

Research on the degradation of bank protection works on mountain rivers

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Abstract: The paper presents the results of the research on the degradation of the shore defence on the Tazlăul Sarat River. Shore defence works operate in an environment where natural risk factors collaborate with anthropogenic ones. The degradation of the shore defences was mainly determined by hydrodynamic erosion. The flow of the June 2016 flood on the upper course of the Tazlăul Sarat river was 342 m³/s, being measured at the Lucăcești Hydrometric Station. On the section of the river that crosses the town of Bolatau there has been significant degradation of the works to fix the bank and protect the road adjacent to the river bed. The shore defence in this area was made of a retaining wall made of concrete with a height of 2-5 m. The bank defence work degradation was integrated into the process of morphological transformation of the riverbed through hydrodynamic erosion. The geometrical change of the bed caused the foundation of the shore defence to be uncovered and its stability lost. The degradation of the bank protection also determined the erosion of the DC 180A communal road over a cumulative length of 200 m in the locality of Bolatau.

1. Introduction

The phenomenon of hydrodynamic erosion of riverbeds is a current problem of study and research at national and global levels. The morphological transformation in the transverse and longitudinal plane of riverbeds is a continuous process under the action of natural and anthropogenic factors. These factors have acted over time with a certain weight (Luca and Brănianu, 2024, Avram, 2020). Initially, the natural factor was primary, but the development of human society has increased the degree of contribution of the anthropogenic factor. In some situations, a correlation occurs between climatic risk factors and anthropogenic risk factors, a situation in which an amplification of the destructive effects on the natural and human environment is achieved (Luca et al., 2018b).

Recent climate change has altered the annual distribution of precipitation across geographical areas, leading to seasonal concentration, a situation that has produced torrential rains with maximum intensity in short periods of time (Mily et al., 2005, Marchi et al., 2010, Avram, 2020). Torrential rainfall of this type has generated rapid floods, with very high flows, which have exceeded the carrying capacity of rivers and have produced significant morphological changes in the riverbed (Neuhold et al., 2009, Marchi et al.,

2010). This situation is present in the eastern part of Romania, and especially in the Siret river basins (Avram, 2020, Romanescu and Stoleru, 2013, Dominte and Luca, 2023, WBA Siret-Bacau, 2018). The prediction of these floods is currently carried out using modern methods (Copacean et al., 2024, Dragomir et al., 2020, Avram, 2020, Tarnovan et al., 2021), but the intensity of the natural phenomenon, accentuated by anthropogenic risk factors, has led to catastrophic floods (Avram and Luca, 2017, Luca, 2018a).

Climate change in the last 50 years has contributed to the acceleration of morphological transformations of watercourses (Bolati et al., 2014, Church, 2006, Romanescu and Stoleru, 2013, Avram et al., 2022). The morphological transformation of the riverbed is represented by erosion and sedimentation phenomena in transverse and longitudinal profiles (Church, 2006, Luca et al., 2019). The hydrodynamic erosion of the riverbed is in conjunction with the degradation of hydrotechnical constructions located in the flow section and in the riparian area of the river (Duta and Karmakar, 2015).

The effect of hydrodynamic erosion on structures varies depending on their geometric and structural characteristics. In riverbeds, small or large structures are located locally or spatially, with a transverse and longitudinal position to the direction of water flow. Small structures with a local position are represented by bridge piers and abutments, anchorages for pipelines, isolated foundations for pillars, etc. In this case, the action of water causes local erosion and sedimentation phenomena. Research is mainly focused on erosion depths and their effect on structures (Schodro, 2007, Man et al., 2019, Zaid et al., 2019).

Hydrotechnical constructions with transverse location in the riverbed are represented by spillways, bottom sills, weirs, water intakes, etc. Those with longitudinal location in the riverbed are of the type of bank defences, riverbed dams, water intakes, etc. Bank defence works are the most affected by hydrodynamic erosion, considering the method of location, the groups of forces acting on them, the materials from which they are made, maintenance works, etc. Their degradation is determined by a complex of natural and anthropogenic risk factors (Daporto et al., 2003, Avram, 2020). Bank defences located in riverbeds formed by weakly cohesive rocks are very vulnerable to flash floods, and the percentage of degradation is relatively high (Luca and Branianu, 2024, See Too, 2023, Luca et al., 2019). Similarly, the river bank in the concave curvature area, but also the bank defences, are more intensely degraded during floods (Rinaldi et al., 2008). Research into the degradation of riverbank defences in watercourses with different hydrological and hydraulic characteristics is important for highlighting the destructive actions specific to each type of construction. The concern for this research is at regional (Avram et al., 2018, WBA Siret-Bacău), state (Rinaldi, 2003, Gouvernement of India, 2012) and even continental (Directive 2007/60/EC, Marchi et al, 2010) levels.

Research in this field is carried out for various situations existing in natural riverbeds (Avram, 2020, Schodro, 2007, 1989, Santilan et al., 2020) or regularized (Church, 2006, Avram, 2020, Luca et al., 2019). Morphological transformations are much more evident in riverbeds formed by weakly cohesive rocks with alternating layers of gravel - sand - loamy sands, ballast, gravel and others (Luca et al., 2019a). Research carried out in this type of riverbeds has highlighted intense hydrodynamic erosion phenomena on the depth and width of the flow section (at the beginning of the flood), followed by sediment deposition in

the final phase of the flood (Luca and Branianu, 2024, Wang et al., 2014, Sagheblian et al., 2020). At the same time, flash floods have substantially transformed the geometry of the riverbed (Santilan et al., 2020, Bolati et al., 2014, Church, 2006, Avram, 2020, Government of India, 2012) and have degraded the regularization and bank defence works to a certain degree (Yang et al., 2022, Rinaldi, 2003, See Too et al., 2023).

This paper aims to present the results of research conducted over 10 years on the behaviour of "heavy-type" bank protection works (made of plain concrete and reinforced concrete) located on a mountain river. The complex action of water and alluvium transported at average flows, but especially at maximum flows, has determined the partial and even total degradation of the bank protection.

2. Materials and Methods

The studies and research were carried out on the upper course of the Tazlaul Sarat River (cadastral code XII-69-33-10) in the area of the Bolatau locality in Bacau County. The Tazlaul Sarat River is a right tributary of the Tazlau River (Figure 1.a). The confluence of the two rivers takes place between the hydrometric stations (HS) Scorteni and Helegiu. Hydrological parameters of the Tazlaul Sarat River are monitored at the Lucacesti HS. The area of the Tazlaul Sarat River's watershed upstream of Lucacesti HS is 95 km², where the river is 26 km long and has an average slope of 36.9‰ (Luca and Avram, 2017). The DC 180A road, which crosses the territory of the Bolatau and Zemes localities, is located for the most part on the banks of the Tazlaul Sarat River (Figure 1.a).

