

LONG-TERM FLOW SIMULATION IN BÂRLAD RIVER BASIN USING ROMANIAN HYDROLOGICAL MODEL CONSUL

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Abstract: The paper presents the preparation of the Romanian hydrological software CONSUL for long term hydrological simulation needs for assessment of climate change impact in extreme events. CONSUL model is a conceptual model based on semi-distributed parameters depending on the physical characteristics of the river basin. According to the schematic representation (physiographic modelling) of how water flows and collects in a river basin the model computes the discharge hydrographs on sub-basins and then performs their routing and composition on the main river and tributaries. The initial values of the model parameters corresponding to some of the model structures was estimated by the generalized relationships of those parameters in function of the morphometric characteristics of the river basin or of the river reaches. These relationships on obtain on the basis of the recorded data at the hydrometric stations using the major rainfall-runoff events. CONSUL model was calibrated (i) individual (based on the 25 rainfall-runoff events) for the simulation of the largest floods occurred during the period 1975-2010 in the Bârlad River Basin, Romania and (ii) globally, by continuous flow simulation from the period 1984-1988. Using the calibrated parameters the model validation was made also by flow simulation (at 6 hours time step) during the years 2006 and 2010. Average precipitation and air temperature (hydrological model input data) for each sub-basin was performed using a pre-processing program of meteorological data from original rectangular grid nodes corresponding to Bârlad River Basin, averaging being achieved as weighted values based on the representativeness of these nodes for each analyzed sub-basin. The flow simulation results with the CONSUL model in the Bârlad River Basin, during both the calibration and validation periods, showed that the model is robust and can be applied successfully for long-term flow simulation in modified climate conditions.

Key words: calibration, deterministic model, flow simulation, rainfall-runoff model, validation

1. INTRODUCTION

Rainfall – runoff process modelling is important in real-time floods forecasting, floods warning, analyses concerning floods hazard management, floodplain mapping or in many other water resource planning and development applications.

In the last period as a result of requirement regarding the future modifications in extreme hydrological events an important application was also to long-term hydrological simulations (Romanescu et al., 2012) based on climate change projections, (Hobai, 2009; Busuioc et al., 2014; Dumitrescu et al., 2014; Marin et al., 2014).

The paper presents the application of the Romanian hydrological software CONSUL to long term hydrological simulation on the Bârlad river

basin, activity performed within the project CLIMHYDEX ("Changes in Climate Extremes and associated impact on hydrological events in Romania").

The CONSUL model has been extensively used for floods modelling and forecasting (Leonte-Neagu et al., 1997; Mic et al., 2006; Stanciu et al., 2009; Stănescu et al., 1997), but it represents also a valuable tool for assessing climate change impact upon water resources on a river basin by long-term flow simulation (Corbuș et al., 2011; Corbuș et al., 2012; Corbuș et al., 2013).

The first step in any rainfall-runoff process simulation on a river basin is to calibrate the parameters used in various hydrological model subroutines by simulation of historical events.

Generally, hydrological model calibration is based on climate parameters from meteorological or

rainfall stations available in the analyzed basin. In this case, as input data high-resolution (10x10 km) gridded historical climate parameters at 6 hour time step are used.

2. THE CONSUL MODEL

CONSUL model is a conceptual model based on semi-distributed parameters depending on the physical characteristics of the river basin: topography, vegetation, and soil.

The general strategy of runoff simulation in large river basins requires double modelling, i.e. both topological modelling of the river basin and rainfall-runoff process modelling.

Being a deterministic hydrological model, CONSUL allows simulation of all phases of the runoff both in the small river basins and in the large, complex, natural and hydro-technical arranged ones. The model calculates the flow hydrographs for each sub-basins, propagation and composition on the main river and their tributaries in conformity with the schematic representation (topological modelling) of the water collection modality in a river basin.

2.1. Topological modelling of the river basin

Runoff in a river basin is generated through a successive integration process over the valley-side, sub-surface and riverbed, of the inlet precipitation amounts. The mathematical modelling of this complex process requires the achievement of a sketchy representation of the way waters flow and gather in a river basin. This sketchy representation - called topological modelling of the river basin - involves the river basin and river network division into homogeneous units. It is considered that over each unit the input data are evenly distributed while the characteristic parameters of the processes taking place at the level of each unit are considered constant in space.

2.2. Rainfall-runoff process modelling

The rainfall-runoff process modelling taking place in a watershed, by using CONSUL model, can be achieved following certain important steps:

- The basin is divided into sub-basins according to a scheme of runoff integration;
- The determination, for each sub-basin, of the snow-melt water, using the degree-day method (Chow, 1971; Şerban, 1984; Şerban et al., 1994);
- Computation, for each sub-basin, of the average rainfall by weighting the values of

rainfall and water coming from snow cover melting, as recorded in the meteorological network (Şerban et al., 1989);

- Calculation of the effective rainfall over each sub-basin by extracting the loss by infiltration and evapotranspiration from the average water inflow; using PNET deterministic reservoir model (Bloomfield et al., 1979; Crawford & Linsley, 1966; Şerban, 1984; Şerban, 1987; Şerban et al., 1989);
- Integration of the effective rainfall on the slopes and in the primary river network finally resulting in the discharge hydrograph in each sub-basin; as a transfer function of the hydrographical system, the instantaneous unit hydrograph was used (Şerban, 1984; Şerban et al., 1989);
- Superposition of the flood waves formed in each sub-basin and their routing along the riverbed, using a non-linear model based on the analytical solution of the Muskingum model (Dooge, 1973; Şerban & Corbuş, 1987a; Şerban & Corbuş, 1987b);
- Flood wave attenuation through the reservoirs, using the reservoir coordinated operation method (Şerban & Pleşa, 1983).

