RAINFALL-RUNOFF MODELLING BASED ON THE SWAT MODEL

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Abstract: The paper outlines the SWAT model used for modeling of the rainfall-runoff relation. The SWAT is a hydrodynamic, physically based model. The model inputs are atmospheric radiation, air temperature, rainfall and snow-cover depth. The model calculates all phases related to water movement: snow accumulation and snowmelt, potential and real evapotranspiration, precipitation on the soil surface, infiltration, as well as base and surface components of the hydrograph. Basic units for modeling are parallelograms defined by gridlines whose discretization is selected according to the desired accuracy of the calculation, as well as the data reliability. The total outflow is obtained by the convolution of the surface and groundwater flow. An illustration of model performance is given for an imaginary drainage area of 100 km^2.
Key words: Rainfall-runoff modeling, snow accumulation and snowmelt, potential and real evapotranspiration, total outflow, surface and groundwater flow.

MODELIERUNG DES PROZESSES NIEDERSCHLAG – ABFLUSS DURCH DIE METHODE SWAT

Zusammenfassung: In der Arbeit wurde die Struktur des Modells SWAT dargestellt, die fuer die Modelierung des Prozesses ,, Niederschlag – Abfluss ,, genutzt wird. Das Modell SWAT ist hydrodynamisch und physisch basiertes Modell. Der Eingang ins Modell sind die Radiation an der Grenze der Atmosphaere, der Luftthemperatur, der Niederschlag und die Hoehe der Schneedecke. Es rechnet alle fuer die Wasserbewegung wichtigen Prozesse : sowie die Schneeakomulation und Schneeschmelze, der Boden, die Perkolation als auchder Grund –u. Flaecheabfluss. Grundeinheit fuer die Modelierung ist die Elementarflaeche im Netz des Rechteckes (Parallelogramms) (grid), dessen Diskretionsmass haengt von sowie der gewuenschten Genauigkeit als auch von der Genauigkeit der Daten ab. Der Gesamtabfluss am Ausgangsprofil des Zusammenflusses bekommt man durch die Konvulation des Gesamtabflusses (des flaechlichen und gruendlichen). Die Ilustration der Arbeit des Modells SWAT wird an einem fiktiven Zusammenflusses der Oberflaeche cca 100 km^2 gezeigt werden.
Schluesselworte: Niederschlag, Abfluss, Schneeakumulation und Schneeschmelze, potenzielle und tatsaechliche Evapotranspiration, Gesamtabfluss, oberflaechlicher Fluss und Grundwasserfluss.

1. Introduction

The physical rainfall-runoff processes are very heterogeneous natural processes and thus their modeling is very complex. The SWAT is a hydrodynamic, physically based model. It requires a large number of input data: weather, topography, pedology, vegetation cover, land use, etc. All processes related to the movement of water and the vegetation may be modeled directly by the SWAT. The SWAT allows simulation of several physical processes.

A river basin is divided into a finite number of rectangles (or, in specific cases, squares). Such a rectangular grid is the basic modeling unit. The discretization depends on the desired accuracy and the reliability of input data. Each field of the grid is a hydrologic response unit (HRU). It is assumed that all input quantities for the HRU are homogeneous, or quasi-homogeneous.

The model was developed in the early 1990's. Its creator is Dr. Jeff Arnold of the USDA University (Texas, USA). The forerunners of the model were: the SWRRB (Simulator for Water Resources in Rural Basins, Williams et al., 1985; Arnold et al., 1990) and the ROTO (Routing Outputs to Outlet, Arnold et al., 1995). The original interface and software environment were developed using Visual Basic, GRASS and ArcView.

2. Basic inputs

First to be established are the weather inputs: constants (extraterrestrial radiation and various time constants) and variables (temperatures, precipitation, etc.) relative to time and space, since they define the moisture and energy for the other processes simulated in the river basin. Reference elevations are generated for the HRU (applying GIS techniques), and the areas and other features are determined as required for the modeling. Then the mean precipitation, temperature and height of the snow cover are computed for each HRU.

a) Average precipitation

$$R_{band} = R + (EL_{band} - EL_{gage}) \cdot \frac{p_{laps}}{1000} \qquad (1)$$

Reference quantities are computed for each HRU applying the above formula since in the case of a sloping terrain the weather quantities vary with altitude (Fig. 1).

