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A COMPREHENSIVE ANALYSIS OF FLOODING MECHANISMS ALONG CRASNA RIVER

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ABSTRACT. A Comprehensive Analysis of Flooding Mechanisms Along Crasna River. Across the world best practice, the flood hazard and risk maps are core instruments used for the development and implementation of flood management policies. These maps sit as base information for developing flood management strategies and plans, designing of new flood defence schemes and assessment of the existing flood scheme performance, elaboration of emergency and action plans, territorial planning (zoning and permissions), land use control, climate changes impacts evaluation, insurance industry etc. Romania did remarkable steps in developing high quality flood hazard and risk maps as core action for an integrated flood risk management. In the second cycle of Floods Directive 2007/60/EC implementation, Romania developed and reported to European Commission (EC) the hazard and risk maps for 526 APSFRs (Areas with Potential Significant Flood Risk). The hazard maps built in second cycle are the result of detailed models developed based on high resolution Lidar (0.5m), calibrated hydrological data and advanced modelling technics. Crasna River is one of the watercourses from the Somes-Tisa Basin which benefited from advanced 2D hydraulic modelling having in-place all the existing infrastructure and which has been well - calibrated on the flood event recorded in 2015. The calibration of the model on 2015 flood event was performed both for flows and levels. The article aims to explicitly present the performance of the existing defence system of Crasna river during extreme flood events with different magnitudes having in hand these high-quality hydraulic model and hazard maps.

Keywords: "Crasna River", "flood hazard", "flood risk", "hydraulic modelling", "calibration",

1 INTRODUCTION

Fluvial floods occur when there is insufficient capacity and/or insufficient protection during high discharges, resulting in banks or flood defence overflow Ferguson et al. (2023). The flow exceeds the natural or artificial channel capacity

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due to the intense surface run-off within the catchment in prolonged periods of precipitation. Jha et al. (2012)

In the process of the second cycle implementation of Flood Directive 2007/60/EC, Romania conducted in 2023 the RO-FLOODS application (Strengthening the capacity of the central public authority in the water field in order to implement the 2nd and 3rd stages of the 2nd Cycle of the Flood Directive, SIPOCA code 734), when the Ministry of Environment, Water and Forests (MEWF) as main beneficiary was contractually supported by the World Bank. Subsequently, JBA Consulting, as leader of an international consortium, was awarded in a consultancy contract for developing Flood Hazard and Risk Maps and Flood Risk Management Plans at national level for the 526 fluvial APFSRs (Areas with Potential Significant Flood Risk) which were previously reported to the European Commission in 2019.

Flood hazard and risk maps were built in baseline conditions for a large spectrum of annual exceedance probabilities (AEPs) but also for future climate change conditions. Crasna River, which is the study area of this paper, was designated in RO-FLOODS as priority strategy for Some-Tisa River Basin benefiting from new updated hazard maps, 2D hydraulic modelling and being largely assessed in multiple mitigation alternatives which was in the end promoted as one of the 30 priority projects of Romania.

Along the years, Somes-Tisa River Bazin recorded historical flood events with repercussions on properties, communities, infrastructure of any kind and agriculture. Implicitly, Crasna River also experienced multiple flood events, many of them recorded in the last two decades (2008, 2010, 2015, 2023) when the authorities had to intervene with emergency measures. In many sectors the existing dike system was close to its maximum capacity and locally the crests of were exceeded, and agricultural lands were flooded.

This paper aims to present a scan of the flood hazard and risk on Crasna River, as an exemplification of good practices in Romania. Thus, should be noted that this good practice was uniformly applied in all RBAs especially on the first order rivers, Romania standing now alongside other EU countries which are much more progressive in integrated flood risk management.

2 STUDY AREA

2.1 Catchment characteristics

The study area of the current paper is Crasna River, one of the largest rivers in Some-Tisa River Basin (RBA) after Somesul Mic and Somesul Mare which join together forming a single major watercourse named Somes River and after Tisa River which is the main collector of all flows formed in the Somes Tisa Basin. According to the National Institute of Hydrology (INHGA), Somes-Tisa River Bazin is the third largest basin in the country and has the highest water resource in Romania, being the only river basin predicted with increase in water resources when comparing the reference scenario 1971-2000 to the future scenario 2021-2050. Chendes et al. (2023).