It must be mentioned that due to the restriction of the available data, the mathematical relationships introduced into the model do not entirely reflect the physical character of the processes related to the runoff modelling. Thus, these relationships are approximations of the physical processes (percolation, infiltration), empirical relationships (evapotranspiration) or other conceptual relationships (interception, retention in the depressions, surface, hypodermic or basic runoff).

The rainfall-runoff deterministic model simulates most of the significant hydrological processes within a hydrographic basin: snow melting, interception, retention in the depressions, evapotranspiration, infiltration, surface runoff, hypodermic runoff, percolation, base runoff. Figure 1 presents the descriptive diagram of CONSUL model.

2.3. Input and output data

The input data used in the application of CONSUL model are:

- Precipitation distributed on the computing time step, recorded at the meteorological stations and at the rain-gauge points from the river basin; it is availability to use directly the estimated mean precipitation over the sub-basins, corresponding to each computing time step;

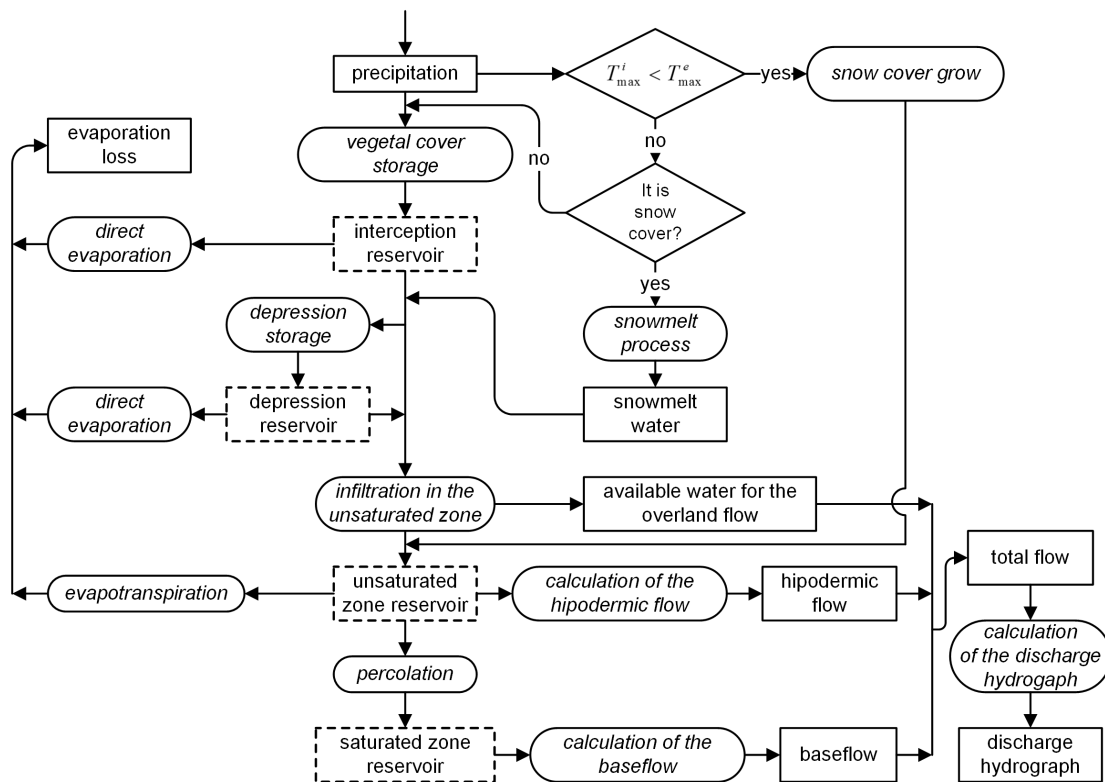


Figure 1. Descriptive diagram of the rainfall-runoff deterministic model CONSUL

- Water equivalent of the snow cover as average on the sub-basin, at the beginning of the simulated interval, estimated on the snow depth and density measured at the meteorological stations;
- Air temperatures recorded at the meteorological station representative to the sub-basin;
- Discharges recorded, at the computing time step, at the gauging stations from the basin.

The output data from the CONSUL model are hydrological balance components for each sub-basin and discharge hydrographs determined in the computing cross-sections, obtained from flow routing on river reaches or from attenuation by reservoirs.

3. TOPOLOGICAL MODELLING OF THE RIVER BASIN BÂRLAD

Rising at an altitude of 370 m from the high hills of the South Western part of Moldavian Plateau, Bârlad River represents a significant left tributary of the Siret River.

Having an average altitude of 212 m Bârlad River Basin is a complex river system that crosses two major relief units: plateau and hills (92% of the basin overlaps Bârlad Plateau) and plain (occurred in the southern extremity of the basin).

After the topological modelling for Bârlad River Basin resulted 56 sub-basins and 30 river

sectors. Figure 2 presents, as example, the first part of the topological scheme of the Bârlad River Basin until the hydrometric station Vaslui.

4. CALIBRATION OF THE CONSUL MODEL PARAMETERS

CONSUL model was applied in the Bârlad River Basin for the simulation of the largest floods from the period 1975-2010.

Continuous flow simulation from the period 1984 - 1988 was also used to calibrate the hydrological model parameters and from the years 2006 and 2010 for validation.

Calculation of average precipitation and air temperature (hydrological model input data) for each sub-basin was performed using a pre-processing program of meteorological data from original rectangular grid nodes corresponding to Bârlad River Basin, averaging being achieved as weighted values based on the representativeness of these nodes for each analyzed sub-basin.

Calibration of CONSUL model parameters was performed in two stages: individual and globally, and to determine the initial values of model parameters were used generalization relationships of these parameters based on morphometric characteristics of the river basin or sector.

