Mathematical modelling and numerical analysis of hydraulic system behaviour. A case study with application in HEC-RAS

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Abstract. The paper presents an analysis of floods within the Bahlueț watershed. The city of Targu Frumos and its surroundings have suffered floods over the years causing significant damage. This study aims to map flooding in the area analysed, using the HEC-RAS hydraulic program. Results were obtained for 1%, 5%, 10%, 20% flood recurrence scenarios over a period of time with heavy rainfall. The results show that flooding occurred in all simulated events. The city of Targu Frumos was flooded when flood events with 1% and 5% probability were simulated. Based on the results obtained, predictions can be made regarding the extent of flooding in order to take additional measures for its prevention and control.

1. Introduction

In small river basins, the most frequent floods are those of the falsh-flood type, which occur during convective, frontal or orographic storms and are of short duration and at the same time of high intensity. The consequences of flash floods can be devastating and result in significant negative impacts on buildings, land and people's lives. [1]

For this purpose, HEC-RAS 2D model will be applied taking into account the conditions within the Bahlueț watershed. The program performs flood simulation and allows characterization of the hazard in space and time, determining water depth, flows, velocities and other necessary parameters in each cross-section. Flood hazard maps facilitate various risk analyses and provide additional support for emergency preparedness and spatial planning in risk areas by local authorities. Given the changing nature of the geomorphology of river regime and flow characteristics, these maps require regular updates and the models used require calibration and further validation with a new dataset.

2. Materials and methods

2.1. Study area

The Bahlueț river basin sum an area of 551 km², shown in figure 1. The average monthly precipitation values collected show that the maximum values are mainly recorded in early summer. The hydrological regime of the basin with a moderately warm humid climate can be considered. [2]

Rivers are characterised by frequent and marked variations in level and flow, resulting in floods and flooding. They are fed mainly by rainfall and snowfall and are classified as moderate rainfall and moderate groundwater.

The main localities crossed by the Bahlueț River are the towns of Târgu Frumos and Podu Iloaiei, where the Podu Iloaiei reservoir built on the same river is located.

The Bahlueț watershed is mainly occupied by agricultural areas. In the course of time it has undergone numerous changes in its appearance which accelerate the processes of instability induced by urbanization and agriculture. [3]

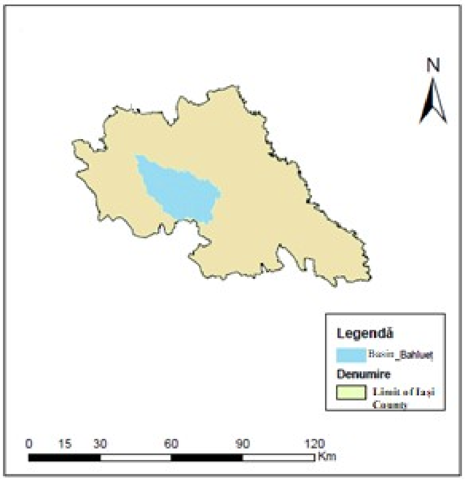


Figure 1. The Bahlueț river basin in Iasi county

2.2. HEC-RAS program

For hydraulic analysis was used the new version 6.0 of HEC-RAS 2D program.

The following data were used to build the hydraulic model of the watercourse:

- Data of profiles
- Manning roughness data (n)
- Upstream and downstream flows and boundary conditions

The following software was used for the study:

- Digital terrain modelling and mapping: ARCGIS and Global Mapper
- Hydraulic modelling: HEC-RAS version 6.0. [8]

The HEC-RAS program is based on Saint-Venant hydraulic equations that can simulate the extent of the floodplain, determine water surface depth and flood velocity distribution:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \quad (1)$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) = -\frac{n^2 pg\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \zeta}{\partial x} + pf + \frac{\partial}{\rho \partial x}\left(h\tau_{xx}\right) + \frac{\partial}{\rho \partial y}\left(h\tau_{xy}\right) \quad (2)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) = -\frac{n^2 pg\sqrt{p^2+q^2}}{h^2} - gh\frac{\partial \zeta}{\partial y} + qf + \frac{\partial}{\rho \partial y}\left(h\tau_{yy}\right) + \frac{\partial}{\rho \partial x}\left(h\tau_{xy}\right) \quad (3)$$

Where: - h is water depth (m)

- p, q are specific flow rates in the x and y directions (m^3/s)
- ζ is surface (m)
- g is gravitational acceleration (m/s^2)

- n is Manning coefficient
- q is water density (kg/m³)
- $h\tau_{xx}, h\tau_{yy}$ are effective shear stress components
- f is Coriolis force

Hydrological modelling, which is an extremely important step in the study of flood protection, allowed us to visualise surface runoff and forecast it in the Bahlueț basin. The data extracted from the two stations considered, Cârjoaia and Târgu Frumos, show that the basin is subject to a precipitation field that varies in time and space. It has been observed that the magnitude is consistent in areas with regular slopes, whether they are steep or not. [2]

The hydrological simulation is an essential first step in modelling of the Bahlueț basin.

