

# Sustainable Water Management Strategies in the Context of Climate Change: Case Study - Zabala River in the Putna Watershed

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**Abstract:** This paper aims to highlight the importance of regulating water uses in the context of sustainable water resources management. This approach is based on a coherent policy and an appropriate strategy, adapted to the current socio-economic conditions of Romania and to the requirements of European policy in this field. The latter is dominated by the implementation in national legislation of the provisions of the Water Framework Directive 60/2000/EEC.

In recent years, in the catchment of the Zăbala stream, there has been particularly heavy rainfall, which has led to a significant increase in the flow rates. These peak flows have caused significant damage, including the formation of floods on the Zăbala watercourse. These floods caused erosion, endangering individual households, annexes, agricultural land, access roads and communal roads near the watercourse.

To significantly reduce the risk of flooding, investment in defence works is needed. These works aim to stop bank erosion and optimise the flow of water into the riverbed, thus giving stability to the bank.

## 1. Introduction

Scientific research is increasingly dedicated to exploring how climate change impacts water management systems, driven by the growing frequency of extreme weather events such as prolonged droughts and devastating floods. These changes demand a comprehensive reevaluation of how water resources are handled, addressing both the physical infrastructure—like dams and reservoirs—and the broader framework, including legal regulations, strategic planning, and adaptive management practices. This holistic approach is essential to safeguard water availability and quality in the face of evolving environmental challenges.

This paper underscores the pressing need to transform current water management strategies to align with the shifting hydrological conditions caused by climate change. It advocates for a detailed revision of dispatcher charts and reservoir operation schedules to reflect the latest water resource dynamics, ensuring they meet the diverse and growing demands of users. This includes prioritizing the protection of aquatic ecosystems, which are increasingly vulnerable to these changes.

The study stands out by offering a detailed and innovative set of adaptation measures that extend beyond merely optimizing existing infrastructure. It proposes integrating well-tested engineering solutions, such as improved water storage systems, with adaptive institutional mechanisms tailored to today's context. At the heart of this approach lies a sustainable water management model that emphasizes proactive

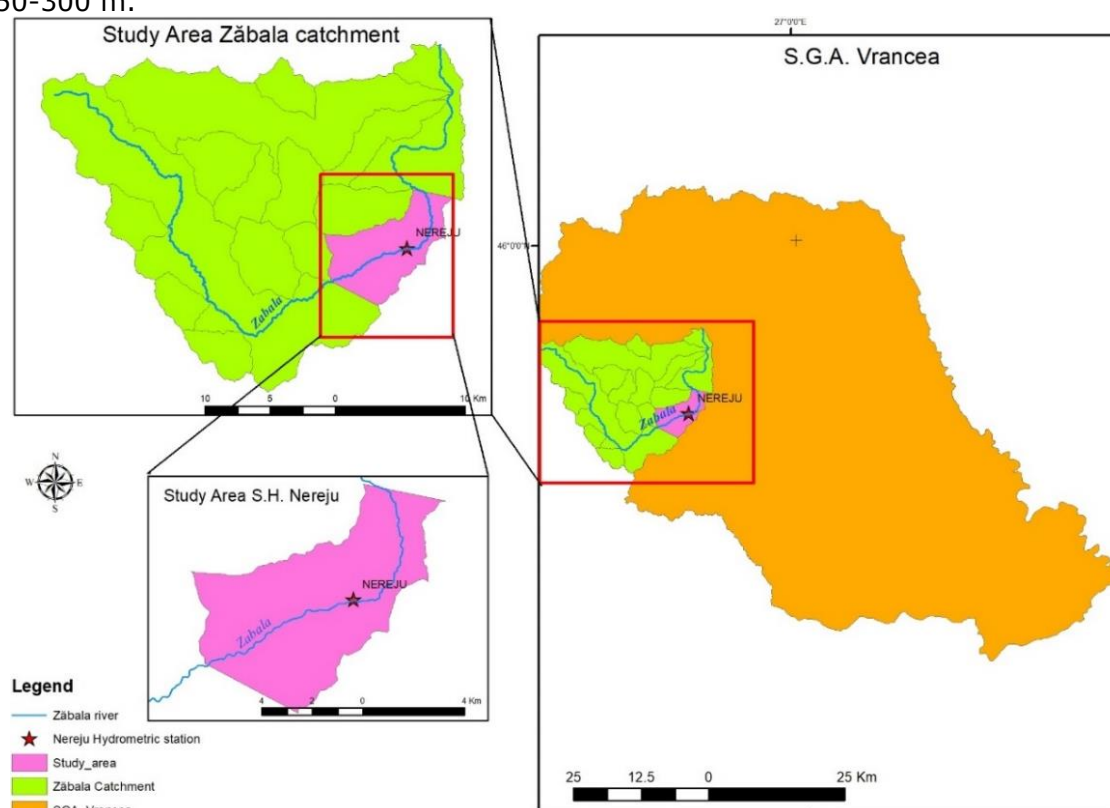
planning, flexible responses to unpredictable conditions, and strong collaboration among institutions to address these complex issues effectively.

A central figure in this transformation is the National Administration "Romanian Waters" (ANAR), which plays a pivotal role in monitoring, protecting, and optimizing the use of water resources across Romania. Through a wide range of critical services—such as ensuring the supply of raw water for drinking and industrial use, conducting thorough monitoring of surface and groundwater quality, preventing floods, and managing accidental pollution—ANAR significantly enhances the nation's hydrological security. These efforts provide a solid foundation for adapting to climate-related challenges.

This paper delivers an integrated perspective on the current difficulties and potential solutions, stressing the importance of coordinated, proactive, and sustainable interventions. By examining the proposed measures and highlighting ANAR's essential contributions, it outlines a modern water governance model. This model not only aligns with European objectives for sustainable development but also adapts to the evolving needs of a society increasingly affected by climate change, particularly as extreme hydrological events become more common and intense.

