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ELABORATION OF CRRS MODELS USING GIS AND GA TECHNOLOGY CALIBRATED AT BOTONEGA CATCHMENT

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Original scientific paper

Catchment runoff modeling is carried out by applying a concept of parametric runoff modeling or CRRS modeling (Conceptual rainfall – Runoff models). The CRRS model provides directives and recommendations for the adequate number of measured inputs (rainfall) and outputs (runoff) as to the most representative parameter method, which provides the most realistic solutions. Elements that define input in CRRS modeling are: hydraulic runoff models where the flow velocity component simulates water translation in the catchment; spatial model of terrain presented through discretization of catchment elements providing information as to terrain inclination, flow direction and flow path along the catchment surface. The CRRS modeling contains also reservoir elements which simulate the effect of catchment retention. The elaboration of CRRS model is planned on the example of the Botonega catchment for which a satisfactory rainfall and catchment data exists as well as appertaining runoff hydrographs necessary for the calibration and operation of the model.

Key words: *Botonega, CRRS model, computer technology, runoff*

Izrada CRRS modela korištenjem GIS i GA tehnologije kalibriranog na slivu Botonega

Izvorni znanstveni članak

Modeliranje procesa otjecanja vode sa sliva izrađeno je primjenom koncepta parametarskog modeliranja otjecanja ili CRRS modeliranja (Conceptual Rainfall – Runoff Models). Za dovoljan broj mjerenih ulaza (oborine) i izlaza (hidrograma), CRRS model daje smjernice i preporuke za odabir najreprezentativnije parametarske metode i daje najrealnija rješenja. Elementi koji definiraju ulaz u CRRS modeliranje su: hidraulički model otjecanja, gdje se komponentom brzine tečenja simulira translacija vode u slivu; prostorni model terena, prikazan kroz diskretizacijski sustav elemenata sliva kao nositelja informacije o nagibu terena, pravcu i smjeru tečenja vode te duljini pređenog puta otjecanja vode po površini sliva. CRRS modeliranje se sastoji i od elementa rezervoara kojim se simulira efekat retencije sliva. Konkretizacija izrade CRRS modela predviđena je na primjeru sliva Botonege za koji postoji zadovoljavajuća baza podataka o oborinama i slivu, te pripadnim hidrogramima otjecanja, potrebnim za tariranje i kontrolu rada modela.

Ključne riječi: *Botonega, CRRS mode, informatika, otjecanje*

1 Conceptual runoff model
Konceptualni model otjecanja

In this paper, the modeling of the catchment water runoff process is created by applying the concept of runoff parameter model or CRRS modeling. The CRRS modeling is made of a relatively small number of structurally arranged elements where each of these elements simulates a certain phase of the catchment process, i.e. a certain phase of gross transformation process and/or effective rain in the corresponding runoff hydrograph. Elements that define the input in the installed CRRS modeling are: hydraulic runoff model where the flow speed component simulates the water translation in the catchment; spatial model of terrain presented through discretization system of catchment elements as an information carrier as to inclination, direction of water flow and the length of passed water runoff on the catchment surface. CRRS modeling consists also of the reservoir elements simulating the effect of catchment retention and the data base of real rainfall events and appertaining measured runoff hydrographs with which the model is being calibrated and consequently improved. The flow diagram of the made CRRS model is presented in Fig. 1.

Elements of CRRS models are described through:

- Concept (hydrologic-hydraulic runoff model)
- Spatial analysis of parameters (GIS model and runoff simulation)
- Mathematical runoff model
- Calibration.

The concept of hydrologic-hydraulic runoff model is based on the description of catchment surface flow of a very thin water layer appearing on the upper parts of the catchment slope before concentrating in the recognizable open bed of lower order [1]. The flow on the catchment surface can be described by the Manning's equation for an uniform turbulent flow through endlessly wide bed with a really low water column, i.e. shallow depth. In that case, the catchment approximates as flat surface with the average slope along the greatest inclination, meaning that the flow is formed vertically on isohypses.

Taking the example of the catchment, which is a limited area (space), the quantification of the runoff process in the sense that all factors included in the runoff are expressed quantitatively and are brought into mutual dependence, is expressed by water balance equation in each point of the space [2].

Terrain parameters are integrated in the CRRS model through separate map layers – the documents elaborated by GIS – in software packages ArcView 8.1.2 and ArcInfo 7.1.2 and ArcMap 9.0. Each map layer provides at least one description of the terrain expressed through the parameters. By overlapping of individual map descriptions, we have obtained terrain features introducing in the model a complete picture of the situation on the terrain, which defines estimated input values in the mathematical model. A part of spatial terrain parameters determined within the GIS technology (catchment size, geometry, terrain inclination, its topography, etc.) affect directly the form of the terrain digital model (Digital Elevation Model – DEM) and indirectly hydrologic characteristics of the catchment (field, flow velocity, model of the "shortest" flowpath on the terrain surface, etc.).

