MATHEMATICAL MODEL OF RAINFALL-RUNOFF TRANSFORMATION - WISTOO

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ABSTRACT: Mathematical model WISTOO (Wizualizacja Integralnego Systemu Transformacji Opadu w Odpływ – Visualization of Integral Rainfall-Runoff Transformation System) is the complex solution of rainfall-runoff transformation problem with use of geographical information system. It is integral, distributed model. Its structure includes main hydrological processes, like interception, evapotranspiration, infiltration, surface and subsurface runoff, groundwater runoff and recipients runoff. Model was readjusted to mountainous and hilly watersheds. Connection of hydrological processes with geographical information systems in one model makes easier simulation of different watershed land-use. Model was created at Cracow University of Technology in cooperation with Warsaw University of Technology.

WISTOO model is adopted for simulation with one hour step for mountainous and hilly watersheds. Long-term simulations can be conducted – up to 185 days (summer half-year). Model is implemented for personal computers with Windows operating system, and uses digital thematic layers (Fig. 1):
- digital elevation model,
- stream network,
- soil structure,
• land-use structure.

In the algorithm, mainly raster square model of spatial phenomena description is used. Raster size depends on scale, but computer program can handle maximum 4 000 000 raster elements (cells).

Computer implementation of algorithm enables tracing of:
• hydrographs in ten arbitrary river cross-sections,
• spatial distribution of: net precipitation, velocity and depth of surface and subsurface flow, soil moisture,
• influence of water reservoir.

Figure 1. Digital thematic layers used in WISTOO model.
From top – land-use, stream network, soils, topography

Computer program contains many helpful tools for data acquisition and pre-processing e.g.:
• preparation of digital elevation model from analogue maps,
• changes in thematic layers content,
• temporal distribution into hour data of measurement data collected 2-3 times a day.

General structure of the model is based on standard water cycle in the watershed (Fig. 2). Input data for the model consist of:

• watershed parameters: terrain slope, coverage retention, rainfall separation coefficient, surface permeability, soil porosity coefficient, soil depth, etc.,
• spatial distribution of measuring stations and type of measured data,
• spatial distribution of gauging stations on streams (maximum 10),
• hydrometeorological data.

Those data sets are pre-processed by dedicated software into WISTOO data format.

As WISTOO is physically-based mathematical model, good watershed identification is an essential issue. None of parameters used in the model is optimized. Parameters are mainly calculated from digital thematic layers. Soil parameter determination in small watersheds with uniform soil pattern is rather easy. When watershed area increases, complicated soil pattern and soil diversity makes determination of parameters more difficult. Model needs also dense net of measuring stations, mainly precipitation stations.

1. INTRODUCTION

1.1. Place of WISTOO model between other rainfall-runoff models

In WISTOO model watershed runoff was solved based on distributed parameters and two-dimensional in plane calculation space. So it is not typical model simulating runoff in watershed closing cross-section. Was assumed, that WISTOO model should enable:
• correct runoff simulation in watershed closing cross-section,
• correct runoff simulation in any upstream cross-section,
• representation of spatio-temporal structure of surface and subsurface runoff.

Those requirements caused, that model is based on hydrodynamic equations, describing partial runoff processes.

Genesis of model development is related to need of numerical assistance in flood protection planning for southern part of Poland. This region is characterized be complex land-use structure and sparse network of meteorological and hydrological stations. Flood protection planning in this region requires:
• quantitative evaluation of flood risk, including places exposed to potential intense water runoff,
• development of suitable behavior strategy and choice of economically justified protective activities, including mainly treatments minimizing intense runoff.

Such formulation of problem resulted in development of simulation model, solving rainfall-runoff transformation in proper spatial scale. Model structure matching runoff regime and support of runoff description on its physical characteristics was a key to success. So far application experiences proved, that such construction of methodology fulfils established demands.

WISTOO model in details describes runoff process, concerning its components and spatial scale. It can be seen as advances rainfall-runoff model. This type of models, besides its practical application, helps in identification of physical characteristics of watershed runoff. In practical applications is used mainly in determination of land-use change on spatio-temporal runoff structure.

1.2. Limitations in model application

Assumed, high level of detail solution in WISTOO model, limits its application possibilities. In general, model structure focuses on mountainous watersheds, but can be also applied for hilly
watersheds. Application criteria can be expressed by following conditions:

- possibility of surface and subsurface runoff representation (including stream flow) by kinematic wave,
- possibility of groundwater runoff representation by one reservoir, which area is equal watershed area and length is equal to stream network length.

Those conditions are fulfilled in mountainous and hilly watersheds. Number of meteorological stations determines precipitation supply precision for analyzed area. It is assumed, that parameters describing topography of the watershed, its surface and subsurface structure, land-use – are identified locally on required level of accuracy.

### 1.3. Required input data

WISTOO model needs input data in GIS format and adequate meteorological data. Required thematic layers:

- digital elevation model - in raster format,
- hydrography network with elevations - verified for flow capacity,
- soil structure and type – according polish or general classification (chapter 4),
- land-use structure - according described classification (chapter 4),
- location of measuring stations.

Hydrometeorological data recorded in one hour or daily system are inputted directly by special procedure. This procedure sorts end exports data in internal data format. First step is to prepare digital thematic layers in order to generate watershed parameters. All thematic layers must be in the same coordinate system with the same resolution.
2. DESCRIPTION OF PARTIAL PROCESSES

2.1. Structure of the model

Structure of WISTOO model is based on well-known water cycle in the watershed (Fig.2), where the following processes can be distinguished: interception, evapotranspiration, infiltration, surface runoff, subsurface runoff, groundwater runoff, and stream net runoff.

![Natural water cycle scheme](image)

Figure 2. Natural water cycle scheme

Developed calculation procedures describe dynamics of particular process on accepted level of accuracy.
### 2.2. Spatial distribution of meteorological parameters

Spatial distribution of meteorological parameters is main source of information related to meteorological situation at certain moment in the watershed. Distribution of meteorological values is calculated based on ground-based measuring systems. Usually, distribution methods are local and depend on measuring net density. These methods are not universal, and in most of the cases transfer to another region is impossible.

#### 2.2.1. Basic methodical assumptions

Basic method in the model for spatial distribution of meteorological parameters is inverse distance method IDM. It enables estimation of meteorological parameters as continuous function. In calculation, only the closest or all measuring stations in the region are used, unnecessarily located in the watershed.

Basic assumption of this method is based on observation, that influence from of measuring station on any point is inversely proportional to distance from that point to the station. So influence of any measuring station decreases with distance. Calculated values for meteorological parameters at any point in the watershed are determined using formula:

\[
P_i = \frac{\sum_{k=1}^{j} \left( \frac{1}{d_k^n} \right) P_k}{\sum_{k=1}^{j} \frac{1}{d_k^n}}
\]

where:  
- \( P_i \) - value of calculated parameter at point \( i \), \( i=1,2,...,m \),  
- \( P_k \) - measured value at point \( k \), \( k=1,2,...,l \),  
- \( j \) - number of measuring stations,  
- \( n \) - index exponent,  
- \( d_k \) - distance form point \( i \) to measuring station \( k \).
Index exponent $n$ depends on watershed topography. Its value changes from 1 for lowlands, to 3 for mountainous regions.

