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DERIVING RAIN THRESHOLD FOR EARLY WARNING BASED ON A COUPLED HYDROLOGICAL-HYDRAULIC MODEL

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Abstract: Flash floods are highly variable phenomena in both time and space. Therefore, tools with the potential to provide early warning are needed to analyse them. In Europe, flash floods often occur on small catchments; it has already been shown that the spatial variability of rainfall has a great impact on the catchment response. The aim of this paper is to use a coupled hydrological-hydraulic model (MIKE SHE/MIKE 11) to determine the rainfall thresholds and transformation coefficients from hourly rain to other durations, which will lead to flooding of the inhabited areas to the ungauged Ungureni catchment. The model was calibrated and validated using a reference discharge previously obtained by UTCB at the downstream gauge section of Teleorman River (Tatarastii de Sus) using MIKE 11 UHM module. Once the rainfall thresholds are determined, they can be used in flood forecasting and issuing warning with lead time for the inhabitants of the two villages located in Ungureni watershed. The method proposed in this paper can be used for other watersheds prone to flooding, so warnings can be issued with lead time.

Keywords: flash flood, MIKE SHE, MIKE 11, hydrological and hydraulic modelling.

1. Introduction

Intense rains that take place on saturated soils or low permeable geological layer, steep slopes terrains or areas covered with impervious materials can cause flash floods. In these conditions, rain runs off over the surface and accumulates in streams and in rivers over a short period of time.

Flash floods are among the most difficult natural hazards to predict in terms of time and place of occurrence. The areas and the hydro meteorological phenomena that lead to flash flood occurrence are challenging to identify. In order to reduce the losses, two types of measures are required: structural measures for reduction of flood hazard, and real time flood forecasting systems to reduce flood risk by issuing warning in advance [1].

The theoretical basis of developing operational flash flood guidance (FFG) systems was studied by Georgakakos (2005), by using analytical methods. He analysed the uncertainty of the threshold runoff to flash flood guidance transformation. Staley et al. (2015) used empirical methods to define the rainfall I-D thresholds for flash flooding and debris flow.

Distributed hydrological models like MARINE [2], [3], SIMPLEFLOOD [4], FEST [1], GBHM [5] were used to study flash floods and to establish the rainfall thresholds for flash flood warnings applying FFG (Flash Flood Guidance) method. The role of geology in the hydrological response of catchments prone to flash floods was studied with the hydrological model CVN-p[6].

According to Guzzetti et al. (2008) rain critical thresholds for predicting flash floods can be defined in two ways: (i) by using empirical or statistical methods applied widely to early warning systems because of their easy implementation[7], [8]; and (ii) by using physically-based numerical models, which are more complex to define and apply [9], [10].

The aim of the paper is to predict a rainfall volume of a given duration over a catchment that generates bankfull flow conditions using coupled MIKE SHE/MIKE 11 modelling system and issue flood warnings using the obtained data.

2. MIKE SHE/MIKE 11 modelling system description

2.1 MIKE SHE

The MIKE SHE model is based on SHE (Système Hydrologique Européen) model. It is a deterministic, fully-distributed and physically-based hydrological modelling system and it integrates all the hydro-geological processes involved in catchment monitoring and evaluation [11], [12]. The Water Movement module has a modular structure which comprises major physical processes of the hydrological cycle: overland flow (OL), rivers and lakes (OC), unsaturated flow (UZ), evapotranspiration (ET) and saturated flow (SZ). MIKE SHE software interface allows the user to select the components to be included in the simulation process (Fig. 1).

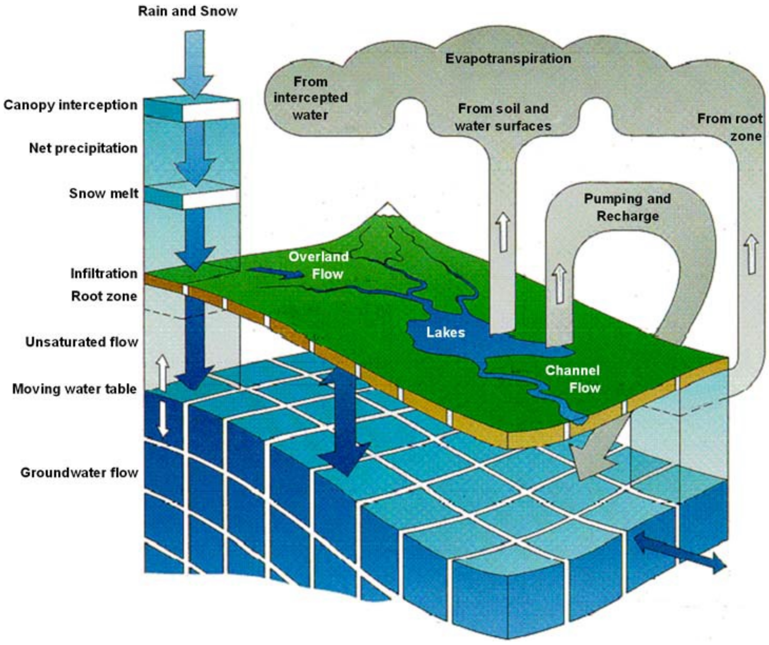

Fig. 1 - Schematic representation of the MIKE SHE model, source: [13]

The partial differential equations describing the processes are solved using finite difference approach. For the overland processes, two-dimensional Saint-Venant equations are used; for the channel flow: one-dimensional Saint-Venant equations; for the unsaturated flow: one dimensional Richards equation; for saturated flow: three-dimensional Boussinesq equation; for interception and evapotranspiration: analytical solutions (Kristensen and Jensen).