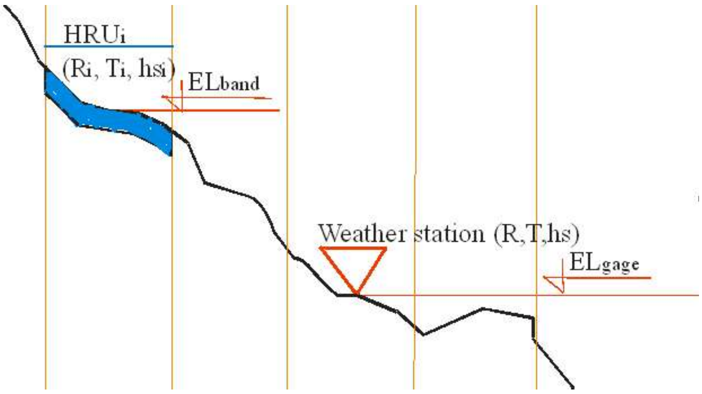

Fig. 1 *Sloping terrain.*

where
R is the rainfall (mm),
T is the temperature (ºC),
hs is the height of snow cover (mm),
EL is the elevation (m.a.s.l.),
band is the average height (m above sea level) of the considered HRU,
gage is the elevation at which precipitation was recorded (weather station),
p_{laps} is the precipitation lapse rate (mm/km). This is a measure of precipitation increase with increasing altitude.

b) Average temperatures

$$T_x = T_x + (EL_{band} - EL_{gage}) \cdot \frac{t_{laps}}{1000} \qquad (2)$$

where
x are the minimum, maximum and mean air temperatures;
band is the average height (m above sea level) of the considered HRU;

gage is the elevation at which precipitation was recorded (weather station); and
t_{laps} is the temperature lapse rate (ºC/km).

c) <u>Snow level</u>

$$h_{s\,band} = h_s + (EL_{band} - EL_{gage}) \cdot \frac{h_{s\,laps}}{1000} \quad (3)$$

where
h_s is the snow level (mm);
EL is the elevation (m.a.s.l.);
band is the average height (m above sea level) of the considered HRU;
gage is the elevation at which precipitation was recorded (weather station); and
h_{slaps} is the snow level lapse rate (mm/km). This is a measure of snow level increase with increasing altitude.
The hydrologic cycle of a single HRU simulated by this model is defined by the balance equation

$$SW_i = SW_{i-1} + (R_{day} + SNO_{melt}) - Q_{surf} - E_a - w_{seep} - Q_{gw} \quad (4)$$

This is illustrated in Fig. 2.

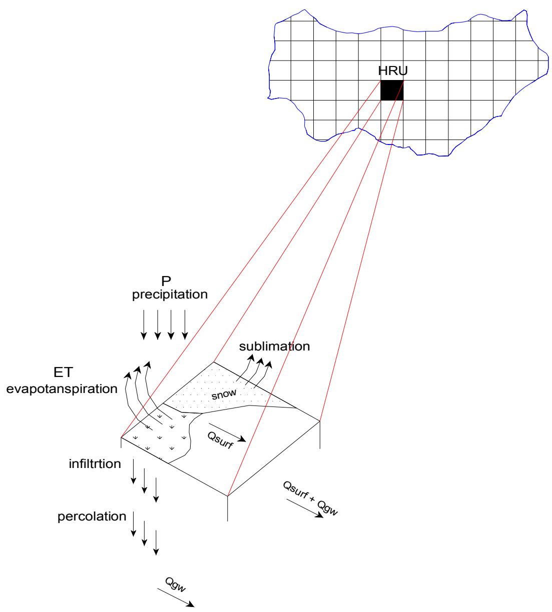

Fig. 2: Balance schematic of the SWAT model.

where
SW_i is the amount of water in the soil profile on a given day t_i (mm);
SW_{i-1} is the amount of water in the soil profile on the previous day t_{i-1} (mm);
R_{day} is the amount of precipitation on day *i* (mm) (when the average temperature of the time step is higher than $T_{s\text{-}r}$), which reaches the ground. A part of such precipitation is trapped by the vegetation canopy and never reaches the ground;
SNO_{melt} is the snowmelt;
Q_{surf} is the amount of surface runoff (mm);
E_a is the actual evapotranspiration (mm);
w_{seep} is the amount of percolation and bypass flow exiting the soil profile bottom on day *i* (mm)
Q_{gw} is the amount of groundwater (return) flow on day *i* (mm).