Long-term observations in mountainous watersheds demonstrated strong influence on topography on meteorological parameters.

2.2.2. Description of spatial precipitation structure used in WISTOO model

In general, precipitation depth increases as terrain raises. Relationship between precipitation depth and elevation is described by gradient precipitation curve. Another factor influencing gradient value is precipitation intensity. For intense rainfall events, inclination of that curve is smaller then for average events.

Precipitation depth is calculated from formula:

$$ R'_x = R_x + A \left( H'_x - H_x \right) R_x $$  \hspace{1cm} (2)

where: $R'_x$ - rectified precipitation depth, [mm],
$R_x$ - precipitation depth calculated by inverse distance method, [mm],
$A$ - gradient curve inclination coefficient, [1/m],
H'x - transfer elevation, [m],
Hx  - terrain elevation, [m].

Transfer elevation $H'x$ is related to elevation of measuring points above sea level. Its value is constant for certain measuring stations net and can also be evaluated from inverse distance method (1) using elevation of measuring station as parameter.

Gradient curve inclination coefficient is calculated as follows:

$$A = \frac{R_1 - R_{i+1}}{(H_1 - H_{i+1}) R_i} \quad (3)$$

where: $R_i$, $R_{i+1}$ - recorded precipitation depth for the lowest and the highest station in the watershed, [mm],

$H_i$, $H_{i+1}$ - elevation above sea level for the highest and the lowest station in the watershed, [m].

In high mountains rainfall inversion phenomenon can be observed. Above certain elevation, precipitation depth decreases with elevation. In such a case, in order to implement precipitation depth – elevation relation, equation (2) must take into account inversion process. It can be realized by transformation of elevation for all the areas above inversion point into corresponding values calculated from gradient curve. From modified digital elevation model, spatial distribution of precipitation can be calculated using only ascending relation (linear or non-linear).

2.2.3. Recommendations for practical application of the model for meteorological parameters determination

Precipitation. Figure 4 demonstrates spatial distribution of precipitation calculated using inverse distance method. Figure 5 shows precipitation distribution calculated by gradient IDM concerning inverse point for the same data from Wielka Puszcza
watershed. Differences in spatial distribution from those two methods are major – with constant maximum precipitation depth.

Figure 4. Spatial precipitation distribution calculated by inverse distance method for Wielka Puszcza watershed

Figure 5. Spatial precipitation distribution calculated by gradient inverse distance method concerning inverse point for Wielka Puszcza watershed
In presented model, inverse distance method is the main used for precipitation distribution calculation. This method needs gradient curve to be elaborated. For many watersheds it is difficult to archive, due to lack of ground-based measuring stations. But if such information is available, model enables use of linear or non-linear function.

Gradient method was successfully implemented in Wielka Puszcza (Cracow University of Technology experimental watershed located in Beskid Mały) and Czarny Dunajec (Tatra Mountains) watersheds. In first watershed inversion point was located at 550-570 m.a.s.l., in second at 1400 m.a.s.l.

Verification on historical data proved, that gradient curve method determines spatial distribution of precipitation much better than inverse distance method. In general, relative precipitation distribution error is up to 50% smaller for gradient method than for inverse distance method. It should be pointed out, that proper location of measuring stations in those watersheds minimizes errors in inverse distance method.

Other meteorological parameters are calculated using similar methodology. Wind velocity and air temperature are strongly related to measurement station location, so gradient method is recommended rather than inverse distance method. Gradient curve inclination coefficient $A$ (3) is determined from current measurements at measurement station. In pre-processing procedures user can declare stations to calculate this coefficient. Atmospheric pressure and sun radiation are treated as homogenous in space.

In general, it is recommended that measurement stations location should cover whole elevation range. Spatial distribution of meteorological parameters uses two algorithms depending on available data:

- only for precipitation,
- for precipitation, air temperature, air relative humidity, wind velocity, sun radiation.
Selection of algorithm is automatic based on available data. Second algorithm can be used when at least two measurement stations collect all necessary meteorological data.

2.3. Interception

2.3.1. Description of the process

Interception process is based on temporal storage of rainfall by plants. Most often for mathematical description of this process Rutter model is used.

\[
\frac{dc}{dt} = (1 - p) R - E_p \frac{c}{s} \quad \text{dla } c < s
\]

\[
\frac{dc}{dt} = (1 - p) R - E_p - D_o e^{b(c-s)} \quad \text{dla } c \geq s
\]

where: 
- \( R \) - rainfall intensity, [mm/min],
- \( p \) - rainfall separation coefficient, [-],
- \( s \) - plants retention, [mm],
- \( c \) - current water depth on plants, [mm],
- \( E_p \) - potential evaporation, [mm/min],
- \( D_o \) - minimal dripping from plants when \( c = s \), [mm/min],
- \( b \) - dripping vs. water depth on plants curve coefficient, [1/mm],
- \( e \) – napierian base.
2.3.2. **Interception process solution used in the model**

In experimental way, simplified model simulating interception process was elaborated. It was found that dripping process has minor influence on rainfall-runoff transformation. So dripping process can be disregarded, simplifying solution of this problem. **Net precipitation** is calculated from relation:

\[
R_{\text{nett}} = \begin{cases} 
  p R & \text{dla } c \leq s \\
  R & \text{dla } c > s
\end{cases}
\]

(5)

where: \(R_{\text{nett}}\) - net precipitation, [mm/min].

Separation coefficient \(p\) defines which part of precipitation reaches directly ground without wetting plants. Retention \(s\) defines maximum precipitation depth, which wets plants. Value of this parameter describes precipitation loss. In algorithm, for every calculation time step current water depth on plants is determined. In first phase of rainfall event for \(c \leq s\), net precipitation \(R_{\text{nett}}\) is defined on the basis of rainfall separation coefficient \(p\). When the retention \(s\) is filled up, net precipitation \(R_{\text{nett}}\) has the value of total precipitation \(R\).
Evaporation process is considered when retention is filling up and after rainfall event. Current water depth on plants is calculated from relation:

\[ c_t = c_o + \left[ (1 - p) R - \frac{c_o}{s} E_p \right] \Delta t \]  \hspace{1cm} (6)

where: 
- \( c_t \) - current water depth on plants at time \( t \), [mm],
- \( c_o \) - water depth on plants at time \( t-1 \), [mm].

Potential evaporation depth is calculated evapotranspiration model. Water depth on plants \( c \) at the moment of filling retention \( s \) is stabilized on \( s \) level. For early spring and late fall (April, October) retention and separation coefficient values independently on plants are taken arbitrary as \( s=0.1 \) [mm], \( p=0.05 \).

2.4. Evapotranspiration

2.4.1. Description of the process used in the model

Evapotranspiration is the process, in which water changes phases from liquid to gaseous (evaporation) or through plant’s metabolism (transpiration). Mechanism of this process is very complex. As a consequence, its descriptions are dependent on significance of factors in specific cases. In presented model only two elements are calculated:
- evaporation from wetted surfaces – potential evapotranspiration,
- plant transpiration – current evapotranspiration (Fig.7).