## 2. Study area

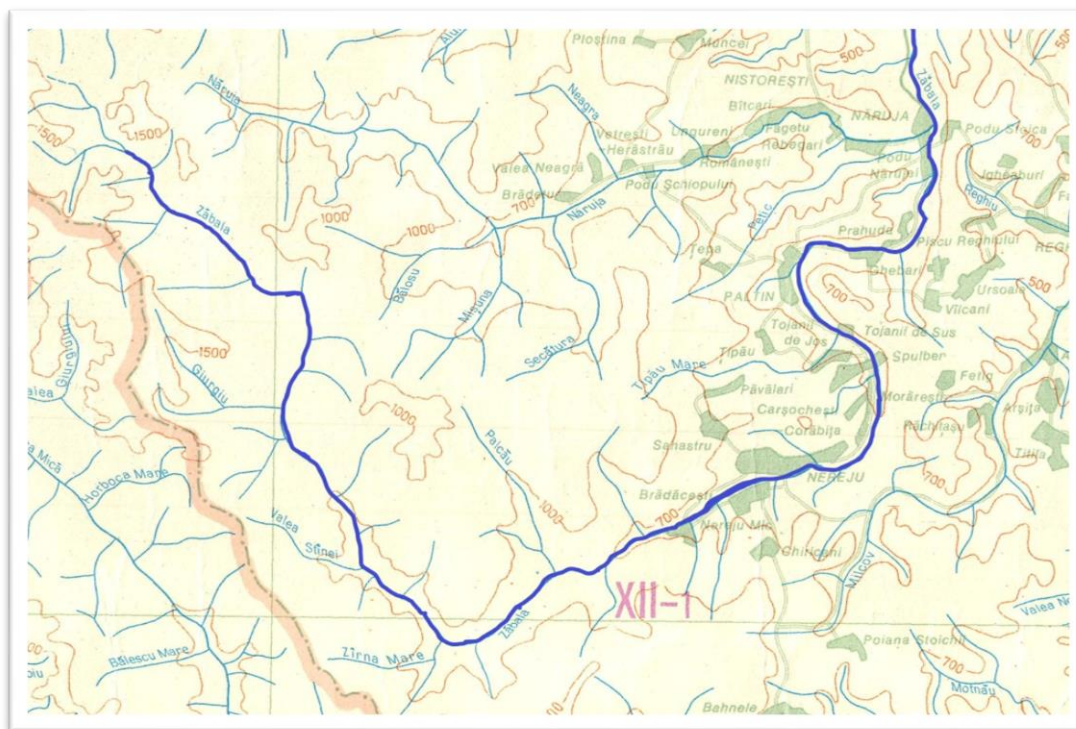
The catchment area of the Zabala River has the largest surface area of the other tributaries of the Putna River (Figure 1). It is characterized by a strong asymmetry being more developed on the left side, resulting in an asymmetry coefficient of 0.85. Its length is 68 km, the width of the riverbed ranging from a minimum of 30 m to a maximum of 250–300 m.



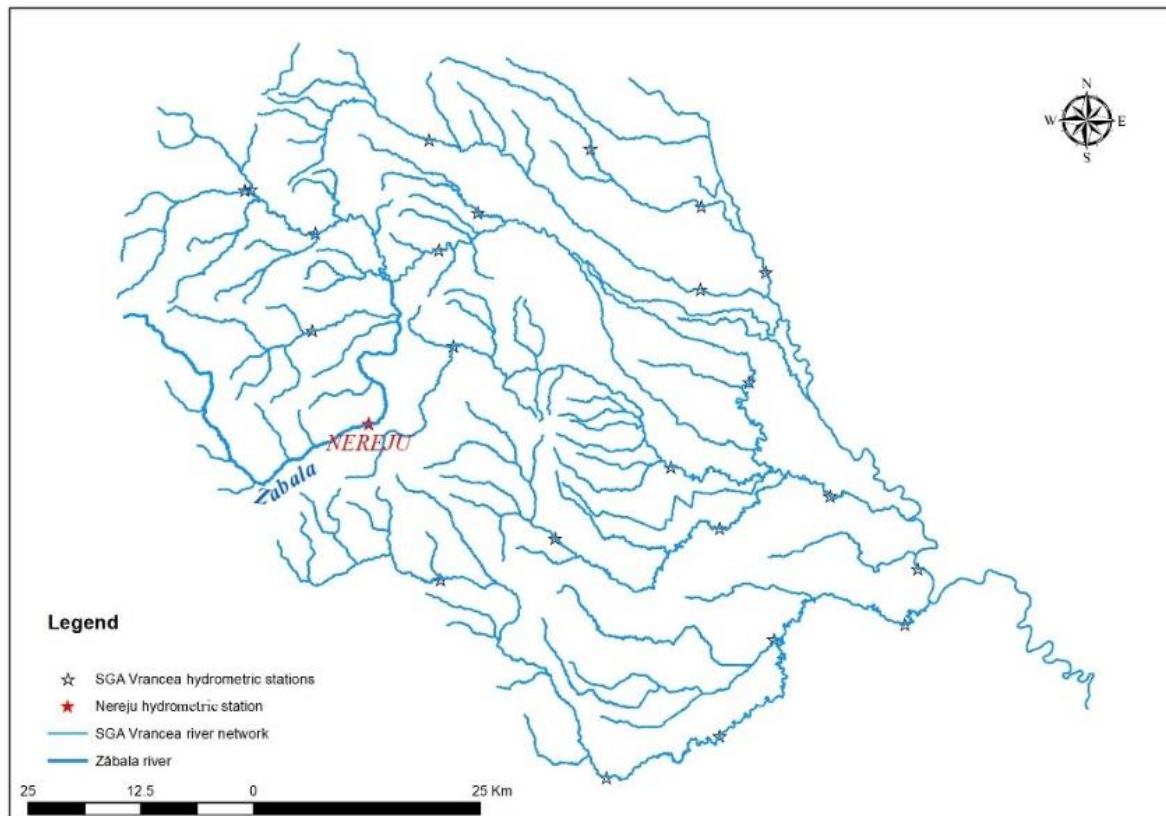
**Fig. 1.** Study area with the Zabala Watershed

The Zăbala River is a (stream) watercourse registered in the "Atlas of Romanian Water Cadastre" with code XII-1.079.09.02.00.0, having a length of 68 km and an area of 554 km<sup>2</sup>. It is a right tributary of the Putna watercourse and is formed at the confluence of two branches Arișoia and Zăbăluța. It has the following tributaries: Țipăul

Mare, Năruja (left), Zăbăluța, Mârdanu, Betegosul, Goru, Căbălașu, Giurgiu, Zârna Mare (right) (Figure 3).