The CRRS model creation in conformity with the described concept is planned on the numerical example of the Botonega catchment, a small torrential catchment for which there exist an adequate data base concerning

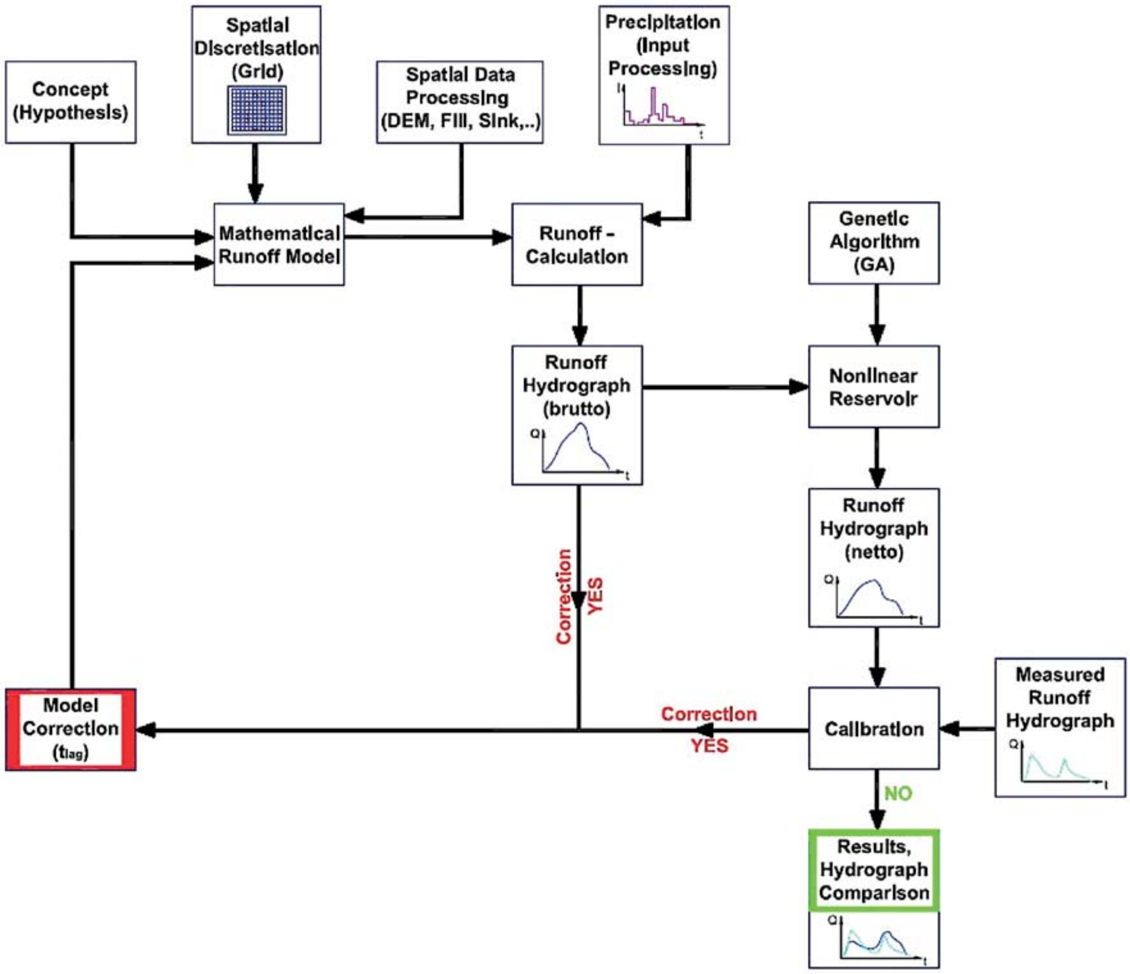

Figure 1 *Flow diagram of Botonega CRRS model*
Slika 1. *Dijagram toka CRRS modela Botonege*

the rainfall and the catchment, and the appertaining runoff hydrographs requested for calibration and control of the model operation.

Mathematical model algorithm of the rainfall -runoff process is made in the C++ language.

The non-linear reservoir method is applied to each calculated kinetic runoff hydrograph in the conceptual model in which the effect of catchment retention was not taken into consideration. In such a way, final computing hydrographs, i.e. model outputs were made comparable with the measured ones. Coefficients of non-linear reservoir are calculated by applying the optimization method using genetic algorithm (GA) made by Matlab R2006a.

The CRRS model control is planned on the numerical example of the Botonega catchment storage basin, a small torrential catchment for which there exists an adequate data base concerning the rainfall and the catchment.

Comparing the results of CRRS models on a number of measured inputs (hyetographs) and outputs (runoff hydrographs), calibration and corrections of the model were made, which enabled systematic elaboration of the CRRS model parameter, which in the most realistic way describes the runoff process on the Botonega catchment for any rainy event.

2
Model concept
Koncepcija modela

The concept of hydrologic and hydraulic model of the surface runoff consists of several elements - phases representing the base for this theory concerning the solution of the problem:

- Hydraulic elements of flow model (determination of flow velocity on the ground surface)
- Hydrologic elements of flow model (estimation of water balance in each node of the discretization grid).

2.1
Hydraulic model of surface flow
Hidraulički model površinskog otjecanja

With the purpose of determining hydrologic and hydraulic elements, the basin surface is covered with a discretization grid and consists of 112 818 nodes at the distance of 25 m. The flow on the terrain surface consists of a thin water layer covering a vast area while the flow in the bed consists of a very narrow water stream along the limited way. That means that the flow in the bed consists of a relatively narrow concentrated water flow along a relatively long bed, which in the nature is formed by the erosive activity of water on its way through the greatest concentration of terrain falls. The surface flow in the form of a thin layer of water, which flows over a wide catchment area, lasts in the nature for a very short period of time. The terrain concentrates the discharge unevenly in meandering furrows and beds. Gradually, the discharge from small beds (beds of lower order) merge forming recognizable river beds, which farther downstream merge again forming at the end a concentrated runoff at the catchment outlet [1].