In the work, a hyraulic modelling of the Bahlueț River within the Bahlueț catchment from Izvoare to the hydrometric station Târgu Frumos with diffuse inputs was performed.

Using statistical calculations, the flow rates of the tributaries of the Bahlueț River were determined . In figure 2 the tributaries of the Bahlueț river are: Pășcănița, Probota, Cucuteni and Rediu and for a better result the contribution of these tributaries must be taken into account.

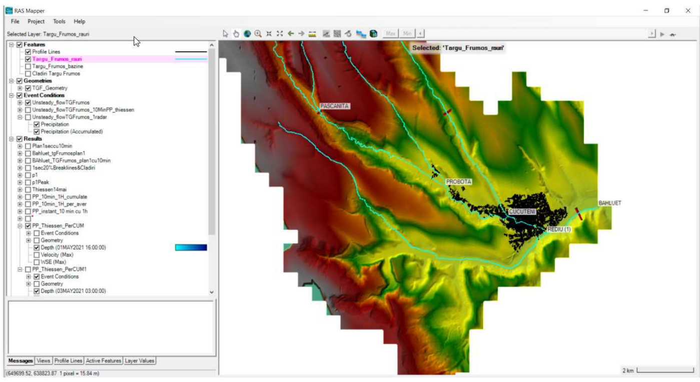


Figure 2. Tributaries of the Bahlueț River

Basins have been delineated for each river as in figure 3:

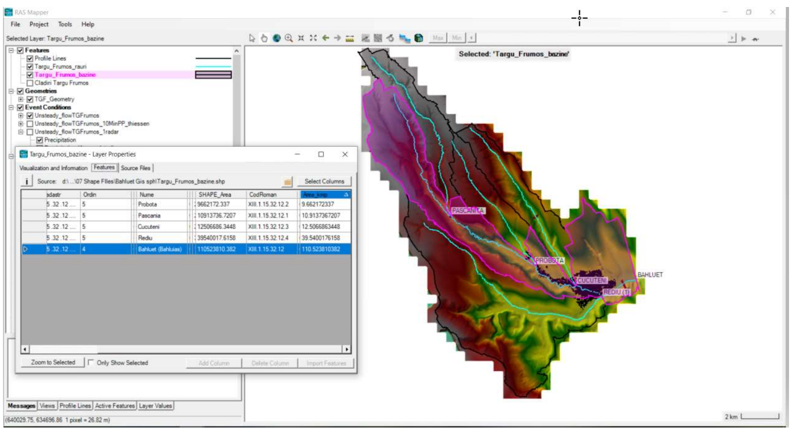


Figure 3. Delimitation of basins

Data on human settlements within the city of Targu Frumos and along the rivers in the study area were entered like in figure 4:

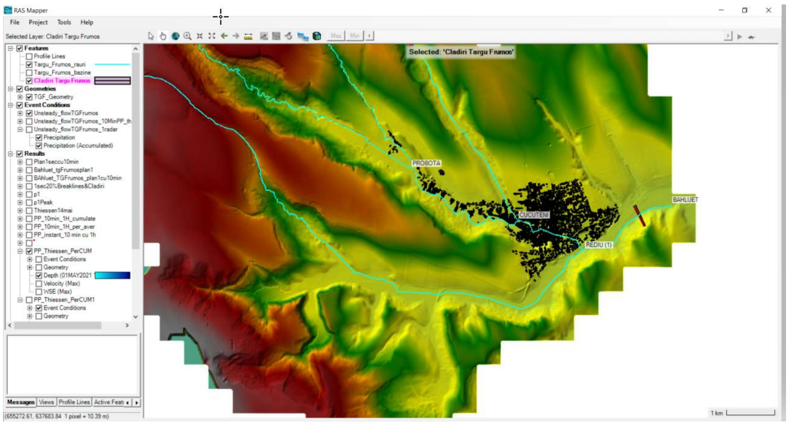
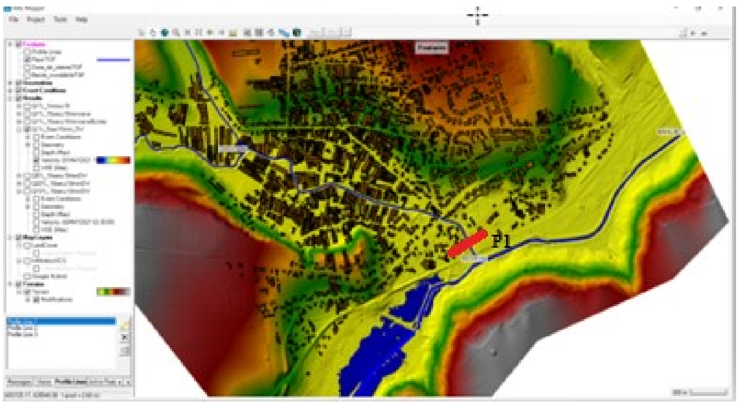


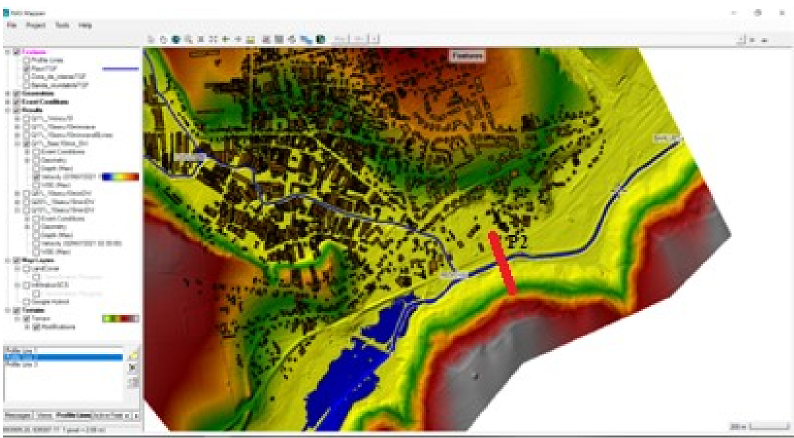
Figure 4. Settlements in the study area

The hydraulic simulation model was built using HEC-RAS, starting from 6 flow sections taken from the digital terrain model made with ArcGIS software.

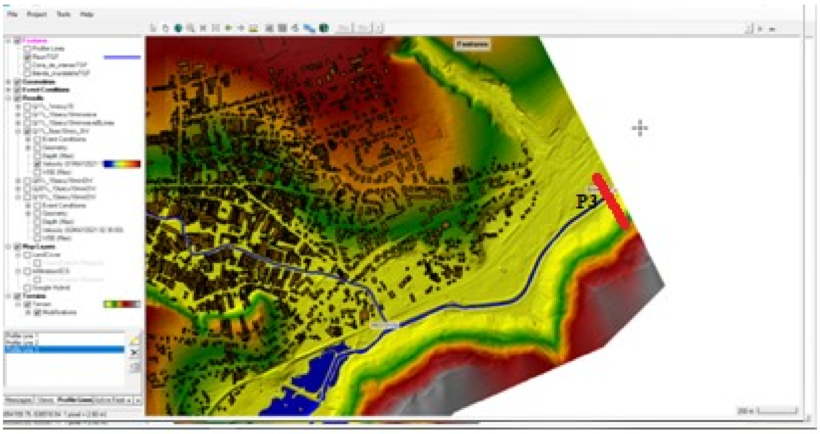
In figure 5 three calculation profiles were established for the input data:



a) Profile no. 1



b) Profile no. 2



c) Profile no. 3
Figure 5. The profiles for points taken into account

To properly represent the hydrology of the stream, lateral stream flows were directed along the stream.

2.3. Simulation of the 2021 flood

After implementing the operational model, the necessary modelling parameters were introduced:

- simulation start: 01 May 2021 at 16:00.
- end of simulation: 03 May 2021 at 03:00
- time step: 10 minutes.

2.4. Manning roughness coefficient n

The roughness coefficient of the bed of the river bed makes it possible to model the water velocity on the bottom of the Bahlueț River and on the banks as close as possible to reality. [4]

The Manning roughness coefficient varies according to the riverbed or floodplain.