Other types of evaporation like evaporation from water and soil surfaces are not taken into account in the model.
high plant's transpiration

low plant's transpiration

soil

subsoil

moisture change

Figure 7. Current evapotranspiration process scheme
2.4.2. Description of evapotranspiration process used in the model

Penman-Monteith equation is the basic describing evapotranspiration process in the model:

\[
E_a = \frac{\Delta (R_n - G) + \rho c_p (\varepsilon - e_e) / r_a}{\lambda \left[ \Delta + \gamma \left( 1 + \frac{r_a}{r_c} \right) \right]}
\]  

(7)

where:
- \( E_a \) - current evapotranspiration, [mm],
- \( \Delta \) - inclination of water vapor pressure curve vs. temperature, [hPa/K],
- \( R_n \) - net radiation, [W/m\(^2\)],
- \( G \) - soil heat flux, [W/m\(^2\)],
- \( \rho c_p \) - volumetric dry air heat capacity, [J/m\(^3\)K],
- \( \varepsilon, e_e \) - maximal and current water vapor pressure, [hPa],
- \( r_a \) - aerodynamic resistance function, [s/m],
- \( r_c \) - superficial resistance function, [s/m],
- \( \lambda \) - latent heat of evaporation, [J/kg],
- \( \gamma \) - psychrometric constant, [hPa/K].

Potential evaporation is determined from equation (7) with assumed superficial resistance coefficient \( r_c \) equal zero. Value of superficial resistance coefficient \( r_c \) is calculated from:

\[
r_c = a + \frac{b_a}{R_n + c_a}
\]  

(8)

where:
- \( a \), \( b_a \), \( c_a \) – empirical parameters determined from experiments for two plant types – high plants (forest) and low- cultivable plants: \( a \) [s/m], \( b_a \) [sW/m\(^3\)], \( c_a \) [W/m\(^2\)].
Aerodynamic resistance coefficient $r_a$ was taken after [Stigter C. J., 1980]:

$$
    r_a = 8.06 \frac{\left( \ln \left( \frac{z_v - d_h}{z_o} \right) \right)^2}{1 + 0.864 v_w}
$$

(9)

where: $z_v$ - altitude of wind velocity measurement, [m],
$d_h$ - base altitude $d_h = 0.63 h_r$, [m],
$z_o$ - height of plants roughness $z_o = 0.13 h_r$, [m],
$h_r$ - average height of plants, [m],
$v_w$ - wind velocity, [m/s].

Calculation procedure starts when input data, like air temperature and relative humidity, wind velocity and sun radiation are prepared. Sun radiation can be substituted by cloud cover values. Additionally, in pre-processing procedure, measuring stations for determination of gradient curve coefficient $A$ have to be defined.

Often, location of meteorological stations eliminates possibility of using this procedure due to lack of measured meteorological parameters or inappropriate location. In order to determine well evaporation values, meteorological parameters must become from mountain tops and valleys. For most of watersheds such observations are not conducted. In such a case values of potential and current evaporation are set obligatory for every month. Those values come from regional measurement calculations or transferred from other similar watersheds.

In the model authors assume, that low plant’s transpiration directly influences soil layer. For forest, evenly water intake from soil surface and subsurface is assumed. This process starts in periods without precipitation. During precipitation and just after event evaporation values are calculated from plants wetting rate:
Infiltration is the process of percolation of part of net precipitation through soil surface and displacement of water in aeration zone. It is the most important process in every rainfall-runoff transformation model. It decides on quantitative separation of net precipitation into: surface runoff, subsurface runoff and groundwater flow. From description of this process depends accuracy of runoff hydrograph representation in watershed closing cross-section.

Necessity of model implementation for every cell increased model complexity. Every model has to take into account soil retention and precisely describe transformation of precipitation in soil profile.

Figure 8. Scheme of procedure simulating infiltration process
In hydrology, many infiltration models are implemented, from empirical ones to more complicated using conductivity and diffusion theory. Selection of appropriate model is always compromise between expected result and computation possibilities. Many computation cells highly limits use of diffusion models due to number of calculation parameters and soil characteristics. Not always there are available data.

From conductive type models, piston Green-Ampt model was selected. Model assumes, that every precipitation event forms wetting front described by two variables: location $z$ and volumetric humidity $\Theta$. Humidity for every front is constant. Saturated front movement velocity is described by Darcy equation.

2.5.2. Application of the model for infiltration

**Front movement velocity.**
Described by Darcy equation, saturated front movement velocity has a form:

$$v = K S_h = K \left( 1 + \frac{h_w + h_k}{z} \right)$$

where: $v$ - infiltration rate, [m/s],  
$h_k$ - capillary height, [m],  
h$_w$ - water depth on soil surface, [m],  
K - soil hydraulic conductivity, [m/s],  
z - wetting front depth, [m],  
S$_h$ - hydraulic gradient, [-].

**Hydraulic conductivity.**
Hydraulic conductivity is estimated from formula:
\[ K(\Theta) = K_o \left( \frac{\Theta - \Theta_s}{\Theta_o - \Theta_s} \right)^\alpha \]  

(12)

where: \( K_o \) - maximal soil conductivity (filtration coefficient), \([m/s]\),  
\( \Theta_s \) - volumetric humidity of permanent plant wilting, [-],  
\( \Theta_o \) - maximal volumetric humidity – soil porosity index, [-],  
\( \alpha \) - exponent index dependent on soil type: \( \alpha \in (3; 4) \), in model \( \alpha \) is equal 3.5.

**Aeration zone structure and its description.**

In natural watersheds streams are supplied from three layers: surface, aeration zone (subsurface) and saturation zone (groundwater). In the model, aeration zone is divided into two sub-layers: soil and subsoil. This is not typical approach in conductance models. Algorithm in presented model enables calculations for those two sub-layers with water exchange between them.

Solution of this problem was derived from infiltration models using diffusion theory. In diffusion models water exchange between nodes or layers is modeled by moisture flux \( q \) depending on diffusion potential, usually described by main component of soil suction pressure:

\[ q_{i}(z,t) = - K(\psi) \left( \frac{\partial \psi}{\partial z} - 1 \right) \]  

(13)

where: \( q_i \) - moisture flux, \([m^3/m^2 \text{ min}]\),  
\( \psi \) - soil suction pressure, \([m]\).

Relation between **volumetric humidity** \( \Theta \) and **soil suction pressure** \( \psi \) is usually presented in form of \( pF = \log(-\psi) \) curve, where \( \psi [m] \) is soil suction pressure. This relation is one of basic soil characteristics.
In the model, simplified, linear description of this characteristic is used (Fig.9), with 0 assigned for humidity equal to porosity coefficient and maximal value for dry soil. Water displacement velocity is defined as:

$$v = K \left( \frac{\Psi_g - \Psi_d}{z} + 1 + \frac{h_w}{z} \right)$$  \hspace{1cm} (14)$$

where: $\Psi_g$ - suction pressure in upper node, [cm],
$\Psi_d$ - suction pressure in bottom node, [cm].

