Simulation of floodplains on rivers in urban areas

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Abstract: The paper presents the result of research on simulating the flooding of a flood on a stretch of river located in an urban area. The study area was located on the section of the Trotuș River that crosses the city of Comănești, Bacău County. The simulation was performed with the HEC-RAS program for several scenarios differentiated by the value of the transit flows (Q1%, Q2%, Q5% and Q10%,). In order to apply the simulation program, it was necessary to carry out complex studies such as topographic, hydrological, hydraulic, how to equip the river with regularization works, the constructive characteristics of the works, etc. The presence of the riverbed regularization works modifies locally flood parameters and implicitly the parameters of the flood band. The simulation highlighted the positive, but also negative, cooperation of the arranged and unarranged river sectors with regularization works for the formation of the flood band. Also, the simulation highlighted the need to rehabilitate the existing regularization works, but also the need to carry out new works.

1. Introduction

The change at European level of the concept of regularization of watercourses, determined by the excessive influence of the hydroclimatic risk factors, also imposed changes in the way of designing and realizing the constructions from the riverbed and the riparian zone of the rivers. This is how the concept of „*green regularization*” came about. Water Directive 2000/60 and C.E. and the legislation of the Romanian government emphasize the concepts of „*continuous river*” and „*more space for rivers*” (Avram, 2020). In this concept, the technical solutions for the design and execution of hydrotechnical works for the arrangement and rearrangement of watercourses must be legislated.

The territory of Romania and in particular the area of Moldova with the Siret and Prut river basins is located in a hydroclimatic transition zone. The climate transition takes place from wetter and thermally moderate oceanic features (flowing from the western sector), to continental features (with large thermal and rainfall discontinuities) from Eastern Europe and northern Black Sea (Apostol, 2004; Vamanu and Olariu, 2000). The Trotuș River hydrographic basin located in the piedmont area of the Eastern Carpathians and near the peripontic territory, is an area suitable for the manifestation of the corroboration between the hydroclimatic risk factors with the anthropic ones.

This river basin is representative of the frequency of rapid floods. A statistical analysis performed by Avram (2020) showed that high flow floods have been present in the last 60 years (eg. 1960, 1970, 1975, 1991, 2004, 2005, 2010, 2012, 2016 and 2018). A flood with high intensity was in 2005, where its effects were disastrous throughout the river

basin (Romanescu and Nistor, 2011; Avram et al., 2018). A flood with disaster effects occurred in 2016, and the hydroclimatic phenomenon was felt in the Siret River basin from north to south (Avram et al., 2018; Luca and Avram, 2017; Luca et al., 2017).

In the last period of time, there have been changes in some parameters of the hydrological regime of the rivers in the Trotuș river basin. A change is represented by the high frequency in short periods of time of floods with maximum flows. The repeated floods determined important morphological transformations in the minor bed of the Trotuș river with influences on the stability of the constructions located in the flow section (Luca, 2019). Repeated morphological transformation of the riverbed has led to partial degradation and even destruction of hydro-urban constructions and installations, or regularization works by hydrodynamic erosion (Luca, 2006; Luca, 2012; Neuhold et al., 2009).

An important parameter in the protection of inhabited areas is the size of the area / flood strip. Current models used to analyse the evolution of river floodplain are diverse (HEC-RAS, Maik 21, Mohid etc.) and are used to research water flow in riverbeds (Avram, 2020; Salemian and Moosavi, 2010). In the last period of time, hybrid numerical models are used to simulate hydraulic phenomena in riverbeds (Villanueva and Wright, 2006; Werner, 2007). Simulation models allow to obtain design data for river regularization works (Avram, 2020; Petre et al., 2016). At the same time, these models are used to analyse the way of endowment with protection works of the riparian area, but also their behaviour to the aggressive action of floods. Flow rates with calculation probability are imposed by the design regulations (Avram, 2020).

The aim of the paper is to present some results obtained by simulating the floods on the Trotuș River on the sector that transits the city of Comănești. An objective of the research was the evolution of the floodplain depending on the presence or absence of works to regulate the Trotuș riverbed in this sector.