A network of grid squares, discretized also on the vertical into a series of layers represent the basic computational unit of the model[11]. MIKE SHE has the flexibility of using variable simulation time steps for different hydrological modeling components and flow characteristics[13], [14].

2.2 MIKE SHE/MIKE 11 coupling

MIKE 11 is based on the complete dynamic wave formulation of the Saint Venant equations and can represent a wide range of hydraulic structures including weirs, gates, bridges and culverts[12]. In the coupling process, data are exchanged between MIKE SHE and MIKE 11. River links are determined from MIKE 11 branches that are specified as coupled reaches (Fig. 2) The two models will exchange water only within the coupled reaches (Fig. 3). Water levels are transferred from MIKE 11 H-point to MIKE SHE river links and it will calculate the overland flow and river-aquifer exchange to each river link from the nearby grid squares. The coupling of models allows flood simulation from MIKE 11 river onto MIKE SHE grid squares if the water level in the river is higher than the grid squares level. Once the MIKE SHE cells are flooded, it calculates the evapotranspiration, infiltration and overland flow.

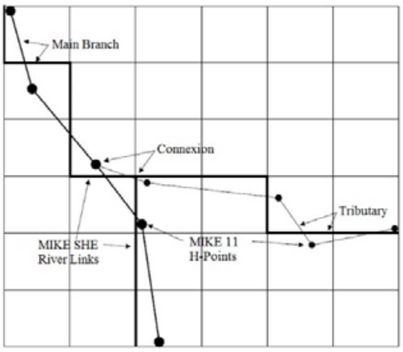

Fig. 2 - MIKE 11 Branches H-points in a MIKE SHE Grid with River Links

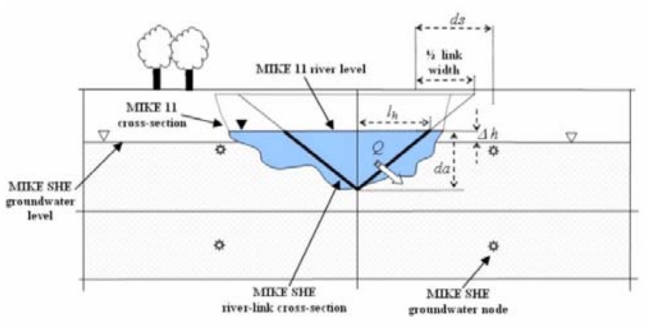

Fig. 3 - Simplified MIKE SHE river link cross-section compared to the equivalent MIKE 11 cross-section

3. Description of the study area

Ungureni watershed is located in Teleorman River basin and has an area of about 21 km^2 (Fig. 4). In the upper basin, Teleorman River has a semi-permanent flow, being fed during rainfall and high groundwater levels. Teleorman tributaries, including Ungureni River, have water flow only during important rainfalls. Inhabited areas are represented by two villages, Vulpesti and Tomsanca, which are in the administrative jurisdiction of Buzoiesti commune. According to the National Statistics Institute, at the 2011 census, the permanent population were 903 inhabitants in Vulpesti and 411 inhabitants in Tomsanca.

Soils with the highest spread within the watershed are Vertisols with two subtypes: Stagnic, met especially on the slopes of the basin and covering an area of 1,324 hectares (62.8%), and Pellic, on a smaller area of 40.34 ha (1.9%). 25% of the basin is occupied by Luvisols with 492.5 ha (23.3%) Stagnic subtype, and 34.6 ha (1.6%) Abruptic subtype. Eutric Cambisols Lithic is found along Ungureni River on an area of 133 ha (6.3%), while at the confluence with Teleorman River Eutric Cambisols Stagnic Gleyic on 49.7 ha (2.4%) and the Fluvic Gleysols on 35.25 ha (1.6%) can be found (Fig. 5,a and Table 1)

Fig. 4 - Ungureni watershed

Land-use data were obtained from Corine Land Cover maps and orthophoto plans. It can be observed that the main land-use is arable. Dismantling large production units and agricultural research institute terrain after 1990 led to the fragmentation of arable areas and the practicing of a weak competitive traditional agriculture with uncultivated surfaces. Land-use spatial variability is shown in Fig. **5**,b, and land-use surfaces and percentages are given in Table 2.