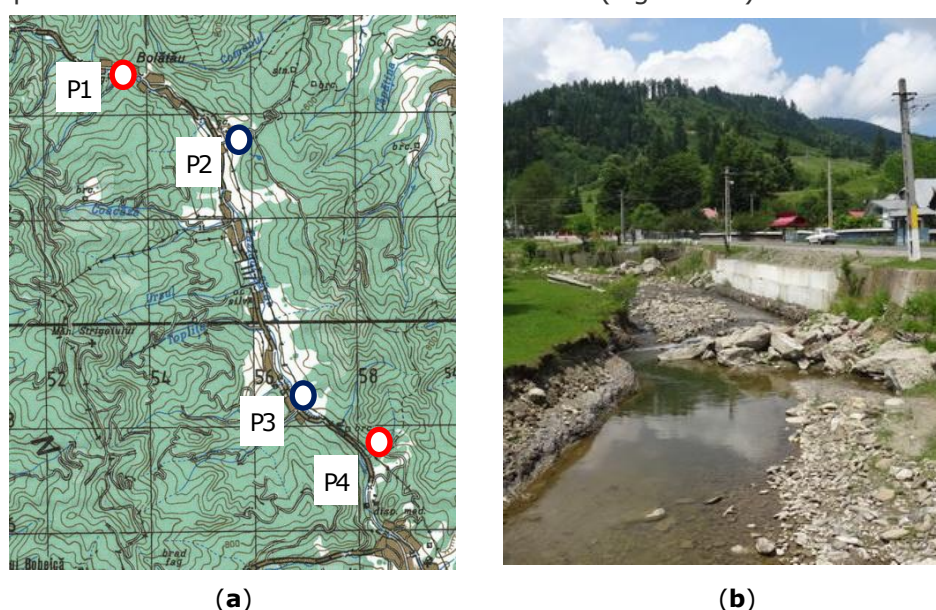


Figure 1. Research area on the Tazlaul Sarat River: (a) – Site plan with the location of the research points (scale 1:100000); (b) – general view of the road location from the riverbed (Luca M, 2019).

A series of pipelines that transport oil and technological fluids with a high degree of pollution are located on the river bank and at the edge of the road.

Data used in the research came from the following sources:

- technical expertise carried out to analyze the degradation of the bank defence works caused by the floods transiting the Tazlaul Sarat River (Luca, 2016, Luca, 2018);

- technical reports on the hydrological events in the Siret River Basin (WBA Siret, 2016 - 2018) and their effects on the morphology of the Tazlaul Sarat River bed;
- hydrological, topographic and geotechnical studies carried out to rehabilitate the bank defence works degraded by floods.

A series of data (topographic, hydrological, and hydraulic) were obtained by the authors through research carried out in the areas of location of the studied bank defence works (Luca, 2016, Luca, 2018). The research was carried out between 2016 and 2024 at different time intervals depending on the occurrence of high-flow floods and the effects produced by them.

Through detailed topographic measurements, the transverse profiles in the analysis sections and the longitudinal profile on the investigated river section were obtained. Through hydrological and hydraulic studies, the maximum flows with the calculation probabilities for the bank defence were obtained; also, specific parameters for the flow section were obtained (flow - water depth correlation, average and maximum velocities). Geotechnical studies highlighted the stratification of the riverbed in each analysis section and the foundation conditions of the bank defence works. On the river section and at the required research points, photographic and video surveys were taken at determined time intervals. Thus, a database was created that allowed a complex analysis of the phenomenon of bank defence degradation over a determined period of time.

The studies and research were carried out for the following objectives:

1. Research of hydrological and hydraulic parameters in the research sections located in the Tazlaul Sarat riverbed with influence on the behaviour over time of the bank defence works.
2. Research of the behaviour and structural degradation over time of the bank defence works in the four study areas.

The primary data were processed with hydrological, hydraulic and statistical calculation programs applicable to the case study considered. Thus, a data bank was created that was completed annually through field research.

3. Results

3.1. Characteristics of the bank defence works in the research area

The consolidation and protection of the road from the destructive actions of water was achieved by the execution of bank defence works adapted to the conditions of the site. The works were executed in the years 1970 - 1980, and the solution used was in accordance with the importance category of the road. The protection work used in this case consists of a vertical retaining wall made of plain concrete and positioned on the river bank (Figure 2.a). In areas where the river is not adjacent to the road, bank defenses made of reinforced concrete slabs were executed. For categories of lower importance of the road, or in the absence of viable investments, a retaining wall made of gabion boxes was executed (Figure 2.b).

The bank defence works were calculated according to the maximum flows provided for in the design standards of the 1970's. Also, this work (vertical retaining wall made of plain concrete) located in the Tazlaul Sarat River bed was executed with the materials and technologies existing in the 1970's. Climate change after 1990 modified the design

standards, and one of the modifications refers to the increase in the calculation flows depending on the importance category of the protected object from floods.

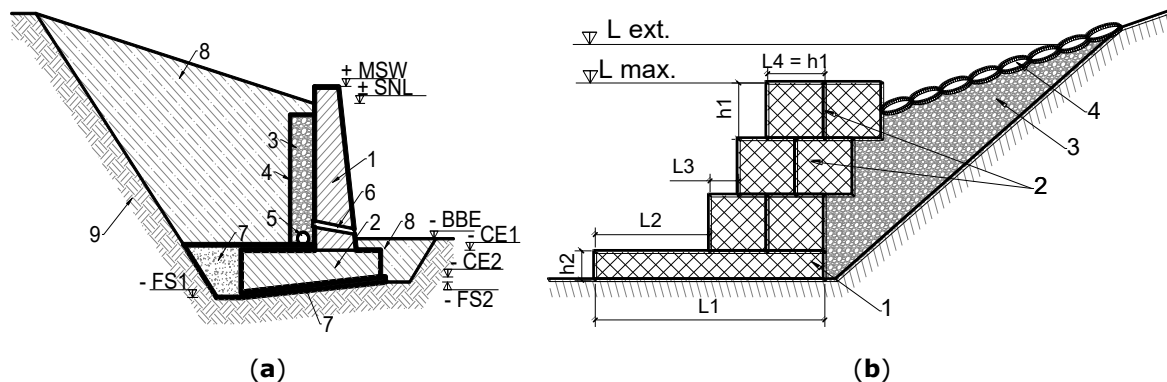


Figure 2. Structural schematics for riverbank protection works: (a) concrete retaining wall, 1 – elevation, 2 - foundation, 3 – filter layer, 4 – geotextile, 5- drain, 6 - discharge pipe, 7 – levelling concrete, 8 – earth fill, 9 – natural terrain, BBE – bed bottom elevation, FS1,2 – foundation share, CE1,2 – concrete elevation, SNL – natural land elevation, MSW – maximum share of the work; (b) gabion retaining wall, 1 – gabion mattress, 2 – gabions, 3 – earth fill, 4 – slope protection, L_{ext} , L_{max} – water level at calculation probabilities (Luca, 2016).