Surface flow cannot be completely explained with the

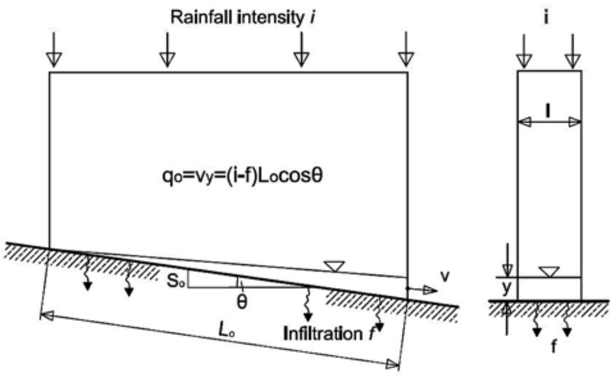

Figure 2 *Steady state flow over a homogenous surface of rainfall intensity*
Slika 2. *Stacionarno tečenje po homogenoj plohi od oborine intenziteta i*

principles of hydromechanics because progressive flowing in the hypothetical water layer of shallow depth along the endlessly wide bed, which meets unexpected obstacles such as vegetation, uneven terrain, etc. is in question. The task is idealized in the way so that the flat flow surface is superposed with a uniform fall vertically on isohypses. In this case, the average water movement speed can be determined on the basis of completely exact hydraulic suppositions and it can be improved in the procedure of a model calibration (Fig. 2).

Continuity equation for incompressible steady state flow along the catchment surface is equal to:

$$\iint_{\text{c.s.}} v \mathrm{d}A = 0, \tag{1}$$

where:
v – water velocity
dA – area differential
c.s. – control surface.

If we put inflow into the control volume (rainfall) in the equation (1), runoff from the control volume with the known infiltration f and water column height through the surface y (measured vertically on the catchment area while the velocity vector is parallel with the catchment area); then the continuity equation has the following form (2):

$$\iint_{\text{c.s.}} v \mathrm{d}A = f \cdot L_{\text{o}} \cdot \cos\theta + v \cdot y - i \cdot L_{\text{o}} \cdot \cos\theta = 0. \tag{2}$$

Discharge for the unit width q_{o} is equal to:

$$q_{\text{o}} = v \cdot y = (i - f) \cdot L_{\text{o}} \cdot \cos\theta, \tag{3}$$

where:
i – rainfal intensity, mm/min
f – infiltration, mm/min
θ – surface inclination angle, °
L_{o} – surface flowpath, m.

The second equation with which the motion of water layer over the basin surface is described is dynamic equation. Supposing that the stream is uniform laminar flow on an inclined plane, it can be shown that the average velocity is equal to:

$$v = \frac{g \cdot I_{\text{o}} \cdot y^2}{3 \cdot \upsilon}, \tag{4}$$

where:
g – gravitational acceleration, m/s^2
υ – kinematic viscosity of fluids, St
I_{o} – bed bottom slope, %
y – height of water column (water depth), m.

Field studies of overland flow indicate that the flow is laminar but that the flow resistance is about ten times larger than for laboratory studies on uniform planes (Darcy-Weisbach friction factor for overland flow is in the range 20 – 200). The increase in flow resistance results primarily from the unevenness in topography and suface vegetation.

When discharge turns into turbulent motion, the friction factor becomes independent of the Reynolds number and depends only on the surface roughness. Manning's equation is used for turbulent flow, which is:

$$v = \frac{1}{n} \cdot R^{2/3} \cdot I^{1/2}, \tag{5}$$

where:
R – hydraulic radius, m
n – Manning's roughness coefficient, m$^{-1/3}$ · s
I – bed bottom slope because the flow is uniform ($I = I_{\text{o}}$ [4]), %.

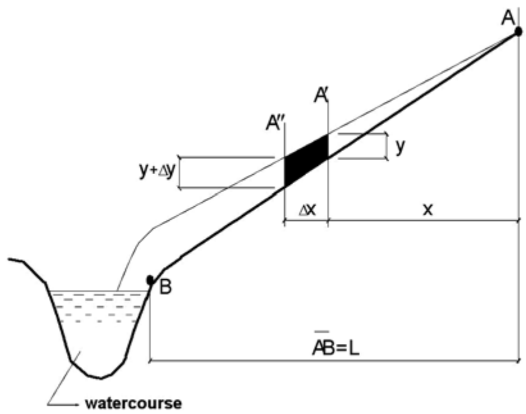

Figure 3 *Design model of the surface flow*
Slika 3. *Proračunski model tečenja po površini*

It can be seen in Fig. 3 that for infinite water bed, the runoff velocity in point A', at the distance x from the watershed A shall be, according to Manning:

$$v_x = \frac{1}{n} \cdot y^{2/3} \cdot I^{1/2}, \tag{6}$$

where:
y – hydraulic radius approximately equal to the depth of water layer y for infinitely wide water bed, m
I – catchment surface slope, %.

The impact of the lag time on the form of the computed hydrograph at the outlet of the Botonega catchment is given by the correction of the above equation in a way that the flow velocity is inversely proportional to the lag time:

$$v_x = \frac{1}{t_{\text{lag}}} \cdot \frac{1}{n} \cdot y^{2/3} \cdot I^{1/2}, \tag{7}$$

where:
t_{lag} – lag time i.e. dimensionless magnitude which is the measure of "time delay" of the catchment.

That is, correction of velocity has been made in a way that the coefficient is introduced into the definition of velocity containing the time delay measure, t_{lag}, as a simulation of the catchment retention property. The function of the coefficient $1/t_{lag}$ is to slow down the water flow over the catchment surface, it is dimensionless and from its origin comes out the magnitude measure or catchment time delay.

On the other hand, the coefficient $1/t_{lag}$ can be interpreted as a correction of Manning's roughness coefficient where the form of its correction $(1/t_{lag})\cdot(1/n)$ increases considerably its value.

2.2 Hydrological model of surface flow
Hidrološki model površinskog otjecanja

For the limited catchment area within the discretion space, the quantification of all hydrological elements taking part in the water balance for each individual cell and forming the runoff hydrograph as well as their codependence, shall be solved with water balance model (Fig. 4) [3].

