JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(11), 389–397
https://doi.org/10.12911/22998993/208290
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Received: 2025.07.08
Accepted: 2025.08.01
Published: 2025.08.15

Integrating bank reinforcements and natural solutions for the regulation and protection of the Toplluha River: A sustainable approach to flood protection

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ABSTRACT

This study examines the management and regulation of a flood prone segment of the Toplluha River in the municipality of Suhareka in Kosovo, focusing on sustainable flood protection through bank reinforcements and natural solutions. The aim of the study is that based on a hydraulic analysis of the riverbed to identify potential solutions that can contribute to improving flood protection and enhance flood resilience. The research was carried out in the Suharekë-Reçan segment, where detailed measurements of cross-sectional profiles were taken, and hydraulic parameters including discharge and water velocity were assessed. Using advanced software, the existing riverbed profiles were analyzed and the designed profiles were developed. These designed profiles were compared with the existing ones, in order to have an insight into their bankfull discharge. Based on the hydraulic analyses and literature review of similar cases, we suggested the construction of natural levees covered with reinforcing vegetation for erosion prevention and long term flood protection. The use of natural levees and reinforcing vegetation has been evaluated as an effective and sustainable method for stabilizing riverbanks. These cost-effective solutions also are known to improve water quality, ecological balance, support habitat conservation and promote biodiversity. This study presents integration of natural solutions in river management thus promoting an ecological approach to protecting flood-prone areas.

Keywords: river regulation, flood protection, natural solutions, levees, bank stabilization.

INTRODUCTION

The regulation of watercourses has been a concern of humans since ancient times, for the exploitation of water resources, protection against floods or enabling river navigation. This field has attracted the attention of many researchers, including (Mamak, 1964, Maddock, 1994, Knighton, 1998), who have investigated the natural regime of water flow and the impact of hydraulic changes.

Rivers are very important for supporting life and preserving the environment, having an important role in ecosystems and environmental functions (See Too et al., 2023; Saad et al., 2023). Water resources are widely used for various purposes, including domestic, agricultural and industrial. They also support recreational activities and provide habitat for aquatic plants and animals (Mustaffa et al., 2023). However, river banks are very fragile and can be eroded by hydraulic action, which can lead to the loss of land, infrastructure, with major consequences for society and the economy (Hague and Zaman, 1989).

Floods are a frequent phenomenon in Kosovo, causing major economic and environmental damage. An example of this is the flood of 1979, which caused severe damage to roads, bridges and houses (KMEPSPI, 2010). Most rivers in Kosovo, do not have sufficient beds to accommodate maximum water flows (MESPI, Kosovo Flood Report, 2023). Poor regulated and poorly maintained river beds, waste disposal and uncontrolled exploitation of natural resources are factors that contribute to the increased risk of massive floods in the country (MESPI, 2023). Toplluha River is frequently flooding Suhareka Region and yet no research is conducted in this area. One of the main problems that occurs in the Toplluha River is that during dry periods there is very low flow rate. This is due to the decrease in water discharge as well as the river use for irrigation. Meanwhile, during periods of extensive rainfall, the river is flooded by the large amount of water. Also, large water flows bring a considerable amount of alluvium, which often creates problems in the surrounding areas.

The main objective of this work is the regulation of the river bed in this area, which is causing considerable damage as a result of the frequent floods. With the regulation of the Suhareka-Reçan segment (L = 1.9 km), the aim is to protect and reduce the damage caused by floods. In addition to regulating the river banks, the construction of levees is suggested as an additional measure to increase flood safety for this segment of the river. Also, frequent floods represent a potential factor for additional safety. The implementation of these measures will contribute to maintaining environmental stability by ensuring sustainable development and effective protection from floods.

STUDY MATERIALS AND METHODS

Study area

The Toplluha River is located in the south-eastern part of the White Drini basin. In the southern part, its basin is bordered by the Lepenc River basin and the Prizren River basin. In the eastern part, it is bordered by the river watershed, while in the northeastern part by the Carralevë River basin. In the northern part, it borders the Mirusha River basin, while in the western part it borders the Drin River (Shehu et al., 2014). This watershed, with an area of about 501 km² (Fang and Zena, 2010), is the second largest in this basin after the Erenik one.