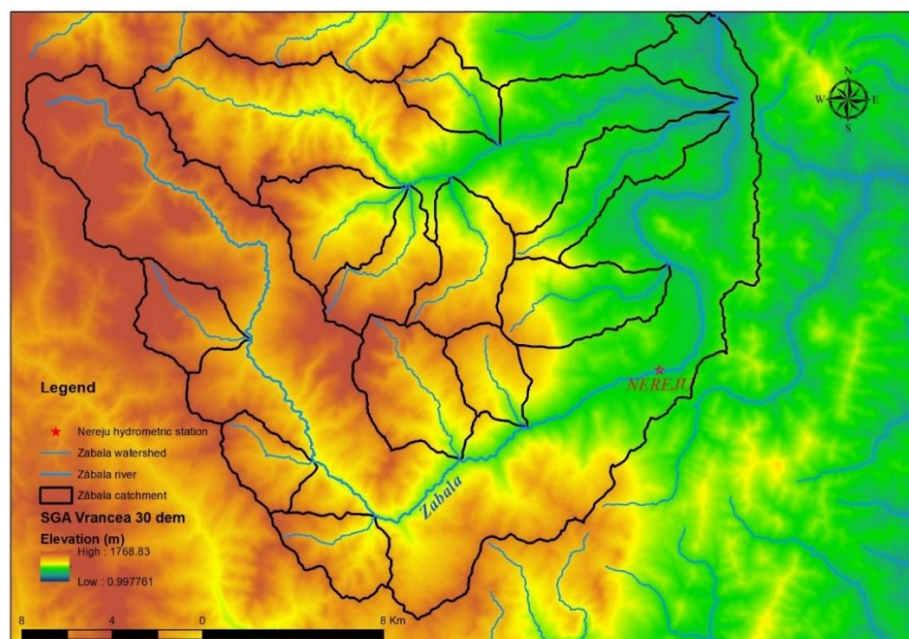


**Fig. 2.** Zăbala Watershed (Water Cadastre Atlas - 1992)



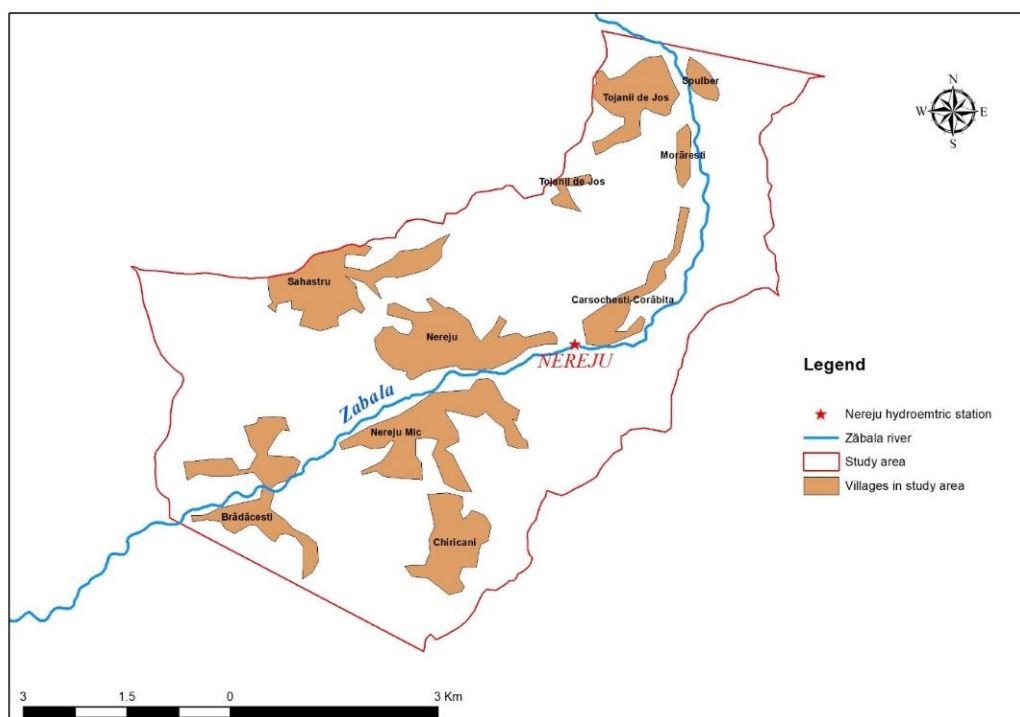
**Fig. 3.** Zăbala watershed with tributaries and hydrometric stations of the S.G.A. Vrancea

Bank erosion and silt deposits were observed in some sections of the watercourse, and due to the floods, the erosion increased and affected the access roads to the villages in the area, electrical networks, houses and household annexes.



**Fig. 4.** Elevation map of the Zabala Watershed

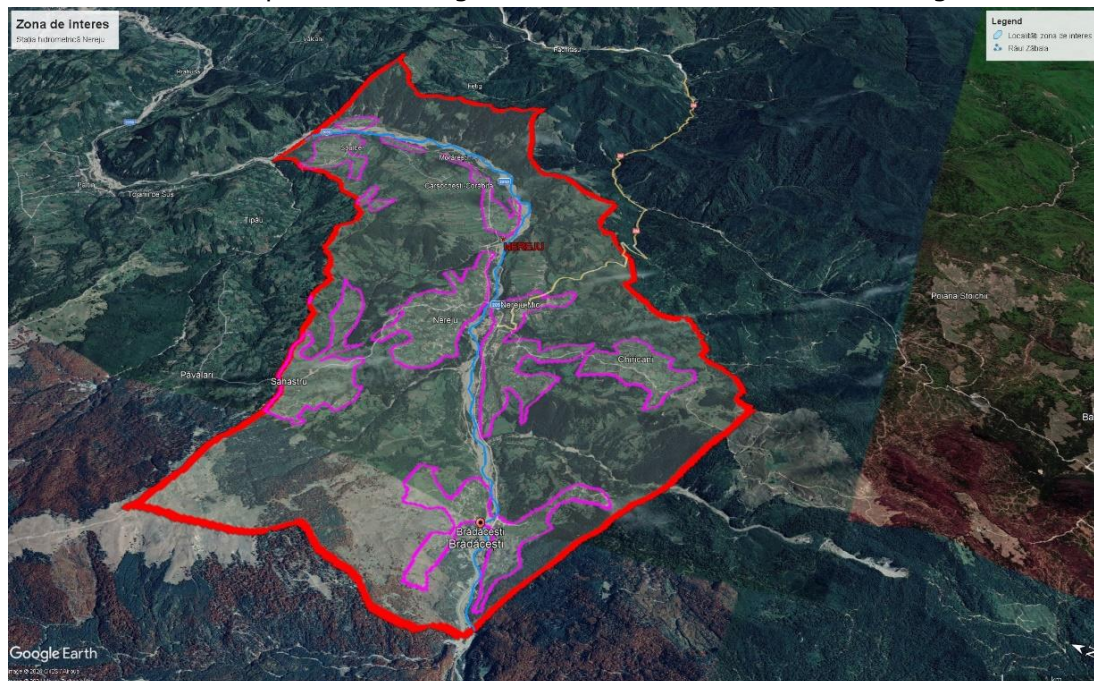
On the banks of the stream are the following rural settlements: Nereju commune, which includes 5 villages Nereju, Nereju Mic, Sahastru, Chiricari, Brădăcești, Spulber commune, consisting of the villages Carsochești-Corăbița, Morărești, Păvălari, Spulber, Tojanii de Jos, Tojanii de Sus and Țipău, commune of Paltin, with the administered localities of Ghebari, Paltin (residence), Prahuda, Țepa and Vâlcani, commune of Năruja, comprising the villages of Năruja, Podul Stoica, Podul Nărujii, Rebegari (Figure 5).