Generally speaking, for a certain delimited space (system) over a certain period of time, the difference of inflow (inlet quantity) and runoff (outlet quantity) through the area that bounds that space must be equal to the change of water quantity in that space (system). This comes out from the axiom about the invariability and constancy of the mass, the principle on which the mass continuity equation is based:

$$\frac{\Delta V(t)}{\Delta t} = Q_u(t) - Q_i(t), \tag{8}$$

where:
$\Delta V(t)$ – state of the system or the volume of accumulated water in the interval t
$Q_u(t)$ – water inflow into the system in the interval t
$Q_i(t)$ – water runoff from the system in the interval t.

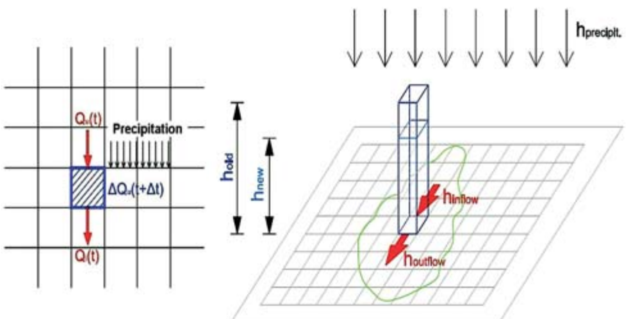

Figure 4 *Picture of water balance model*
Slika 4. *Slika proračunskog modela vodne bilance*

One minute time intervals are observed and the state of water balance is calculated for each interval separately:

$$t_1, t_2, ..., t_n$$

When $t \in \{t_1, t_2, ..., t_n\}$ is any of observed intervals, and $t = t_i$ is the observed time interval, then $t + \Delta t = t_{i+1}$ is the next time interval.

Then, the calculation of the height of water column in each cell of the discretion space in each interval is:

$$\begin{aligned} h_{\text{new}}(t+\Delta t) &= h_{\text{old}}(t) - h_{\text{runoff}}(t+\Delta t) + \\ &+ h_{\text{inf low}}(t+\Delta t) + h_{\text{precip.}}(t+\Delta t), \end{aligned} \tag{9}$$

where:
$h_{new}(t+\Delta t)$ – height of water column in the interval $t+\Delta t$ in the observed cell of the discretion space
$h_{old}(t)$ – height of water column representing the remaining water in the observed cell of the discretion space from the previous interval t
$h_{runoff}(t+\Delta t)$ – height of water column that runs off from the cell of the discretion space in the interval $t+\Delta t$
$h_{inf\ low}(t+\Delta t)$ – height of water column that inflows into the observed cell from the neighboring cells of the discretization space in the interval $t+\Delta t$
$h_{precip.}(t+\Delta t)$ – height of water column of rain that falls on the cells of the discretion space in the interval $t+\Delta t$.

3 Spatial analysis of parameters
Prostorna analiza parametara

For determination of spatial parameters of the terrain, three digital cartographic background documents were sufficient:
- topographic maps
- hydrographic maps
- digital elevation model of terrain (DEM model).

Through the DEM model, the terrain elevation is defined in each grid node. By means of thematic layers of physiographic catchment characteristics and their overlapping with discretion grid in the GIS, all remaining knowledge about the terrain is allocated to the nodes (in digital form): ID number of the node, surface slope in the node, flow direction of water in the node and X,Y coordinates of the node. It is important to point out, that the node carries all information about the catchment, which is contained in the field of 25×25 m and with the centerpoint in the node.

Hydrologic analysis is carried out in several steps (within GIS over the Spatial Analyst Tool module – hydrology) as follows:

FLOWDIRECTION function – direction of surface flow
SINK function – defining of springs/sinking holes
FILL function – filling of sink holes – springs/swallow points
FLOWACCUMULATION function – runoff quantification
FLOWLENGTH function – determination of the length of water flow.

4 Mathematical runoff model
Matematički model otjecanja

From the mathematical standpoint, the states of hydrological system are described by state matrices while the physical processes that are active within the hydrological system are presented by transformations of matrix elements. The procedure of matrix transformation is presented by a non-linear algorithm, which describes the structure and behavior of the system at any moment and it is based on iterative procedure of meeting hydrological balance relations. Algorithm is written in the C++ language and some important parts of program routines are presented in the "pseudocode" record, which is recognizable and the same in all programming languages.

For the purpose of easier and more realistic presentation of the system of model matrices and their transformation on the non-linear algorithms, the matrices as to their structure are divided into two groups: matrices of model constants and matrices of model variables.

4.1 Model constant matrices

Matrice modelskih konstanti

Model constant matrices are:

Incidence matrix, elements of which show the spatial position of the cell in the discretion grid, i.e. the type of the cell;

Direction matrix consisting of elements that show the direction of runoff from the observed cell marked • into the neighboring cell by means of one of the following numbers as it is already shown in Fig. 5.

Roughness coefficient matrix is a constant matrix and adopts various values of the Manning's roughness coefficient. In the scope of analyzing the sensitivity of the model, five cases of terrain roughness values have been analyzed depending on the pedologic change of soil type, slope and overgrowing of the terrain (n = 0,125; 0,11; 0,08; 0,05 and 0,035).

Matrix of the basin surface slope; consists of elements determining the slope from the observed cell towards the neighboring cell. Considering that slope can be computed in the observed cell towards each neighboring cell, the slope is computed for the direction of water flow (Fig. 6).