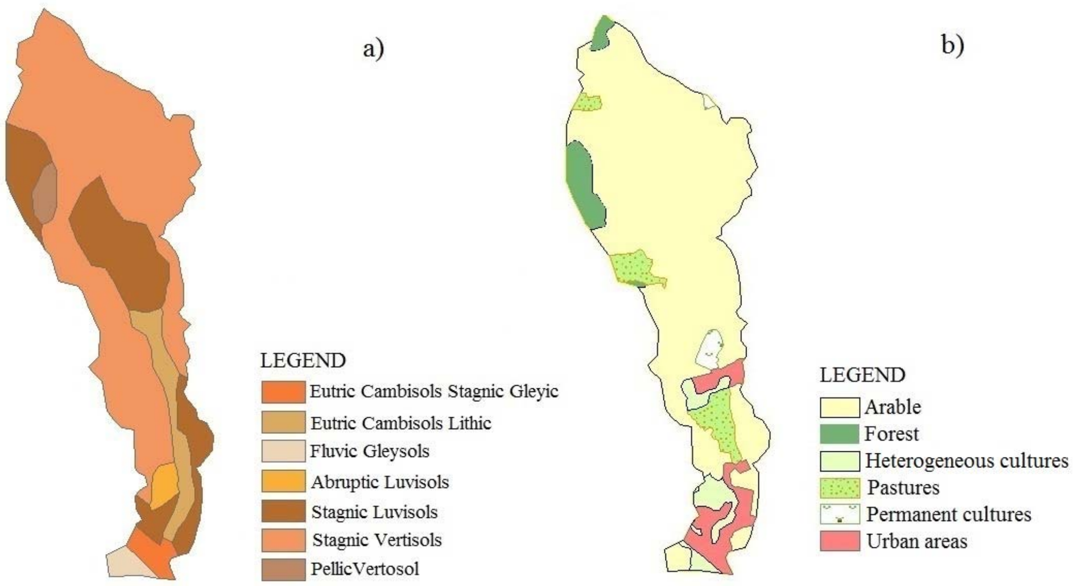

Fig. 5 - a) Soil types; b) Land-use

Table 1

Soil types and area occupied in Ungureni watershed

Crt. Nr.	Soil type	Symbol	Occupied area	
			ha	**%**
1	Eutric Cambisols Stagnic Gleyic	ECglst	49.7	2.4
2	Eutric Cambisols Lithic	ECli	133	6.3
3	Fluvic Gleysols	GSfv	35.25	1.7
4	Abruptic Luvisols	LVap	34.6	1.6
5	Stagnic Luvisols	LVst	492.5	23.3
6	Stagnic Vertisols	VSst	1,324	62.8
7	PellicVertisols	VSpe	40.34	1.9

Table 2

Land-uses and area occupied in Ungureni watershed

Crt. Nr.	Land-use	Occupied area	
		ha	**%**
1	Arable	1,629	77.2
2	Heterogeneous Cultures	92	4.4
3	Permanent Cultures (vineyard)	30	1.4
4	Pastures	123	5.8
5	Forests	95	4.5
6	Urban areas	140	6.6

3.1.Input data for MIKE SHE model

MIKE SHE is a physically based model which uses representative data from the area to be hydrologicaly modeled.

3.1.1 Topography

The MIKE SHE model, which covers an area of 21 km^2, was set up using grid squares of 30 × 30 m^2 and it was converted in MIKE SHE format using ArcGIS 10.1 (Fig.6)

3.1.2 Climate data

Data necessary for the MIKE SHE model consist in: precipitation rate and reference evapotranspiration. Synthetic precipitations corresponding to the probability of exceedance of 0.1%, 0.2%, 0.5% and 1% introduced in the model as time series in *.dfs0 file were used.

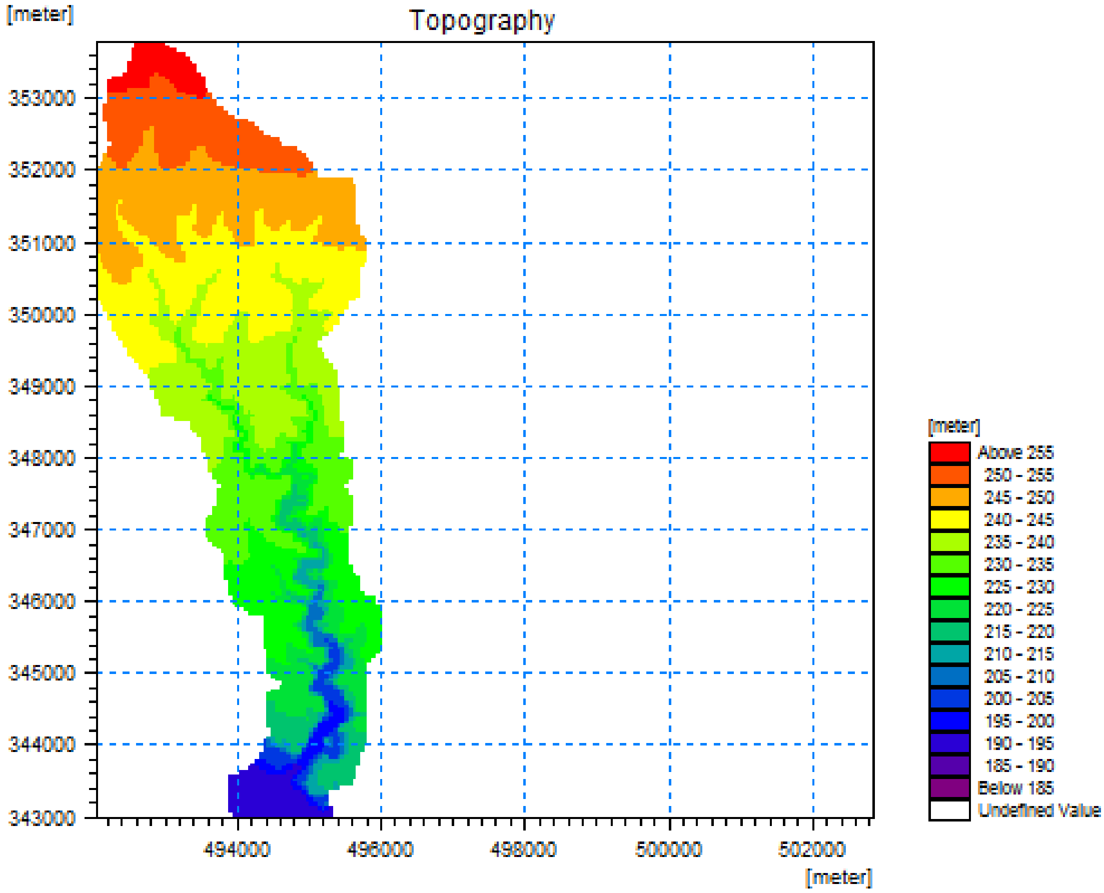

Fig. 6 – Ungureni catchment topography, *.dfs2 file

3.1.3 Hydrogeological data

The saturated zone component within the MIKE SHE model consists of a single unconfined layer, in which the same hydraulic parameters were employed throughout the model area. The values used for the specific yield and storage coefficient were the default values, preseted by the model. The hydraulic conductivity parameter was the subject of calibration and the determined values are 5×10^{-6} m/s for horizontal hydraulic conductivity and 3×10^{-7} m/s for the vertical hydraulic conductivity.