Crasna River has length of about 134 km joining Tisa River on Hungary territory. The catchment is 2000 km2 with an average altitude of about 235mdMN. The Crasna river collects the flow from 52 watercourses with a total network of 696 km, the main tributaries being Zalau, Maja and Maria (Fig. 1). The average density of the hydrographic network is 0.34 km/km^2 decreasing from upstream to downstream. (P.P.P.D.E.I, 2015). For the reporting done to the EU Commission, Crasna River was split in 4 APSFRs: 09-A041 – upstream of Vars'll reservoir, 09-A042 – between Varsolt dam and Acas, 09-A043 – between Acas to Moftinu non-permanent storage, 09-A044 – from Moftinu till the country border.

Fig. 1. Location of the study area within the Somes Tisa River Basin (Source of layers: ROFLOODS project)

2.2 Historical flood events

In the last 50 years, major floods were recorded on the Crasna River in 1970, 1979, 1980, 2001, 2005, 2008, 2010, 2015, 2023 (Table *1*). There is a decrease in maximum flows noticed by the peak flow trends of period 1990 ÷ 2006 compared against the period 1965 ÷ 1989.

The most representative floods recorded on the Crasna River are:

- The flood dated in 12.06.1970, duration 6 days;
- The flood dated in 12.06.1998, duration 37 days;
- The flood dated in 23.07.2008, duration 3 days.

The floods were caused by intense and torrential runoff, flow area variations and multiple meanders and channel obstruction due to woody vegetation.

Table 1. ***Maximum flows and exceedance probabilities associated to the historical flood events of Crasna River (source: RBA Somes Tisa 2024)***

Gauging station	**Year**	**Peak flow (m^3/s)**	**AEP (%)**	**Gauging station**	**Year**	**Peak flow (m^3/s)**	**AEP (%)**
Crasna	1973	197	3.8	Supuru de Jos	1970	275	6
	1995	155	7		1974	140	18.5
	1997	201	4		1978	159	15.8
	1998	204	3.6		1988	167	14.8
	2001	195	3.9		1989	217	9.9
	2023	80	19		2015	128*	20.7
					2023	113	23.7
Șimleu Silvaniei	1962	128	13.8	Domanești	1965	223	11.6
	1966	116	15.7		1966	320	6.2
	1970	128	13.8		1970	342	5.3
	1973	121	15.1		1974	270	8.5
	1974	203	6		1980	155	18
	2023	15*	51		2015	52.2**	35
					2023	55**	34.8

The June 1970 flood was the largest known till the date. The flood was noted for the remarkable flood levels, but also for the prolonged duration. The recorded peak flow was 342 m^3/s, which means 142 m^3/s more over the channel capacity. The long propagation time allowed to execute intervention measures such as dikes crest raising on about 11 km of dikes, breach closing for 112 m and restrict infiltration on about 5.5 km of dikes. The total flooded area included 27,300 ha, with a flood volume of 15 mil.m^3. Despite all the measures taken, the existing defense line was breached, causing significant damage which emerged for the enforcement of the existing flood defence system. In the post-event years, the dikes condition was restored, crests were raised, and new non-permanent storages were built in 1980 at Moftinu Mare and 2007 at Supuru de Jos.

However, the most recent floods (2015, 2023) experienced on Crasna River resulted in full channel capacity and the necessity for emergency interventions to prevent dike overtopping in local sectors.

2.3 Existing flood defences

As shown by the catchment map (Fig. *1*), Crasna river has a highly modified flow regime, the flows being controlled by the Varsolt permanent reservoir and two lateral non-permanent storages, Supur and Moftin, all of them having flood attenuation purpose. Also, the main channel is bordered with dikes on both banks for about 79km, from Giurtelecu Simleului till the country border.