3. Typical balance equations for a single HRU

3.1. *Snow accumulation and snowmelt*

a) Measured snow level available

The snowmelt process is modeled for each HRU separately, by establishing a reference elevation for each HRU, determining whether snowmelt occurs and computing the amount of snowmelt for the elevation and the surface area of the HRU in each time step. The height of snowmelt for each time step is computed from the formula

$$\mathrm{SNO_{melt}} = \mathrm{b_{melt}} \cdot sno_{\mathrm{cov}}\left[\frac{T_{snow}+T_{\max}}{2} - T_{melt}\right] \tag{5}$$

where

SNO_{melt} is the amount of snowmelt on a given day (mm);
b_{melt} is the melt factor for the day (mm/day°C);
T_{melt} is the base temperature above which snowmelt is allowed (close or equal to zero) (°C);
T_{max} is the maximum air temperature on a given day (°C); and
T_{snow} is the snow pack temperature on a given day (°C).

$$T_{snow(dn)} = T_{snow(dn-1)} \cdot (1-l_{sno}) + \overline{T_{dn}} \cdot l_{sno} \tag{6}$$

where

l_{sno} is the snow temperature lag factor;
sno_{cov} is the fraction of the HRU area covered by snow; and
$\overline{T_{dn}}$ is the average daily temperature (°C).

b) Measured snow level not available

If measured snow levels are not available, the SWAT model distinguishes between rainfall and snowfall depending on the boundary temperature T_{s-r}. This boundary temperature is not necessarily equal to zero on the Celsius scale, but is usually equal or very close (±1°C). The snowmelt process is modeled for each HRU separately, by determining the reference elevation for each HRU and computing the water content of the snow cover for such HRU elevation and the area in each time step:

$$SNO^{i} = SNO^{i-1} + R^{i} - SNO_{melt}{}^{i-1} - E_{sub}{}^{i-1} \tag{7}$$

where

SNO is the water content of the snow cover on the current day (mm), and
SNO_{melt} is the amount of snowmelt on the given day (mm).

The height of snowmelt is computed from the formula

$$\mathrm{SNO_{melt}} = \mathrm{b_{melt}} \cdot sno_{\mathrm{cov}}\left[\frac{T_{snow}+T_{\max}}{2} - T_{melt}\right] \tag{8}$$

where

b_{melt} is the melt factor for the day (mm/day °C);
T_{melt} is the base temperature above which snowmelt is allowed (close or equal to zero) (°C);
T_{max} is the maximum air temperature on a given day (°C);
R is the precipitation when air temperature is less than T_{s-r} (mm);
T_{s-r} is the rain/snow boundary temperature (°C); and
T_{snow} is the snow temperature (°C).

$$T_{snow(dn)} = T_{snow(dn-1)} \cdot (1-l_{sno}) + \overline{T_{dn}} \cdot l_{sno} \tag{9}$$

where

l_{sno} is the snow temperature lag factor;

E_{sub} is the amount of sublimation on a given day, computed only when $T>T_{melt}$; and
T_{dn} is the average daily temperature (°C).

$$E_{sub} = \frac{E_s}{1+\text{cov}_{sol}} \tag{10}$$

where
cov_{sol} is the soil cover index for albedo determination (for snow level > 0.5mm, cov_{sol} = 0.5), and
Es is the maximum sublimation (soil evaporation).

$$E_s = E_o' \cdot \text{cov}_{sol} \tag{11}$$

The potential evapotranspiration, based on free water in the canopy

$$E_o' = E_o - E_{can}\text{, if } E_0>E_{can} \tag{12}$$

$$E_o' = E_o \quad \text{, if } E_0<E_{can} \tag{13}$$

where
E_o is the potential evapotranspiration;
$E_{can} = R_{INT}$ is the amount of evaporation from free water in the canopy on a given day
sno_{cov} is the fraction of the HRU area covered by snow.