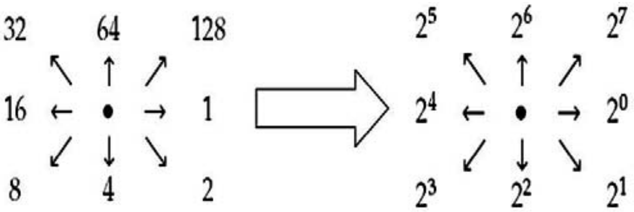

***Figure 5** Scheme of runoff direction from the observed point into the neighboring point*

***Slika 5.** Shema smjera otjecanja iz promatrane točke u susjednu*

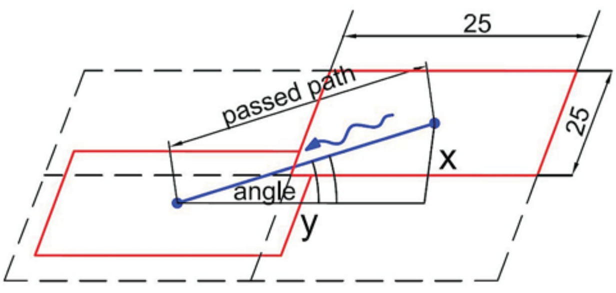

***Figure 6** Scheme for defining the runoff angle from the observed point into the neighboring point*

***Slika 6.** Shema definicije kuta otjecanja iz promatrane točke u susjednu*

Matrix of flowpath length from one cell into the other consists of elements defining the distance from the centre of the observed cell to the center of the neighboring cell in which the rainfall inflows. Considering that the 25×25 m size of cells is fixed, the horizontal matrix component of the water flow length is of a simple form and contains two groups of values: 25 or for catchment cells and 0 for the cells that do not belong to the catchment.

4.2 Model variables matrices

Matrice modelskih varijabli

When determining matrix models variables, the procedure is carried out in several phases supposing that each cell (i; j) belongs to the catchment and that all above mentioned matrices of model constants are defined in the following sequence:

1. The height of water column is calculated within the observed computed time interval for each cell (i; j) so that the quantity that has run off during the calculation phase has been deducted from the previous height, and the quantity that has flown in from the neighboring cells (as the result of rain falling uniformly on the catchment with the intensity in conformity with the designed hyetograph for concrete rain event) is added to the mentioned height. If we use designations:

${}_{\text{new}}h$ – height of water column in the cell (i; j)

${}_{\text{old}}h$ – height of water column that represents the remaining water in the cell (i; j) from the previous interval

outflow (i; j) – height of water column for water flown out from the cell (i; j)

inflow (i; j) – height of water column for water flown into the cell (i; j)

precip. – height of water column for precipitation fallen in the observed time increment,

then we obtain:

$$ {}_{\text{new}}h(i,j) = {}_{\text{old}}h(i,j) - outflow(i,j) + inlow(i,j) + precip. \quad (10)$$

2. For each cell (i; j) for the first time increment, i.e. for the first computing phase, the value of the inflow (i; j) matrix is set to zero.
3. Based on the height of water column (i; j) of the cell (i; j), *velocity* (i; j) shall be computed for each cell (i; j) applying the following formula:

$$ velocity(i,j) = \frac{\sqrt{\left(\frac{h(i,j)}{1000}\right)^3} \cdot \sqrt{slope(i,j)}}{kh(i,j)} \quad (11)$$

4. Using previously computed *velocity* (step 3) and the methodology for obtaining the matrix *outflow* (i; j), over the *ratio* (i; j), for each cell the quantity of water that flows out of the cell (i; j) can be calculated:

$$ ratio(i,j) = \begin{cases} 1, & \dfrac{path(i,j)}{s(i,j)} > 1 \\ \dfrac{path(i,j)}{s(i,j)}, & \dfrac{path(i,j)}{s(i,j)} \le 1 \end{cases} \quad (12)$$

$$ outflow(i,j) = ratio(i,j) \cdot h(i,j) \quad (13)$$

5. In this methodological step, two situations are possible:
- If the cell is not on the border with the lake and if the flow direction from the cell (i; j) is into (r, s), then the quantity of water inflow (r, s) is increased by the amount of runoff (i;j).
- If the cell (i; j) is a part of the border with the lake, then the hydrograph ordinate of the previous moment is increased by the runoff (i; j) in the observed computing moment.
6. Return to the first step.

5 Calibration
Kalibracija

For the needs of model calibration 9 rainfall events were used for which the measurements of the water runoff discharge on the Botonega storage reservoir barrier are recorded. In other words, there exist water balance estimates of the flood wave based on the water level recorder data on the storage reservoir and of the spillway and outlet operation from the storage reservoir. For that purpose, data on hours-long measurements of discharge are taken over. It was also done for related events, so that the base of pluviometric data was provided for the Botonega station in the form of rainfall with five-minute increments by the State Meteorological and Hydrological Service. It should be pointed out that the measured flood wave on the barrier is in fact the result of water balance estimate and the storage reservoir volume. Now, based on the storage-elevation-disharge curves of reservoir, spillway and outlet, the values of inflow into the storage reservoir are obtained.

Output model hydrograph was compared with the measured hydrograph for each observed rainfall event. To make those hydrographs comparable, corrections of model hydrograph is introduced by the effect of catchment retention. Namely, in addition to surface runoff, direct runoff includes also groundwater runoff which is far slower than the surface runoff so that the effect of catchment retention is achieved introducing the principle of one non-linear reservoir.

Generally, nonlinear reservoir is a time-varying system described with two equations:

1) reservoir equation:

$$V(t) = K(t)\cdot Q^k(t)\,, \tag{14}$$

2) continuity equation:

$$\frac{\Delta V(t)}{\Delta t} = U(t) - I(t) \tag{15}$$

where:
V – reservoir volume, m^3
ΔV – volume change in the period t, m^3
U – inlet, m^3/s
I – outlet, m^3/s
t – time, s
K – characteristic of the reservoir (storage coefficient) dependent or independent on time, s
k – transformation exponent (reservoir transformation effects).