3.2. Results regarding the structural condition of the shore defense works in the research area

The research area includes a river section with a length of 8,146 km adjacent to the DC 180A road. The importance category of the DC180A road required the construction of a bank defence consisting of retaining walls built in the riverbed. The retaining wall was made of simple concrete cast in place. On the researched river section, significant degradation of the concrete bank defence works occurred. The degradation of the works was generated by the combination of a set of natural and anthropogenic risk factors. Among the natural factors, the floods from May-June 2016, as well as those from 2018 and 2019 were highlighted (Luca, 2018a). Among the anthropogenic factors, the lack of maintenance and repair works of the concrete structures, as well as the absence of rehabilitation works of the riverbank protection were highlighted.

Four research points (P1 – P4) were selected on the river section (Figure 1.a). Points P1 and P4 were positioned in areas where significant degradation of the bank protection occurred. Points P2 and P3 were positioned in areas where the road was excessively eroded by water action, due to an almost completely degraded bank protection. By processing and interpreting the database collected in ten years of research, a series of conclusions regarding the process of structural degradation of the river bank protection resulted.

In the research area P1 (Figure 1.a), by processing the data collected in situ, the following can be mentioned:

A – The retaining wall (Figure 2.a) was made of plain concrete on plots with a length of 1.0 – 1.50 m, to achieve the curvature of the bank. The dimensions of the retaining wall are: total height 2.50 - 2.80 m, elevation height 2.0 – 2.20 m, width at the crown 0.50 m;

B – The riverbed is described by a narrow parabola and with an extension to a higher elevation towards the right bank (a width of 15.0 m to 35.0 m in 2016) (Figure 3). The maximum depths are located towards the left bank, where the road and the bank defence are. The riverbed is formed by rocks of different hardness (sandstones, marls, disodilic shales, clay shales, etc.), which are arranged in strongly folded structures. On these rocks there are layers of sediments deposited over time. The water current directed towards the left bank favoured the erosion of the sediments, the lowering of the bed bottom and, implicitly, the degradation of the bank defence. Rapid floods were a factor intensifying the morphological modification of the riverbed (Luca, 2016, Luca and Avram, 2017).



Figure 3. Upstream view of the Tazlaul Sarat riverbed in research area P1, year 2016 (Luca, 2016).

C – The results of the research on the structural and functional condition of the Tazlaul Sarat riverbank protection work analyzed in June 2016 were the following:

- the plain concrete retaining wall presented different lengths as a mode of degradation;
- the sectors with compact elevation but with cracks and fissures in the wall (Figure 4.b);
- dislocated wall sections in the process of collapsing into the riverbed (Figure 4.b);
- completely destroyed wall with structural elements carried downstream by water (Figure 4.a);
- the concrete in the foundation and elevation had an expired service life, which worsened the structural condition of the retaining wall.

D - The degradation mechanism was formed by the following processes:

- uncovering the concrete leveling layer, as well as the foundation of the protection work by lowering the bottom of the riverbed to depths of 0.70 – 1.20 m in the area of the contact with the retaining wall;
- modification of the supporting layer of the retaining wall caused the loss of stability of the plots, especially in the area of the curvature of the riverbed and their displacement from the normal operating position;
- the expulsion of mortar from the joints of the concrete piers, which allowed water to infiltrate behind the retaining wall and wash away the filter layer in the ballast; this situation led to the total loss of stability of the piers in the retaining wall structure;

- the tilting and overturning of the concrete piers in the riverbed, their breakage and the transportation of concrete pieces downstream.



Figure 4. Details regarding the mode of degradation of the bank defence at research point P1: (a) – total destruction of the retaining wall and the advance of the riverbed into the road structure; (b) – stages of degradation of the retaining wall, with its displacement from the site (Luca, 2016).

E – The completely destroyed retaining wall section was replaced in 2017 with a work of gabion boxes filled with stone (Figure 3.a). The surface of the gabion in contact with the water was protected by plastering with cement mortar (Figure 5).



Figure 5. General view of the rehabilitation of the bank defence at research point P1: 1 – initial plain concrete retaining wall; 2 – sector rehabilitated with a gabion retaining wall (author's photo, 2019).

F – Conclusion: The partial and total degradation of the retaining wall was the result of the combined action of the morphological transformation process of the riverbed at average and maximum flows and the absence of maintenance and rehabilitation works of the concrete structure of the retaining wall during the exploitation period.

In the research area P4 (Figure 1.a), by processing the data collected in situ, the following can be mentioned:

A – The retaining wall (Figure 2.a) was made of plain concrete (Figure 6,a, Figure 6.b) on plots with a length of 1.0 – 1.50 m in the area of the bank curvature. The dimensions of the retaining wall are: total height 4.00 - 4.50 m, elevation height 3.20 – 3.50 m, width at the crown 0.80 m.

B – The riverbed is asymmetrical, being described in cross-section by a rectangle with an extension towards the right bank at a higher elevation (the width varied from 18.0 m to

32.0 m in 2016) (Figure 6.a). The maximum depths are located towards the left bank, where the road and the bank defence are located. The flash floods of the last 25 years have continuously modified the riverbed morphologically vertically (Luca and Avram, 2017).