3.1.4 Soils' properties

Unsaturated zone modelling was made using Richard's equation. The van Genuchten parameters of the retention curve are specified in Table 3. Soils' data were obtained from the National Research and Development Institute for Soil Science, Agro-chemistry and Environment Bucharest – ICPA, and introduced in the model using *.uzs files (Fig. 7).

Table 3

Retention curve characteristics

Crt Nr	Soil type	Symbol	Density (kg/m^3)	K_{sat} (m/s)	θ_s	pF_{fc}	α	n
1	Eutric Cambisols Stagnic Gleyic	ECglst	1,520	7.52315E-07	0.279	2.3	0.039	1.105
2	Eutric Cambisols Lithic	ECli	1,410	4.86111E-07	0.330	2.6	0.024	1.097
3	Fluvic Gleysols	GSfv	1,380	1.75926E-06	0.346	2.2	0.042	1.135
4	Abruptic Luvisols	LVap	1,640	3.58796E-07	0.231	2.5	0.032	1.095
5	Stagnic Luvisols	LVst	1,640	3.58796E-07	0.231	2.5	0.032	1.095
6	Stagnic Vertisols	VSst	1,530	2.31481E-07	0.275	2.7	0.022	1.082
7	PellicVertisol	VSpe	1,530	2.44213E-06	0.275	2.0	0.050	1.195

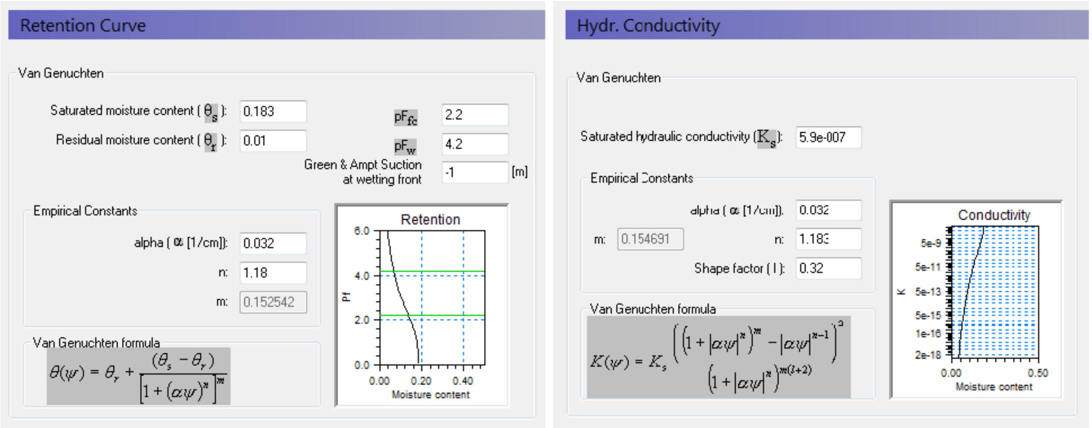

Fig. 7 - Retention curve and hydraulic conductivity of the unsaturated soil

3.1.5 Land-use data

Many processes in the MIKE SHE model depend on the vegetation properties in the catchment. Thus, evapotranspiration is a function of the Leaf Area Index (LAI) and Root Depth (RD), overland flow depends upon interception, Manning's roughness coefficient is different for various types of vegetation cover and infiltration is influenced by soil moisture. For the LAI and RD parameters, the default values have been used. For the roughness coefficient, MIKE SHE uses M, the inverse of n, a calibrated parameter along with detention storage. The calibrated values are presented in Fig. 8 and Table 4.

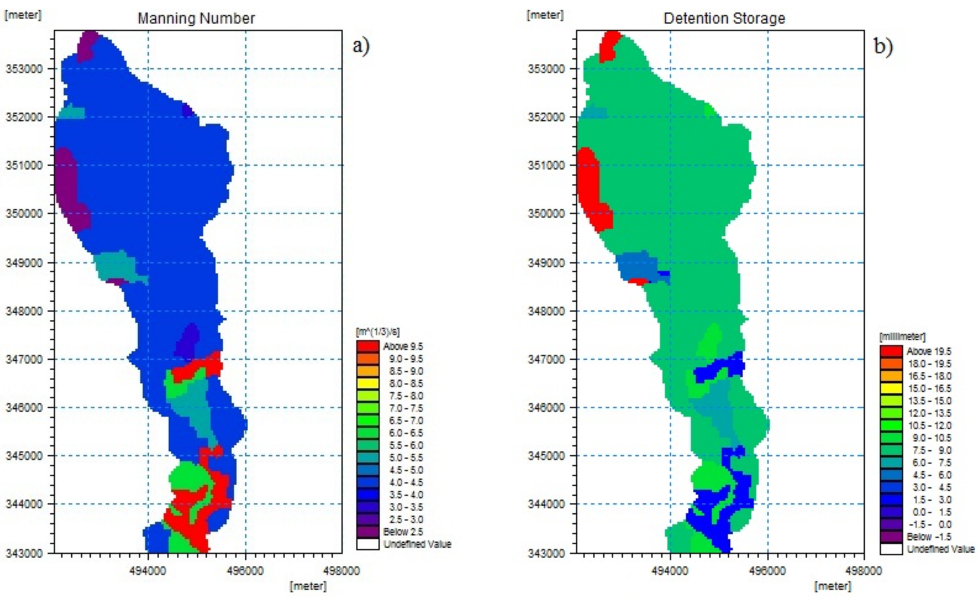

Fig. 8 - a) Manning's M; b) Detention Storage

Table 4

Calibrated values used for Manning's M and Detention Storage DS

Crt. Nr.	Land-use	M $(m^{(1/3)}/s)$	DS (mm)
1	Arable	4	8
2	Forest	2	20
3	Heterogeneous cultures	6	10
4	Pastures	5	6
5	Permanent cultures	3	9
6	Urban areas	10	2