2. Materials and Methods

The studies and researches were carried out on a section of the Trotuș River that passes through the city of Comănești, Bacău County (Avram, 2020). The city is located on both banks of the Trotuș River and is located in the Comănești Depression in the Eastern Carpathians (Figure 1.a). The research section is delimited by two sections on the Trotuș River: upstream of the confluence with the Asău River, and downstream at the confluence with the Urmeniș River (Atlas geographic, 1985).

The main criterion for choosing the river section is represented by its arrangement in recent years with shore regularization and defence works (Figure 1.b). The second selection criterion is represented by the intensely populated and economically and socially developed area, which must be protected from floods. In the hydrographic basin of the Trotuș River, a complex of hydroclimatic risk factors of natural and anthropic origin has been manifested in the last 40 years. These factors have particularly influenced the evolution of the hydrological and hydraulic parameters of the Trotuș and Asău Rivers in the area of Comănești (Avram, 2020).

The research material consisted of topographic, hydrological, hydraulic and geotechnical studies carried out on the research area. A special study analyzed the type of riverbed regularization works and the shore defences works carried out on the research section. The processed data referred to the age of the works, the execution material, the

flood behaviour, the recovery measures and the operating conditions (Avram, 2020). The detailed research was conducted between 2014 and 2019.

Figure 1. The location of the research area on the Trotuș river: (a) the area of Comănești and Lunca-Asău localities (scale 1: 100.000); (b) how to regulate the Trotuș riverbed in Comănești (Avram M., 2020).

The primary processing of topographic data, respectively situation plans, a longitudinal and transversal profile was performed in AutoCAD. Graphics were exported to Microsoft Office Excel, HEC-RAS, and ArcGIS. The simulation of the water flow on the river section was performed with the HEC-RAS program. A large volume of photo surveys taken from the research sector was used in the research.

3. Results and discussion

The Trotuș River basin has become representative for the presence and frequency of rapid floods. The flood with the highest flow took place in 1991 (3720 m³/s at S.H. (Hydrometric Station) Vrânceni). In 2005 there was a flood with a maximum flow of 2845 m³/s, and its impact on the economic and social framework was particularly strong (Avram, 2020; Avram et al., 2018; Romanescu and Nistor, 2013). It is also possible to mention the values of 2525 m³/s in 2016 and 2450 m³/s in 2018. The maximum flood flows have presented very low probabilities of occurrence in the last 20 years. Thus, in 2005, the following probabilities of occurrence were registered on the Trotuș River: 0.5% at S.H. Tg. Ocna ($Q_{\max} = 1429 \text{ m}^3/\text{s}$); 0.5% to S.H. Vrânceni ($Q_{\max} = 2845 \text{ m}^3/\text{s}$); 0.5 - 0.1% to S.H. Onești ($Q_{\max} = 2296 \text{ m}^3/\text{s}$). The recorded values exceeded the sizing and verification probabilities of the hydrotechnical constructions located in the riverbed and on the shore.

The length of the sector considered in research on the Trotuș River was 6.181 km. The main tributaries of the Trotuș River on this sector are Asău and Urmeniș (on the left), Agache, Crăciunești and Șupan (on the right).

In the research area on the Trotuș River, but also on its tributaries, in 2013, 2015 and 2018, shore defence works, riverbed recalibration and stabilization of the longitudinal profile were carried out. The shore defence is made of gabions (L = 9.01 km) and concrete walls (on the right bank of the Trotuș river and the Șupan brook, L = 1.423 km). In the riverbed, bottom thresholds were made from gabions (on the Trotuș river, Șupan stream, Urmeniș stream), recalibration of the minor riverbed (Trotuș river, Șupan stream, Urmeniș stream, L = 10.433 km). Over time, rehabilitation works have been

carried out on works degraded by water action (Figure 2, Figure 3) (ABA SIRET, 2018, Avram, 2020).

Figure 2. Trotuș riverbed on the research sector (Comănești city): (a) calibrated riverbed and defense works on both banks; (b) defense works only on one bank (Avram, 2020)

Figure 3. The endowment with works for the regularization of the research sectors on the Trotuș river: (a) calibrated riverbed and with shore defence works; (b) partially calibrated riverbed and with incomplete shore defence works (Avram, 2017).