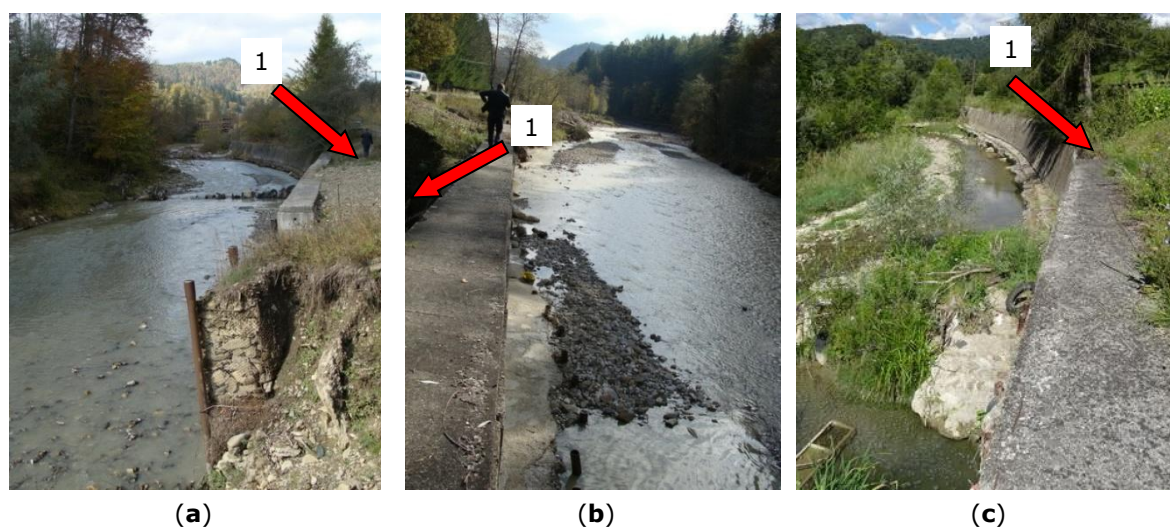


Figure 6. General view of the Tazlaul Sarat River bed in the area of research area P4, Oct. 2016: (a) – upstream view, 1 - erosion zone; (b) – downstream view; (c) – upstream view of the rehabilitated sector, year 2024 (author's photo, 2024).

C – The results of the research on the structural and functional condition of the Tazlaul Sarat riverbank protection work analyzed in June 2016 in the P4 area were as follows:

- the plain concrete retaining wall presented a satisfactory structural condition at the elevation, but the foundation and the levelling concrete layer were partially of limited lengths;
- the lowering of the riverbed bottom caused the appearance of gaps under the foundation, through which water penetrated behind the retaining wall (Figure 8.a); a series of gaps were closed with concrete, but the lowering of the riverbed opened them after a period of time;
- large areas of erosion behind the retaining wall that continued into the road structure (Figure 7.a and 7.b); road traffic was limited on the road in the damaged area;
- bank erosion led to the uncovering and suspension of pipelines for the transport of oil and technological fluids during drilling works; in these areas, there were discharges of waste that affected the land and the water in the river (WBA Siret, 2016).
- short lengths of the retaining wall were completely degraded and were rehabilitated with gabion masonry (Figure 6.a); the gabion work is degraded and non-functional;
- the concrete in the foundation and elevation of the retaining wall has an expired exploitation period, which determines a high risk to the safe operation of the riverbank protection work.

D - The degradation mechanism was formed by the following processes:

- the water current, directed towards the left bank by the curvature of the riverbed, intensified the erosion of the sediments in the riverbed; over time, a lowering of the riverbed bottom occurred below the foundation level of the retaining wall; sediment erosion continued locally under the foundation of the bank defence;

the high hydraulic gradient during floods due to the increased water level in the riverbed generated a liquid flow, which penetrated through the gaps under the foundation behind the bank protection; the ballast in the retaining wall filter, as well as the bank fill material and the road structure were entrained in the riverbed; the suction phenomenon generated by the rapid decrease in the water level at the end of the flood evacuated a large part of the material behind the retaining wall (Figure 8.b);

- the erosion pit extended into the riparian area and degraded the road structure.



Figure 7. Details regarding the degradation of the bank defence at research point P4: (a) – erosion pit behind the retaining wall and the advance of the riverbed in the riparian area, 1 – erosion pit; (b) – hydraulic installations located in the river bank (Luca, 2016).

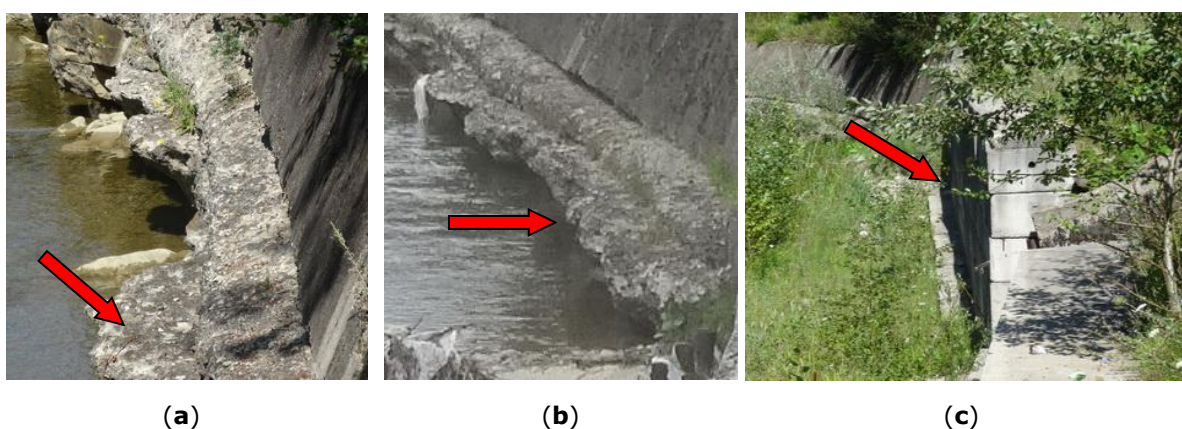


Figure 8. Structural condition of the retaining wall foundation in the P4 research area, year 2016: (a) – substructures at the foundations; (b) – voids under the foundation generated by the lowering of the thalweg over time (Luca, 2016); (c) – bank defence rehabilitated by using gabions (photo author, 2024).

E – In the erosion pit area, substructures were built under the foundation of the wall with cement concrete in 2017. Geotextile layers were used to block the washing of non-cohesive material when creating the filter and the backfill behind the wall. The bank protection located downstream of the road erosion area, which was completely degraded, was replaced in 2017 with a work of gabion boxes filled with stone (Figure 3.a). The surface of the gabion in contact with the water was protected by plastering with cement mortar (Figure 8.c).

F – Conclusion: The formation of erosion pits behind the retaining wall was the result of the combined action of the morphological transformation process of the riverbed at average and maximum flows and the absence of maintenance and rehabilitation works of

the concrete structure of the protection work during the exploitation period. Research areas P2 and P3 are similar in riverbed shape, with smaller dimensions of the retaining wall and erosion mode of the bank and road.

In the research area P2 (Figure 1.a), by processing the data collected in situ, the following can be mentioned:

A – The retaining wall made of plain concrete on the left bank of the river (Figure 9.a), at the edge of the road, has been degraded over time.



Figure 9. General view of the erosion of the left bank of the Tazlaul Sarat River, research area P2,: a – upstream view highlighting the destruction of the bank defence, year 2016 (1 - simple concrete retaining wall) and the degradation of the communal road DC 180A (Luca, 2016); b – downstream view of the new bank protection work (2 - gabion retaining wall) (Author's photo, 2019).