In the Toplluha River basin, the average rainfall is about 781.1 mm per year, of which 232.9 mm flow, while 548.2 mm evaporate. The largest amount of rainfall is in November (40.8 m^3 10^6) while in the other months the total rainfall is about 9.76%. The groundwater recharge coefficient is lower (21.5%) while the evaporation coefficient is much higher (78.5%) (Avdullahi et al., 2008) (Figure 1).

Valid records for the Toplluha River are gained from the hydrometric station in the village of Piranë, which has provided important data for the analysis of the river's water regime. Based on historical records held by the Hydrometeorological Institute of Kosovo for a 30-year period (1948–1978), the data for the minimum, average and maximum values of annual flows are: Q_{Min} = 0.04 m^3/s, Q average = 3.47 m^3/s, Qmax = 55.40 m^3/s (IHMK, ARPL, 2020). Historical data after this period of time are fragmented and unusable.

For our study area, geodetic measurements were carried out every 50 m with high accuracy. The determination of the measuring stations of the cross-sections using the GPS program was carried out in detail by applying advanced programs. At the measurement sites, cross-sectional profiles of the existing bed were taken, ensuring the real shape of the Suhareka-Reçan segment. After creating the digital terrain model, a location plan was drawn up (Figure 2).

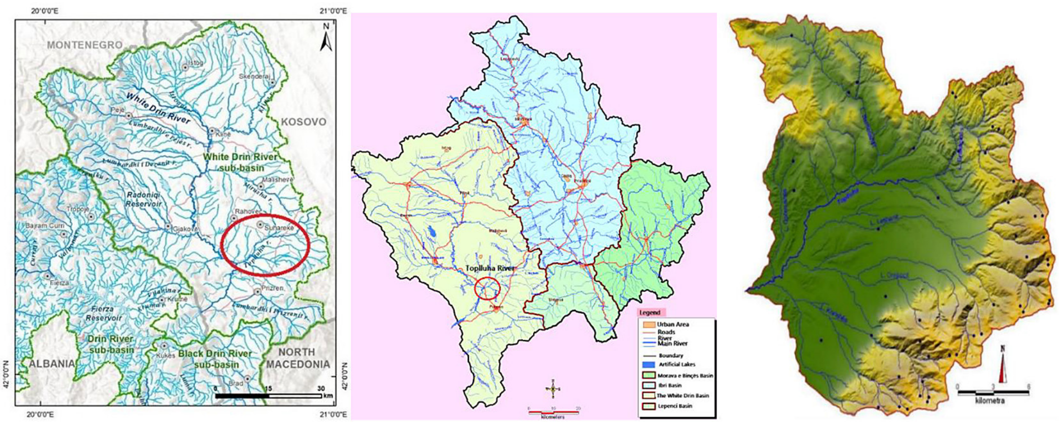

Figure 1. Toplluha River hydrographic network at the Europe level (left), national level (middle) and basin level (right). Source: Drin Corda, 2016 (left), MESPI, 2020 (middle), own work (right)

To achieve the objectives outlined in the introduction, geometric measurements of 40 cross-sectional river profiles were conducted. These profiles were analyzed using all the necessary hydraulic parameters. The cross-sectional profiles of the unregulated river bed are presented graphically (P1–P40), followed by the creation of the longitudinal profile of the unregulated bed for the study area (st 00–st 40).

Using the calculated hydraulic parameters for each cross-sectional profile, the velocities and flows were calculated by applying Manning's equations. Also, the discharge curves were presented in graphic form, where for each profile the existing depth in the river was measured, and the flow was read in the diagram. A regulated river profile was suggested, based on the discharge curve. A comparison of the of the unregulated river bed profiles with the regulated (suggested) one was made, then the amount of excavation and filling work was determined. After studying and analyzing some of the possible options for bank reinforcements, the bank reinforcements made with natural stone-grade material were adopted as the solution. In addition, the construction of levees is suggested to increase safety against floods in this river segment.