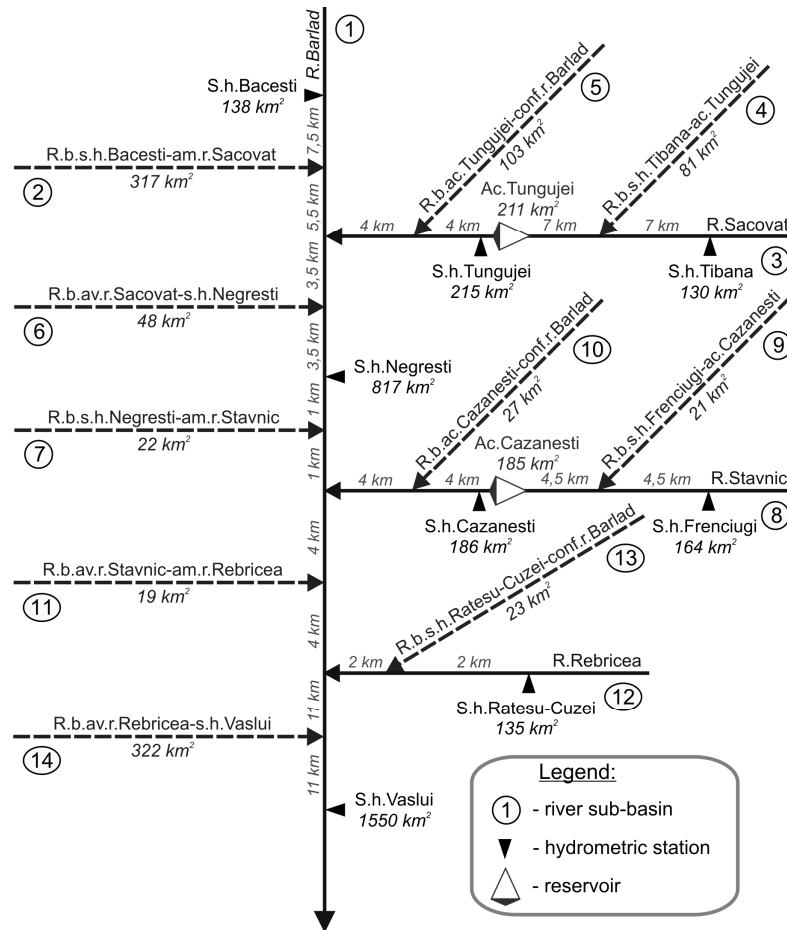


Figure 2. Topological modelling of the river basin Bârlad until the hydrometric station Vaslui

4.1. Model parameters

The parameters of the CONSUL model are corresponding to the model structures:

- a) *Determination, for each sub-basin, of the snow-melt water, having the parameters:*
 - T_e - the equilibrium temperature whereof any heat exchange between the snow cover and the environment (near 0°C);
 - M - the melting factor or the degree - day factor ($\text{mm} / ^{\circ}\text{C} / \text{day}$), which is estimated from the scientific references in function of wind speed and forest cover coefficient.
- b) *Computation, for each sub-basin, of the average rainfall by weighting the values of rainfall and water coming from snow cover melting, as recorded in the meteorological network.*
- c) *Calculation of the effective rainfall over each sub-basin by subtracting the loss of infiltration and evapotranspiration from the average precipitation inflow; using the following parameters:*
 - PI - the interception capacity (mm);
 - FOM - the maximum infiltration capacity of soil

(mm/hour);

- FC - the minimum infiltration capacity of soil (mm/hour);
 - CH - the hypodermic runoff parameter;
 - UDM - the nominal capacity of the depression (mm);
 - PS - the hypodermic runoff threshold (mm);
 - $USZN$ - the nominal capacity of the reservoir corresponding to the non-saturated zone (mm);
 - CB - the base runoff parameter;
 - PSB - the base runoff threshold (mm).
- d) *Integration of the effective rainfall on the slopes and in the primary river network finally resulting in the discharge hydrograph in each sub-basin, with the following parameters:*
 - K_r - the recession coefficient of the hydrograph;
 - T_L - the delay time between the rainfall gravity centre and surface flow hydrograph gravity centre.
 - e) *Composition of the flood waves formed in each sub-basin and their routing along the riverbed having the parameters:*
 - K - a parameter associated to the discharge routing hydrograph. It varies depending on the

discharge being routed along the river reach;

- X – the attenuation coefficient.

f) *Flood wave attenuation through reservoirs and their conjunctive operation*, model parameters representing the characteristics of the reservoirs (characteristic levels, reservoir capacity curve etc.) and of the outlets (characteristic levels, dimensions, discharge coefficient etc.).

From the total number of parameters only about 10 parameters are usually changed in the calibration action.

4.2. Estimating the initial values of CONSUL model parameters based on generalization relationships

In order to determine the initial values of the parameters corresponding to some of the model structures on use generalized relationships of those parameters in function of the morphometric characteristics of the river basin or of the river reaches. These relationships on obtain on the basis of the recorded data at the hydrometric stations, by using as many major rainfall-runoff events.

4.2.1. Determination of the parameters of the infiltration structure

In order to determine the parameters of the infiltration model structure on used the PNET program, elaborated on the basis of the PNET model (Şerban, 1987), which is based on the hypothesis that runoff in a watershed is similar to the runoff in a sequence of four interconnected reservoirs: the interception reservoir, the depression reservoir, the reservoir of the non-saturated zone and the reservoir of the saturated zone. The interception reservoir simulates the interception process through which the precipitations are retains on the forest canopy and on the vegetation cover. The depression reservoir and the reservoir of the non-saturated zone simulate the most important processes taking place at the soil level and in the aeration zone, i.e.: retention in depressions, infiltration, percolation, surface runoff and subsurface flow. The reservoir of the saturated zone simulates the base runoff.

The determination of the infiltration parameters have been achieved function of the soil type (Table 1)

at the selected gauging stations for runoff formation characteristic zones in the selected river basin. For each gauging stations, rainfall-runoff events have been selected so that it better covers the entire domain of the possible flood formation situations (rainfall with diverse intensity and duration, produced in certain antecedent soil moisture contents). These parameters are determined at the gauging stations, using about 10 rainfall-runoff events, by means of the PNET program, elaborated on the basis of the above mentioned mathematical model.