The regularization works had a positive impact on the protection of the city of Comănești against floods. They removed from the incidence of floods about 378 households, 448 annexes, 3 bridges and 12 footbridges, social objectives (a hospital, two churches, town hall, schools and colleges, etc.) and economic objectives in the last 10 years (ABA SIRET, 2018). The regularization of the Trotuș River has a positive impact on the aquatic and riparian environment by contributing to the restoration of the biotope, the natural environment and the sanitation of the riverbed. The design of the regularization works was carried out according to the requirements imposed by the norms in force. However, some sectors of the Trotuș River in the Comănești area does not have regularization and shore protection works, a situation that influences the size of the floodplain in the city.

One of the research directions focused on the verification of the structural parameters of the existing works (old works, with degradation processes in various stages) and of the new ones carried out in the last period of time to the destructive action of the floods. The data obtained were used to analyse the evolution of the floodplain in transit of the maximum flows required by the operating rules for the existing

regularization works on the researched river sectors. 49 cross sections were fixed along the length of the research section (Figure 4). In each section and on the section, topographic measurements of the minor and major riverbed were made. The cross sections at distances of 110 - 130 m between them were numbered downstream to upstream from 1 to 49.

Figure 4. Location of the research section on the Trotuș river in the city of Comănești (scale 1: 25.000): 49 - 1 arrangement of the cross sections in the simulation program (Avram, 2020).

The cross section of the Trotuș River in the city of Comănești has an approximately rectangular shape for the minor riverbed (Figure 5). The water depth at average flows is 0.60 - 1.80 m (Figure 2.). The riverbed consists of alluvial deposits in which sand, ballast and boulders predominate (Avram, 2000).

The simulation of the water flow on the research section on the Trotuș river was performed with the HEC-RAS program in four scenarios differentiated by the value of the maximum flows considered in the design norms of the regularization works. The flows used were with the calculation probabilities of 1%, 2%, 5% and 10%. The value of the flows was variable along the length of the simulated river section due to the contribution given by the tributaries. Thus, in Scenario I, the calculation flow with $p = 1\%$ was $Q_{\max,1\%} = 800 \text{ m}^3/\text{s}$ on the upstream sector and $Q_{\max,1\%} = 920 \text{ m}^3/\text{s}$ on the downstream sector. (Avram, 2020).

In the first stage, a flow simulation was performed on the analysis section for the four scenarios. The data processing resulted in movement parameters in each section and on various sectors of analysis. The processing and interpretation of the data resulted in the evolution of the flood zone. In the second stage, the behaviour of the regularization works and their influence on the size of the flood zone were analysed comparatively in sections and by research sectors. The analysis was performed especially in the sections and on river sectors where there is a negative impact on the riparian social and economic environment (Avram, 2020).

Figure 5. Schematization of the Trotuș riverbed: (a) general view of the riverbed at the entrance to the simulation sector; (b) riverbed scheme; (c) topographic survey of the flow section (Avram, 2020).

For a more correct definition of the behaviour of regularization works, but also of the riparian area to the action of floods, in accordance with the results of the first set of simulations, more detailed research was performed on sections with special problems regarding the flood area. For example, a series of results, obtained on the river section delimited by sections P16 - P13 in Scenario I, are presented. This section highlights several situations of formation of the flood zone depending on the condition of the Trotuș riverbed:

- a - riverbed in its natural state;
- b - calibrated riverbed and equipped with shore defence works on a single shore;
- c - calibrated riverbed and equipped with shore defence works on both banks.

On the river sector delimited by sections P16 (Figure 6.a) and P13 (Figure 7.b), recalibration works of the riverbed and bank protection were carried out, a situation that determined the increase of the flow and implicitly of the water depth (Figure 6.a and Figure 6.b).

Figure 6. The way of water flow on the Trotuș river delimited by sections P15 and P16 in the area of Comănești city: (a) section P15 at average flows; (b) transit of the flood in 2016 in section P16 (photo: Avram, 2016).