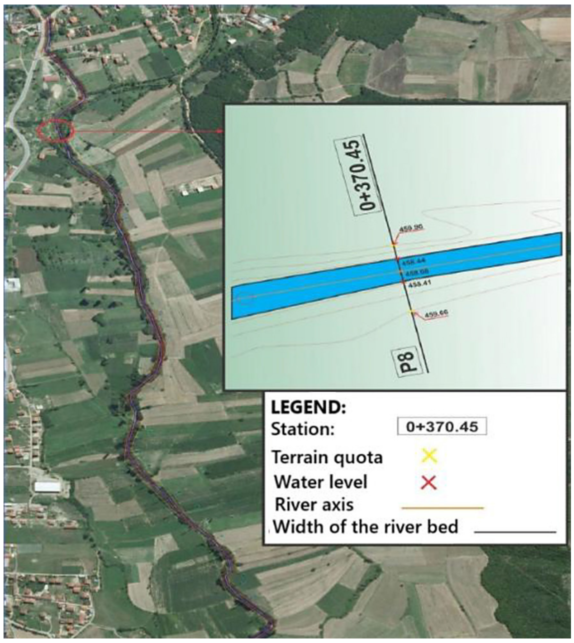

Figure 2. Situation Plan, Reqan-Suhareka River segment, L = 1.9 km

RESULTS AND DISCUSSION

Analysis of the existing riverbed

From the performed geodetic measurements and existing flow data on the area, wetted perimeter, slope, water depth and bed width were generated. The measurements, based on assumed depths (0.2–2.0 m), were used to calculate hydraulic parameters with Manning's formulas (Chow, 1959; Song et al., 2016):

$$P = b + 2 \times h \times \sqrt{(1+m^2)}\,; \quad A = (b + m \times h) \times h\,; R = \frac{A}{P} \tag{1}$$

$$v = \frac{1}{n} \times R^{\frac{2}{3}} \times i^{\frac{1}{2}}\,; \quad Q = A \times v = A \times \times v = A \times \frac{1}{n} \times R^{\frac{2}{3}} \times i^{\frac{1}{2}} \tag{2}$$

For each river bed profile, out of 40 in total, flow diagrams have been created and presented. The calculation of hydraulic parameters, flow velocity and flow rate will be presented in detail for a cross-section profile, and also for other ones. The calculation is done based on assumed depths of (0.2–2.0) m, which are presented below in tabular form. Flow diagrams have been calculated depending on the water depth, where for each profile the existing water depth in the river has been measured, and the flow has been read in the diagram. In the profile (P1 0 + 010.00), the water depth during field measurements has resulted to be h = 0.49 m, while the maximum flow rate Qmax = 11.964 m³/s has been determined from the diagram (Figure 3, 4 and Table 1, 2).

Developing regulated riverbed profile

Based on the conducted hydraulic calculations, the optimal dimensions of the regulated channel profile for the river segment were determined. The design of this segment was based on the hydraulic flow characteristics and the requirements for flow management and protection of the surrounding area.

Manning's coefficient value of $n = 0.030$ was used in the hydraulic calculations, adapted to the physical characteristics of the riverbed and the applied stabilization measures. This value corresponds with those reported in the literature for riverbeds reinforced with large natural stones