Varsolt Reservoir – Controls the flows in the upper catchment of Crasna river since 1979 and it is located 96 km upstream Hungarian border in Salaj County. The dam is made from local materials and clays, with a maximum height of 14 m and the dam length of about 2160 m (Fig. *2*). The 2nd importance class was associated for the dam desing which means that the structure was designed for 1%AEP flow and verified for 0.1%AEP flow. The main purposes for this reservoir are water supply for localities from Salaj County, fish farming and flood attenuation with a total volume of 39.4 mil.m^3, respectively the volume at Normal Retention Level (NRL) of 16.1 mil.m^3.

Fig. 2. ***Varsolt reservoir (online source)***

Supuru non-permanent storage – With a total volume of 5 mil.m^3, Supuru storage sits at the confluence between Crasna River and its right tributary the Maja (Fig. 3). The lateral spillway is located on the right dike of the Crasna river, having the crest at 101.89 mdMN and the length of 200 m.

Moftin non-permanent storage - Includes two compartments with total volume of 7 mil.m^3 and it is located in the lower catchment, on the right bank, upstream of Moftinu Mare locality (Fig. *4*). The lateral spillway is in the right dike of Crasna having the crest level at 120.19mdMN and length of 56m.

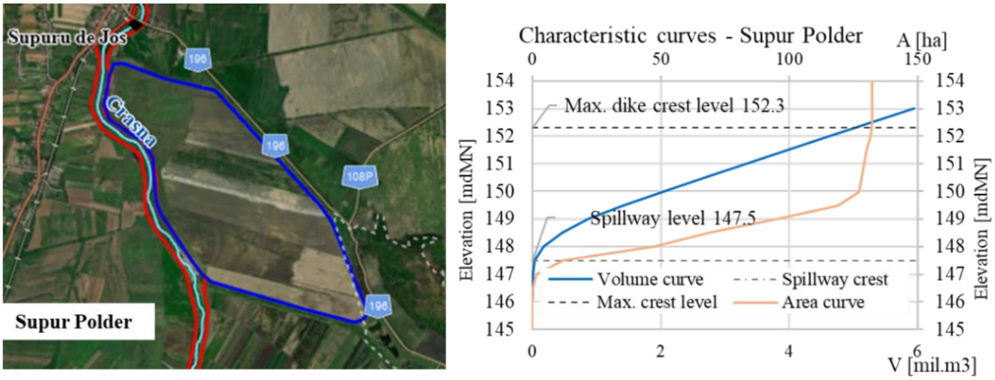


Fig. 3. Characteristics of Supuru non-permanent storage

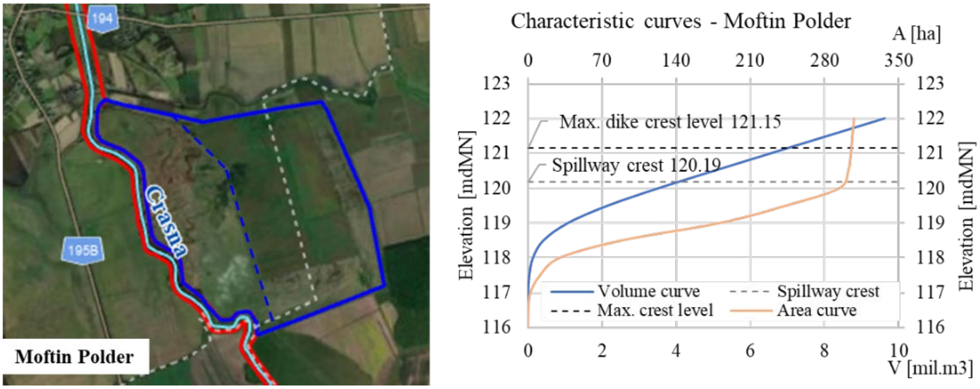


Fig. 4. *Characteristics of Moftin non-permanent storage*

Varsolt reservoir was not physically included in the model because hydrographs in modified flow regime were provided by INHGA downstream of the dam, but the non-permanent storages and all the dike system were modelled.