Expression $\Psi_g - \Psi_d$ stands for **capillary height** $h_k$. This placement of potential difference between soil and subsoil in stead of capillary height enables automatic control of infiltration process.

Water movement in new formula depends on bottom layer humidity. When upper layer humidity decreases comparing to bottom layer, hydraulic gradient decreases and as the result infiltration intensity decreases. When humidity difference between layers is high, water movement in soil layer is stopped until humidity gradient decreases. In such situation infiltration rate has negative values, it means, humidity transfer goes from subsoil to soil layer. Lack in connection between soil and subsoil due to higher soil hydraulic conductivity causes over-drying of soil layer. In longer dry periods, humidity can reach values close to plant wilting point.
Runoff occurrence conditions

Both surface and subsurface runoff appear when water inflow exceeds infiltration capacity. Runoff starts when $v < R$ (where: $v$ – infiltration rate, $R$ – precipitation intensity). Excess height $(R - v)$ is input value for surface and subsurface runoff transformation models. Subsurface runoff starts when wetting front passes through surface part of the soil. Water velocity in this layer depends also from water depth $h_w$. This depth is determined from subsurface runoff transformation model considering soil filtration coefficient $\mu$.

In every time step, moisture volume balance in soil and subsoil is calculated. Supply volume of every layer is equal:

$$V = R \Delta t$$

(15)

and total volume of absorbed moisture:

$$V = \sum_{i=1}^{3} v_i \Delta t \Delta \Theta_i = \sum_{i=1}^{3} z_i \Delta \Theta_i$$

(16)
where: $\Delta\Theta_i$ – width of humidity front, [-].

Real velocity of humidity front movement is equal:

$$v_i = \frac{K(\Theta_i) - K(\Theta_{i-1})}{\Theta_i - \Theta_{i-1}}$$  \hspace{1cm} (17)

Based on field experiments, three fronts were used for description of humidity movement: one basic and two variables for movement during rainfall event description. Creation and removal of fronts is based on assumptions:

- new fronts are created always when existing fronts are not able to get supply water and maximal humidity is smaller than soil porosity coefficient,
- if supply water volume exceeds absorption possibilities of existing fronts, two fronts (with maximal moisture) are connected into one, with volume equal sum of source fronts and humidity equal humidity of removed front,
- in dry periods, moisture is transferred between fronts,
- if front with higher moisture content runs ahead of another, those two fronts are connected,
- variable front is removed when reaches soil or subsoil boundary (groundwater table) and removed front is connected with basic front,
- front width ($\Delta\Theta$) can not be smaller than 0.001$[cm^3/cm^3]$, in such a case, this front is added to adjacent front and outcome front volume is a sum of two source fronts.

**Outputs from the model are:** exceed rainfall, input values for subsurface runoff and groundwater runoff.

**Initially conditions.**
Key element is determination of initially conditions of the process, i.e. initial humidity. This problem is solved with assumption that volume of water supplying groundwater reservoir is equal watershed runoff:
\[ Q_k = \sum_{i=1}^{n_z} F_i R_{g_i} = \sum_{i=1}^{n_z} F_i R_{p_i} \]  \hspace{1cm} (18)

where: \( Q_k \) - groundwater runoff in watershed closing cross-section, 
\( F_i \) - cell area, 
\( R_{g_i} \) - groundwater table supply, 
\( R_{p_i} \) - subsoil layer supply, 
\( n_z \) - number of elements supplying groundwater table.

Determination of initial humidity distribution starts from subsoil layer in iterative mode. Initial condition is that humidity in every element is equal porosity coefficient (maximal volumetric humidity). Iteration process is over when volume of water supplying groundwater reservoir is close to watershed runoff. Calculations are conducted with 24 hours time step. Similar procedure is used for soil layer humidity distribution. Initial humidity is equal subsurface humidity. Balance of inflow and outflow from the sub-soil layer is evaluated for each computational element.

### 2.6. Surface and subsurface runoff

Surface runoff is the water flow process over terrain surface. It is formed as result of excess rainfall over certain area, i.e. when infiltration soil capacity is smaller than net rainfall intensity.
Subsurface runoff process covers horizontal water movement in aeration zone. It is caused by water excess in this zone. This phenomenon is a consequence of hydraulic gradient between soil and subsoil layers. Soil hydraulic conductivity is two orders of magnitude higher subsoil conductivity. Due to difference on boundary between those layers, subsurface runoff from water excess is formed.
2.6.1. Detailed description of runoff process

Surface and subsurface runoff processes are described by kinematic wave equation:

\[
\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial h}{\partial t} = R_E
\]

\[
q = \alpha_k h^N
\]

where: 
- \( q \) - unit flow, \([m^3/m \cdot s]\),
- \( h \) - water depth, \([m]\),
- \( R_E \) - excess rainfall or subsurface supply, \([m/s]\),
- \( \alpha_k, N \) - kinematic wave coefficient.

In used model parameters are set like for turbulent flow, according Manning theory:

\[
\alpha_k = \sqrt{\frac{S_z}{n_h}}
\]

\[
N = \frac{5}{3}
\]

where: 
- \( S_z \) - terrain slope, \([-]\),
- \( n_h \) - hydraulic resistance coefficient, called roughness coefficient, \([1/m^{1/3}]\).

Assumption was made that water exchange between cells takes place on the boundary between them. In presented procedure, **implicit four-point Preismann scheme** was used. Partial derivatives are written in the form:

\[
\frac{\partial q_x}{\partial x} \approx \beta \frac{q^{i+1}_x - q^{i-1}_x}{\Delta x} + (1 - \beta) \frac{q^i_x - q^{i-1}_x}{\Delta x}
\]
\[ \frac{\partial q_y}{\partial y} = \beta \frac{q_{i+1}^y - q_{i}^y}{\Delta y} + (1 - \beta) \frac{q_{i}^y - q_{i}^y}{\Delta y} \quad (22) \]

\[ \frac{\partial h}{\partial t} = \frac{h_{i+1}^t - h_{i}^t}{\Delta t} \quad (23) \]

\[ R_E = \beta R_{E_{i+1}}^t + (1 - \beta) R_{E_i}^t \quad (24) \]

where: \(\beta\) - weight coefficient \([0,5 \div 1,0]\),

\(R_E\) - excess rainfall or subsurface supply, \([\text{mm/s}]\).

Developing equation (19) for \(h_{sr}^{t+1}\) and assuming, that \(\Delta x\) is equal \(\Delta y\) we get nonlinear equation:

\[ a h_{sr}^{5/3} + b h_{sr} + c = 0 \quad (25) \]

where: \(a = \frac{\alpha \beta}{\Delta x}\)
\[
b = \frac{1}{\Delta t}
\]
\[
c = \frac{\beta q_{\text{id}}^{i+1}}{\Delta x} + \frac{(1 - \beta) (q_{\text{id}}^i - q_{\text{o}}^i)}{\Delta x} - \frac{h_{\text{sr}}^i}{\Delta t} - \beta R_E^{i+1} - (1 - \beta) R_E^i
\]

\(q_{\text{id}}\) - inflow sum for cell, \(q_{\text{o}}\) - outflow sum for cell.