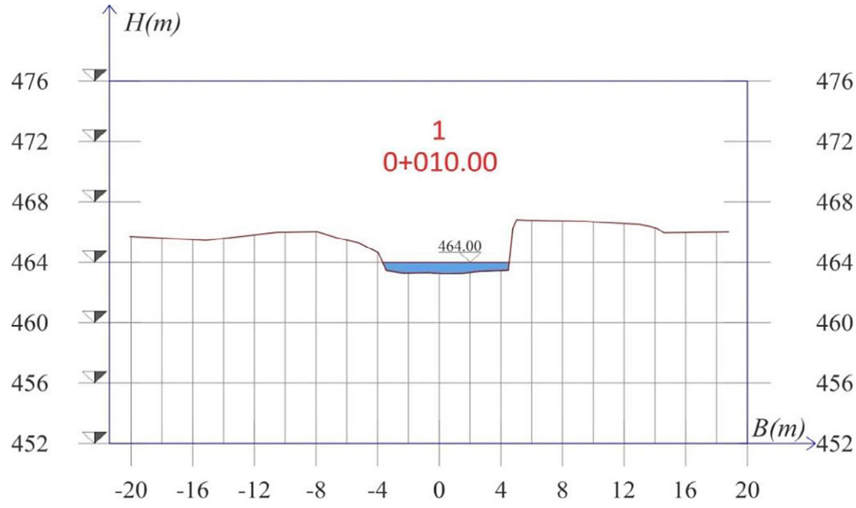

Figure 3. Transverse profile (P1 0 + 010.00) of the examined river segment; source: own work

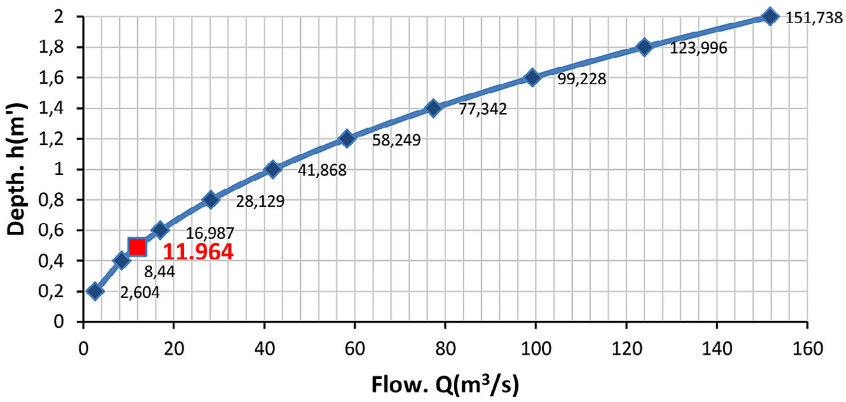

Figure 4. From the flow diagram, for height h = 0.49 m, the maximum flow rate Qmax = 11.964 m³/s was determined

(Chow, 1959) and channels with controlled natural structures (Froehlich, 2009).

The regulated channel profile, designed based on these parameters, ensures a more stable flow by reducing velocity to levels that minimize the risk of erosion, while maintaining sufficient capacity to handle maximum discharges. Although the cross-sectional area is slightly reduced, natural stones and vegetative cover increase flow resistance, enhancing energy dissipation and reducing erosion (Table 3)(Figure 5).

Bank reinforcements and natural solutions

Stabilizing the river and protecting its banks from erosion with rockfill is a widely used engineering practice (Task Committee on Channel Stabilization Works, 1965). The design of river banks depends on many factors, including functionality under different hydraulic loads, feasibility, environmental constraints, and material availability (Ventini et al., 2021). Bank erosion is influenced by numerous factors, including the water level within the channel, groundwater flow, bank vegetation, and sediment properties on the banks (Deng et al., 2018; Simon et al., 2000; Simon and Collison, 2002; Zhao et al., 2022). In this context, the reinforcement of the banks of the Toplluha River aims to prevent erosion of the riverbed.

The paper assessed the impact of bank protection measures through planting plants and natural covers to strengthen the banks, reducing the impact of anthropogenic factors and stabilizing the riverbed, especially in the locality of the village of Reçan, at stations P7 0+310.48 and P8 0+370.45. These reinforcement were shown to be effective in preventing the illegal exploitation of inert materials, promoting the restoration of natural balance through plantings