This situation required the replacement of the old work on a limited length of the bank with a new protective work made of large reinforced concrete slabs. The curvature sector of the riverbed was not completely protected, and the flood of June 2016 destroyed the rest of the bank defence and eroded the road adjacent to the Tazlaul Sarat riverbed.

B – The riverbed in the P2 research area has two branches separated by an alluvial formation partially covered by vegetation. The left branch of the river carries about 70% of the flow. The cross-section of the two branches has the shape of a trapezoid. The left branch had in 2016 a maximum width of 20 m and a maximum depth of 2.80 m. The right branch was 40.0 m wide and 3.10 m deep. The partial protection of the left branch of the river over a short length (Figure 9.b) with large reinforced concrete slabs created a higher water velocity and, implicitly, a high potential for riverbed erosion. The June 2016 flood mainly occurred on the left arm, a situation in which there was a sharp erosion of the riverbed bottom and the left bank and, implicitly, the degradation of the bank defence consisting of a concrete retaining wall (Figure 9.a) (Luca, 2016, Luca and Avram, 2017).

C – D - E. The results of the research on the structural and functional condition of the Tazlaul Sarat riverbank protection work analyzed in June 2016 in the P2 area highlighted the total degradation of the retaining wall. The flood also dislocated the rest of the retaining wall, eroded the bank and advanced into the road resistance structure (Figure 9.a). The riverbank protected by a new work behaved well under the flood action. The concrete retaining wall bank protection was replaced in 2017 with a wall made of gabions (Figure 9.b).

F – The conclusion is the same as that of the research areas P1 and P4.

In the research area P3 (Figure 1.a), by processing the data collected in situ, it resulted that the erosion process of the bank and the road is similar to that of the area P2. The analysis carried out in 2016 revealed that only fragments of the concrete retaining wall were left on the riverbank (Figure 10).

The retaining wall parameters were: total height 3.50 m, elevation 3.00 m and width at the crown 0.60 m. The curvature sector of the riverbed was not protected, and the flood of 2016 eroded the riverbank and subsequently the road adjacent to the Tazlaur Sarat River (Figure 10). The water level exceeded the road elevation and flooded part of the riparian properties (Luca, 2016).

The riverbed in the P3 research area had a mixed trapezoidal shape in 2016. Geometric parameters of the flow section were: bottom width 25.00 m, surface width 47.30 m, maximum depth 5.20 m. The bed had layers of non-cohesive sediments (ballast) with alternating arrangement along the length. The flood had a negative impact on the oil and technological fluid transport pipelines located in the riverbed and bank (Figure 10.c).

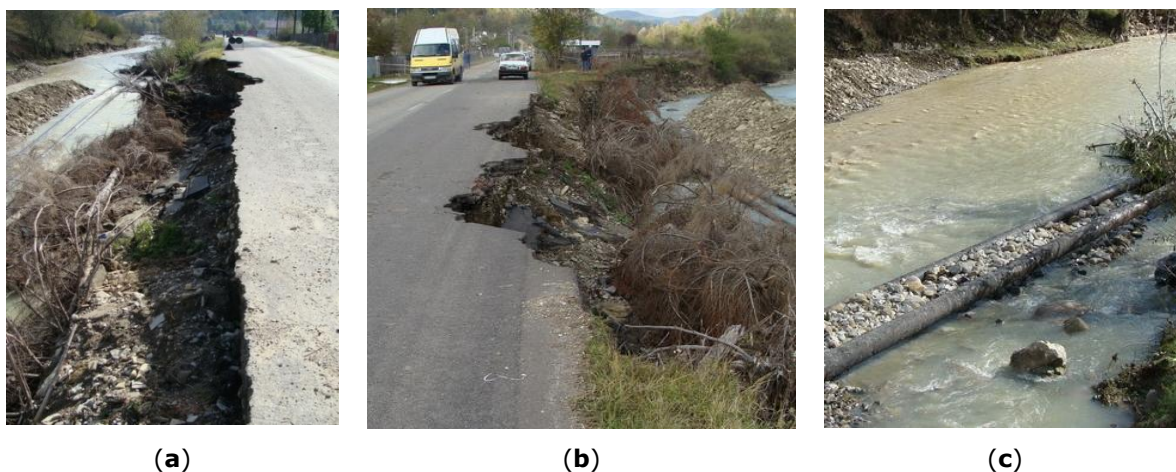


Figure 10. Details regarding the hydrodynamic erosion of the defence work and the left bank of the Tazlaur Sarat River, research area P2: a – upstream view of the erosion advance on the bank and on the road; b – downstream view (1 – remains of the concrete retaining wall); c – pipes located in the riverbed and bank (Luca, 2016).

The pipes were uncovered and moved, creating a risk of rupture and pollution of the water and the riparian area. The combination of natural risk factors (maximum flows, rapid flooding) and anthropogenic ones (advanced wear of the bank protection) caused excessive erosion of the bank and the road.

The rehabilitation of the degraded bank defence work (Figure 11.a) was carried out in 2017 through the execution of a gabion retaining wall, where the surface in contact with the water was plastered with cement mortar (Figure 11.b).



Figure 11. General view of the erosion of the right bank of the Tazlau Sarat River, research area P3: a – upstream view highlighting the erosion of the bank and the DC 180A road in 2016 (1 – remainder of the retaining wall); b – downstream view in 2019 of the riverbank defence rehabilitation work (2 – gabion wall located at the edge of the road) (photo author, Oct. 2019).

3.3. Results regarding the hydraulic modelling of the design parameters of the bank defence works in the research area

The destructive effects of the June 2016 flood (Luca, 2016, Manolachi, 2018) required an analysis of the hydrological and hydraulic parameters in the degraded sections of the riverbank defence works. The analysis had the role of defining the design data for the new works, which would be correlated with the change in flow conditions in the morphologically modified riverbed by the flood.

The design of riverbank defence works in rivers with beds formed in poorly cohesive rocks also requires the calculation of the erosion depth for certain flow conditions. Likewise, sediment erosion rates must be calculated to forecast the morphological evolution of the riverbed over time.

Table 1. Flood parameters on the Tazlau Sarat River in 2016 measured at Lucacesti S.H. (W.B.A. Siret, 2016)

Q_m (m ³ /s)	p (%)	H_{max} (cm)	$Q_{max\ 1\%}$ (m ³ /s)	$Q_{max\ 2\%}$ (m ³ /s)	$Q_{max\ 5\%}$ (m ³ /s)	$Q_{max\ 10\%}$ (m ³ /s)
342	≈ 3	360	545	425	290	200

Q_m – measured flow; p – probability of occurrence; H_{max} – water quota.