For solution of equation (25) Newton-Raphson method was used, where \(h_{\text{sr}}^{i+1}\) value is calculated from relation:

\[
h_{\text{sr}}^{i+1} = h_{\text{o}}^i + \Delta h
\]  

(26)

where: \(\Delta h = \frac{f(h_{\text{sr}})}{f(h_{\text{o}})}\),

\(h_{\text{o}}\) – water depth from previous time step.

Calculations are conducted until \(\Delta h\) is smaller than arbitrary accuracy \(\varepsilon\).

2.6.2. Practical solution of the problem

Two numerical procedures are used for problem solution: for surface runoff and subsurface runoff. Both procedures are based on pre-processed data set describing calculation order. In topological structure of the watershed cells forming it have:

- supplying cells,
- draining cells.

Important feature of those procedures is connection between each other and relation to infiltration process. In subsurface runoff transformation process, water depth can exceed layer depth. Part of the water in this case moves from aeration zone to surface forming secondary surface runoff.

In the model this problem was solved by determination of maximal supply, which will not exceed runoff considering layer
depth in one time step. Excess runoff is transferred to surface runoff procedure. Transformed water depth is calculated from soil depth and filtering coefficient $\mu$, according equation (27).

$$R_{gr} = \frac{(q_{gr}^i - q_{d}^i)}{\Delta x} \beta + \frac{(q_{o}^{j,i} - q_{d}^{j,i})(1 - \beta)}{\Delta t} + \frac{Hg - h_{gr}^{j,i}}{\beta} - \frac{(1 - \beta)R_{E}^{j,i}}{\beta}$$ (27)

where: $q_{gr}$ – maximal outflow from cell calculated from soil layer depth $Hg$ and filtering coefficient $\mu$.

Water flowing on surface and in aeration zone encounters different soil types and obstacles. For example, when water flows from impermeable into natural surface (soil) infiltration process starts. In this case direct influence between runoff and infiltration takes a place. In general, checking soil infiltration capacity at every cell solved this problem. When water supply is smaller than infiltration capacities, and there is water on the surface, part of it is taken. Part of the water taken is calculated from balance, with assumption that the outflow from cell in time step $t_j$ is equal zero. Then:

$$R_{w} = \frac{-q_{d}^j \beta + (q_{o}^{j,i} - q_{d}^{j,i})(1 - \beta)}{\Delta x} \beta - \frac{h_{gr}^{j,i}}{\beta} - \frac{(1 - \beta)R_{E}^{j,i}}{\beta}$$ (28)

Calculated from equation (28) soil and subsoil infiltration depth is source part of infiltration process. When sum depth (supply $R$ and infiltration $R_{w}$) exceeds infiltration capacity of the layer, only part of the water needed for balance compensation resulting from potential infiltration is taken. Infiltration intensity is negative part of equation describing surface and subsurface transformation process.

2.7. Groundwater runoff
Groundwater runoff consists of streams supply from saturation zone. In general, for groundwater table determination in saturation zone one or two-dimensional Boussinesq models are used. Geological structure of mountainous watersheds is usually so complex, that it is difficult to define water table. In WISTOO model this process is simplified. Groundwater is described by one reservoir with area equal to watershed area and width equal to the total of all lengths of river channels in the watershed.

Total outflow from this reservoir is equal watershed runoff at time $t_0$, i.e. from beginning of calculations. Value of side supply for stream cells was divided proportionally to stream length. Groundwater supply depth is sum of partial supply from all cells. Accepted solution of stream supply from saturation zone simplifies complicated calculation procedure to formula:

$$q_g = K_f h_g S_{gr}$$  \hspace{1cm} (29)

where: $K_f$ - filtration coefficient, [m/s],
$h_g$ - groundwater reservoir depth, [m],
$S_{gr}$ - average watershed slope, [-].

One stream cell is supplied according following formula:

$$q_i = q_g \frac{N_z}{N_z}$$  \hspace{1cm} (30)

where: $q_i$ – side stream supply for one cell,
$N_z$ – total number of stream-cells.

Filling up of groundwater reservoir was calculated from relation:

$$h_g^{j+1} = 1 - \frac{L_r K_f S_{gr} \Delta t}{\mu F_g} h_g^j + \frac{R_g \Delta t}{\mu}$$  \hspace{1cm} (31)
where: \( L_r \) - total streams length, [m],
\( F_g \) - groundwater reservoir supply area, [\( m^2 \)],
\( R_g \) - average groundwater supply from aeration zone, [m/s].

Base on groundwater reservoir outflow, initial condition for infiltration process in subsoil zone is calculated. Total supply in time \( t_0 \) is equal total watershed runoff.

### 2.8. Recipients system runoff (streams)

Runoff from recipients system (streams) is the process of water flow in streams supplied by: groundwater runoff, surface and subsurface runoff (Fig. 2). This unsteady flow in whole range of water levels, from low to high. Total runoff along streams was described by one-dimensional kinematic wave equation:

\[
\frac{\partial Q}{\partial x} + \frac{\partial F}{\partial t} = q_b
\]
\[
Q = \alpha_k R_h^{N-1} F
\]

where: \( Q \) - runoff, [m\(^3\)/s],
\( R_h \) - hydraulic radius, [m],
\( q_b \) - side supply, [m\(^3\)/m s],
\( \alpha_k, N \) - kinematic wave parameters,
\( F \) - flow cross-section area, [m\(^2\)].
For the model purposes those parameters were accepted for turbulent flow according Manning theory. Solution and calculation schemes are analogue to surface and subsurface runoff transformation. Stream channel cross-section was approximated as rectangular, with width equal cell size. Side supply is sum of surface, subsurface and groundwater runoff. Initially conditions are determined from groundwater zone side supply.

3. STRUCTURE OF COMPUTER PROGRAM FOR WISTOO MODEL

Computer application of WISTOO model consists of: procedure responsible for data preparation (INPUT) and main calculation procedure (Fig.14). Pre-processing can be divided into following procedures:

- digital elevation model preparation support,
- watershed parameters from thematic layers generation,
- meteorological data preparation.

First procedure has auxiliary character. Is used only if digital elevation model is not available. Two following procedures, described bellow, are important for proper model operation.
3.1. Watershed parameters procedure

WISTOO model is the distributed mathematical model, using dense calculation grid. Every cell must have defined parameter set needed for calculations. Those parameters are determined from thematic layers like: digital elevation model, stream network topography, soil type and structure, watershed land-use. Special
tool procedure generates important watershed parameters from that information. Basic data flow is based on water flow direction, thus one of principal issues is determination of supply order for every cell in the watershed. Sequence of cell supply is created (Fig. 15).

All source cells are of order 0. Those cells supply order 1 cells, they supply order 2 cells etc. At the end of this chain streams cells are located. Stream cells have similar assigning sequence. Every cell gets unique identifier. Created file describes calculation sequence in successive time steps.