3 METHODS AND MODELS

Models can be distinguished based on spatial characteristics (1D, 2D, 3D) or level of complexity (lumped models, distributed models, hydraulic models, coupled models). Jha et al. (2012). Selection of the type of model depends very much on the input data and the purpose of the model and implicitly the expected outputs.

3.1 Input data

The hydraulic model of Crasna River was built mainly based on topographical and hydrological data all updated in 2022-2023. Downstream of Acas locality where the floodplains or Crasna become extremely wide with multiple old braided paths the Lidar with 0.5m resolution measured in cycle 2 (2022) was available while upstream of Acas where the catchment is more linear the Lidar with 1m resolution previously measured in cycle 1 (2012) was complementary used. Hydrological data consisting in hydrographs in natural and modified flow regime made was made available by INHGA for all modelled scenarios. The natural flow regime data was used to calculate lateral inflows due to the tributaries but also uniform lateral inflows due to the rests of the catchment.

3.2 Model description

To assess the flood hazard for the modelled scenarios along Crasna river, a fully 2D hydraulic model was built using the HECRAS software. The 2D domain was defined as rectangular grid with a cell size of 10m in the main channel and 40m in the floodplains (Fig. *5*). For an accurate representation of the existing infrastructure (longitudinal or contour dikes, spillways, roads, railways) which work as flow barriers, the grid was discretized in smaller cells using breakline elements to capture the maximum elevation of the crests. All the simulations used Shallow Water Equations, which are the most complex equations that include the acceleration component and Coriolis forces, and which consider all flow directions. The Lidar was processed to include the bathymetry of the main channel based on channel survey, having all the channel capacity available and correctly represented.

Simulations were performed and hazard maps were derived for a range of probabilities such as 33%, 10%, 1%, 0.5% and 0.1% and climate change scenario which considers 10% increase in peak flow for the 1% AEP event, however for the clarity purpose only the 1%AEP will be presented and discussed in this paper. However, these maps are in hand for authorities to be used and available at ant moment for public consultation on Inundatii.ro portal.