The simulation of the water movement on the sector delimited by sections P16 - P13, with a length of 260.29 m, in Scenario I, was performed for the maximum flow, $Q_{max,1\%} = 920 \text{ m}^3/\text{s}$. The bed of the P16 - P13 sector (Figure 6) is calibrated and arranged with

regularization works (calibrated bed, bottom sill, energy sink) and shore defense (simple concrete support walls and plastered gabions) (Avram, 2020).

Figure 7. View of the sections and sectors of analysis on the Trotuş river: (a) section P14; (b) section P13 (photo Avram, 2018).

The analysis of the obtained results highlights a series of special situations at the transit of the flood with $Q_{\max,1\%} = 920 \text{ m}^3/\text{s}$. Although the P16 section safely transits the flows with $p = 1\%$ and $p = 2\%$, for a minor riverbed width of 59 m, it results that the area of the left bank is flooded. This situation is determined by the discharge of water from the upstream sections, respectively P28 (arranged with defence works on the left bank and partially on the right bank), P27 and P26 (arranged with defence works on the left bank, and the right bank is undeveloped). The processing of data from section P16 (Table 1) shows an increase in water gloss from 58.97 m to 277.53 m for $Q_{\max,1\%} = 920 \text{ m}^3/\text{s}$ and the extension of the floodplain in the riparian area (Figure 8).

Table 1. Modeling results for the P 16 profile on the Trotsu river

No. Pr.	p (%)	$Q_{\max, \text{tot}}$ (m ³ /s)	$Z_{\min}$ (m)	Z (m)	$Z_{\max}$ (m)	v (m/s)	L (m)	L_a (m)
P16	1%	920	370,00	374,49	375,19	3,98	277,53	58,97
	2%	775	370,00	374,30	374,95	3,75	247,63	58,97
	5%	535	370,00	373,93	374,42	3,15	157,78	58,97
	10%	445	370,00	373,70	374,13	2,92	113,65	58,97
Nr. Pr. - profile number; p - calculation probability; Z - water levels; L - width at the free surface of the water; L_a the width of the minor riverbed

Figure 8. Flood change and flood limits in section P16 for the flow gap considered on the research sector on the Trotuș River (Avram 2020)

In section P16 at $Q_{\max 1\%} = 920 \text{ m}^3/\text{s}$ resulted $H_{\max.1\%, P16} = 5.19 \text{ m}$, and at $Q_{\max.2\%} = 775 \text{ m}^3/\text{s}$ is obtained, $H_{\max.2\%, P16} = 4.95 \text{ m}$. The values are determined by the arrangement of the left and right bank with defence works from concrete gabions at the top. Shore defence clamps the riverbed and causes an increase in water speed and thus flow (Avram, 2020).

Section P15 is the narrowest of the four analysed ($L_{a, P15} = 54.44 \text{ m}$), and sections P14 and P13 make a diffuser-type bed where the width increases progressively to values of 66.34 m and 76.32 m. The speeds decrease on the river sector P13 - P14, a situation that determines the deposition of alluvial material.

In section P15 at $Q_{\max 1\%} = 920 \text{ m}^3/\text{s}$ results $H_{\max.1\%, P15} = 4.58 \text{ m}$. The value is determined by the arrangement of the left bank with shore defence works (gabions), while the right bank is partially equipped with protection works. The graphical representation of the results of the similarity in this section (Figure 9) indicates the extension of the floodplain to a width of 496.56 m (the minor riverbed is 54.44 m wide (Avram, 2020)). by the discharge of water from the upstream sections (P28, P27, and P26) on routes in the riparian zone.

The results of the simulation were analysed in comparison with the studies carried out in the years 2008 - 2010 in the Siret River basin within the P.M.R.I. 1 on floodplains (ABA Siret, 2012). Research conducted in 2016-2019 shows that the flood limit for the flow with a probability of 1% has decreased by about 20% in the area of Comănești compared to the limit presented by the P.M.R.I. 1 (Figure 10) (Avram, 2020). The reduction of the flood limit in this area is also determined by the influence of the regularization works carried out on the Trotuș River after 2010. The comparative analysis was performed to identify and ascertain the influence of the regularization works on this sector, especially on the flood limit. in the context of the presence of existing hydroclimatic risks.