**Fig. 5.** Rural settlements in the study area

Between 2005 and 2022 there were particularly heavy rainfalls, with maximum flows causing significant damage in the Zăbala river basin.

As a result of these floods, households with annexes, bridges, viaducts, county road 205D and municipal roads along the Zăbala river basin were damaged.



**Fig. 6.** Study area, delimitation on Google Earth map

### 3. Materials and Methods

Flood Hazard and Risk Maps (F.H.R.M.) provide essential information to raise awareness of the population and authorities and to guide spatial planning in view of flood risk.

These maps show the areas likely to be flooded, water depth, water velocity and other relevant features, giving a complete picture of the flood threat. By using these maps, communities can take preventive measures and develop risk management strategies, thus protecting lives and property.

A.E.P. (Annual Exceedance Probability) A.E.P. (Annual Exceedance Probability) is the probability that a given flow will be exceeded in a calendar year.

As a general rule, these scenarios can be categorised into three main categories:

- Floods with a low probability of exceedance, 0.1% A.E.P. representing the event with an average occurrence once every 1000 years;
- Floods with a medium probability of exceedance, 1% A.E.P. representing the event with an average period of occurrence once every 100 years; (0.5% AEP can also be included in this category).
- Floods with a high probability of exceedance, 10% A.E.P. representing the event with an average occurrence every 10 years;

Annual Exceedance Probability (A.E.P.) influence the flood risk assessment and the determination of potential damages. The lower the maximum flow has a A.E.P. (e.g. 0.1%), the more rare and severe the event. In addition, areas flooded during such an

event may affect buildings, infrastructure, agricultural land and other assets, and the higher the water level (e.g. maximum flow with 1% A.E.P. the higher the potential damage.

For the determination of the maximum flow rates with a probability of exceeding 1%, long term monitoring data from the Nereju hydrometric station on the river Zăbala were statistically processed. Correlations and generalization relationships valid in the area were also used (Table 1).

The levels corresponding to the design flows were determined on the cross-sectional profiles raised in the respective sections, and the morphometric data corresponding to these sections were taken from the Romanian Water Cadastre-1992 (for the cadastred ones) or were measured on the map. Local slopes and roughness coefficients were also determined during field measurements.

It is important to note that for the determination of the sections analysed, the maximum flows refer to the natural flow regime and do not include the safety surcharge. The elevations refer to the morphometric situation of the riverbed at the time of the measurements.

Reference characteristics for the Zăbala watercourse:

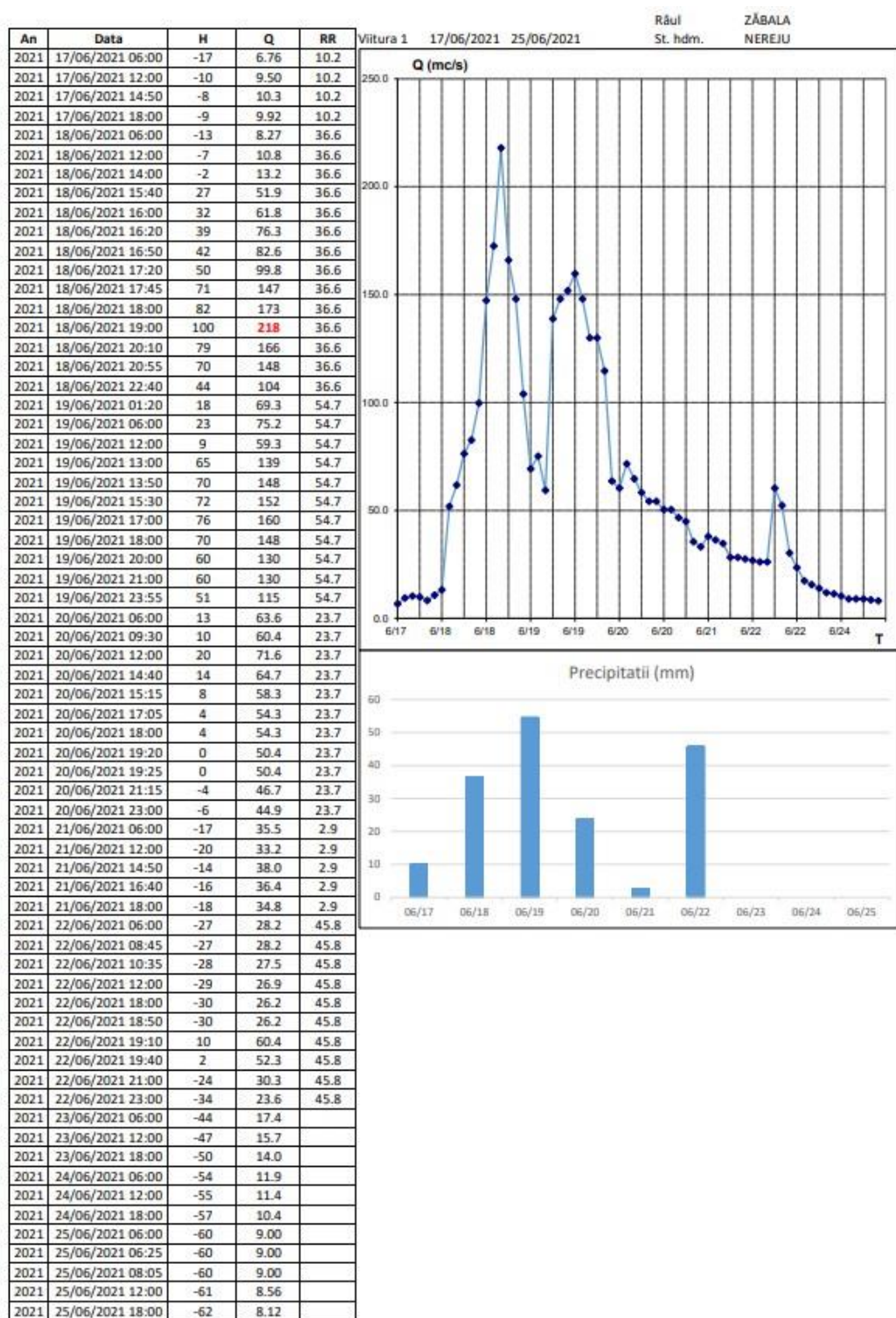
- Area of the related catchment ( $F$ ) = 535 km<sup>2</sup>;
- Average altitude of the catchment ( $H_m$ ) = 986m;
- Maximum flows and levels with different exceedance probabilities.

For the determination of the maximum flows with different probabilities of exceedance, long monitoring data from the Nereju hydrometric station on the Zabala River were statistically processed and the correlations and generalization relationships valid in the area were used.