Table 1. Soils classification on the hydrologic type

Type	Texture	Infiltration potential
A	Gross	Very great
B	Gross to medium	Great
C	Medium	Average
D	Medium to fine	Low
E	Fine	Very low

Parameter PI has been determined in terms of the vegetation cover rate of the basin, α_p , $PI = 2 + 6 \alpha_p$, parameter CB was determinate from the table 2. All the others parameters have been determinate by means of the PNET program and then have been used to the carried out of the regionalization presented in the figures 3 - 7. As for the parameter PSB it has not been obtained a regionalization relationship, it will be finally adopted through the global calibration of the flood simulation model.

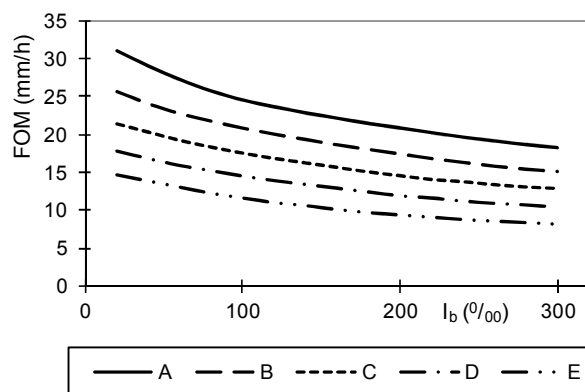


Figure 3. Variation of the maximum infiltration capacity function of soil type and land slope

Table 2. Coefficient of the base runoff CB function of the basin surface and the land slope

F (km^2)	I_b (‰)				
	<100	100-200	200-300	300-400	>400
<500	0.05-0.08	0.08-0.11	0.11-0.14	0.14-0.17	0.17-0.20
500-1000	0.04-0.07	0.07-0.10	0.10-0.13	0.13-0.15	
>1000	0.03-0.06	0.06-0.08	0.08-0.10		

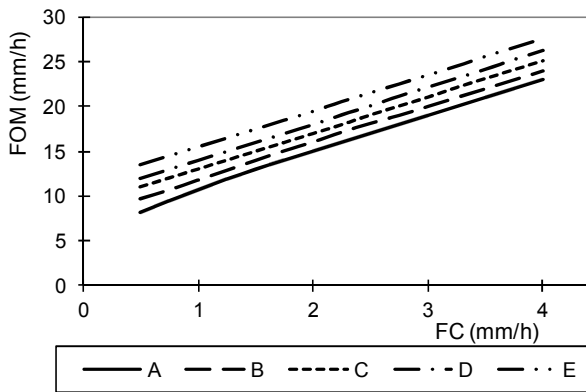


Figure 4. Variation of the minimum infiltration capacity function of the soil type and the maximum infiltration capacity

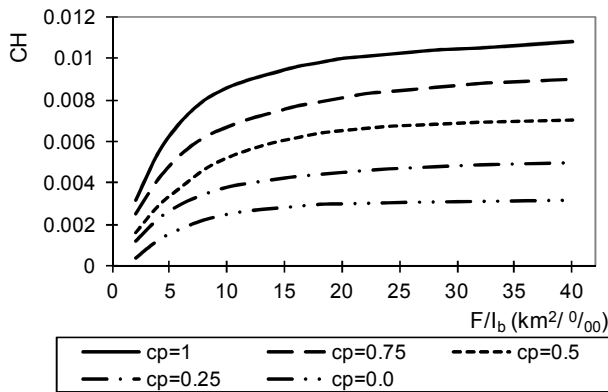


Figure 5. Variation of the hypodermic runoff parameter function of the F/I_b and the forest cover coefficient cp

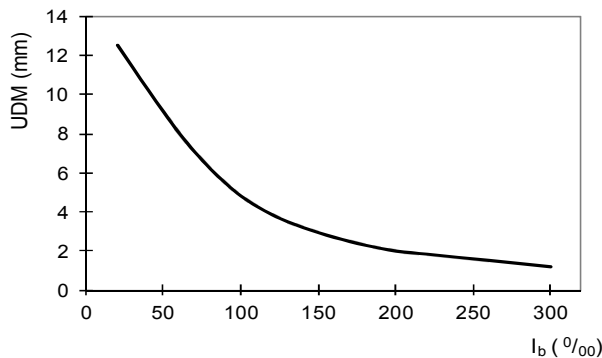


Figure 6. Variation of the nominal capacity of the depression function of the land slope

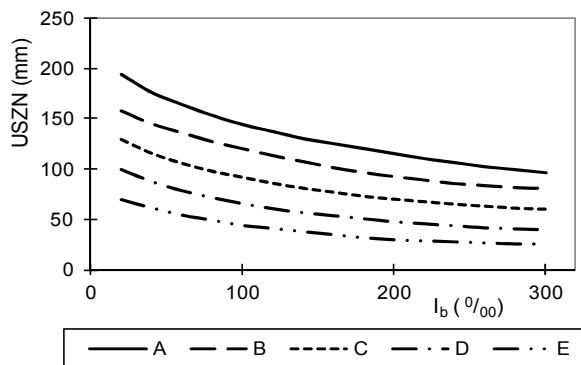


Figure 7. Variation of the nominal capacity of the reservoir corresponding to the non-saturated zone function of the soil type and land slope

On the basis of the previously presented regionalization relationships the parameters of the infiltration structure for all the rest sub-basins in the Bârlad hydrographic basins have been determined.

4.2.2. Determination of the parameters of the runoff integration over small watersheds (unit hydrograph)

One of the structures of the flood forecasting model is the integration of the effective rainfall over small watersheds and in the primary river network, finally resulting in the discharge hydrograph formation in each sub-basin.