Figure 9. Flood change and flood limits in section P15 for the flow gap considered on the research sector on the Trotuș river (Avram 2020)

Figure 10 showed in red the flood limit on the section studied before arranging with hydrotechnical works (P.M.R.I. 1 study), and in light blue the flood limit resulted by modelling performed in the research was indicated. Currently, regularization works are being carried out on the Trotuș River and its tributaries. After the completion of these works, a remodelling of the flood limit is required and it will certainly result in a reduction.

Figure 10. Comparative analysis of flood limits for Qmax 1% on the Trotuș River in the area of Comănești (Avram, 2020)

From the analysis of the final results obtained on the research sector P16 - P13 on the Trotuș River, a series of defining aspects are highlighted with an influence on the value of the flood band and the behaviour of the regularization works.

The hydroclimatic risk factors, especially the fast and frequent floods of the last years, significantly influenced the behaviour of the shore regularization and defence works executed in the Trotuș riverbed that crosses the researched area from Comănești and Asău localities. The erosion phenomena of the riverbed determined the unveiling of the shore defence foundation, a situation that led to the loss of the construction stability, the cracking and breaking on pieces and the uncovering of the shore.

The anthropic risk factors, especially the absence of the riverbed calibration works, but also the non-execution of the shore defence constructions on a relatively long length along the Trotuș River, contribute to the flooding of the riparian area in Comănești locality. Floods are also produced by water transfer from the undeveloped to the landscaped sections, an aspect confirmed by the research carried out (Avram, 2020). The old shore defence works were dimensioned for flows with calculation probabilities of 5% and 2%, a situation that is no longer appropriate for the transit of floods in the current period. Flow calculation probabilities need to be modified to take into account hydroclimatic risks.

The researched river section includes almost the entire area of Comănești, being an intensely populated urban area. This section has been arranged in recent years with a series of regularization and shore defence works, which has led to a reduction in flooding in the riparian area. Carrying out simulations of the flood transit at determined time intervals contributes to the analysis of the protection mode of the riparian area continuously equipped with regularization works.

The old shore defense works must be resized with the modified flows and imposed by legislative acts in the field of water management. In the last 30 years, the probabilities of exceeding the sizing and verification flows have changed. In this context, the old regularization works must be examined and redesigned in order to limit the destructive effect of the floods and implicitly to reduce the flood band.

5. Conclusions

1. The flood limit obtained by simulating the river sector with regularization works at the maximum flow with the probability of 1% was reduced by about 17 - 20% compared to the one calculated 12 years ago.

2. The differentiated way of endowment with regularization works characterized the behaviour of river sectors in flood transit, a situation highlighted by the presence of river sectors that safely transport the maximum flows, but also sectors that partially or totally flood the riparian area.

3. A number of sectors, although the maximum flows are safe to pass through, are flooded due to discharges into upstream or downstream river sectors.

4. The configuration of the banks and their low height, the small width of the riverbed, the absence of regularization works or their non-dimensioning at flows with lower probabilities influence the extension of the flood limit in the major riverbed.

5. The execution of the regularization works on this river sector determined the decrease of the roughness coefficient, a situation that increased the water speed and the transited flow. However, the large and well-defined current sections do not ensure sufficiently safe transit of debts with a probability of 1% and 2%, but only those of 5% and 10% in certain sectors.