3.1.6 Input data for MIKE 11 model

For channel flow, the unidimensional hydrodynamic model MIKE 11 has been used; a stretch of 2 km of Ungureni River (Fig. 9), represented by 18 cross-sections (Fig. 10) was modelled. Along the river channel there are two hydrotechnical works, a culvert and a bridge on DJ 504 road. The model was run for a 6 days period.

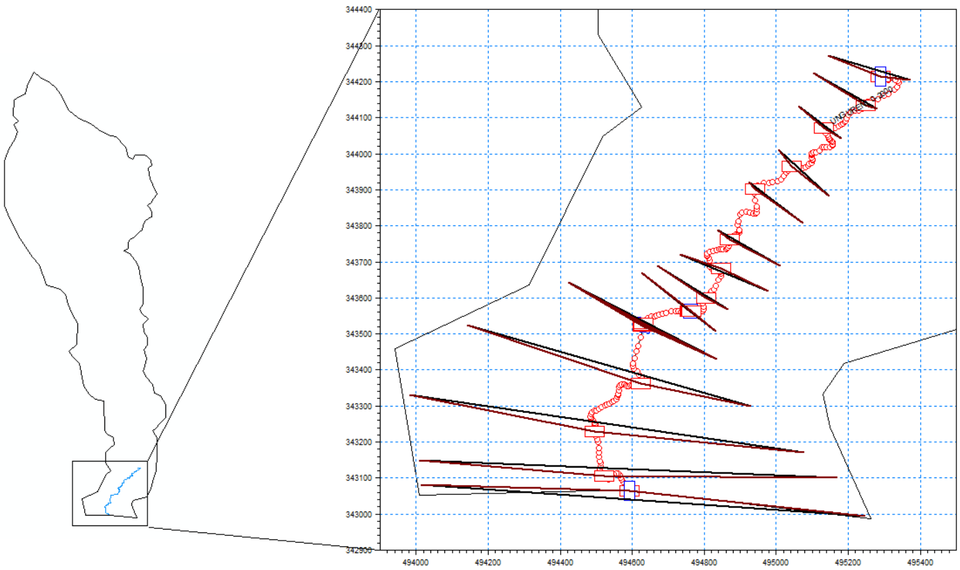

Fig. 9 – Modelled river stretch

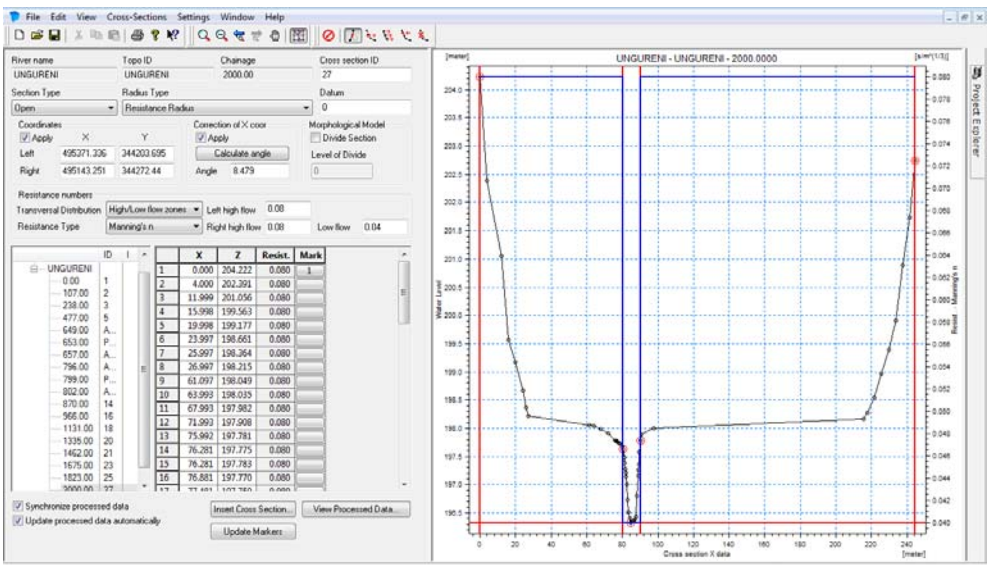

Fig. 10 – Cross-section MIKE 11 file

4. Model testing and validation

For model calibration and validation, the obtained results were compared to a reference discharge (Fig. 11), previously obtained by UTCB at the downstream gauge section of Teleorman River (Tatarastii de Sus) using MIKE 11 UHM module. For model calibration the flood with the probability of exceedance of 0.1% was used, while for model validation the floods with the probability of exceedance of 0.2%, 0.5% and 1% were employed.