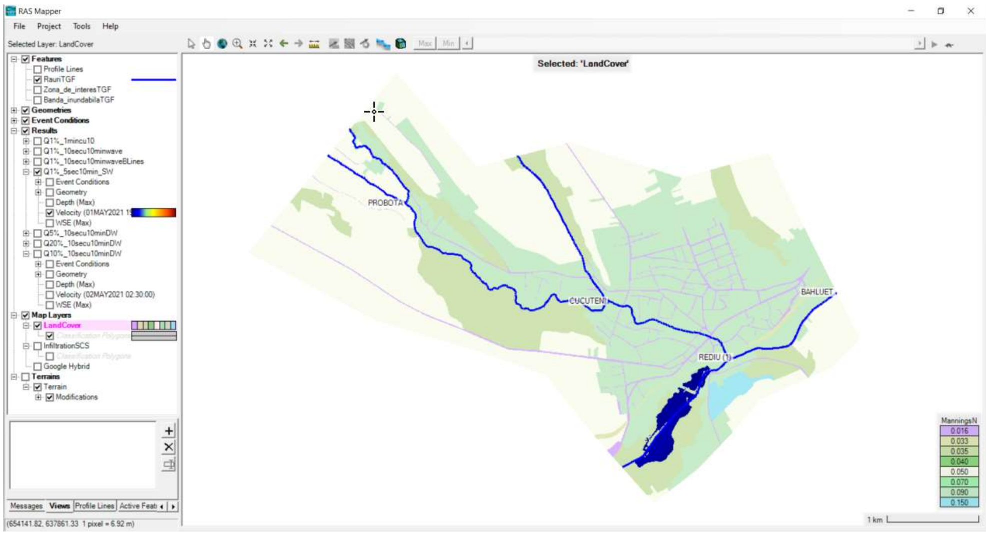


Figure 6. Manning roughness coefficient n

In figure 6 the Manning Coefficient *n* is set according to land use and within the study catchment it can vary from 0.016 to 0.15 for the main bed and the lowest value of 0.016 for sparsely forested areas.

2.5. Places likely to be affected by floods

For the analysis of the extent of flooding of the Bahlueț River, all the necessary elements were taken into account: geometry, embankments, banks, minor and major riverbeds of the Bahlueț River. These are located by chaining them. Also indicated are the places likely to be affected by floods, in figure 7.

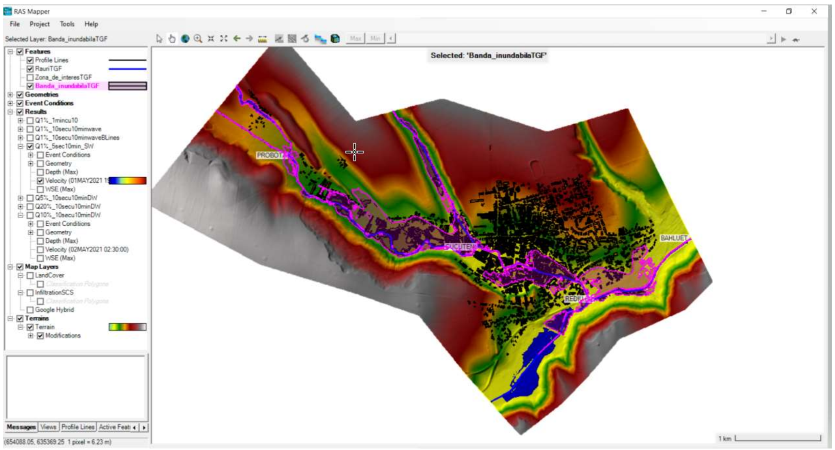
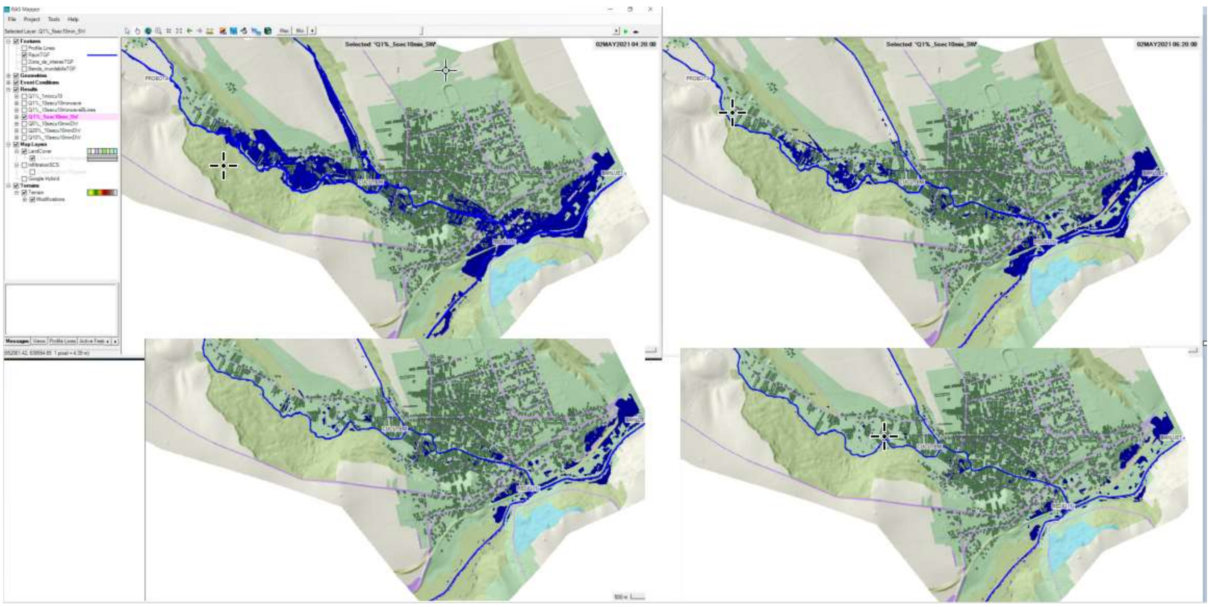