From thematic layers (DEM, soil type and structure, land-use) information is read and processed into following parameters:

- location - x, y coordinates from DEM,
- identifiers of cells supplying every cell,
- slope from DEM,
- velocity modulus $\alpha$ for kinematic wave, where hydraulic resistance coefficient is determined from land-use,
- precipitation separation coefficient $p$ and plants retention $s$ used in net precipitation procedure from land-use,
• soil porosity coefficient and maximal soil and subsoil conductivity from soil type and structure,
• soil depth and types,
• soil permeability parameter. This parameter is divided into eight categories:
  - 0 - natural,
  - 1 – water outlet ex. catch basin gate, water intake,
  - 2 - impermeable,
  - 3 - 75% impermeable,
  - 4 - 50% impermeable,
  - 5 - 25% impermeable,
  - 6 – surface without soil layer, ex. field way,
  - 7 – barrier, making water transfer impossible.

Table 1. Identifiers of soil types used in WISTOO program

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Rocks</td>
</tr>
<tr>
<td>102</td>
<td>Gravel and stony</td>
</tr>
<tr>
<td>103</td>
<td>Fine gravel</td>
</tr>
<tr>
<td>104</td>
<td>Fine to coarse sand</td>
</tr>
<tr>
<td>105</td>
<td>Fine sand</td>
</tr>
<tr>
<td>106</td>
<td>Dusty sand</td>
</tr>
<tr>
<td>107</td>
<td>Sandy clay</td>
</tr>
<tr>
<td>108</td>
<td>Light clay</td>
</tr>
<tr>
<td>109</td>
<td>Dust</td>
</tr>
<tr>
<td>110</td>
<td>Clay</td>
</tr>
<tr>
<td>111</td>
<td>Stiff clay</td>
</tr>
<tr>
<td>112</td>
<td>Silt</td>
</tr>
<tr>
<td>113</td>
<td>Peat light decomposed</td>
</tr>
<tr>
<td>114</td>
<td>Peat decomposed</td>
</tr>
<tr>
<td>115</td>
<td>Skeletal soils</td>
</tr>
</tbody>
</table>

Soil permeability parameter was defined from land-use:
• impermeable surfaces for bituminous roads,
• urban areas are divided into four categories: compact urban (75% impermeability), compact rural (small towns or small urban constructions - 50% impermeability),
sparse urban (peripheral housing estates – 25% impermeability), sparse rural. Last category is treated in the model as natural.

**Table 2. Identifiers used for land-use**

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Land-use type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Asphalt or concrete roads</td>
</tr>
<tr>
<td>2</td>
<td>Pavement roads</td>
</tr>
<tr>
<td>3</td>
<td>Macadam or partially permeable roads</td>
</tr>
<tr>
<td>4</td>
<td>Field or forest ways</td>
</tr>
<tr>
<td>5</td>
<td>House</td>
</tr>
<tr>
<td>6</td>
<td>Dense urban area</td>
</tr>
<tr>
<td>7</td>
<td>Sparse urban area</td>
</tr>
<tr>
<td>8</td>
<td>Dense rural area</td>
</tr>
<tr>
<td>9</td>
<td>Sparse rural area</td>
</tr>
<tr>
<td>10</td>
<td>Sidewalks or pavements partially permeable</td>
</tr>
<tr>
<td>11</td>
<td>Concrete or impermeable areas</td>
</tr>
<tr>
<td>12</td>
<td>Areas 50% impermeable</td>
</tr>
<tr>
<td>13</td>
<td>Pastures with low grass</td>
</tr>
<tr>
<td>14</td>
<td>Pastures with high grass</td>
</tr>
<tr>
<td>15</td>
<td>Bushes or weeds</td>
</tr>
<tr>
<td>16</td>
<td>Sparse bushes or trees</td>
</tr>
<tr>
<td>17</td>
<td>Coniferous forest</td>
</tr>
<tr>
<td>18</td>
<td>Deciduous forest</td>
</tr>
<tr>
<td>19</td>
<td>Mixed forest</td>
</tr>
<tr>
<td>20</td>
<td>Fields – different cultivation</td>
</tr>
<tr>
<td>21</td>
<td>Fields – grains</td>
</tr>
<tr>
<td>22</td>
<td>Meadows, lawns</td>
</tr>
<tr>
<td>23</td>
<td>Sink basins or other surface water intakes</td>
</tr>
<tr>
<td>24</td>
<td>Barrier for horizontal water flow in aeration zone</td>
</tr>
<tr>
<td>25</td>
<td>Impermeable rocks</td>
</tr>
<tr>
<td>26</td>
<td>Fractured rocks – permeability like for rock waste</td>
</tr>
<tr>
<td>27</td>
<td>75% impermeable areas</td>
</tr>
<tr>
<td>28</td>
<td>50% impermeable areas</td>
</tr>
</tbody>
</table>

Thematic layers prepared in GIS format must fulfil certain conditions according map attributes. As mentioned in paragraph 1, those conditions are related to digital elevation model and
For soil type and structure, land-use conventionally numbers are assigned to different classes. Classes are presented in Tables 1 and 2. For soil type and structure two classifications are presented: according polish regulations (82 categories) and general soil division. Table 1 shows this second classification.

3.2. Meteorological data procedure

In meteorological data preparation procedure as first the calculation period for simulation is selected. It is based on data introduced from measuring stations or climatic stations. Saved data can be visualized – it helps in period selection.

Data can be introduced into database as hour or temporal sum values (for precipitation and runoff as daily values). One of the procedures converts this type of data into hour values.

3.3. Calculation procedures

Calculation procedures of WISTOO model consist of three modules:

- rainfall-runoff transformation with hydrographs visualization (maximal ten cross-sections including observed),
- rainfall-runoff transformation with spatial visualization of selected processes (net precipitation, surface or subsurface water depth and velocity, soil humidity),
- hydrograph transformation through water reservoir.

3.3.1. Rainfall-runoff transformation procedures
First two procedures use previously prepared watershed parameters and meteorological data. Last one uses results of rainfall-runoff transformation model.

Input for rainfall-runoff transformation procedure are data files containing:

- watershed parameters,
- precipitation stations location,
- calculation cross-sections location; this can be done before program start,
- meteorological data.

Results are presented in form of graphs or bitmaps on-line during calculation on computer screen. In rainfall-runoff transformation procedure hydrographs for all selected cross-sections and net rainfall spatial distribution are displayed. Hydrological processes are displayed as bitmaps.

Procedures responsible for hydrological processes simulation are managed by main program. Those procedures correspond to hydrological processes described in chapter 2. In main program connection between procedures and data exchange is established and controlled. Only processes determining rainfall-runoff transformation at certain moment are calculated. It highly reduces computation time.

When the calculation starts all input data are checked from homogeneity point of view. If by accident, data files from wrong layer are selected, program displays message and calculation is stopped. User must select correct data. Use of first two procedures is simple and no additional computer knowledge is needed.