3.2. *Surface flow*

The SWAT uses the SCS CN model to compute the values of surface flow. Depending on ground moisture, surface flow does or does not occur:

$$Q_{surf} = \frac{(R_{day}+SNO_{mlt})^2}{R_{day}+SNO_{mlt}+S} \quad \text{, if } SW^i>0.2S=I_a \tag{14}$$

$$Q_{surf} = 0 \quad \text{, if } SW^i<0.2S=I_a \tag{15}$$

where
I_a is the initial abstraction which includes surface storage;
R_{day} is the amount of rainfall on a given day; and
S is the retention parameter computed from the equation

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10\right) \tag{16}$$

where
$CN=f$ is the soil category (A, B, C or D), vegetation, method of cultivation, land use.

3.3 *Evapotranspiration (ET)*

The potential evapotranspiration is computed by the Hargreaves method, which is the simplest (it only requires average, minimum and maximum air temperatures).

$$\lambda \cdot E_o = 0.0023 \cdot H_o \cdot (T_{\max} - T_{\min})^{0.5} \cdot (\overline{T} + 17.8) \tag{17}$$

where

$$\lambda = 2.501 - 2.361 \cdot 10^{-3} \cdot \overline{T}\,; \tag{18}$$

λ is the latent heat of vaporization;
T_{min} is the minimum daily temperature (°C);
T_{max} is the maximum daily temperature (°C);
$\overline{T}$ is the reference temperature (°C); and
H_o is the extraterrestrial radiation (MJ/m^2day).
H_o depends on the day of the year and the latitude, as shown in Fig. 3.

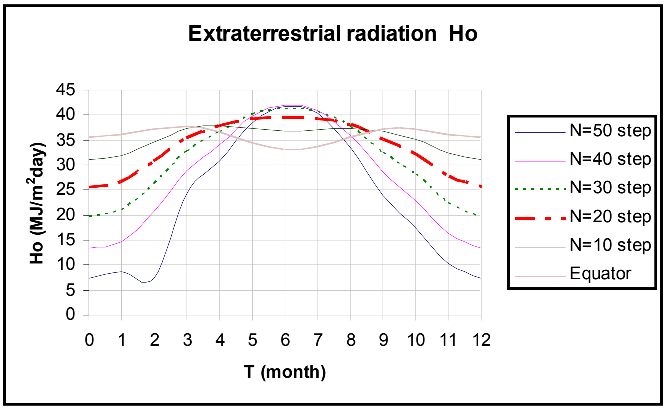

Fig. 3: *Extraterrestrial radiation, Ho.*

3.4. *Rainfall reaching the ground*

If there is vegetation, not all of the rainfall registered by weather stations (R_{day}') will reach the ground. A portion of the rainfall will remain on leaves and tree trunks. A part of such rainfall will evaporate, and a part will be consumed by the vegetation for its growth.The amount of free water in the vegetation canopy is computed from the relations

$R^i_{int}=R^{i-1}_{int}+R'_{day}-Ea^{i-1}$ and $R_{day}=0$ when $R'_{day} \leq can_{day} - R^{i-1}_{\text{int}}$ (19)

$R^i_{int}=can_{day}$ and $R_{day}=R'_{day}-(can_{day}-R^{i-1}_{int})-Ea^{i-1}$ when $R'_{day} \geq can_{day} - R^{i-1}_{\text{int}}$ (20)

where

$R^{day}{}'$ is the amount of precipitation on a given day before canopy interception is removed

R^{day} is the amount of precipitation on a given day (mm); and

E^a is the actual evapotranspiration (mm).

The following logical condition is introduced:

$$R_{\text{int}} \leq can_{day} \tag{21}$$

This condition ensures that the amount of free water in the canopy cannot be greater than the maximum amount of water that can be trapped by the canopy on a given day. Canopy storage is a contributing factor to the process of evapotranspiration, i.e. a part of the water trapped by the canopy may have a significant effect on infiltration, surface runoff and evapotranspiration. The canopy storage varies daily and is a function of the leaf surface area. When rainfall occurs in areas of dense vegetation, water can reach the ground only after the canopy storage is sated.

$$can_{day} = can_{\max} \cdot \frac{LAI}{LAI_{\max}} \tag{22}$$

where

can_{day} is the maximum amount of water that can be trapped in the canopy on a given day;
can_{max} is the maximum amount of water that can be trapped in the canopy when the canopy is fully developed;
LAI is the leaf area index of the canopy (m^2/m^2); and
LAI_{max} is the maximum leaf area index of the canopy (m^2/m^2).
LAI and LAI_{max} are presented in tabular form in the database (GIS content) for each plant species separately.