On the profile, the coordinates of the rating curve were calculated and the corresponding maximum flow rates with different exceedance probabilities were marked. The values of the indicated elevations refer to the morphometric conditions of the bed at the time of the measurements. Any change in the river bed in the section analysed results in the cancellation of the values indicated.

The calculation elements are shown below:

- Stereo coordinates 70 x = 630664,83; y = 467968,124;
- Area of the related catchment ( $F$ ) = 234 km<sup>2</sup>;
- Average altitude of the catchment area ( $H_m$ ) = 1181 m.

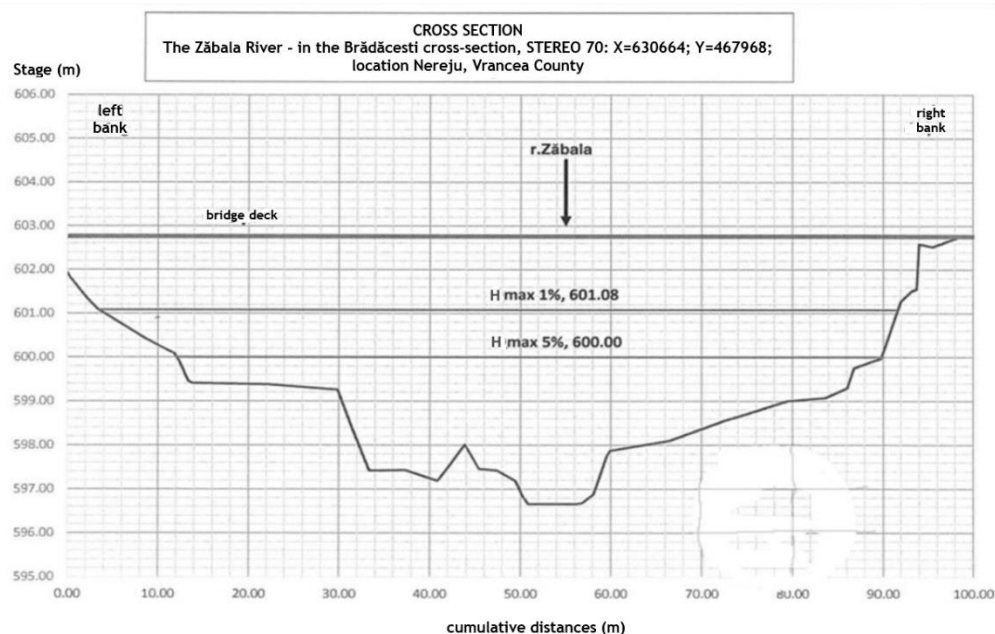
**Table 1.** Flood on the river Zabala in June**Table 2.** Maximum flows with different exceedance probabilities

| Probability of exceedance (%) | 1%     | 2%     | 5%     | 10%    |
|-------------------------------|--------|--------|--------|--------|
| Maximum flow (mc/s)           | 650    | 514    | 315    | 240    |
| Corresponding elevation (m)   | 601,08 | 600,68 | 600,00 | 599,64 |

For a more in-depth analysis of the watercourse, the yearbooks produced by the Hydrology Office were analysed (Figure 7).

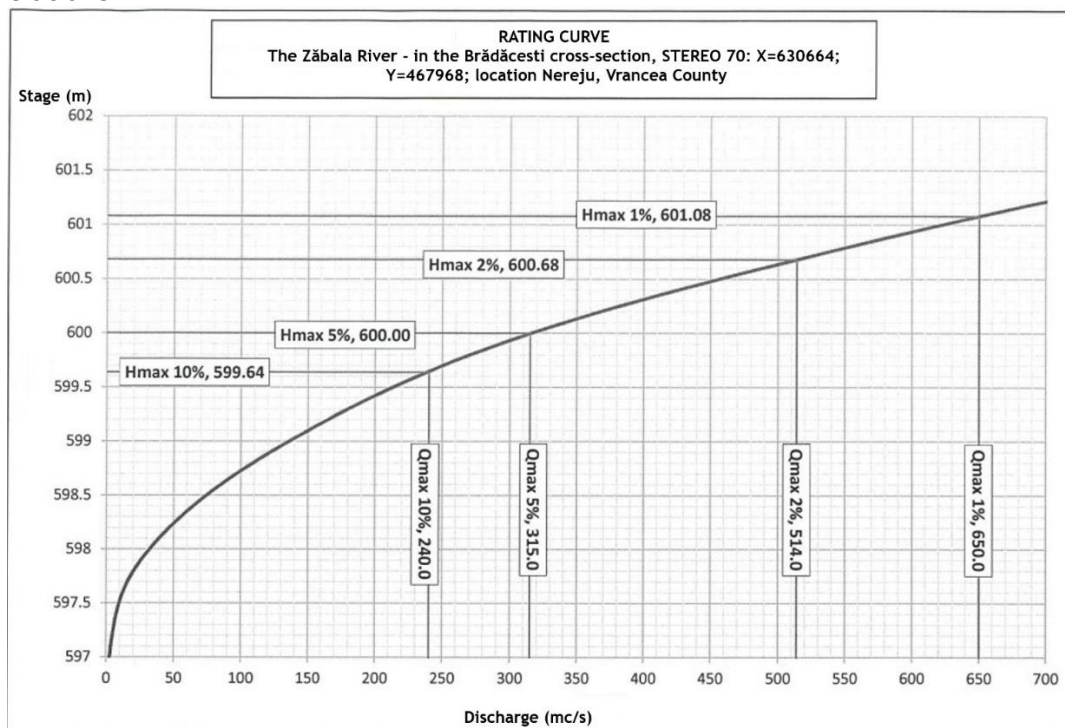
The hydrometric station dispatcher carried out observations and control measurements, cross-sectional profile surveys and slope measurements.

The liquid flow measurements, 160 in number, were carried out in the profile of the high-water mark and downstream of the low water mark.



**Figure 7.** Cross-section profile of Brădăcești section

The methods used to determine the mean daily flow and the rating curve are well supported by the quality of the hydrometric material provided, the parameters obtained for the mean, minimum and maximum runoff being consistent with the zonal correlations.