The parameters of the unit hydrograph (IUH) for the IMH model (Şerban, 1984; Şerban et al., 1989) are determined as follows:

$$T = \frac{5}{3} \left(M_1 - \sqrt{1,2 \cdot m_2 - 0,2 \cdot M_1^2} \right) \text{ and} \quad (1)$$

$$K = M_1 - \frac{T}{2}$$

where: T is the time interval between the end of rainfall and the moment the water entered in the main river network, K - the parameter of the decrease branch of the hydrograph; M_1 and m_2 - the moments of the unit hydrograph, by first order taken as against the origin of the unit hydrograph and by the second order taken as against the centre of the area of the unit hydrograph, computed in terms of the shape factor of the IUH (S_2) and the leg time between the mass weight of the rainfall hyetogramme and the mass weight of the surface flow hydrograph (T_L) with the formulas:

$$M_1 = T_L \text{ and } m_2 = S_2 \cdot T_L^2 \quad (2)$$

The recession coefficient (K_r) have been computed using the relationship:

$$K_r = e^{-t/K} \quad (3)$$

The unit hydrograph moments (M_1 and m_2) have been determined on the basis of the direct data or by the regionalization relationships for the parameters T_L and S_2 . For the establishing the regionalization relationships in zone have been used hydro-meteorological data from the representative gauging stations of the river basin Bârlad. These stations have been selected from the characteristic flow formation zone. For each gauging station, as many rainfall-runoff events have been taken into consideration and on the basis of these data, in the first stage, the parameters of the infiltration structure and effective rainfall have been implicitly determined. The effective rainfall values are the

input data in the computing model of the unit hydrograph parameters. Single floods produced by the rainfall with the different intensity have been selected. For establishing the parameters have been tested many types of models. The best results from the simulations have been obtained for the IMH model.

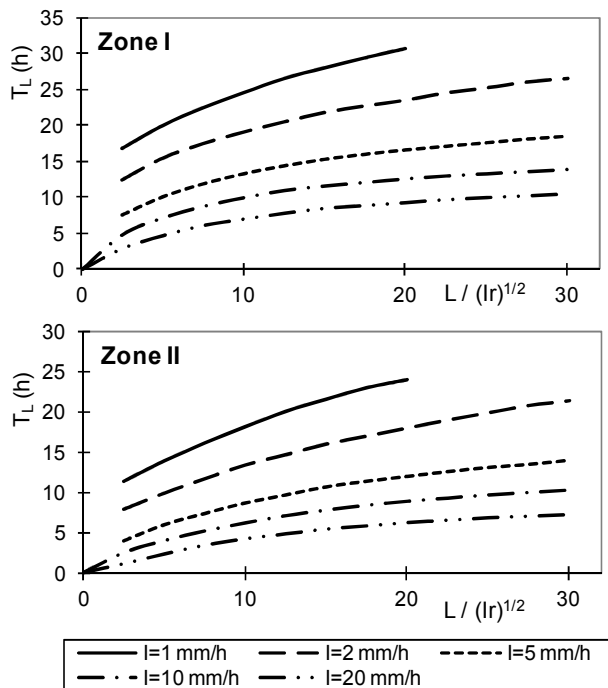


Figure 8. Regionalization relationships for the parameter T_L

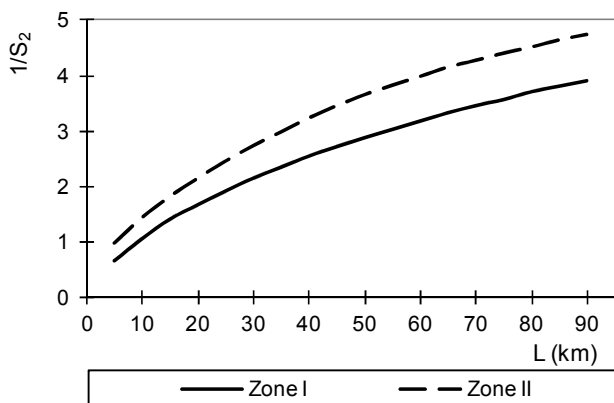


Figure 9. Regionalization relationships for the parameter $1/S_2$

On the basis of these parameters, for the Bârlad River Basin, the regionalization relationships in terms of the morphometric elements of the reception basins (length and river slope) have been carried out. Two zones have been resulted (Fig. 8 and 9):

- Zone 1 which includes sub-basins from the Bârlad River Basin up to the downstream section of the Vaslui River Basin;

- Zone 2, which includes the rest of sub-basins.

The above presented regionalization relationships have been used for the determination of the unit hydrograph parameters in the ungagged sections from the Bârlad River Basin.

4.2.3. Determination of the parameters of the flood routing through the river reaches

For the simulation of the flood routing through the characteristic river reaches a nonlinear model based on the system theory have been used (Dooge, 1973; Şerban & Corbuş, 1987a; Şerban & Corbuş, 1987b).

The parameters X and K of the model used for the flood routing have been determined for the characteristic river reaches having Δx length, on the basis of the data from the gauging stations and of the morphometric characteristics of the riverbed.

The pre-determination of the attenuation parameter X have been made depending on the morphometric characteristics of the river reaches conform to table 3.