The assumption that the constants K and k are known is introduced. In order to find transformed magnitudes q_i, as many nonlinear equations need to be solved applying iterative methods, as there are nontrasformed magnitudes Q_i known, according to the equation (16):

$$\left|\ \frac{Q_{i-1}+Q_i}{2}\cdot\Delta t - \frac{q_{i-1}+q_i}{2}\cdot\Delta t\ \right| = K\left|q_i - q_{i-1}\right|^k, \tag{16}$$

where:
Q_i – ordinate of original hydrograph at the moment t_i, m^3/s
Q_{i-1} – ordinate of original hydrograph at the moment t_{i-1}, m^3/s
q_i – ordinate of transformed hydrograph at the moment t_i, m^3/s
q_{i-1} – ordinate of transformed hydrograph at the moment t_{i-1}, m^3/s
K – transformation coefficient, s
k – transformation exponent (transformation effects of the reservoir).

In the procedural method for determining the nonlinear reservoir parameters K and k, one of the numerical methods of optimization algorithms was used – i.e. the genetic algorithm processed within the Matlab R2006a commercial program.

If a series of nontransformed data obtained by the application of a conceptual mathematical model (output gross hydrograph obtained by the mathematical model created here) is marked with Q_i and a series of measured runoff data with I_i, then $i = 1, 2, ..., m$.

The procedure is as follows:

1. For each K and k a series of transformed data $q_1, q_2, \ldots, q_m$ is calcualted by using nonlinear reservoir (Eq. 16),

For the above mentioned series $q_1, q_2, \ldots, q_m$, the "distance" of transformed and measured data is calculated as a FITNESS FUNCTION:

$$\sqrt{\sum_{i=1}^{m}(q_i - I_i)^2}, \tag{17}$$

where:
q_i – ordinate of transformed hydrograph at the moment t_i, m^3/s
I_i – ordinate of measured hydrograph at the moment t_i, m^3/s.

2. The CONDITION function is defined so that the volume integrated under the transformed hydrograph is equal or approximately equal to the volume integrated under the measured hydrograph for the same event. This is one of the most important calibration conditions. Since the conceptual model is elaborated with gross precipitation, this condition presents the reduction of translation hydrograph to the value of effective precipitation.

3. In addition to the above defined CONDITION, the minimum of the function is sought (Eq. 17). In other words, those pairs K and k are sought for which the "distance" between transformed magnitudes q_i and measured magnitudes I_i is minimum. It may now be stated that the objective of the calculation in the genetic algorithm is to determine the constants K and k, so that the FITNESS

FUNCTION reaches the minimum, provided that the function value CONDITION is approximately equal to zero [4].

The output model hydrograph transformed by the GA method is compared to the measured hydrograph for 9 observed rain events. The following may be concluded from the comparisons:

In the cases when the rainy period lasted long enough before the occurrence of a water wave, so that the soil saturation was considerable, the impact of evapo-transpiration, interception, water remaining in the valleys, infiltration and other processes of the hydrological cycle were not dominant. Furthermore, the impact of the catchment retention was not dominant either, because water practically poured down directly from the catchment area without considerable time lag. These resulting hydrographs were steep, the concentration time was between 4 and 5 hours or even less. Such a flood wave was recorded on 21-24 October, 1993 as an extreme case (Fig. 7), generated by the long-lasting heavy precipitation events, causing numerous floods in Europe.

- In all other cases (8 events), the soil saturation at the moment of the flood wave occurrence was negligible, so that the system losses were considerable. Equally so, an important catchment retention impact was recorded, which somehow should have been introduced into the model, because the occurrence of the measured hydrograph is considerably delayed in relation to the time of rain occurrence.

For the first group of hydrographs (21-24 October, 1993), there is no visible difference between the computed hydrograph being a direct output from the mathematical model and the one to which a nonlinear reservoir, i.e. genetic algorithm is applied. As it is shown in Figure 7, the computed hydrograph as an output from the mathematical model ("hydrograph calculated") and the hydrograph GA-transformed overlap very well along the time axis, and they are very similar in respect of volume. In the calibration procedure, the model correction is not necessary in this case.

For all other cases, the impact of the catchment retention characteristics is dominant so that calculated hydrographs considerably depart from the measured ones on two bases:

1. Departure par the time axis – calculates hydrographs are displaced to the left in relation to the measured ones, and
2. Departure par volumes – mathematical model does not take the catchment losses in calculation so that hydrograph gross values are calculated.

When calculating the hydrograph transformation through GA and application of the function CONDITION, satisfactory results that would be comparable with the relevant measured hydrographs cannot be obtained for some cases in which the catchment delay is considerably pronounced.

Model calibration for departure par time axis was performed in a way that the mathematical model structure was changed by the correction of velocity, so that in its definition the term delay – t_{lag} is introduced as a measure of the catchment retention characteristic. The coefficient function of which is to slow down the water flow over the catchment surface is a dimensionless quantity and from the origin, i.e. the time of the catchment delay which is calculated for each individual case, results the size measure.

Model calibration for the "departure par volumes" was made by correcting the gross into the net rain with the runoff coefficient calculated for each rain event separately. Namely, by the ratio of the measured and model hydrograph, the measure of precipitation loss in the catchment was obtained in the form of a "threshold" expressed in the height of water column in millimetres. This "threshold" corrects the gross hyetogram in the mathematical model so that the calculation is made only with the effective values, i.e. the values exceeding the "threshold".