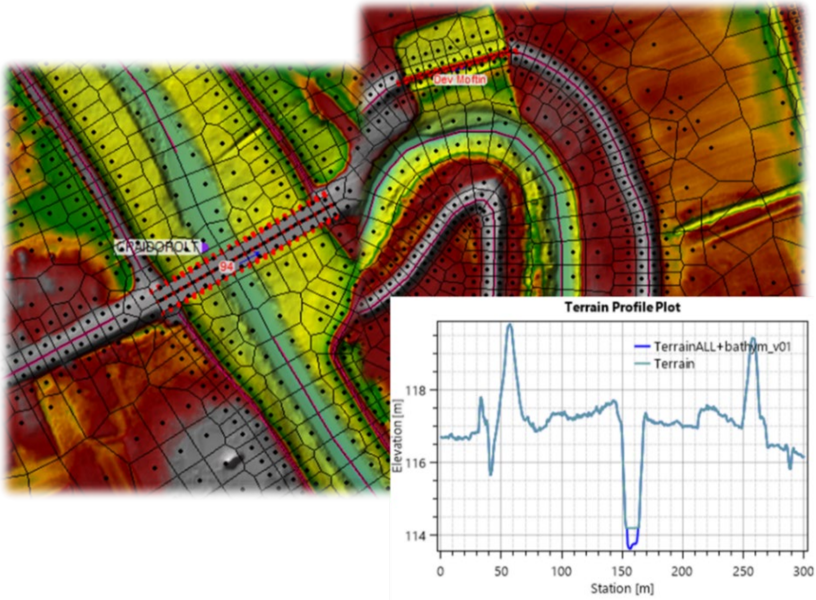


Fig. 5. *Model grid and channel representation within the calculation domain*

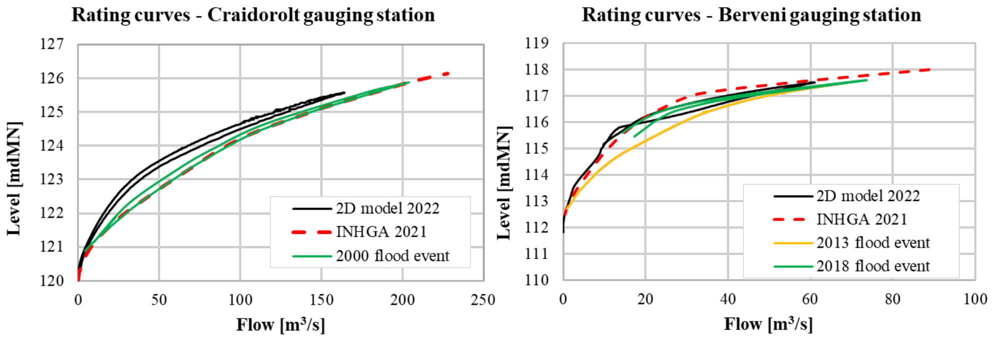
3.3 Calibration

The process of adjusting various parameters within the model in order to have a good match between the simulated results and observed measurements is known as calibration. World Bank, (2016).

The calibration process for Crasna was complex and included calibration of the rating curves, calibration on hydrographs of the 2015 flood event, calibration of parameters for Moftin non-permanent storage but also calibration of the downstream boundary condition at the Hungarian border. The model was calibrated at the three gauging stations Craidorolt, Domanesti and Berveni.

Initially, the observed rating curves provided by INHGA were compared with the modelled rating curves to make calibration checks. The calibration process principally informed the channel roughness selection. The roughness coefficient used in the main channel varied from is 0.03 to 0.035 while for the dikes corridor 0.05 to 0.09 were selected.

The comparison between the modelled rating curves and the observed rating curves for a different range of years is presented in Fig. *6* which reveal a good calibration at the gauging stations.



Rating curves - Craidorolt gauging station

Rating curves - Berveni gauging station

Fig. 6. ***Examples of rating curves calibration at Craidorolt and Berveni***

Thus, an extensive calibration was conducted for Crasna system based on the flood event from May 2015 which was further used in the second calibration stage. Moftin non-permanent storage was operated in the model replicating the conditions reported by the RBA during the 2015 event. The model was calibrated both on flows and levels showing a good match of the modelled versus recorded hydrographs of 2015 event (Fig. *7*). Only slight differences can be observed in the hydrographs shape which manifest due to the different behaviour of the real system and the modelled one, but they are in acceptable margins. On the hydrographs example presented below the deviation in peak flow it is less than 1% and the difference in the peak water level is 2cm.

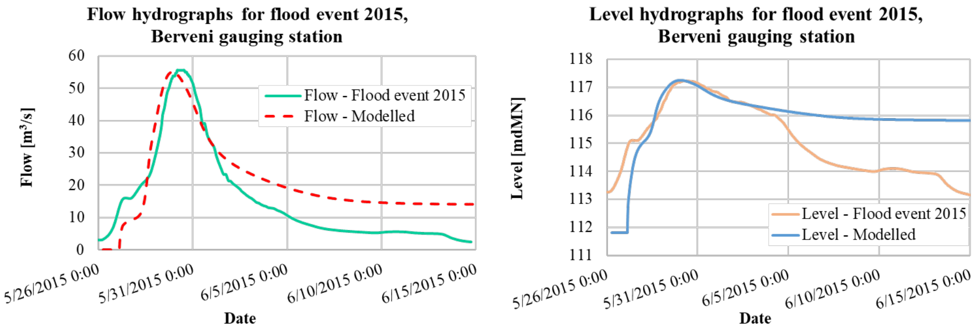


Fig. 7. *Example of hydrographs calibration at Berveni, flood event 2015*

Another indicator of the good calibration performed for the flood event 2015 is shown in Table *2* which presents the comparison of the representative hydraulic parameters at Moftin non-permanent storage resulted from the 2D model versus the real records.