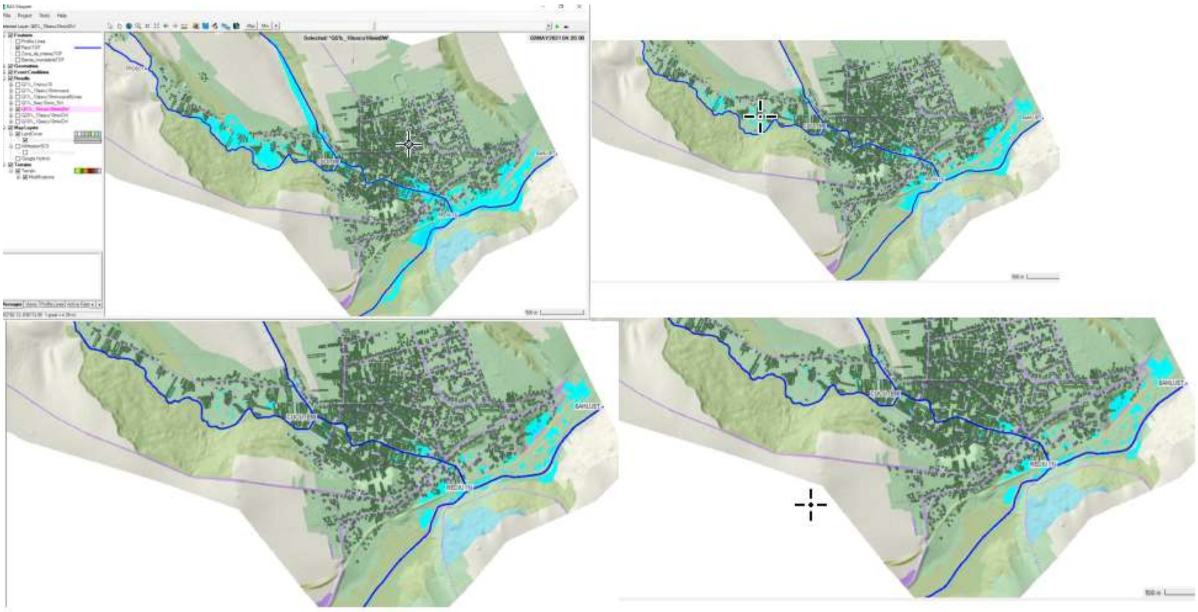
Figure 7. Flood-prone band

3. Hydraulic simulation results

Hydraulic simulation was performed for heavy rainfall scenarios for floods with 1%, 5%, 10%, 20% probability. Calculated maximum flows and water levels are presented for each area likely to be affected. [6]