3.5. *Actual evapotranspiration*

Once the potential evapotranspiration and the amount of water trapped in the canopy are determined, it is possible to compute the actual evapotranspiration:

if $E_0 < R_{int}$, then $E_a = E_0$ (23)

if $R_{INT} = 0$, then $E_a = E_0$ (24)

if $E_0 > R_{int}$, then $E_a = R_{int}$ (25)

3.6. *Percolation*

A portion of the water from the HRU percolates into the deeper reaches of the ground. The rate of penetration depends on the ground pore size, structure, fraction density, moisture and other parameters.

Percolation is computed as follows:

$$w_{seep} = SW_{excess}\left\{1-\exp\left[\frac{-\Delta t}{TT_{perc}}\right]\right\} \tag{26}$$

where SW_{excess} is the drainable volume of water in the soil layer on a given day.

$$\begin{aligned} SW_{excess} &= SW - FC; \quad SW > FC \\ SW_{excess} &= 0; \quad SW < FC \end{aligned} \tag{27}$$

where

FC is the water content of the soil profile at field capacity (mm), and

SW is the water content of the soil layer on a given day (mm).

$$FC = WP + AWC \tag{28}$$

where *WP* is the water content at the permanent wilting point (mm).

$$WP = 0.4 \cdot \frac{m_c \cdot \rho_b}{100} \tag{29}$$

where

ρ_b is the soil bulk density (kg/m^3);

m_c is the percent clay content;

AWC is the available water capacity (user input); and

TT_{perc} is the travel time for percolation.

$$TT_{perc} = \frac{SAT - FC}{k_{sat}} \tag{30}$$

where

SAT is the amount of water in the soil when completely saturated (mm);

k_{sat} is the saturated hydraulic conductivity for the layer (mm/h); and

Δt is the time step.

The percolation travel time is unique for each layer and depends on the amount of water in the soil layer when fully saturated and the water content of the soil layer.

3.7. *Groundwater outflow*

Groundwater outflow is a part of the overall basin outflow, which occurs regardless of rainfall or snowmelt. Depending on the subsurface retention capacity, the outflow may be higher or lower, but in the case of sub-basins of the Drina River basin it is significantly less than the surface flow. Its formula is therefore relatively simple, even though the natural process is somewhat more complex.

$$Q_{gw} = \frac{8000 \cdot k_{sat}}{L_{gw}^2} \cdot h_{wtbl} \quad \text{(mm)} \tag{31}$$

where

k_{sat} is the saturated hydraulic conductivity for the layer (mm/h);
h_{wtbl} is the water table height (m); and
L_{gw} is the distance from the ridge or sub-basin divide for the groundwater system to the main channel.

4. Total outflow from the basin

Under the initial condition that there are *k* HRUs for a basin, the outflow from the basin is the sum of surface flow and groundwater outflow from all of the HRUs in the considered time step *j*.

$$Q_j = \sum_{i=1}^{k} Q_{surf}^{i} + Q_{gw}^{i} \tag{32}$$

The SWAT provides two flow components: Q_{surf} and Q_{gw}. In the case of the first component there is a flow lag between the point of origin and the outflow profile. For the second component it is assumed that groundwater outflow is constant and thus there is no lag.

4.1. *Flow rate at the basin outflow profile*

The surface flow Q_{surf} travels for some time before it reaches the outflow profile. This is a consequence of overland flow in the drainage area and channel flow. The surface flows of all HRUs are superimposed on the outflow profile. The time required for the HRU flow to reach the outflow profile is the flow (travel) time. Each HRU has its own flow time:

$$t_{conc} = t_{ov} + t_{ch} \tag{33}$$

where

t_{ov} is the overland flow time of concentration, and

t_{ch} is the channel flow time of concentration.

$$t_{ov} = \frac{L_{slp}^{\ 0.6} \cdot n^{0.6}}{18 \cdot slp^{0.3}} \tag{34}$$

where
L_{slp} is the sub-basin slope length (m);
n is Manning's roughness coefficient for the sub-basin; and
slp is the average slope of the sub-basin (m/m).

$$t_{ch} = \frac{0.62 \cdot L \cdot n^{0.75}}{Area^{0.125} \cdot slp_{ch}^{0.375}} \tag{35}$$

where
L is the channel flow length (km);
n_{ch} is Manning's roughness coefficient for the channel;
Area is the sub-basin area (km^2); and
slp_{ch} is the average channel slope along the channel length (m/m).