3.3.2. Runoff transformation through water reservoir

Hydrotechnical infrastructure (water reservoir) is also implemented into model. Special subroutine is here used. Use of runoff transformation through water reservoir requires water management knowledge. Besides inflow hydrograph, many additional parameters characterizing reservoir (use capacity, flood reserve, etc.) and work mode must be introduced. This procedure is adopted for polish conditions and regulations.
Four policies for normal and water deficiency modes and three for flood modes are used. Any mode can be selected and influence its influence on watershed closing cross-section hydrograph can be analyzed.

For normal conditions four policies can be used:

- **standard** – it is the simplest mode, assuming that one water consumer is taken into consideration. Water resources are used for current reservoir work without limitations.
- **standard parametric I type** – it is modified standard policy, with two groups of consumers. Modification enables better water use. Initial reservoir filling, water inflow, used demands and target filling is taken into account.
- **standard parametric II type** – it is also modification of standard policy, but critical filling term is introduced, i.e. minimal filling below which restrictions in water consumption are introduced.
- **‘N-days’ type** – used in deficiency periods. One or group of consumers is concerned. Assuming low inflows during \( n \) days, reservoir can not become empty.

Flood period is the period from moment when water inflow to reservoir exceeds permitted inflow and use capacity is filled up, to the moment of flood reserve formation. Flood reserve reconstruction starts when inflows is smaller than restricted inflow \( Q_{doz} \). For such conditions there are three policies:

- **fixed policy** – assumes, that during peak flow storage outflow is equal restricted outflow. Cut off of peak flow occurs only when peak flow volume is smaller than flood reserve. When flood wave volume is bigger than flood reserve, restricted outflow will be exceeded. Can be used when flood reserve is sufficient.
- **partly fixed policy of type I** - when flood reserve is filling, restricted outflow is increased \( \alpha (Q - Q_{doz}) \) where: \( Q \) is inflow. When flood reserve is filled up, outflow is determined like for fixed policy. Parameter \( \alpha \) is
optimized, $\alpha \in [0,1]$. For $\alpha = 0$ partly fixed policy of type I becomes a fixed one.

- **partly fixed policy of type II** - For this policy procedure is according rules:
  - when flood reserve is filling, outflows can not exceed inflow,
  - when flood reserve is filling, next outflow cannot be smaller then previous one,
  - when flood reserve is filling, outflow can not be smaller than restricted outflow.

4. **RANGE OF MODEL APPLICATION**

As mentioned in introduction, WISTOO model is developed for mountainous and hilly watersheds, where main source of water supply is surface and subsurface runoff. Model can be applied to watersheds with areas from few to few thousands square kilometers. Increasing watershed area, calculation time and computation demands increases too.

Input parameters for the model are calculated from digital thematic layers. Basic format used for digital layers, for both raster and vector maps, is compatible with IDRISI program developed at Clark University - USA [Estman J.R., 1995]. Use of this geographical information system in many polish universities in didactic process and its simplicity were main reasons for this format selection.

Basic element for calculations is square cell with size specified by user. Correctness of cell size determines runoff process simulation accuracy. In general, better accuracy can be archived by decreasing of cell size. Increasing of cell size causes deterioration of watershed surface representation and consequently description of water transport dynamics. Bigger cell produces deformations of watershed topography by averaging. Also parameters responsible for rainfall-runoff transformation changes: slope, surface water pathways. Moreover, uncontrolled
deformation of impermeable and semi-impermeable areas takes a place. Too wide streams width (corresponding to cell size) changes flow dynamics.

From field experiments result was stated, that the biggest recommended for WISTOO model cell size is 25x25 meters. Up to now, positive and well documented by measuring data model applications covered:

- determination of flood runoff hydrographs in uncontrolled watersheds in different cross-sections,
- determination of influence of land-use change on runoff hydrograph in selected stream cross-sections,
- determination of areas with intense surface runoff, including secondary surface runoff causing surface erosion,
- determination of small water reservoir influence on flood risk reduction,
- determination of potential location for inlet into storm sewerage system.

Model, thanks to its flexibility according required measuring data sets, can be applied both for well and not fully gauged watersheds. For watershed with areas above 100 km², data with one-day time resolution can be used. In polish conditions with sparse network of precipitation monitoring and one-day recording resolution for precipitation and runoff, WISTOO models meets demands.

For small watersheds with areas below 100 km² temporal and spatial resolution of data must be high. For smaller watershed input data demands are higher. Additionally, in small watersheds geological parameters must be taken into account: water layer shape and subsoil layer depth in aeration zone. This additional information is used for determination of groundwater part in runoff supply. For most of mountainous regions, underground watersheds do not coincide with topographical watershed. Value of groundwater supply has influence on infiltration initial conditions accuracy.

WISTOO model enables use of daily resolution data records. Special function distributes daily values into hour values. Hour
hyetograph assumes 24-hour term of precipitation event. That is why it should be used mainly for long-term events. This possibility must be used with care.

Theoretical hyetographs not always reflect real flood wave shape. Lack of information concerning hyetograph total time, maximal intensities time and values is main source of errors.

5. **EXAMPLE OF WISTOO MODEL APPLICATION FOR ŁOSOSINA RIVER WATERSHED**

Model WISTOO was applied for different watersheds, among others: Ropa, Czarny Dunajec, Łososina, Wielka Puszcza, Lęśnianka watersheds. Those watersheds are diverse in respect of runoff regime and available input data. Physical foundation of WISTOO model and spatial (distributed) description of supply and runoff parameters enabled use of this model for all different cases.

As an example, application for Łososina river watershed (413 km² area) is shown. Only two gauge stations and two precipitation stations recording observations once a day, are located in this watershed. Most of hydrological models can not operate with this number of hydrometeorological data. With WISTOO model simulation results are satisfactory.

5.1. **Watershed characteristics**

Łososina river watershed is located in Beskid Wyspowy region and is typical mountainous watershed for Upper Vistula river basin. It has big slopes and dense streams network (Fig.16). Maximal elevations exceeds 1000 m.a.s.l., (Mogielnica 1170 m), and outlet is situated on 225 m.a.s.l. For this area digital elevation model was prepared based on square cells 25x25 m. Slopes (Fig.17), surface flow directions and cell order was determined.
Figure 16. Streams network in Łososina watershed with marked gauge and precipitation stations. 1-3 precipitation stations; 4-5 gauge stations.

Figure 17. Slopes in Łososina watershed – lighter areas correspond to flat terrain (minimal slope).
There are five types of soil in the watershed: clayey, skeletal, fen, dust, sandy. Skeletal soils are in initial phase of evolution. Most of the area is covered by clay and silt soils with rock waste, stones, fine stone bits, sand.

Land-use (Fig.18) was divided into five classes: fields and croplands (1), forest (2), sparse rural areas (3), dense rural areas (4), main asphalt roads (width above 15m) (5).