Table 1. Calculation based on assumed depths

P1 0+010.00							
h (m)	P(m')	A (m²)	I (%)	R (m')	m	v (m/s)	Q (m³/s)
0.2	9.023	1.689	0.02	0.187	2.515	1.542	2.604
0.4	10.105	3.578	0.02	0.354	2.515	2.360	8.443
0.6	11.188	5.669	0.02	0.506	2.515	2.996	16.987
0.8	12.270	7.962	0.02	0.648	2.515	3.533	28.129
1.0	13.353	10.455	0.02	0.783	2.515	4.005	41.868
1.2	14.436	13.150	0.02	0.910	2.515	4.430	58.249
1.4	15.518	16.045	0.02	1.034	2.515	4.820	77.342
1.6	16.601	19.142	0.02	1.153	2.515	5.184	99.228
1.8	17.683	22.441	0.02	1.269	2.515	5.526	123.996
2.0	18.766	25.940	0.02	1.382	2.515	5.850	151.738

Table 2. River width and slopes for all profiles

Profile	M	b	Profile	m	b
P1 0+010.00	2.515	7.940	P21 1+020.12	2.140	6.110
P2 0+060.06	4.405	5.890	P22 1+069.79	2.040	4.690
P3 0+110.10	1.835	4.240	P23 1+119.98	3.465	6.820
P4 0+160.14	2.905	4.640	P24 1+160.97	1.545	5.150
P5 0+210.16	2.910	6.300	P25 1+210.01	2.040	6.640
P6 0+260.55	4.145	8.390	P26 1+243.70	1.005	5.470
P7 0+309.75	2.230	6.830	P27 1+301.15	1.760	4.770
P8 0+370.45	1.995	5.160	P28 1+370.25	2.720	4.620
P9 0+420.20	2.140	5.520	P29 1+419.97	2.080	4.440
P10 0+470.10	2.640	5.240	P30 1+470.11	4.315	3.850
P11 0+520.07	2.525	6.510	P31 1+519.95	2.520	5.440
P12 0+570.11	1.605	4.550	P32 1+569.89	2.240	5.070
P13 0+620.19	2.385	6.120	P33 1+620.02	2.045	3.140
P14 0+670.35	2.495	6.400	P34 1+670.14	2.600	4.930
P15 0+720.34	1.775	6.290	P35 1+720.06	3.485	4.340
P16 0+770.01	1.450	7.400	P36 1+770.03	2.120	3.460
P17 0+820.49	1.075	4.650	P37 1+820.06	3.210	6.650
P18 0+870.08	1.420	4.480	P38 1+869.94	2.055	6.460
P19 0+921.15	1.130	3.380	P39 1+920.00	2.120	5.080
P20 0+970.07	1.690	5.530	P40 1+970.01	3.630	4.210
			Total:	94.405	216.800
			Average:	2.360	5.420

and natural structures, and reducing bank erosion by local water currents, especially at station P6 0+260.55.

Vegetation directly protects the banks from erosion by reducing the shear stresses near the banks (Md. Shofiul Islam, 2011). Bank reinforcement also contributes to reducing the impact of the power of running water during periods of heavy rainfall, which often bring significant amounts of alluvium. Bank reinforcement is realized with graded stone material. It is a time-tested technique, very durable and easy to construct (Bariteau et al., 2013). However, the placement of steeply sloping fill composed of igneous rocks can artificialize the banks, significantly reducing the potential for vegetation and limiting access to water for both animals and humans (FEMA, 2008). In

Table 3. Integrated profile calculation

h (m')	P(m)	A (m²)	I (%)	R (m)	η	b	m	v (m/s)	Q (m³/s)
0.2	7.077	1.300	0.02	0.184	0.03	6.0	2.5	1.523	1.980
0.4	8.154	2.800	0.02	0.343	0.03	6.0	2.5	2.312	6.473
0.6	9.231	4.500	0.02	0.487	0.03	6.0	2.5	2.920	13.140
0.8	10.308	6.400	0.02	0.621	0.03	6.0	2.5	3.431	21.957
1.0	11.385	8.500	0.02	0.747	0.03	6.0	2.5	3.880	32.976
1.2	12.462	10.800	0.02	0.867	0.03	6.0	2.5	4.285	46.278
1.4	13.539	13.300	0.02	0.982	0.03	6.0	2.5	4.658	61.956
1.6	14.616	16.000	0.02	1.095	0.03	6.0	2.5	5.007	80.113
1.8	15.693	18.900	0.02	1.204	0.03	6.0	2.5	5.336	100.853
2.0	16.770	22.000	0.02	1.312	0.03	6.0	2.5	5.649	124.281