Table 2. *Calibration of the hydraulic parameters at Moftin non-permanent storage in flood event 2015*

Parameter	Flood event 2015 (Source RBA Somes Tisa)	Calibrated 2D Model	Deviation
Flow over the lateral weir	93.11 m^3/s	90.18 m^3/s	- 3%
Maximum flood level on the lateral weir	121.15 mdMN	121.09 mdMN	- 6cm
Gates flow	11.13 m^3/s	13.56 m^3/s	+ 21%
Total volume accumulated within the non-permanent storage	6.15 mil.m^3	6.70 mil.m^3	+ 9%

The roughness coefficients resulted in the flood event calibration are 0.024 to 0.04 for the main channel while for the dikes corridor varied from 0.057 to 0.095. Although different coefficients resulted in rating curve calibration, for conservative reasons the Manning's values resulted from the flood event calibration were used when performing final simulations.

Berveni gauging station is 3.8 km far from the Hungarian border and the model showed that level hydrographs are impacted by the downstream boundary condition (BC). The model couldn't be extended beyond the border so in order to eliminate any impacts on the results, sensitive tests were carried out for the downstream BC until the selected BC provided calibrated hydrographs at Berveni station.

4 RESULTS

4.1 Performance of the flood defence works

Once the model was calibrated, simulations were performed for a range of flows with different AEPs. This section aims to present general conclusions on the hydraulic efficiency of the existing flood defence infrastructures and to highlight weak locations where the case. The performance was evaluated for 1%AEP event which is representative for the non-permanent storages and dikes design.

Supur non-permanent storage

- The spillway overtops for flows higher than 100 m^3/s.
- The maximum water level in the storage is 151.56 mdMN, the contour dike not being overtopped and still having available storage volume up to the maximum crest of the contour dike.
- The attenuation produced by the storage is reduced (maximum 5%) because the spillway crest is placed at low level, allowing the water to return in the river in short time after filling the storage.

Moftin non-permanent storage

- The spillway activates when the flow exceeds 30 m^3/s, which is associated to the 33% AEP, although the Operation Rule Document states that the storage should be activate when the 5%AEP flow is exceeded.
- The water level in the storage is 121.40 mdMN, which overtops the contour dykes in several locations.
- Even for low flows such as 10%AEP the contour dykes are locally overtopped (on the north-eastern sector).
- The storage provided significant attenuation of about 40% of the flow, respectively 54% on volume.

The main conclusion is that Supur storage is not working at full capacity in the current conditions while the Moftin non-permanent storage has the capacity exceeded being overtopped which outcomes the need for more storage and redesign.

Dike corridor

Although the maximum flows are attenuated by the permanent reservoir and the two non-permanent storages, the modelling results shows multiple weak locations in the dikes defence lines where the dike crest still overtops for 1%AEP, the flood water being stored behind the dikes or being propagated downstream along the floodplains but with no possibility to return in the channel. The overtopping is in general shallow (Fig. *8*) occuring at the longitudinal dikes and sometimes at the dikes built on the tributaries for back water effect reduction.

Therefore, the main causes for the predicted flooding at the localities from Crasna catchment are the deficiencies in non-permanent storage functionality and local poor conditions of the dikes which do not provide full protection at the current maximum flows.

4.2 Flood hazard maps

The main outputs of the model are the hazard maps which were derived further in risk maps providing the first maps of this kind developed for Romania and which were also reported to the EC. The risks maps were obtained from hazard maps and detailed exposure data which is a geospatial mapping of the types of assets located in the flooded areas. In general, the exposure analysis aims to determine the economic assets and activities covered by the flood. The impacts of flood on different assets identified in exposure data need to be understood and represented using damage curves. Kang et all (2005).