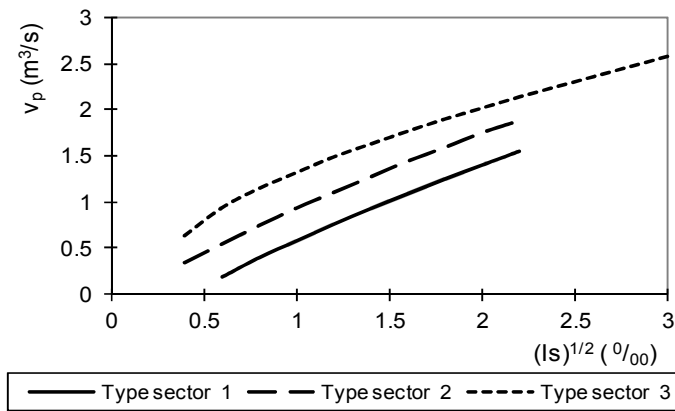
Table 3. X attenuation parameter values based on the morphological characteristics of the river reach

Characteristics of the river reach	X
Embankment river reaches or channels	0,4...0,5
River reaches having little developed flood plains	0,2...0,4
River reaches having well developed flood plains with the slope above 0,5%	0,0...0,2
River reaches having very large flooding areas with the slope under 0,5%	-3,0...0,0

Parameter K , which represents the runoff duration of floods along the considered river reach, has been computed for a certain river reach between two river stations on the basis of the biggest floods recorded at the two stations. Thus, the biggest floods recorded in the three studied basins (at least three floods) have been selected and the mean runoff duration through the considered river reaches have been computed. Further on, the regionalization relationships have been carried out and presented in the figures 10 and 11. The parameter K for all other reaches has been assessed by applying the formula:

$$K = \frac{L}{v_K}, \quad (4)$$

where: L is the length of the reach in km; v_K – the routing velocity corresponding to the parameter K ;



Sector type	Characteristics
1	River reaches heavy meandered and non-embanked, with abundant vegetation, situated in the lower hills zones, plains and large inter-mountainous depressions
2	River reaches moderate meandered, with moderate vegetation, situated in the sedimentary zones of the mountains and foothills
3	River reaches little meandered, with little vegetation, situated in the crystalline zones of the mountains and the heavy fragmented plateau

Figure 10. Variation of the routing velocity in function of the slope and the characteristics of the river reach

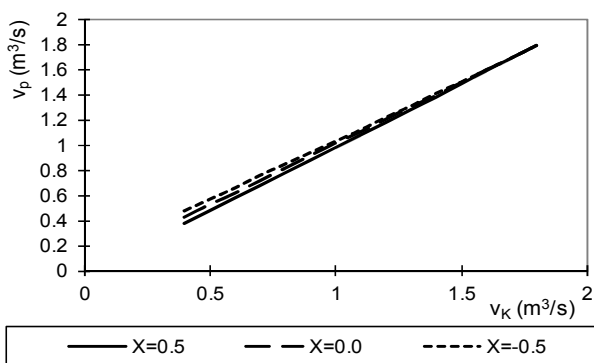


Figure 11. Variation of the velocity v_K in terms of the velocity v_p and the attenuation parameter X .

Parameter v_K have been determined in terms of the flood routing velocity (v_p) and the slope of the river reach (Is).

4.3. Individual calibration of hydrologic model parameters

Individual calibration of CONSUL model parameters was based on 25 significant historical rainfall-runoff events. In order to cover a wide range of possible situations where training the chosen floods (June and July 1975, April 1979, April and May 1984, June and July 1985, May and June 1988, May, June, July, August and September 1991, September 1996, March and August 2002, April and May 2005, March, April and May 2006, September 2007, June and July 2010). For closing cross-sections, of the sub-basins controlled by the hydrometric stations existing in Bârlad River Basin, the parameters of infiltration and unit hydrograph were determined. Knowledge of these parameters allowed the determination of the parameters for un-gauged sub-basins. Also, by the simulation of 25 floods to the gauging stations located at the downstream end of a reach, the parameters of the equation propagation were calibrated.

As example, figure 12 shows the discharge

hydrographs, simulated (with CONSUL model) and observed runoff, at 6 hours time step, during the flood occurred in June 1985, for the control cross-sections corresponding of the sub-basins outlet. Simulated discharge hydrograph for this kind of sub-basin is computed based only by the rainfall distribution and relationships between model parameters and physically measurable watershed characteristics established for each sub-basin. These relationships are then assumed to hold for ungagged sub-basins having similar hydrologic characteristics.

Examples of simulated and observed discharge hydrographs for cross-sections situated at the downstream end of a reach are presented in figure 13. Also, to highlight the calibration of CONSUL model parameters during the recession of floods and low water period, as example, simulated and observed hydrographs (in April 1979) in the cross-sections corresponding of hydrometric stations situated on the main river Bârlad are presented in figure 14.

4.4. Global calibration of hydrologic model parameters

Global calibration of CONSUL model parameters was done by the continuous simulation of flow for the period 1984-1988. The global calibration allowed the recalibration of parameters for infiltration and unit hydrograph for ungagged sub-basins and also the parameters recalibration of propagation equation.

5. VALIDATION OF HYDROLOGICAL MODEL

For model validation, the model parameters obtained during calibration phase and the observed runoff at hydrometric stations on Bârlad River and their tributaries were used. The validation of CONSUL model parameters was done by continuous flow simulation from the years 2006 and 2010. An

example of observed and simulated discharge hydrographs in the validation phase is presented in

figure 15, where T represents the number of values at 6 hour time step).