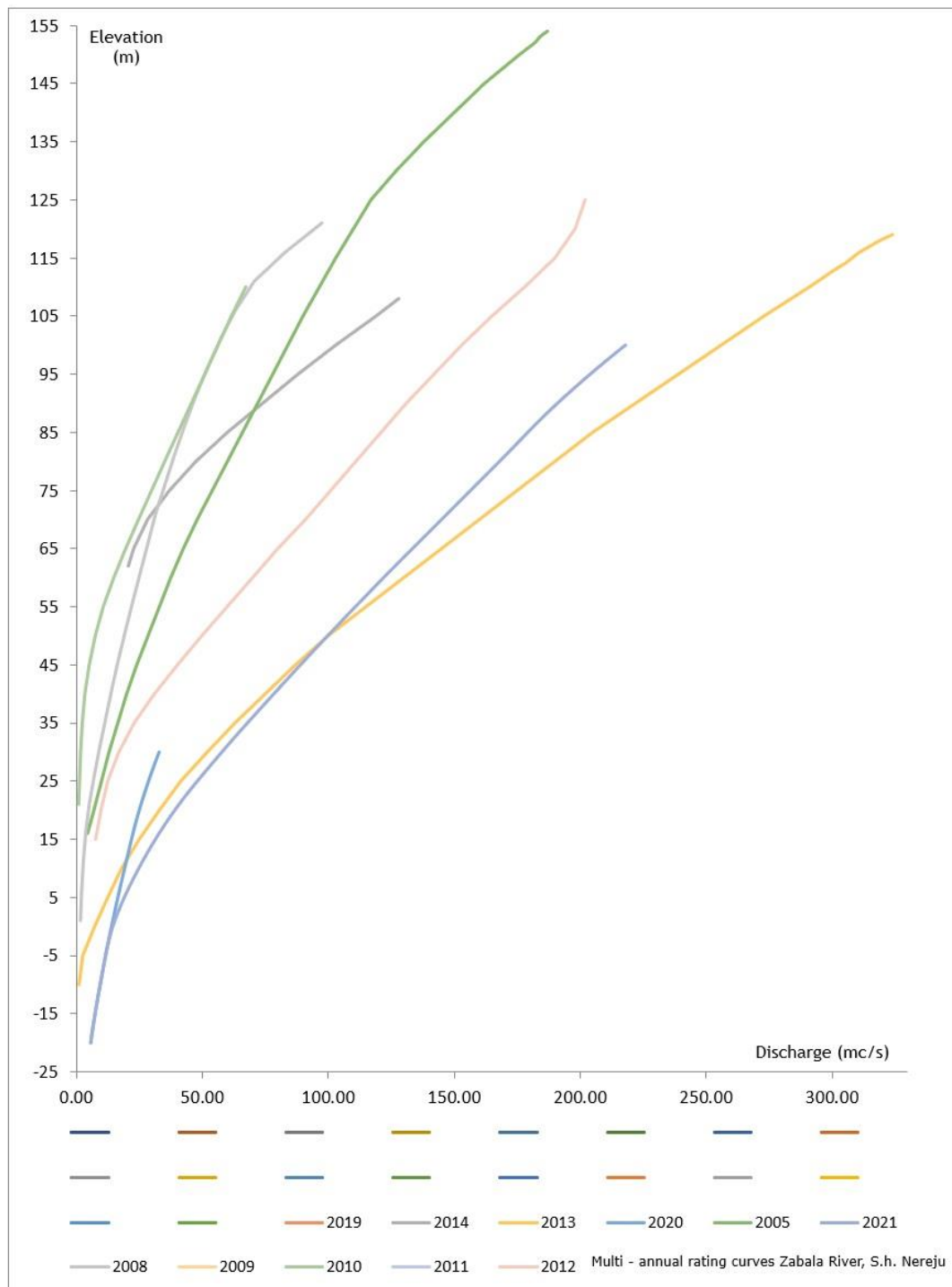


**Figure 8.** Rating curve

Water temperature measurements were taken throughout the year, except during winter events, and a good correlation was found between air and water temperature. As a winter phenomenon that influenced the liquid runoff, it was the ice at the shore.

Precipitation was measured by the rain gauge equipped with the hydrometric station, located at the observer's home, at the times set according to the instructions and whenever necessary.

Due to the large number of liquid flow measurements made by the hydrometer worker, the interpolation method was used to obtain the daily average flows, the rating curve method being used only during high water and flood periods.



**Figure 9.** Multi - annual rating curves Zabala River, S.h. Nereju, 2005-2021

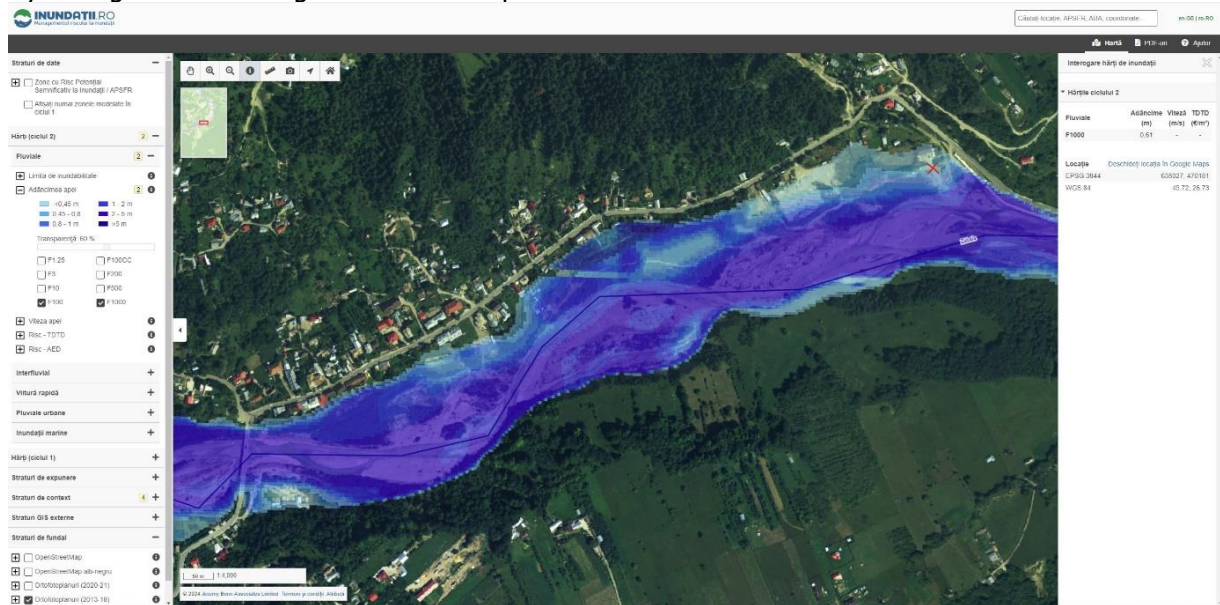
In order to be able to conclude how to approach construction on the (stream) watercourse, a multi-year rating curve from 2005 to 2021 was drawn.

The rating curve is the curve that expresses the relationship between water flow and level in a given section.