6 Analysis of model sensitivity
Analiza osjetljivosti modela

During the elaboration of the CRRS model, the model sensitivity to a number of factors was noticed, which quantitatively and qualitatively change the runoff hydrograph. The greatest changes were noticed at the level of genesis and presentation of measured data. Since there are no measurement sections or spillways on the Botonega storage reservoir, there is no way to measure the inflow into the storage reservoir. The measured water waves are volumetrically obtained by a balance equation. On the basis of the water level change in the storage reservoir and the volume of free storage space, as well as the known water level for each event, the inflow increase was calculated in time. This shows that the genesis of occurrence of the measured and computed water wave is quite different. Therefore, comparing them, some differences related to the description of catchment surface runoff are expected in advance.

Since systematic measurement of hydrographs by state institutions does not exist in the Republic of Croatia, all the mentioned data are the result of searching through the unofficial databases established for other purposes and therefore, of dubitable authenticity and reliability. Some parameters important for the description of the runoff by the same or similar methodology as described herein are completely omitted from the measurement. This in the first place refers to the catchment absorption (infiltration), which failed when calculating effective rain. But, the soil saturation was then incorporated into the model by other mechanisms (previous rain, nonlinear reservoir and t_{lag} were analyzed). Wind impact was not taken into consideration, as it is not dominant in the physical description of runoff from small mountain catchments.

With the purpose of "precise" model calibration, the model sensitivity to the following elements was analyzed:

1. Periods of recording of available measured hydrograph values (hourly, hours-long)
2. Roughness
3. Lag time (hydrograph time delay).

When calculating the computed hydrograph, a rainy event in the form of a 5-minute record of gross precipitation is taken as the input datum in the mathematical model. The consequence is the output result – the runoff hydrograph also in the form of a 5-minute record, which means very detailed and precise, as well as the description of the hydrograph in the course of time.

For some rain events, the measured hydrograph values related to the inflow into the Botonega storage reservoir were measured at intervals of 7 or 10 hours. Because of such great span of measurement time, a 5-minute record cannot be used for a quality comparison of the computed hydrograph, so that the results should be adjusted. During this "precise" model calibration, it should be mentioned that the information about runoff becomes less accurate, and therefore for practical reasons, the data of much better quality are reduced to a level of rough and scanty presentation. Due to the lack of a better database, approximate values are taken deliberately.

By comparing the hydrographs obtained for different Manning's roughness coefficient values, it is evident that the model reacts to roughness. However, this parameter does not have a dominant influence on the model in the domain of real roughness parameter values. In other words, by changing the Manning's coefficient value in the equation related to the velocity of water flow over the terrain, in the domain of real values the mathematical model does not offer important differences in the catchment runoff values. Consequently, the image of runoff hydrograph for the given area is not considerably changed. The conclusion may consequently be reached that the model is not sensitive to the change of the Manning's coefficient value in the domain of real values of that parameter.

For the sensitivity analysis of the conceptual model and the model hydrographs, for the lag time description output result, 5 different wordings have been selected [5]:

- T1 = time difference between the measured hydrograph maximum and the hyetogram gravity center for fallen gross rain,
- T4 = time difference between the measured hydrograph gravity center and the hyetogram of fallen gross rain
- T5 = time difference between the measured hydrograph gravity center and the beginning of the hyetogram for the fallen gross rain
- T7 = time difference between the measured hydrograph maximum and the beginning of the hyetogram for the fallen gross rain
- T8 = time difference between the measured hydrograph maximum and the hyetogram maximum for the fallen gross rain, and
- Tc = catchment time of concentration.

Transformation step of model hydrograph into final – outflow hydrograph by nonlinear reservoir and by the application of genetic algorithm, is reduced to searching for constants k and K so that the FITNESS FUNCTION is as near as possible to the zero value. For different values of lag time, different values of k and K pairs are obtained, as well as the fitness function values. By comparing the fitness function values for different lag time formulations in relation to the observed rain events that have been analyzed, the T1 wording offers the best result, i.e. the smallest fitness function.

6
Results
Rezultati

The chapter presents resultant model hydrographs before and after the GA transformation for all observed rain events and the respective comparisons with relevant measured hydrographs, by previously described methodology including all previously described steps.

Basic hydrological input parameters (precipitation, 5 min. and hydrograph measured) and the output paramteres (hydrograph computed and GA transformed throw nonlinear reservoir) are presented in each graph.

Compared graphs of the output computed hydrograph (after calibration, meaning after GA transformation) and the relevant measuring hydrograph for the same rainy event are presented in Figures 7, 8, 9, 10.

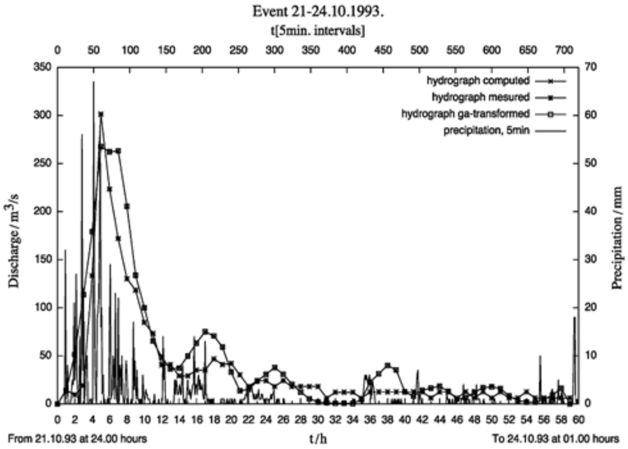

***Figure** 7 Comparison of output computing hydrograph and measured hydrograph for rainfall event from 21.10-24.10.1993*
***Slika** 7. Usporedba izlaznog računskog hidrograma i mjerenog za kišni događaj od 21.10.-24.10.1993.*