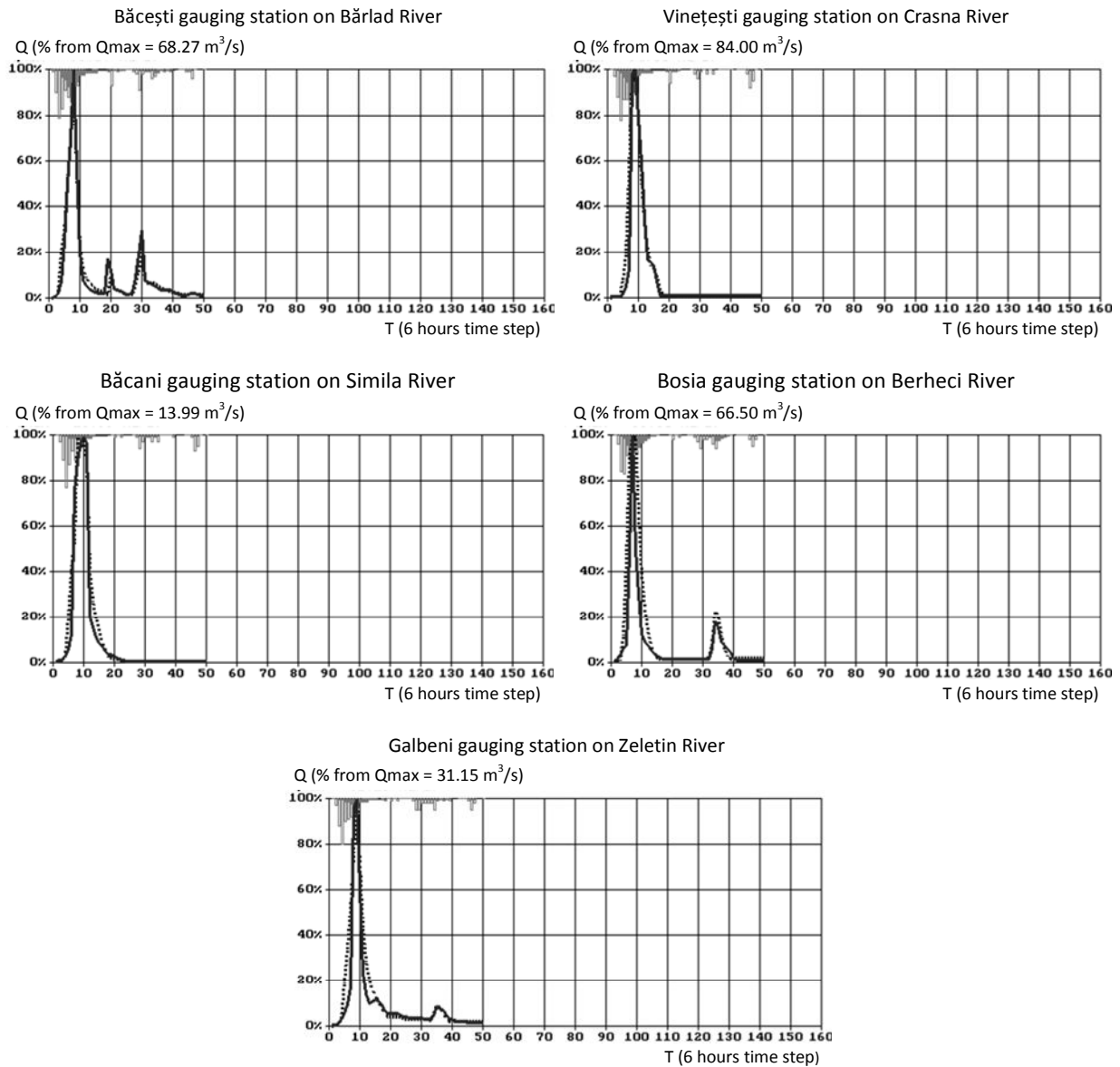


Figure 12. Simulated (-----) and observed (—) discharge hydrographs for the control cross-sections corresponding of the sub-basins outlet, for the flood produces in June 17, 1985

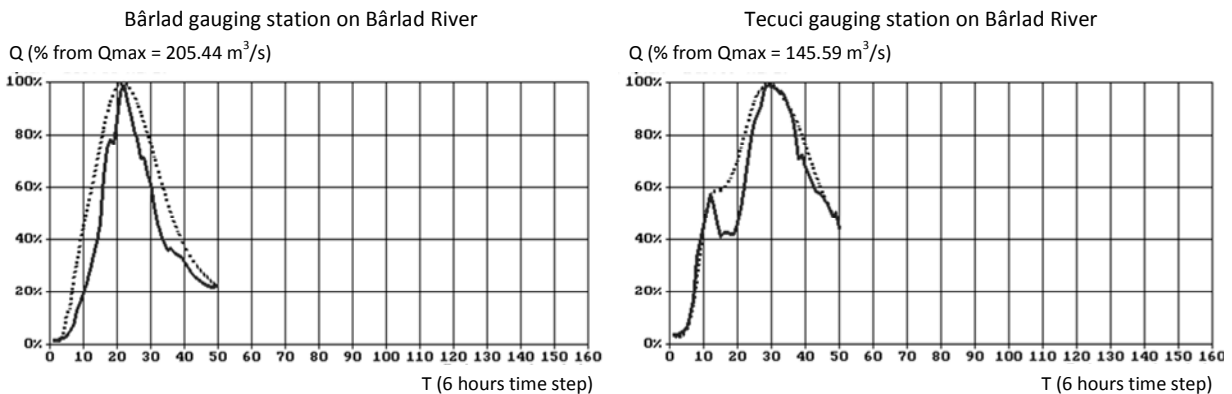


Figure 13. Simulated (-----) and observed (—) discharge hydrographs at hydrometric stations situated on Bârlad River for the flood produces in June 17, 1985