The research of the process of morphological modification of riverbeds under the action of hydrodynamic erosion force is carried out in nature, as well as on physical and numerical models. The forecast of hydrodynamic erosion phenomena of riverbeds is developed with the data obtained through hydraulic modelling of flow processes in the riverbed. At the current stage, a series of numerically solved hydraulic-mathematical software are used (Avram, 2020, Dutta and Karmakar, 2015, Saghebian et al., 2020, Recking et al., 2019, Chen and Liu, 2017, Chen et al., 2023).

Flood parameters of June 2, 2016 on the Tazlaul Sarat River were measured at the Lucacesti SH. The initial river flow was 6.70 m³/s at 10:00, and the water level was 0.69 m.

The peak of the flood was recorded at 16:30 with a maximum flow of 342 m³/s (Table 1) and a maximum level of 3.60 m (W.B.A. Siret, 2016). The flow increased 50 times in about six hours. The probability of exceeding the maximum flow was 3% at the Lucacesti SH.

For each research profile (P1, P2, P3 and P4) the flow rates were determined with the calculation probabilities of the Tazlaul Sarat River bank protection works. The flow rates were determined and processed according to the area of the watershed corresponding to each section located on the Tazlaul Sarat River (Table 2).

Through topographic measurements carried out in the four research areas (P1, ..., P4), the transverse profiles of the Tazlaul Sarat riverbed, generated by the flood of June 2016, were obtained. By processing the data from the topographic study, a geodesic slope of 1.619% was obtained on the 8146 m long research section of the Tazlaul Sarat River.

Table 2. Flow rates with calculation probability for bank defence works on the Tazlaul Sarat River in research sections P1 - P4.

p (%)	1%	2%	5%	10%
P1: Q _{max} (m ³ /s)	202,0	160,0	109,0	74,50
P2: Q _{max} (m ³ /s)	216,0	170,0	116,0	80,00
P3: Q _{max} (m ³ /s)	324,0	256,0	175,0	120,0
P4: Q _{max} (m ³ /s)	364,0	288,0	197,0	135,0

An important parameter of the riverbed degradation phenomenon is the erosion rate, especially in riverbeds formed in weakly cohesive rocks. In order to determine the velocities in the flow section at the flow rates with the calculation probabilities specific to the bank defence works considered, a hydraulic modelling was performed. In the modelling, a permanent non-uniform gradual varied movement of the water was assumed for the four flow rates considered in the analysis (Luca, 1994, US Army Corp of Engin., 1993). The average water velocity (v) was calculated with the relationship (Luca, 1994):

$$v = C\sqrt{RJ} \quad , \quad (1)$$

where R is the hydraulic radius, J – hydraulic slope, C - Chézy coefficient.

The Chézy coefficient was determined with the Manning relationship,

$$C = \frac{1}{n} R^{0.167} \quad . \quad (2)$$

The calibration of the hydraulic model was performed in each analysis section by the value of the weighted average roughness coefficient (n_{med}) depending on the length of the controlled irrigated perimeter. The values considered for the roughness coefficient n were the following (Avram, 2020, Luca and Branianu, 2024):

- for the bottom of the riverbed: a - small gravel, $n = 0.030$ - 0.035 ; b - large gravel, $n = 0.040$ - 0.045 ; c – riverbeds in mountainous areas with boulders and rock fragments, $n = 0.045$ - 0.050 ;

- for the banks of the riverbed: a – natural state, $n = 0.050$; b – protection with concrete slabs with medium degradation, $n = 0.030$ - 0.035 ; protection with concrete slabs with reduced degradation, $n = 0.020$ - 0.025 ;

- for the riparian area: a – pastures and agricultural crops, $n = 0.050$ - 0.055 ; b – shrubs and trees 0.060 – 0.075 ; constructions and obstacles, $n = 0.060$ - 0.080 .

The maximum speeds allowed in natural riverbeds from which the erosion phenomenon begins (v_{er}) are (Luca, 1994): 0.60 – 1.30 m/s for gravel with diameter $d = 2.5 - 10$ mm; 1.20 – 2.80 m/s for large gravel with $d = 20 - 70$ mm; 2.80 – 4.50 m/s for boulders with $d = 70 - 200$ mm.

The results of the hydraulic simulation are presented for profiles P1, P4 and P3. Profile P2 was modified during the research period by regularizing the riverbed.

Hydraulic modelling of flow parameters in Transverse Profile P1 (Figure 12) allowed the estimation of maximum flow-specific velocities with calculation probabilities $p_{1\%}$, $p_{2\%}$, $p_{5\%}$ and $p_{10\%}$ (Table 3). The sediments in the riverbed of this research area are largely composed of large gravel (Figure 12).

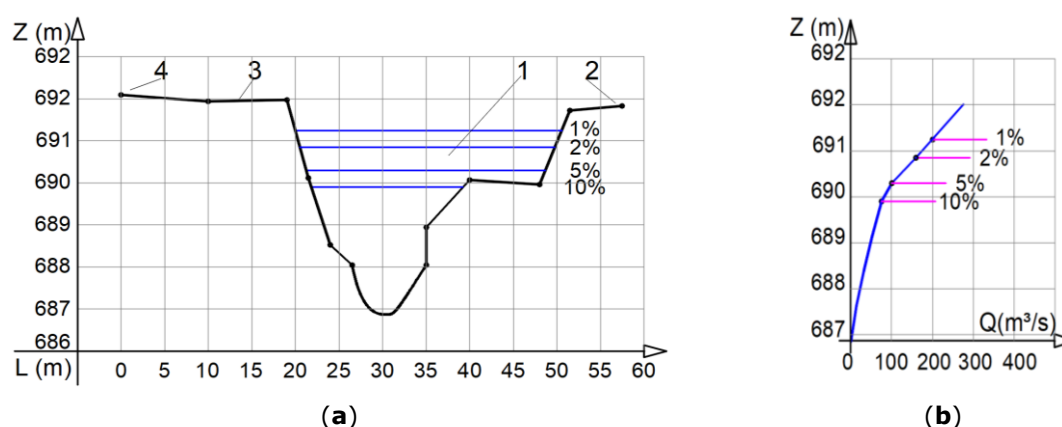


Figure 12. Hydraulic parameters in the P1 research area on the Tazlaul Sarat River: (a) cross section with characteristic levels, 1 - water level, 2 - right bank, 3 - left bank/road, 4 - constructions; (b) - correlation of level - flow to exceedance probabilities.

Table 3. Results regarding the simulation of maximum water velocities (v_{max}) in the research area P1 on the Tazlaul Sarat River (selective values).