The surface runoff from a single HRU is computed from the equation

$$Q_{surf} = (Q_{surf}^{'} + Q_{stor,i-1})(1 - \exp(\frac{-sur_{lag}}{t_{conc}})) \tag{36}$$

where
$Q_{surf}^{'}$ is the amount of surface runoff generated in the sub-basin on a given day;

$Q_{stor,i-1}$ is the surface runoff stored or lagged from the previous day; and
sur_{lag} is the surface runoff lag coefficient.

4.2. Data required to run the SWAT model

<u>a) Data required to compute the concentration time:</u>
L_{slp} – the sub-basin slope length (m);
n – Manning's roughness coefficient for the sub-basin ($m^{-1/3}s$);
slp – the average slope of the sub-basin (m/m);
L – the channel flow length (km);
n_{ch} – Manning's roughness coefficient for the channel ($m^{-1/3}s$);
$Area$ – the sub-basin area (km^2);
slp_{ch} – the average channel slope along the channel length (m/m); and
sur_{lag} – the surface runoff lag coefficient.

<u>b) Required input data for each HRU:</u>
A_i – the area of each HRU (all equal, except boundary HRUs) (km^2);
z_i – the reference elevation of each HRU (m.a.s.l.);
CN – numerical identification of each HRU, derived from the following information:

- Soil category (A, B, C, D)
- Vegetation (forests, pastures, fields, arable land, etc.);
- Cultivation method;
- Land use;

SWo – the initial amount of water in the soil (mm);
SAT - the amount of water in the soil when completely saturated (mm);
k_{sat} – the saturated hydraulic conductivity for the layer (mm/h);
AWC – the available water capacity (mm);
h_{wtbl} – the water table height (m);
L_{gw} – the distance from the ridge or sub-basin divide for the groundwater system to the main channel (m);
sno_{cov} – the fraction of the HRU area covered by snow;
ρ_b – the soil bulk density (kg/m^3);
m_c – the percent clay content;
LAI – the leaf area index of the canopy (m^2/m^2);
LAI_{max} – the maximum leaf area index of the canopy (m^2/m^2); and
can_{max} – the maximum amount of water that can be trapped in the canopy when the canopy is fully developed.

5. Illustration of the swat model in use

Originally, the model was developed for daily discretization, but it may equally be used at other levels (e.g. hourly discretization). Given below are illustrations of the SWAT model when used for daily discretization of an imaginary drainage area of about 100 km^2. The input parameters are entered by the user, or are GIS-generated and the user makes adjustments. If there are blanks in the archived information, input weather data are retrieved from the database and entered. Shown below are several input data windows. An important component considered by the SWAT is the snow level (Fig. 4):

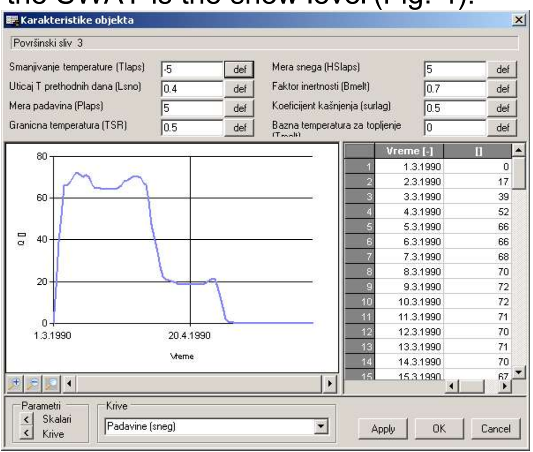

Fig 4 *Database information: Snow level.*

Precipitation (rainfall) is the most important measured input quantity. Applying predefined criteria, the SWAT retrieves precipitation values from a specific weather station and corrects such values, or adjusts them to each HRU. Such precipitation information is illustrated in Fig. 5.