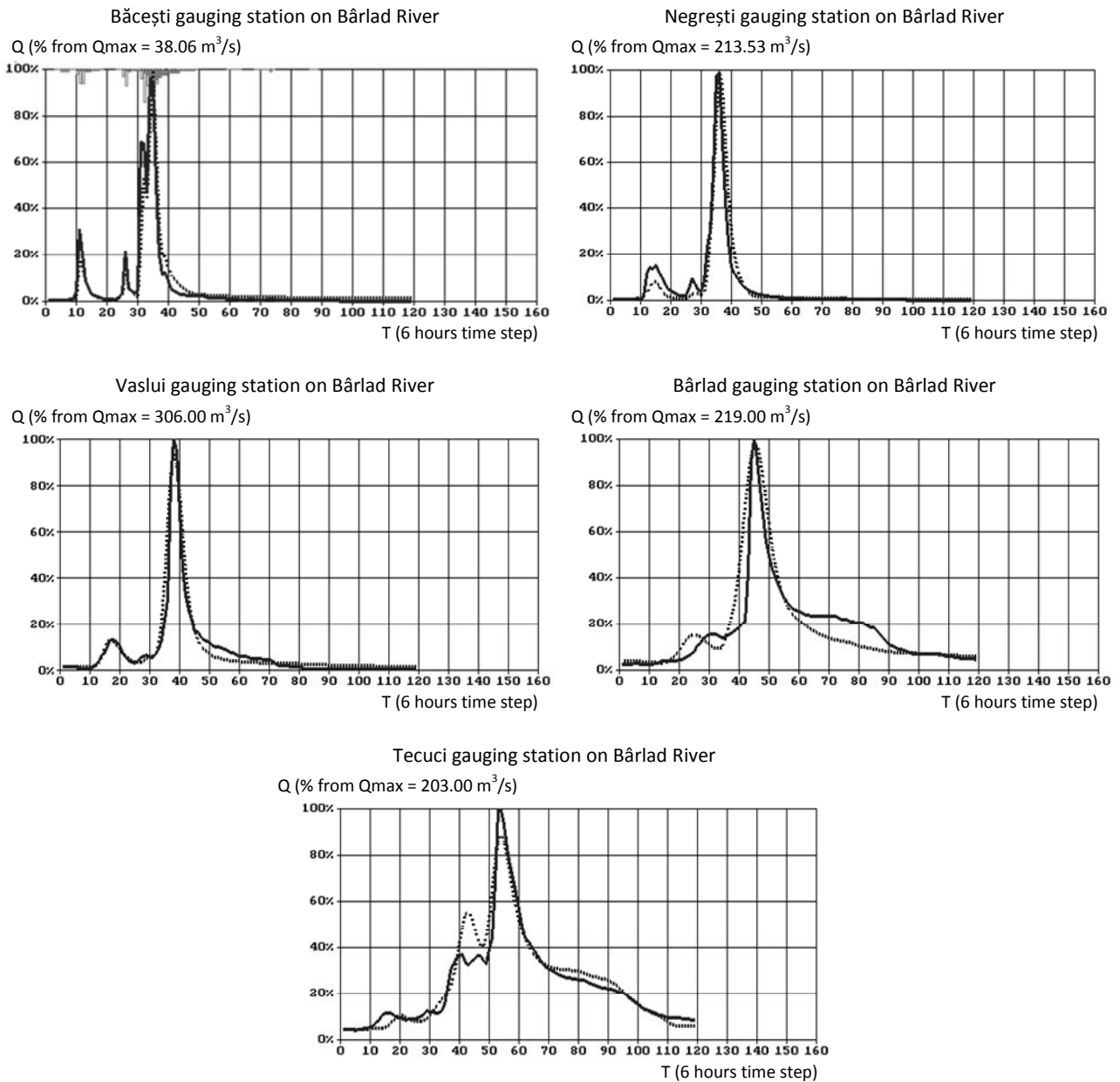


Figure 14. Simulated (----) and observed (—) discharge hydrographs in the cross-sections corresponding of hydrometric stations situated on the main course of the Bârlad River, April 1979

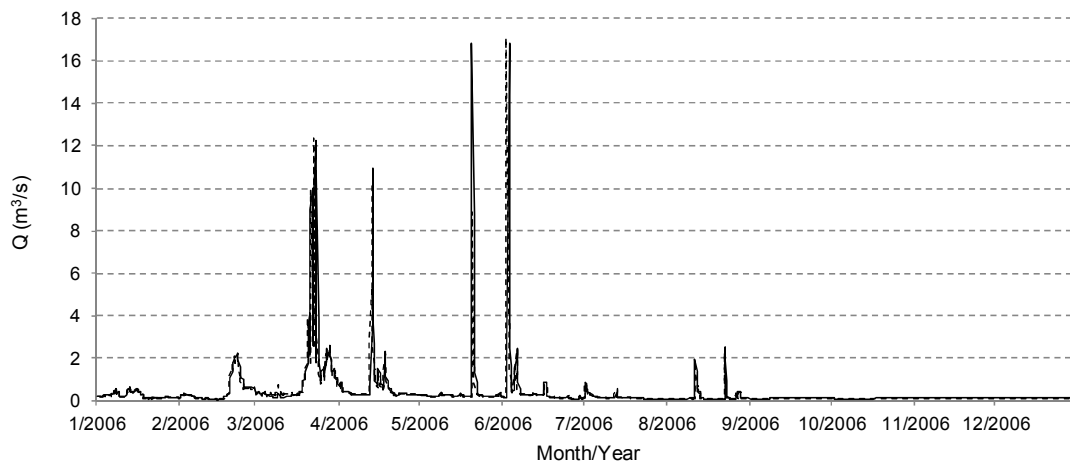


Figure 15. Observed (—) and simulated (----) discharge hydrographs at Băcești hydrometric station on the Bârlad River in 2006 - validation phase

6. CONCLUSIONS

The CONSUL model has been tested usually in the research studies with good results. Fields in which has been applied refer to: Operational flood forecasting; Studies of the assessment of man activity impact on the natural hydrological regime; Providing of maximum discharges with different return probability needed in the design of hydraulics structure (dams, dikes, bridges, etc.); Studies of the assessment of climate change impact on the hydrological resources.

The model has been used for the simulation of the largest floods in the Bârlad River Basin from the period 1975-2010 and for continuous flow simulation from the period 1984 - 1988 (calibration phase) and from the years 2006 and 2010 (validation phase). Mainly, the calibration was done visually, by matching the simulated discharge hydrographs with those observed, in order to reproduce the flow characteristics as well, while keeping the model parameters within their natural values.

The flow simulation results with the CONSUL model in the Bârlad River Basin, during both the calibration and validation period, showed that the model gives the best results, in particular in the case of floods generated by precipitation evenly distributed in space. Deviations of flow hydrographs simulated by CONSUL model and observed are due to both model errors and insufficient meteorological and hydrological data. The main error is caused by the uncertainty related to the average precipitation computed values on each basin and its variable spatial and temporal distribution.

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