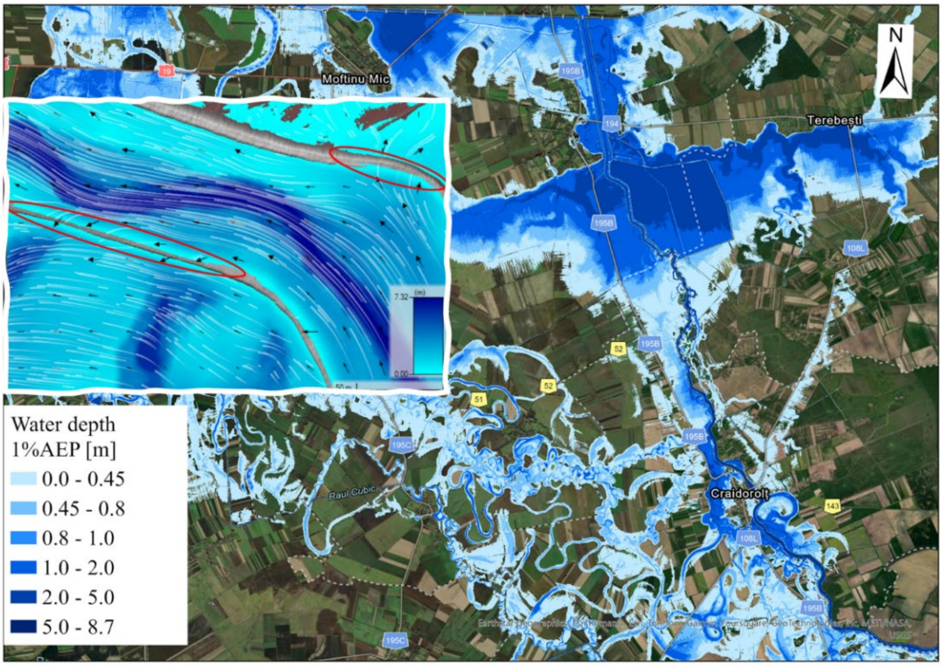


Fig. 8. ***Extract of flood hazard maps for 1%AEP (Craidorolt – Moftin sector), Crasna River***

The hazard analysis showed that flows as 33%AEP can be conveyed by the Crasna system in the current conditions while extreme events such as 1%AEP and 0.1% AEP generate large flooded areas. Even flows such as 10%AEP cause local overtopping of the dikes, for example at Craidorolt or the contour dikes at Moftin storage.

4.3 Model validation

The process of verification against local measurements and performing reality checks is known as model validation. Recently, Crasna 2D model was used for flood propagation of the event recorded at the end of 2023 and real-time prediction of the potential affected areas where interventions are needed. The model indicated a very good predictability confirmed by the reality check done during the event and post event.

5 DISCUSSIONS

The hazard and risk maps are key instruments for an integrated flood risk management and Romania has taken a great leap in this direction during the second cycle of the Flood Directive implementation.

Many watercourses from the Romanian river network and especially critical sectors of the first order rivers are currently benefiting from advanced models built on accurate data such as Lidar at 0.5m and up to date hydrological data but also using the most recent calculation tools and instruments.

The immediate outcome of the advanced 2D modelling produced in RO-FLOODS were the hazard and risk maps. Moreover, the models have also a long-term benefit, being made available for the RBA`s internal usage in performing any future specific flood risk assessments or simulations other potential scenarios. These models are intended for future use as ready-to-use instruments at the disposal of RBAs.

This article presented only one example of good practice, detailing the entire modelling process applied for Crasna River which is one of the main rivers of Somes-Tisa River Basin. As seen in the hazard map presented in the article the floodplain of Crasna is extremely braided the water flowing in multiple directions and parallel to the dike corridor. Only a fully 2D model could capture completely the flooding mechanism for a river with this type of morphology. Nowadays, with current computing capabilities (for example HECRAS), optimized models can be provided that simulate multiple scenarios in a relatively short time.

A detailed understanding of the flood hazard and risk for different probabilities is crucial in implementing appropriate flood attenuation and risk reduction measures such new flood schemes, territorial planning, forecasting, and early warning systems. Also, as flood risk varies over time it is relevant to explore how the flooding mechanisms will amplify and how this can be mitigated in the light of predicted climate changes. Crasna River has a complex catchment and because of this it is important to accommodate the information provided by the hazard and risks maps in the future decision-making process. The model and hazard maps for Crasna indicated extremely large flooded areas, exceedance of dikes and storage capacities which immediately emerge our recommendation for exploring the floodplain in future assessments in order to create more flood storage in current conditions but also for making the existing flood scheme more resilient to climate change.

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