P (%)	Q_p (m³/s)	Q_s (m³/s)	n_{med}	C (m ^{0.5} /s)	v_m (m/s)	v_{max} (m/s)	v_{max}/v_{er}
1	202.0	201.97	0.065	17.235	3.083	3.694	$v_{max} > v_{er}$
2	160.0	161.43	0.065	17.080	2.973	3.567	$v_{max} > v_{er}$
5	109.0	111.94	0.065	16.660	2.691	3.229	$v_{max} > v_{er}$
10	74.50	75.77	0.065	16.609	2.658	3.190	$v_{max} \approx v_{er}$

Q_p – flow with calculation probability; Q_s – simulated flow; n_{med} – average roughness coefficient; v_m – average speed; v_{max} – maximum speed.

The values of the maximum calculated water velocities are located in the range of 3.69 – 3.19 m/s for the flows with calculation probability considered. From the comparative analysis of the maximum velocities calculated in the riverbed for the flows considered in the research, an excess of the erosion velocities is noted ($v_{er} = 1.20 - 2.80$ m/s).

The hydraulic modelling of the flow parameters in the Transversal Profile P4 (Figure 13) allowed the estimation of the maximum velocities produced by the flows with the calculation probabilities $p_{1\%}$, $p_{2\%}$, $p_{5\%}$ and $p_{10\%}$ (Table 4). The sediments in the riverbed in the research area are formed by a mixture of large gravel, boulders and rock pieces (Figure 6). The right bank has an extension occupied by shrubs and trees, and further on it is a wooded slope.

The left bank is protected by the retaining wall. The way the riverbed is occupied at various levels significantly influences the value of the average roughness coefficient n .

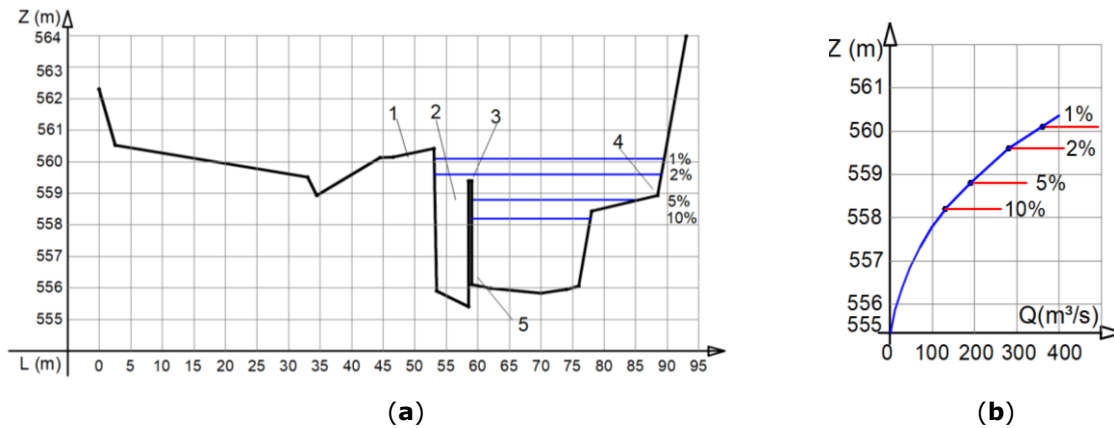


Figure 13. Hydraulic parameters in the P4 research area on the Tazlaur Sarat River: (a) cross section with characteristic levels, 1 - road, 2 - eroded left bank, 3 - retaining wall, 4 - right bank, 5 - erosion under the wall foundation; (b) - correlation of level - flow to exceedance probabilities.

The values obtained by simulation for the maximum water velocity are in the range of 3.80 – 3.06 m/s for the flows with calculation probability considered (Table 4). From the comparative analysis of the maximum velocity values for the flows considered in the research with the erosion velocity value ($v_{er} = 1.20 - 2.80$ m/s) it is noted the formation of an active erosion process in the riverbed.

Table 4. Results regarding the simulation of maximum water velocities (v_{max}) in the P4 research area on the Tazlaur Sarat River (selective values).

P (%)	Q_p (m ³ /s)	Q_s (m ³ /s)	n_{med}	C (m ^{0.5} /s)	V_m (m/s)	V_{max} (m/s)	v_{max}/v_{er}
1	364.0	364.84	0.071	16.243	3.169	3.803	$v_{max} > v_{er}$
2	288.0	287.28	0.069	16.310	2.958	3.549	$v_{max} > v_{er}$
5	197.0	197.74	0.0685	16.272	2.861	3.439	$v_{max} > v_{er}$
10	135.0	135.97	0.070	15.553	2.551	3.062	$v_{max} > v_{er}$

Q_p – flow with calculation probability; Q_s – simulated flow; n_{med} – average roughness coefficient; v_m – average speed; v_{max} – maximum speed.

The configuration of the roughness on the wetted perimeter of the riverbed at various flood flows determined a higher speed towards the left bank, where the retaining wall is located. This situation favoured a pronounced hydrodynamic erosion of the riverbed bottom towards the left bank and implicitly its descent below the foundation of the retaining wall.

The most pronounced degradation of the retaining wall occurred in profiles P1, P2 and P4, where the defence work is located on the left bank and generally on curved sections of the riverbed. The retaining wall was partially structurally degraded on the straight sections of the riverbed. Significant degradation occurred at the foundation of the wall, due to the lowering of the riverbed bottom over time through the erosion of weakly cohesive rock layers.

Hydrodynamic erosion in profile P3 occurred on the right bank, being influenced by the curvature of the riverbed. By hydraulic modelling of the flow parameters in

Transversal Profile P3 (Figure 14), the maximum velocities were estimated in the case of flood transit with the design flows considered in the research (Table 5).

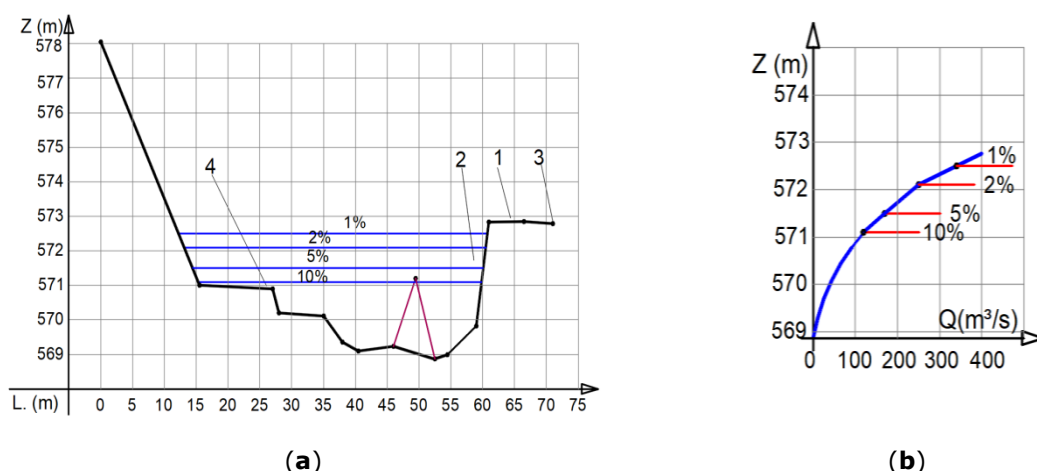


Figure 14. Hydraulic parameters in the P3 research area on the Tazlaul Sarat River: (a) cross section with characteristic levels, 1 - road, 2 - eroded right bank, 3 - private properties / homes, 4 - left bank; (b) - correlation of level - flow to exceedance probabilities.