References

1. A.B.A. SIRET-Bacău Rapoartele de sinteză privind apărarea împotriva inundațiilor, fenomenelor hidrometeorologice periculoase, accidentelor la construcții hidrotehnice și poluărilor accidentale din județul Bacău, anii 1991, 2004, 2005, 2010, 2016, 2018.
2. Apostol L., (2004). *Clima Subcarpaților Moldovei*. Edit. Universității Suceava.
3. Avram Mihaela, (2020), Cercetări privind impactul factorilor de risc hidroclimatic asupra lucrărilor de regularizare a râurilor. Teză de doctorat. Universitatea Tehnică „Gheorghe Asachi” din Iași, Romania.
4. Avram, M., Luca, M., (2017), Analysis of phenomena with hydrologic large risk in the hydrographic basin of the Trotuș River. *Present Environment & Sustainable Development” Al. I. Cuza University of Iasi”, vol. 11(2)*, pp. 77-87.
5. Avram Mihaela, Luca M., Marcoie N., Chirica Ștefania, (2018). Studies and research on maximum flows of the Trotuș River in 1990 – 2017. *Present Environment & Sustainable Development” Al. I. Cuza University of Iasi”, PESD Vol. 12, no. 2*, pp. 109-119, ISSN 1843-5971, ISSN 2284-7820.
6. Ichim I., Bătuca D., Rădoane M., Duma D., (1989), *Morfologia și dinamica albiilor de râuri*, Editura Tehnică București.
7. Luca M., Avram Mihaela, (2017), Analysis of the hydroclimatic risk parameters at the high level of the Tazlăul Sărat River in 2016 year. *Present Environment and Sustainable Development, ”Al. I. Cuza University of Iasi”, vol. 11, nr. 2*, pp. 97-108. ISSN 1843-5971 ISSN 2284–7820 (online).
8. Luca M., Sion P. V., Avram Mihaela, Chirica Ștefania, (2019). Monitoring of degradation process of the shore defence works in erodible riverbeds. *PANGEEA, Journal of Environmental Department and Romanian Geographic Society of Romania, Issue 19, edited „1 Decembrie” University of Alba Iulia*, Aeternitas Publishing House Alba Iulia, p. 30-37, ISSN 1841-1517, DOI: 10.29302
9. Luca, M., Avram Mihaela, Marcoie N., (2017), Analysis of the floods effects in june 2016 in the Voronet river hydrographic basin. *The Annals of ”Dunărea de Jos” University of Galați, Fascicle IX, Metallurgy and Materials Science, nr. 2*, pp. 5-10. ISSN 1453-083X.
10. Neuhold C., Stanzel P., and Nachtnebel H. P., (2009), Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application. *Natural Hazards and Earth System Sciences, nr. 9* pp. 789-799.
11. Petre I., S., Puiu C., S., Bartha I., Toma D., (2016), Aspects Regarding Flood Modeling with MOHID. *Bulletin of the Polytechnic Institute from Iași*, Published by Technical University ”Gheorghe Asachi” from Iasi, *Tome 62 (66), No. 1-2*, Section Hidrotehnica, Edit. Politehniun, p. 55-66 ISSN 1224-3892.
12. Romanescu G., Stoleriu C. (2013). Causes and Effects of the Catastrophic Flooding on the Siret River (Romania) in July-August 2008. *Natural Hazards*, 69:1351-1367.

13. Romanescu, G., Nistor, I., (2011), The effect of the July 2005 catastrophic inundations in the Siret River's Lower Watershed, Romania. *Natural Hazards*, vol. 57(2), pp. 345-368.
14. Salemian A., Moosavi J., H., (2010), Floodplain mapping delineation in Beshar River by using Arcview techniques and HEC-RAS model. *"Ovidius" University Anals, Constanza, year XII, Issue 12, Series-Civil Engineering*, 423-430 pp., ISSN 1584-5990.
15. Vamanu E., Olariu P., (2000), Rolul factorilor locali în precizarea relațiilor de generalizare a undelor de viitură din spațiul hidrografic Siret. *Lucrările Seminarului geografic „D. Cantemir” vol. 20*, Iași.
16. Vamanu E., Olariu P., (2002). Riscuri hidroclimatice în Spațiul hidrografic Siret în contextul modificărilor geografice. *Culegere de lucrări, Sesiunea științifică anuală INMH București*.
17. Villanueva I., Wright N.G., (2006), Performance of several hybrid numerical schemes to determine flooding extent. *River Flow*, Lisbon, pp. 343-350.
18. Werner M., (2007), Comparison of modeling approaches used in practical flood extent modeling. *Journal of Hydrology*, 45, pp. 202-215.
19. ***Atlasul geografic al României, (1985). Editura Didactică și Pedagogică, București.

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