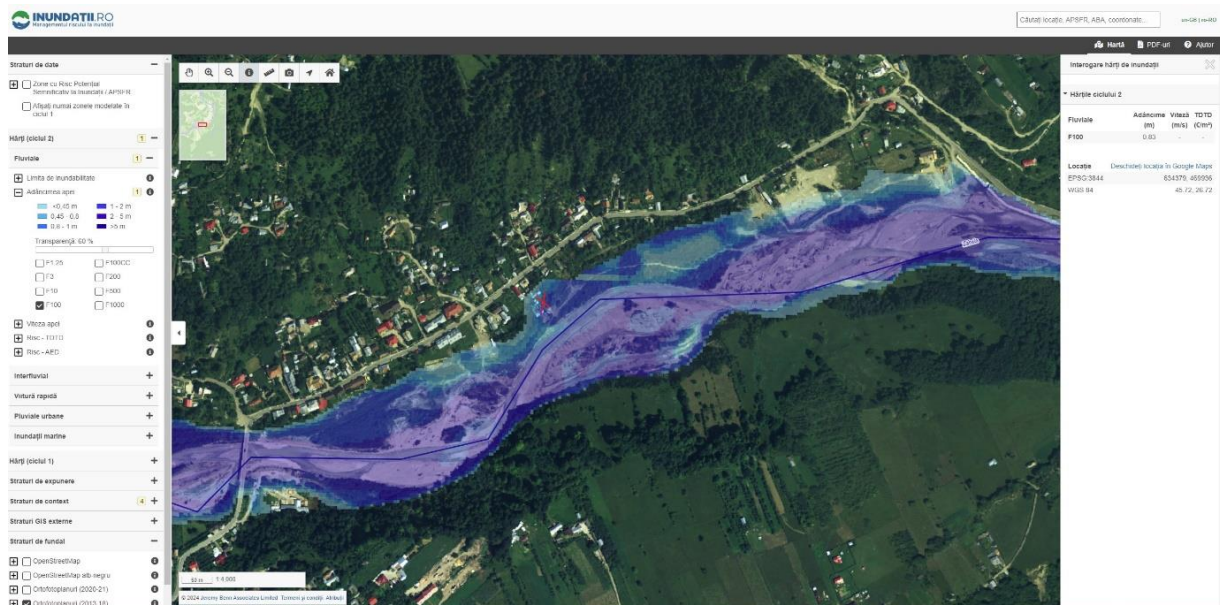
The rating curve does not retain its shape until the slope is stabilised and the water flow is not influenced in any way.

#### 4. Results

In the following figures (10 and 11) screenshots of the results obtained from the hydrological modelling with water depth in the area of interest are extracted.



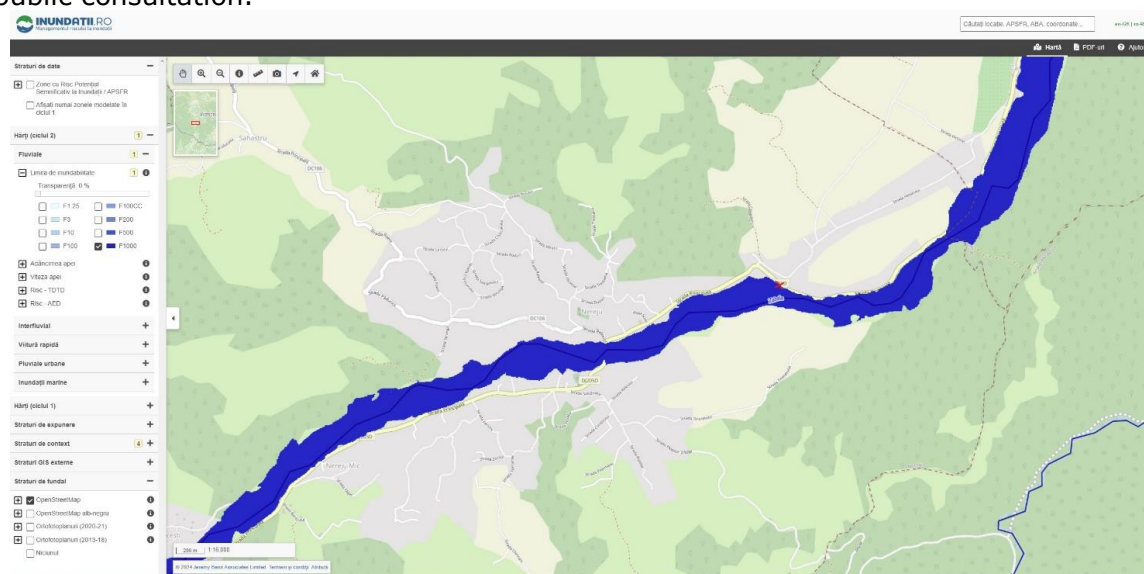
**Figure 10.** Map of 0.1% water depth on the Zabala River, S.h. Nereju



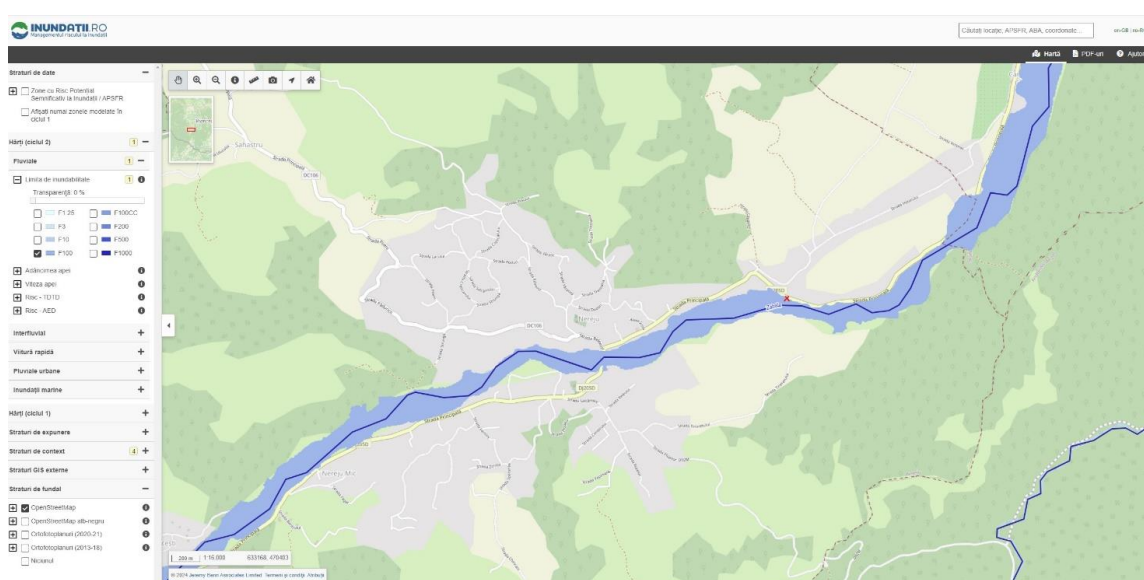
**Figure 11.** Map of 1% water depth on the Zabala River, S.h. Nereju

In the figures below (12, 13) are extracted screenshots of the results obtained from hydrological modelling with the 0.1% (representing the event with an average period of occurrence once every 1000 years) and 1% (representing the event with an average period of occurrence once every 100 years) floodability band.