The sediments in the riverbed in the research area were formed by a mixture of large gravel with alternations of small gravel (ballast layers) and boulders (Figure 11). The left bank, which is occupied by layers of ballast, grassy areas, shrubs and trees, gently climbs in steps towards a wooded slope. The roughness coefficient towards the left bank is very variable and depends on the level of vegetation development.

Table 5 Results regarding the simulation of maximum water velocities (v_{max}) in the P3 research area on the Tazlaul Sarat River (selective values).

P (%)	Q_p (m ³ /s)	Q_s (m ³ /s)	n_{med}	C (m ^{0.5} /s)	V_m (m/s)	V_{max} (m/s)	v_{max}/v_{er}
1	324.0	324.11	0.0723	15.612	2.916	3.499	$v_{max} > v_{er}$
2	256.0	256.77	0.0685	16.259	2.788	3.346	$v_{max} > v_{er}$
5	175.0	175.10	0.0660	16.508	2.716	3.260	$v_{max} > v_{er}$
10	120.0	119.35	0.0650	11.151	2.377	2.853	$v_{max} \approx v_{er}$

Q_p – flow with calculation probability; Q_s – simulated flow; n_{med} – average roughness coefficient; v_m – average speed; v_{max} – maximum speed.

The values obtained by simulation of the maximum water velocities in the P3 area are in the range of 3,499 – 2,853 m/s for the flows considered in the analysis (Table 5). From the comparative analysis of the maximum velocities for the flows considered in the research with the erosion velocity value ($v_{er} = 1.20 - 2.80$ m/s) it is found that an active erosion process is initiated and maintained in the riverbed. The distribution of roughness on the wetted perimeter of the riverbed at various flood flows determined a higher velocity towards the right bank (initially occupied by the retaining wall) and a reduced one towards the bank occupied by shrubs and trees. This situation favoured a pronounced hydrodynamic erosion of the riverbed towards the right bank and further of the road structure (Figure 10.a).

4. Discussions

The detailed analysis of the degradation of the riverbank protection works in the four research areas highlighted the role of natural and anthropogenic risk factors in the structural evolution over time of the concrete retaining wall. The riverbank protection work also had the role of stabilizing the structure of a road that is the only means of transport between a series of mountain villages located on the riverbank. The degradation of the protection work was mainly influenced by two natural risk factors, namely:

- the geotechnical structure of the site where the river bed was created and evolves, namely layers of rocks with different hardness; the bed is based on disodilic shales, clay shales, sandstones, etc.; alluvial transport from the slope brings layers of non-cohesive sediments into the bed and forms them over time;
- the hydrological regime of the river characterized by the presence of rapid floods and high flows, which in recent times have been influenced by climate change; the high frequency of floods (every 2 - 3 years) and the high value of flows (some maximum flows exceeded the design value of the bank defence) have contributed to important morphological changes in the Tazlau riverbed.

Also, the degradation of the bank defence work was influenced by the following anthropogenic risk factors:

- design parameters (maximum flows) considered 50 - 60 years ago no longer correspond to current values modified by climate change;
- a faulty way of operating the works, exemplified by the lack of annual intervention and repair works, as well as rehabilitation of degraded areas;
- failure to apply riverbed regularization works on sectors where the bank defence was strongly influenced by the action of water and alluvium.

The degradation mechanism of concrete embankment protection works has also been investigated in hilly rivers. In this case, the degradation phenomenon occurs in distinct and representative stages (Luca et al., 2019), and an important role is given to the water circulation behind the protection work.

The important influence of the anthropogenic risk factor is presented by See Too K.L. et al., (2023) in the case of the degradation of the protection work executed on the bank of the Kelantan River in an urban area in Malaysia. The old embankment protection gave way to floods, and the river bank broke. The study carried out showed the importance of natural (hydrological, hydraulic and geotechnical) and anthropogenic (lack of maintenance) factors in the destruction of the protection work consisting of sheet piles supporting the river bank.

The mechanisms of bank erosion and failure are analyzed on the Arno River in Italy by Dapporto et al., (2003), and natural risk factors had a significant influence. The morphological changes of the riverbed generated by the location of constructions in the flow section are analyzed by Rinaldi (2003), who presents the effects of clogging and erosion produced by them. The erosion of river banks formed by rock stratifications under the action of water current is investigated by Dutta and Karmakar (2015), as a result of field experiments and hydraulic modelling in the laboratory. The specialized literature shows a greater attention to the mechanism of river bank degradation than to bank defence works.

Conclusions

River bank defence works are subjected to a series of natural and anthropogenic risk factors during operation. Natural and anthropogenic risk factors contribute to the degradation over time of defence works made of concrete and reinforced concrete.

River bank defence works made in the form of a concrete retaining wall, which are located in riverbeds formed by layers of poorly cohesive rocks, present a high risk of loss of stability through suspension of the foundation following vertical erosion of the riverbed.

The bank defence works investigated and which were partially or totally degraded, presented a number of their own characteristics, namely: an operating period that was exceeded in duration, they were designed for flows that are no longer current under climate change conditions, they were not included in rehabilitation and modernization programs, and others. River bank defence works in mountainous areas are degraded by vertical and horizontal erosion of the riverbed due to high water velocities during floods, but also at average flows, according to the hydraulic simulation performed, a situation also favoured by the continuous morphological modification of the riverbed.

The main forms of destruction of the "concrete retaining wall" type bank defence works were represented by the suspension of the foundation and its rupture, the penetration of water behind the work and the washing of the support layer, the cracking and split of the concrete structure followed by the entrainment of debris into the riverbed, and others.

The research carried out over a period of 10 years has highlighted the need to revise the design norms, especially regarding the design flows and to adopt more elastic constructive solutions in order to be able to work with the morphological modification of the mountain riverbeds. Also, a rehabilitation of the constructive structure must be carried out at intervals in order to increase its resistance to multiple actions generated by the natural and anthropogenic environment.

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