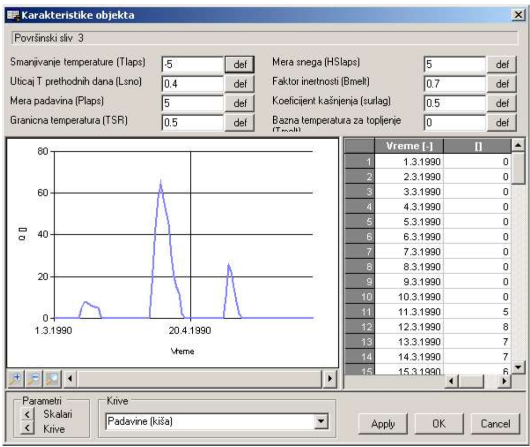

Fig. 5 *Database information: Registered rainfall.*

The SWAT requires a number of input parameters, each of which has its own physical meaning, and it is thus a so-called *green-box* model. The previous section addressed the input parameters and, in view of their number, only some of these parameters will be illustrated here.Figure 6 shows the leaf area index of the canopy on a given day:

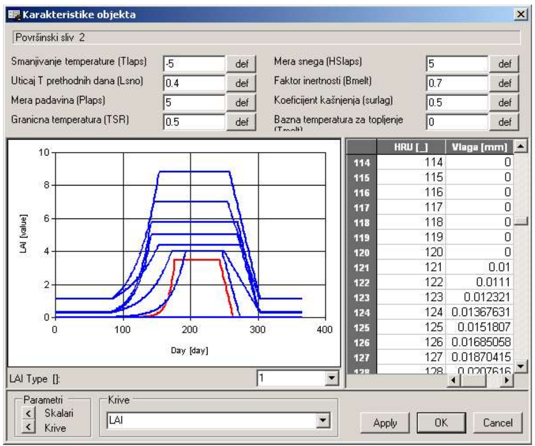

Fig. 6 *LAI values for different types of vegetation.*

One of the components that governs the time required for water to travel from a particular HRU to the outflow profile is shown in Fig. 7.

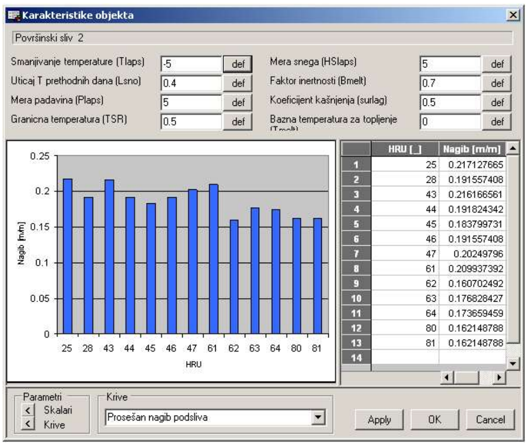

Fig. 7 *Average slope of a sub-basin.*

Once all input quantities are verified, the simulation can begin. The simulation provides output data, the most important being the flow hydrograph of the considered sub-basin. An example of such a simulation is given in Fig. 8.

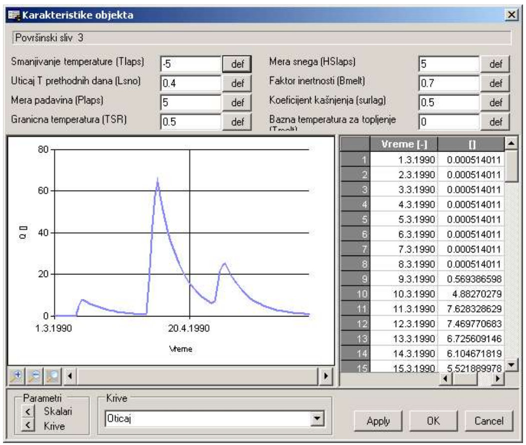

Fig. 8 Discharge hydrograph of the outflow profile.

As conceived and shown here, the SWAT allows the generation of rainfall-runoff for all sub-basins of an entire basin. It would be used for all upstream sub-basins that are not influenced by the river reservoir. The outflow hydrographs of the downstream profiles would represent inflows into the reservoir. Other models would be used to transform such hydrographs through reservoirs and to propagate them to the outflow profile of the entire considered basin.

6. References

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