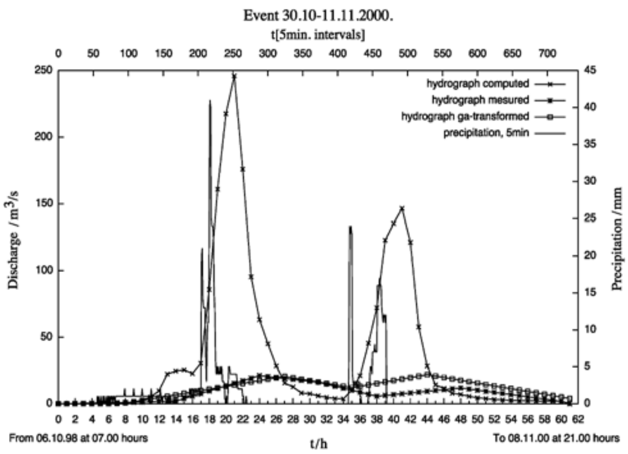

***Figure 9** Comparison of output computing hydrograph and the measured hydrograph for the rainfall event from 30.10-11.11.2000*
***Slika 9.** Usporedba izlaznog računskog hidrograma i mjerenog za kišni događaj od 30.10.-11.11.2000.*

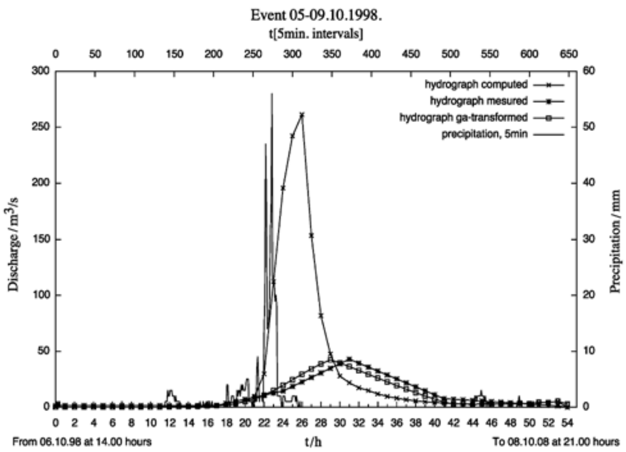

***Figure 8** Comparison of output computing hydrograph and the measured hydrograph for the rainfall event from 05-09.10.1998*
***Slika 8.** Usporedba izlaznog računskog hidrograma i mjerenog za kišni događaj od 05.-09.10.1998.*

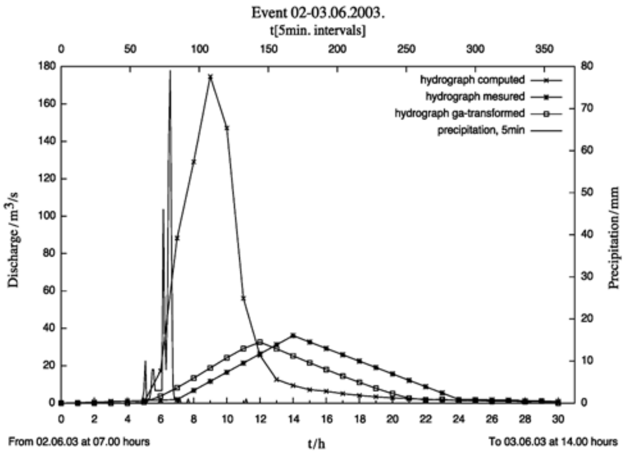

Figure 10 *Comparison of output computing hydrograph and the measured hydrograph for the rainfall event from 02-03.06.2003*
Slika 10. *Usporedba izlaznog računskog hidrograma i mjerenog za kišni događaj 02.-03.06.2003.*

7 Conclusion
Zaključak

The impact of all analysed and exhibited spatial catchment parameters on the flow phenomenon in presented model show, as expected, nonlinear character. This is particularly the case during extremely heavy rains, and it is difficult determine it precisely.

The estimated runoff model shows that the process of determination of the surface runoff, interpreting the surface runoff on an endlessly small water layer height according to Chezy or Manning equation, with all previously described limitations, provides promising results but only in the domain of the corrected method. The mentioned principle does not take into consideration a very important catchment characteristic – the retention characteristic. As a possible improvement of this approach, the correction of Manning equation for the calculation of speed in the coefficient domain is introduced by which the Manning roughness coefficient is multiplied and the measure of that correction is reciprocal to the value of the lag time magnitude. The only foothold of this solution is the fact that the more the catchment retardation is expressed the slower the speed of water flow on the surface should be, and vice-versa. Such a solution could be very significant if you want to relate the time of catchment concentration as a special case of time lag and the speed of surface flow or the occurrence of an output hydrograph. The reliability of this solution depends of course on the validity and extensiveness of input rainfall knowledge and the knowledge of the terrain.

The deficiencies occurring due to complexity of computational model and its close connection with physiographic terrain characteristics can be overcome by the implementation of a number of information routines (within GIS – and GA). Therefore precise terrain documentation was created to overcome the issues of complex mathematical calculations by genetic optimization procedure.

The biggest problem in establishing a CRRS model is the taring step of the "coarse" and the "fine", as well as the sensitivity analysis due to large limitations in measurings within hydrometry or in their scarcity. Furthermore, there are both limitations in the measurement technique and measurement limitations in time and space. Therefore it was necessary to determine significant extrapolations of such measurements so that the CRRS model created by means of such information would be applicable in description of hydrological processes. Such an approach of modelling hydraulic phenomena can be included into other aspects of solving hydroengineering problems (floods, drought, water contamination etc.).

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