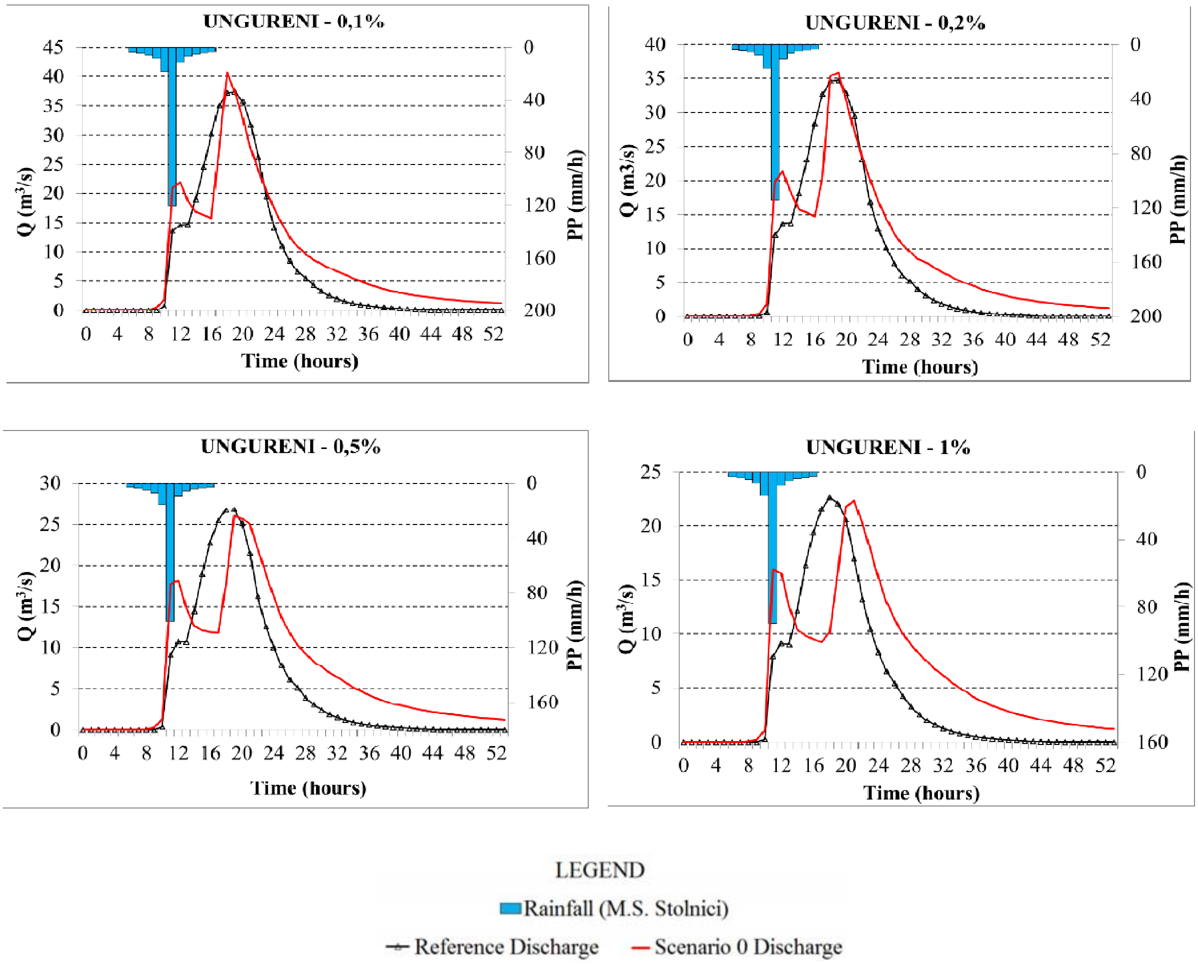

Fig. 11 – Simulated hydrographs for Scenario 0 versus the reference floods with maximum discharge corresponding to the probability of exceedance of 0.1%, 0.2%, 0.5% and 1%

Following the Scenario 0 simulation, the Water Balance module was used to quantify each water transport mechanism during simulation (Table 5). The water balance output includes areal normalized flows (storage depths), storage changes, and model errors for individual model components (e.g. unsaturated zone, evapotranspiration etc.), all expressed in mm.

Table 5

Water Balance for model calibration and validation (values expressed in mm)

Exceedance probability	Precipitation	Interception	Evapotranspiration	Surface Change	Surface =>River	Subsurf. Change	Aquifer =>River	River=> Aquifer	Error
0.1%	-190.6	5.45E-08	2.11181	32.5410	128.505	25.6777	6.42E-02	-1.80E-03	-1.6909
0.2%	-181.4	5.45E-08	2.15053	32.4682	120.549	24.7736	0.0628039	-0.0017756	-1.4144
0.5%	-159.0	5.45E-08	2.15004	32.4011	99.075	24.1755	0.0634842	-0.0016243	-1.1908
1%	-141.5	5.45E-08	2.14111	32.3451	82.1613	23.6744	0.0636777	-0.0014949	-1.1039

For the hydrological model assessment three efficiency criteria: coefficient of determination (r^2), Nash-Sutcliffe efficiency (E) and index of agreement (d) were used (Table 6).

Table 6

Efficiency criteria values for model calibration and validation

Exceedance Probability	r^2	E	d
0.1%	0.91	0.89	0.97
0.2%	0.88	0.85	0.96
0.5%	0.75	0.71	0.92
1%	0.61	0.54	0.86

Efficiency criteria showed a satisfactory agreement between the reference and the simulated discharge: values ranging between 0.89 and 0.97 for calibration and 0.54 and 0.96 for validation.

Using ArcGIS, the flood limits for the chosen probabilities of excedance were represented (Fig. 12). It can be noticed that the settlements in the catchment are sensitive to bankfull discharge.