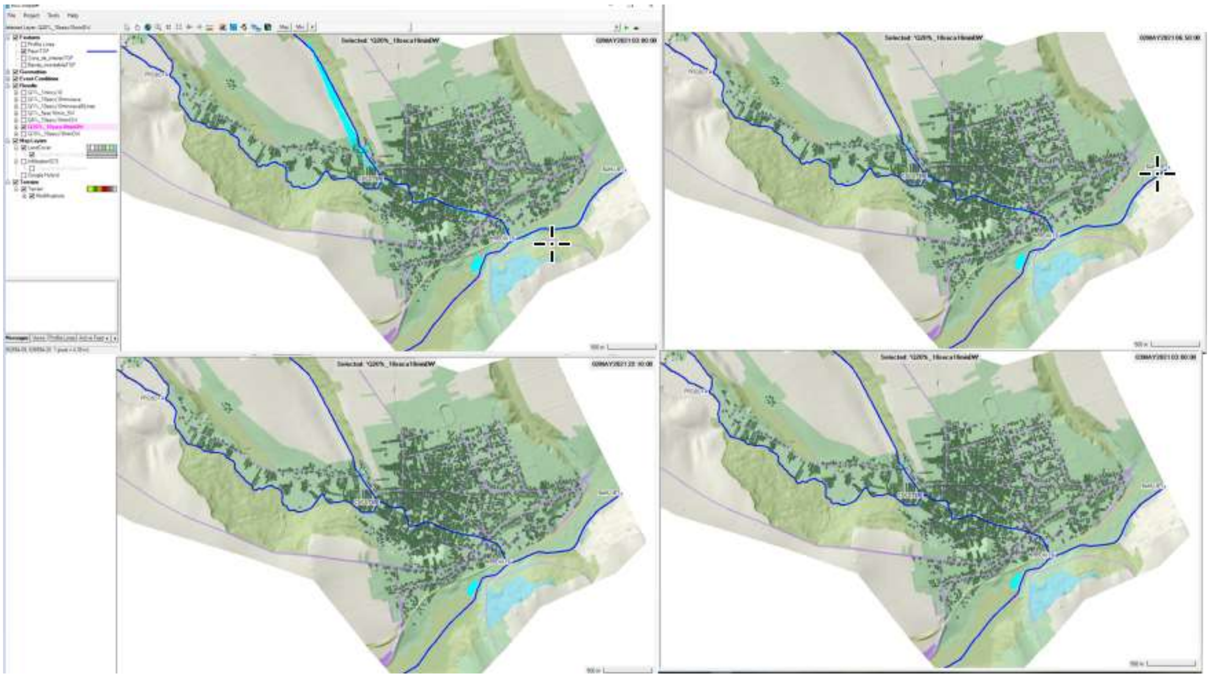


a) Flow results with 1 % probability



b) Flow results with 5 % probability

c) Flow results with 10 % probability



d) Flow results with 20 % probability

Figure 8. Flow results for each calculation probability

The figures above show a situation of the affected areas.

In figure 8 it can be seen for each scenario describing the set of relevant flood information either the arrival time of the wave front at different points of the studied section or the maximum water level rise or maximum discharge.

The simulated water depths exceeded the river bed and caused flooding of the plain and the town of Targu Frumos.

The flooding resulting from the simulation can be explained by the fact that:

- there are settlements along the river and upstream of the Târgu Frumos dam
- the main section is characterised by different low points and the existence of meanders along the river.
- the recorded maximum flows are higher than the transitional capacity.

The figures show areas flooded during periods of heavy rainfall once, 5 times, 10 times and 20 times per 100 years.

The results show the picture of flood-prone areas and allow the definition of flood scenarios, weak and vulnerable points at risk from floods.

It can be seen that homes would be easily flooded in these simulated floods. [5]

4. Conclusions

This study makes it possible to determine the discharge areas in the Bahlueț catchment, the sub-basin from the Izvoare to Tg. Frumos.

The floods recorded within the basin reflect the potential hazard and vulnerability to flooding. This calls for caution in development and flood protection will not only be achieved through works but also through often less costly preventive measures. These relate to mapping flood risk areas, land use regulation, river maintenance and watershed development. [7]

Flood risks are increasing in intensity therefore educating the population on flood-prone areas of watercourses in local flood defence plans and discouraging the construction of houses in these areas would mitigate material damage and even loss of life.

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