![Figure 18. Spatial distribution of land-use](image)

**5.2. Simulation results for Łososina watershed**

Simulations were performed for monthly periods: July 1970 and June 1974. In precipitation distribution calculations, two additional stations from neighboring watersheds were used. The stations are situated in the Dunajec watershed. Łososina is a left hand side tributary of Dunajec. Figure 19 shows five hydrographs. Two of them are from gauge stations. Calculated hydrographs are from gauge cross-sections (2) and watershed closing cross-section.
Figure 19. Observed and calculated hydrographs (31 May - 30 June 1974) where:
1. stream network with calculation marked cross-sections,
2. calculation and gauge cross-sections co-ordinates,
3. procedure name bar (rainfall-runoff transformation with hydrograph visualization),
4. calculation period,
5. maximal net precipitation for every calculation step and current
calculation time,
6. spatial net precipitation distribution with color legend,
7. runoff [m³/s],
8. hydrographs - observed and calculated,
   a/ calculated for watershed closing cross-section,
   b/ calculated in cross-section 5,
   c/ observed in cross-section 5,
   d/ calculated in cross-section 4,
   e/ observed in cross-section 4,
9. time [h].

Figure 20 demonstrates results of runoff simulation for year 1970. Simulation was performed for two gauge cross-sections and
in watershed closing cross-section. First three curves are for
simulated values, last two for observed. Cross-sections direction is
upstream.

Besides standard runoff hydrographs simulations,
simulations of surface runoff were prepared. Four processes can be
simulated and visualized by the program: net precipitation, soil
moisture, surface and subsurface runoff. Two last processes in
standard version are displayed as transformed water depth and flow
velocity. Solving detailed problems, spatial runoff distribution is
presented by unit runoff (runoff for unit width e.g. running meter).
Secondary surface runoff from aeration zone can also be traced.
Examples of spatial distribution of surface and subsurface runoff
velocities in different time steps are shown on Figures 21-24.

Two other procedures displaying spatial distribution of soil
moisture and net precipitation are used sporadically, mainly for
didactic purposes.
Figure 20. Calculated and observed runoff hydrographs (7-31 of July 1970)
Figure 21. Surface runoff velocity distribution (1 of June 1974, 23:00 h)

Figure 22. Surface runoff velocity distribution (2 of June 1974, 6:00 h)
Figure 23. Subsurface runoff velocity distribution (1 of June 1974, 23:00 h)

Figure 24. Subsurface runoff velocity distribution (2 of June 1974, 6:00 h)
6. A FEW WORDS ABOUT THE MODEL

WISTOO model is continuously developed and improved. More flexible land-use description is of special interest. One of possible solutions is the use of a grid with variable size. It enables more detailed representation of features small in size, but influencing runoff formation.

Second direction of model development is related to hydrotechnical constructions on streams and in the watershed. It will be focused mainly on water reservoirs and stream cascades. Module aiding in hydrotechnical construction design can be one of the results of model development.

Basement of the model on geographical information systems and physical processes of runoff formation should facilitate achievement of those two goals. Sophisticated studies should be possible to perform using WISTOO model:

- Simulation analysis of historical runoff conditions,
- Model verification and identification of its parameters,
- Influence of land-use change of runoff formation forecast.

Fast development of computer sciences, especially data processing, enables further development of the model. Today WISTOO is a very reliable model even with minimal set of input data, comparing to other models. Those facts and new ideas how to improve the model, make hope, that WISTOO has big chance to be even more reliable and competitive.
Symbols used in text

A - gradient curve inclination coefficient, [1/m],
a – empirical parameters determined from experiments for two plant types – high plants (forest) and low, [s/m],
α - exponent index dependent on soil type,
αk – kinematic wave coefficient.
b - dripping vs. water depth on plants curve coefficient, [1/mm],
b_a – empirical parameters determined from experiments for two plant types – high plants (forest) and low, [sW/m^3],
β - weight coefficient,
c - current water depth on plants, [mm],
c_a – empirical parameters determined from experiments for two plant types – high plants (forest) and low, [W/m^2],
c_t – current water depth on plants at time t, [mm],
c_o – water depth on plants at time t-1, [mm],
D_o – minimal dripping from plants when c = s, [mm/min],
d_h – base altitude, [m],
d_k – distance from point i to measuring station k,
Δ - inclination of water vapor pressure curve vs. temperature, [hPa/K],
E_a – current evapotranspiration, [mm],
E_p – potential evaporation, [mm/min],
e – napierian base,
e_a – current water vapor pressure, [hPa],
ε – maximal water vapor pressure, [hPa],
F – flow cross-section area, [m^2],
F_i – cell area,
F_g – groundwater reservoir supply area, [m^2],
G – soil heat flux, [W/m^2],
γ - psychrometric constant, [hPa/K],
H_h, H_o – elevation above sea level for the highest and the lowest station in the watershed, [m],
H_x – terrain elevation, [m].
H’_x – transfer elevation, [m],
h - water depth, [m],
h_g - groundwater reservoir depth, [m],
h_k - capillary height, [m],
h_o - water depth from previous time step,
h_r - average height of plants, [m],
h_w - water depth on soil surface, [m],
K - soil hydraulic conductivity, [m/s],
K_f - filtration coefficient, [m/s],
K_o - maximal soil conductivity (filtration coefficient), [m/s],
L_r - total streams length, [m],
λ - latent heat of evaporation, [J/kg],
N - kinematic wave coefficient,
N_z - total number of stream-cells,
n – index exponent,
n_h - hydraulic resistance coefficient, called roughness coefficient, 
    \[1/m^{1/3}\],
n_z - number of elements supplying groundwater,
P_i - value of calculated parameter at point i, i=1,2,...,m,
P_k - measured value at point k, k=1,2,...,l,
p - rainfall separation coefficient, [-],
Ψ - soil suction pressure, [m],
Ψ_d - suction pressure in bottom node, [cm],
Ψ_g - suction pressure in upper node, [cm],
R - rainfall intensity, [mm/min],
R_s - excess rainfall or subsurface supply, [mm/s],
R_g - average groundwater supply from aeration zone, [m/s],
Rgi - groundwater table supply,
R_h - hydraulic radius, [m],
R_j, R_{i+1} - recorded precipitation depth for the lowest and the 
    highest station in the watershed, [mm],
R_n - net radiation, [W/m^2],
R_{nett} - net precipitation, [mm/min],
Rp_i - subsoil layer supply,
R_x - precipitation depth calculated by inverse distance method, 
    [mm],
R’_x - rectified precipitation depth, [mm],
ra - aerodynamic resistance function, [s/m],
rc - superficial resistance function, [s/m],
ρ cp - volumetric dry air heat capacity, [J/m³K],
Q - runoff, [m³/s],
Qk - groundwater runoff in watershed closing cross-section,
q - unit flow, [m³/m s],
qb - side supply, [m³/ m s],
qd - inflow sum for cell,
qr - moisture flux, [m³/m² min],
qgr - maximal outflow from cell calculated from soil layer depth
Hg and filtering coefficient µ,
qi - side stream supply for one cell,
qo - outflow sum for cell,
Sgr - average watershed slope, [-],
Sh - hydraulic gradient, [-],
Sz - terrain slope, [-],
s - plants retention, [mm],
Θo - maximal volumetric humidity – soil porosity index, [-],
Θs - volumetric humidity of permanent plant wilting, [-],
v - infiltration rate, [m/s],
vw - wind velocity, [m/s],
z - wetting front depth, [m],
z₀ - height of plants roughness, [m],
zv - altitude of wind velocity measurement, [m].
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