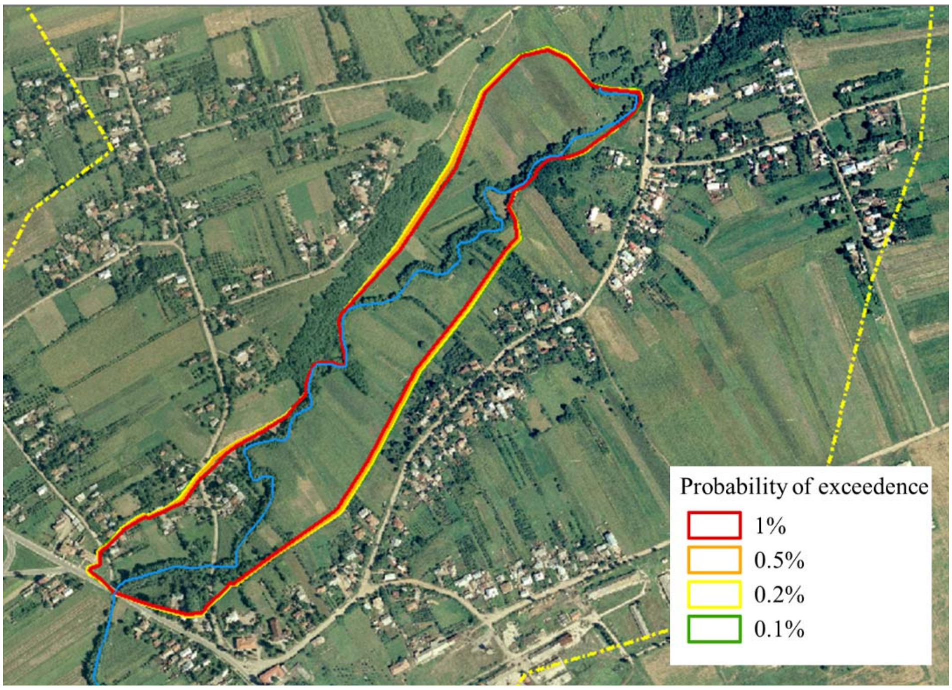

Fig. 12 – Flooding limits for Ungureni River

5. Rainfall threshold determination

Extreme hydro meteorological phenomenon monitoring is an important step in understanding what is happening and what alternative can be adopted for risk reduction. Usually, the meteorological monitoring network is not dense enough to reflect the time and space rainfall distribution. In this case, the radar and satellite monitoring network is an important source of information.

In the Methodology of torrential watersheds diagnosis presenting a significant risk of flash floods endangering the human settlements [15], among other approaches the method of rainfall threshold is presented. The rainfall threshold values for different rain duration (from 1 to 6 hours) will then be used for issuing warnings in case of torrential rainfall that could generate the settlements flooding.

In this study, the value of the hourly rainfall threshold was determined considering successive values for the rain, namely 80 mm, 90 mm and 100 mm. The lowest value for the hourly rain that produces bankfull flooding on the lowest area is 90 mm, resulting in an affected area of 2 ha (Fig. 13).

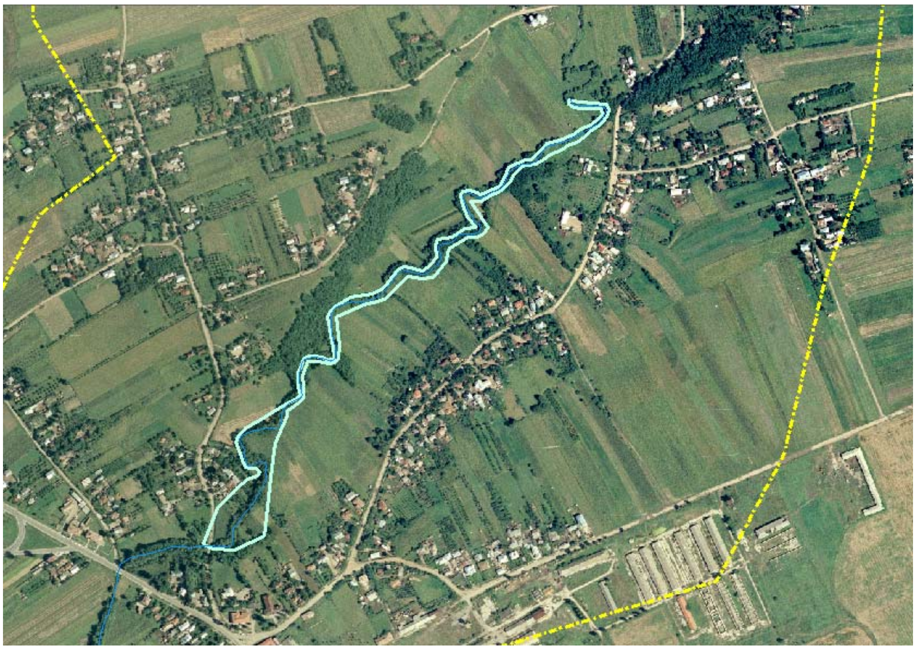

Fig. 13 – Flooding limits for the hourly rain of 90 mm

In Fig. **14**, the threshold values determined for the hourly rainfall and other durations (2, 3 and 6 hours) that can lead to flooding are presented. The medium intensity of the rainfall threshold is derived in Fig. **15**.

