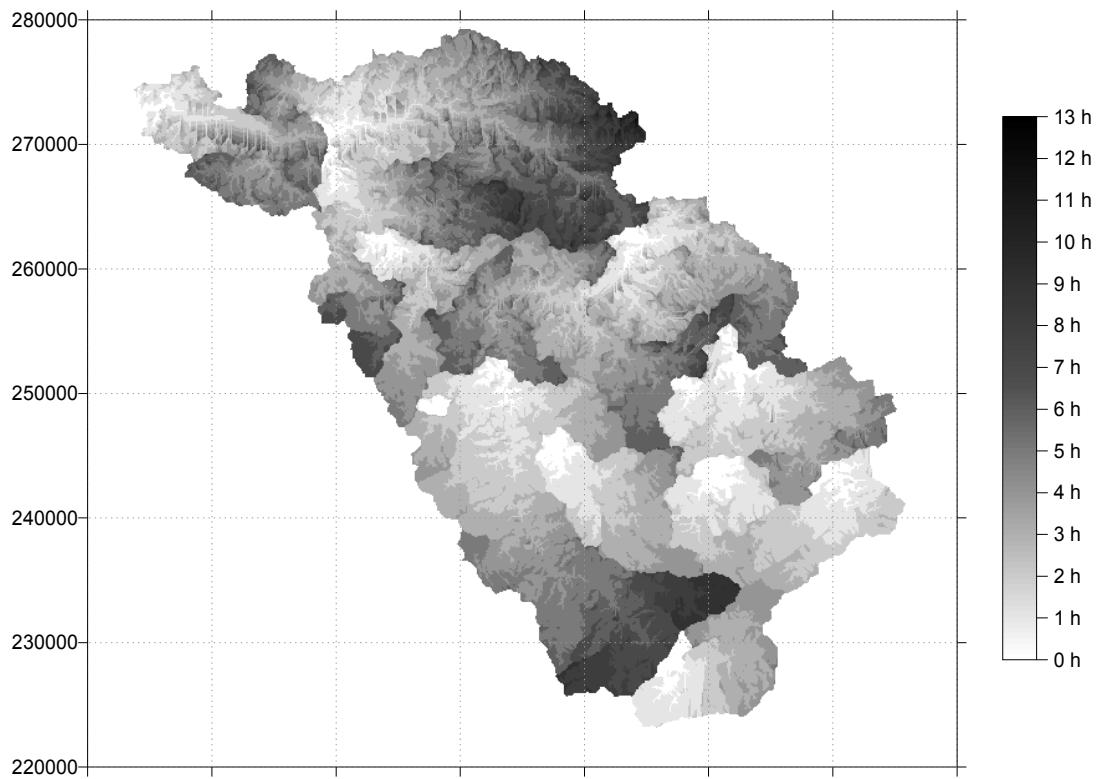


Figure 4: flow travel time grid for the river gauge network of the Thur-basin, hour zones