These results can be found on the flooding.ro platform where they are available for public consultation.



**Figure 12.** Map with 0.1% flood limit on the Zabala River, S.h. Nereju



**Figure 13.** Map with 1% flood limit on the Zabala River, S.h. Nereju

## 5. Discussion

The results of the hydraulic analysis and the proposed measures for the Zăbala watercourse provide important insights into the dynamics of small to medium-sized rivers subjected to frequent flood events. The findings confirm the initial hypothesis that isolated and localized interventions—such as minor bank protections or temporary recalibration works—are insufficient to ensure long-term riverbed stability and effective flood risk reduction. These observations are consistent with previous studies on river engineering and flood mitigation, which emphasize the need for integrated structural and non-structural approaches to stabilize channels and reduce erosion processes.

The introduction of concrete thresholds (sills) along the Zăbala watercourse, combined with green and green-gray measures such as vegetative barriers, riparian forest management, and small log sills, represents a comprehensive approach to dissipating hydraulic energy and mitigating bank erosion. Similar strategies have been successfully applied in European river basins with comparable geomorphological

conditions, where hybrid solutions were shown to improve both flood protection and ecological functionality of the river system. Furthermore, the calculated design flow of  $Q_{1\%} = 675 \text{ m}^3/\text{s}$  confirms the adequacy of the proposed Class IV hydrotechnical works under Romanian regulations and aligns with international best practices for low- to medium-risk catchments.

The implications of these measures extend beyond immediate flood protection. By stabilizing the riverbed and controlling erosion, the interventions are expected to safeguard local communities, agricultural lands, and transport infrastructure, while contributing to sustainable land use in the floodplain. On a broader scale, the combination of structural works with environmentally friendly solutions supports the objectives of the EU Water Framework Directive, aiming to maintain or improve the ecological status of surface water bodies while ensuring human safety and socio-economic resilience.

Despite the expected benefits, certain limitations and uncertainties remain. The actual lifespan of the concrete thresholds depends heavily on maintenance and exposure to hydrological extremes, while temporary recalibration works are inherently short-lived. In addition, potential ecological impacts, such as alterations to aquatic habitats or sediment dynamics, must be monitored closely to avoid unintended long-term effects.

Future research should focus on detailed hydraulic modeling of sediment transport and on the cumulative impact of hybrid measures under different flood scenarios. Long-term monitoring programs would also provide valuable data on the efficiency of thresholds in dissipating energy and on the potential for natural river self-stabilization. Comparative studies with other small mountainous rivers could refine the design of cost-effective, sustainable interventions that balance engineering requirements with environmental protection.

## 5. Conclusions

In free-flowing streams, the movement of water is generally turbulent, creating an irregular yet energetic flow pattern. In straight reaches with regular cross-sections, this movement may partially transition toward a quasi-laminar regime, where the water surface appears almost horizontal. Under such conditions, upstream-propagating surface waves can only develop when the current is slow enough to allow their formation. However, any variation in the cross-section of the channel introduces local disturbances, which in slow-flow conditions often generate positive or negative eddies, influencing local sediment transport and promoting minor erosional or depositional phenomena.

The transition from fast flow to slow flow occurs primarily through hydraulic jumps or through undulations in the water surface, both of which represent mechanisms of energy dissipation. In contrast, a natural transition from slow to fast flow is not possible in a riverbed with uniform slope and cross-section unless a significant slope break occurs or local roughness conditions change substantially. Such transitions and energy exchanges are of critical importance in understanding and predicting riverbed stability and the onset of erosion.

The long-term stability of a river channel is largely determined by its slope, alignment, and the balance between water velocity and sediment transport. When a watercourse is excessively shortened or straightened in an attempt to improve flow conveyance, the natural equilibrium is disturbed. This often leads to an increase in flow energy, which the river dissipates through the creation of new meanders or through bank erosion processes. As a result, it becomes insufficient to provide bank protection only in concave areas; a more comprehensive approach is required, which includes convex sections and long straight alignments. Sustainable river training works should therefore aim to maintain the hydraulic and morphological stability of the bed while minimizing the need for extensive structural defenses, always considering local hydrological conditions, soil characteristics, and land-use constraints.

On the Zăbala watercourse, the combined effect of local floods and level fluctuations generates backwater phenomena that significantly enhance bank erosion. Historical

interventions consisting of isolated, localized works—such as limited bank protection or point recalibration—have proven both expensive and short-lived. A more effective and lasting measure is the construction of thresholds (sills), which act to decrease the slope and velocity of the flow, thereby reducing the erosive energy of the water and enabling a more controlled discharge downstream. Properly designed and strategically located, these structures can mitigate the destructive impacts of flooding while maintaining ecological and social compatibility.

Within the Flood Risk Management Plan (FRMP) for the Zăbala river, a combination of green, gray, and hybrid (green-gray) measures has been proposed to manage flood risk and enhance long-term river stability. These include the creation of permanent or temporary reservoirs to attenuate peak flows, the construction of secondary defense lines to protect vulnerable villages, local riverbed regulation and stabilization works, targeted forest management in floodplain and riparian areas, and small-scale hydrotechnical structures made from natural or mixed materials, such as log sills or vegetative barriers. Additionally, four concrete thresholds are proposed at key points along the river. Each threshold is designed with upstream and downstream bank protection works, and in some locations, local riverbed recalibration is required to optimize the hydraulic efficiency and durability of the intervention.

The proposed works are designed for a 1% exceedance probability flood ( $Q_{1\%} = 675 \text{ m}^3/\text{s}$ ) and are classified as Class IV under Romanian hydrotechnical standards. Their implementation aims to restore the cross-section of the river to optimal hydraulic parameters, stabilize the bed and banks, and prevent progressive erosion that threatens nearby houses, roads, and agricultural land. Concrete structures are expected to last 30 to 60 years, depending on maintenance and environmental exposure, while recalibration works are temporary and function primarily to facilitate structural interventions.

In conclusion, the proposed interventions on the Zăbala watercourse are intended to integrate flood protection, bank stability, and environmental sustainability. By combining structural and natural measures, and by carefully managing the slope, velocity, and energy dissipation of the river, these works aim to reduce the frequency and intensity of flooding events, protect local communities, and ensure the long-term functionality of the riverbed within a sustainable water management framework.

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