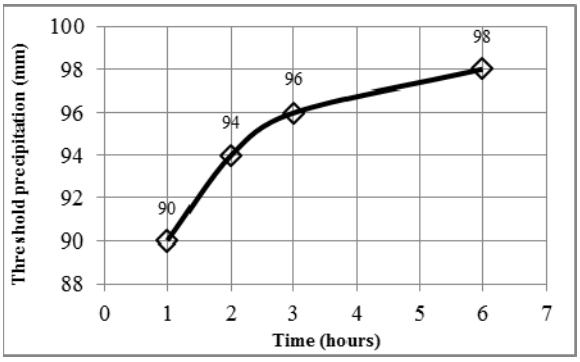

Fig. 14 – Threshold rainfall

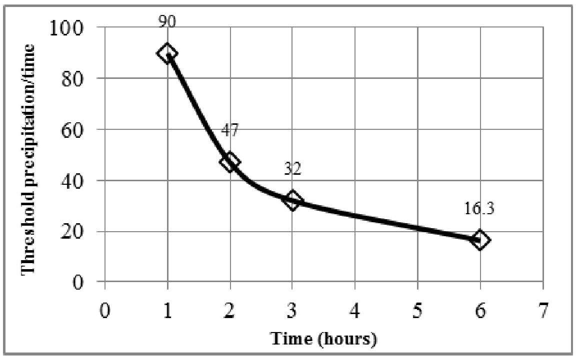

Fig. 15 – Threshold rainfall medium intensity

The transformation coefficients from hourly rain to the total depth of the rain for other duration for constant precipitation that leads to flooding are presented in Table 7. The transformation coefficients thus determined were used for the calculation of the composite rain hyetographs (Fig. 16), representing the following input data in MIKE SHE and then in MIKE 11.

Table 7

Coefficients for hourly rain conversion into other duration

Rainfall duration (hours)	1	2	3	6
Transformation coefficients	1	1,044	1,067	1,089

The simulations using constant values for the hyetographs and the composite hyetographs thus obtained led to an average difference of the water levels in the river of about 3 cm, which do not change the flooded area, meaning that the transformation coefficients were correctly determined.

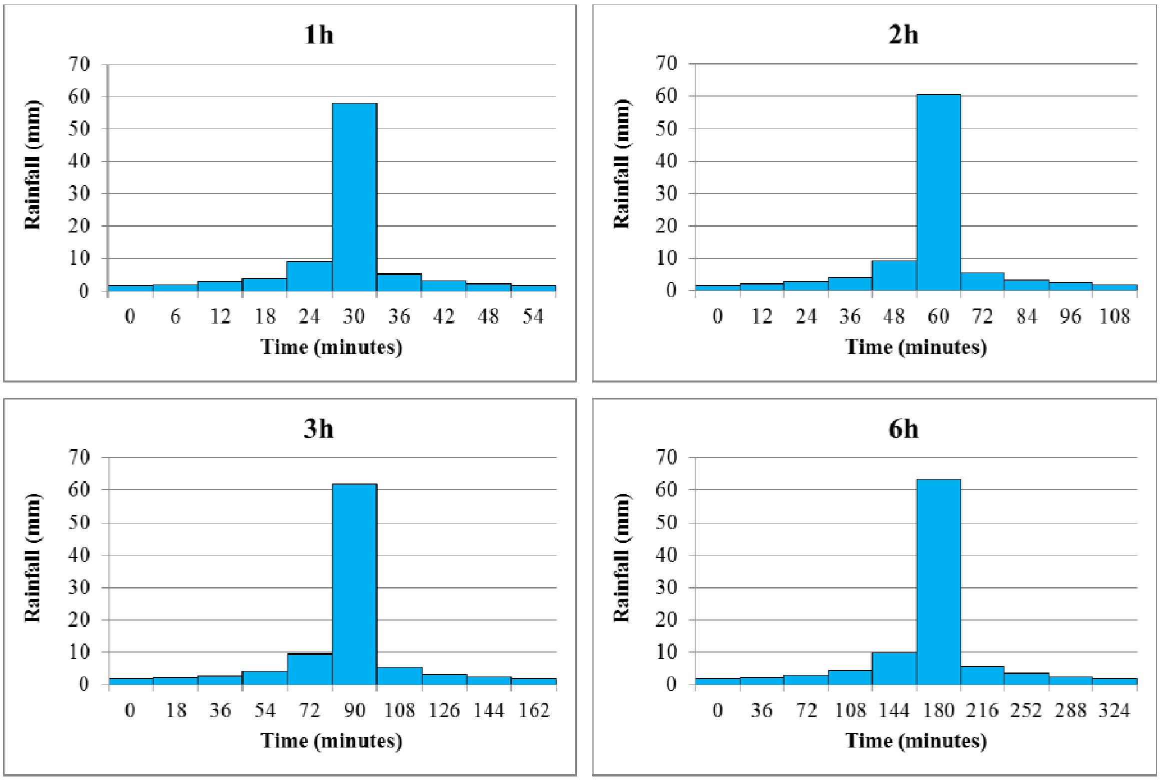

Fig. 16 – Rainfall hyetographs for different durations

6. Conclusions

The model described in this paper is based on a coupled hydrological/hydraulic model of the Ungureni watershed, located in Teleroman River basin. For this 21 km^2 ungauged catchment available and literature data were used. Synthetic rainfall for a duration of maximum 6 hours were used as input data and the simulation period of the basin reaction covers 6 days. Based on the calibrated and validated model the rainfall thresholds and transformation coefficients from hourly rain to other durations were obtained.

Issuing warning information to the public when forecasted rainfall exceed the derived thresholds is a simple and widely-used method for flood warning. Rainfall thresholds and correspondig warnings contribute to reducing the consequences and the resources involved in emergency response of flood events [16].

In flash flood forecasting, the main difficulties lie in the flash flood timescale. The rapidity of hydrological responses reduces the forecast time and leaves short lead time for early warnings. Thresholds are critical elements in a flood forecasting and warning system. However, the threshold method is a criterion model by which warning levels are less gradable in terms of emergency and severity [17]. This apparently weak point could still be easily overcome by deriving flooding maps for different values of the total depth of the rain and disseminating them to interested people. This approach is perfectly possible taking into account that according to the Table 7 the total depth of the rain is important for flooding, while its duration has less influence.

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