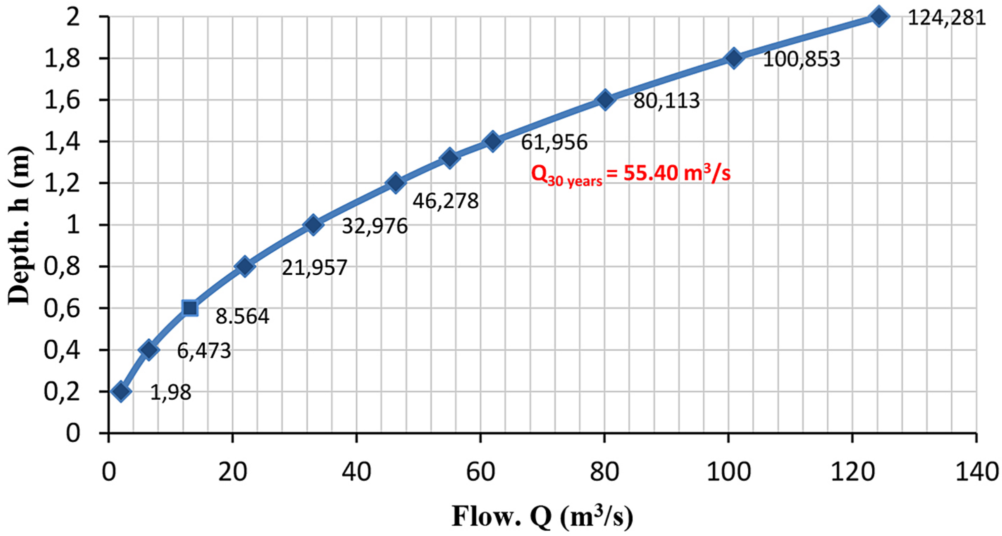

Figure 5. For the maximum annual flow Q_{30} = 55.40 m³/s, we read, h = 1.32 m

addition, this type of reinforcement has resistance to waves and water currents, as well as a positive impact on aesthetics and the environment, providing a natural appearance and ecologically acceptable.

Despite detailed analyses and research, the lack of accurate and complete climate change data continues to be a major obstacle to accurately predicting flood risk levels. This insufficient information can lead to inaccurate assessments of protection needs and possibly insufficient infrastructure to cope with extreme rainfall events. Therefore, in addition to river bank regulation, the construction of levees along the riverbed is necessary to further increase flood safety.

Levees are critical infrastructure for flood management in many parts of the world. For example, they have been in continuous use along the Yellow River in China for thousands of years (Chen et al., 2012), along the Po River in Northern Italy since Roman times (Marchi et al., 1995, Di Baldassarre et al., 2009) and as integral components of modern flood management systems on a national scale (Netherlands, 2020 al., 2004, van Stokkom et al., 2005, Pilarczyk, 2006, Rijke et al., 2012). River levees are one of the main flood control and water supply infrastructures, which provide important protection for people's lives (Zhou et al., 2022). This measure not only reduces the risk of floods, but also ensures that the infrastructure and livelihoods of residents are protected from the damage that may be caused by floods.

In addition, hazard maps along the Toplluha River were analyzed, which include flow patterns for Q10, Q100 and Q500. These maps illustrate the potential flood risk, identifying residential areas that may be flooded during periods of extreme rainfall, highlighting the ongoing risk to these areas. This shows that flood risk is a present and ongoing threat to the areas around the river. The construction of levees will help improve flood safety, reducing the risk of potential impacts. These factors promotes the construction of levees as an effective and necessary measure to improve safety and reduce the risk of flooding in this segment of the river (Figure 6).

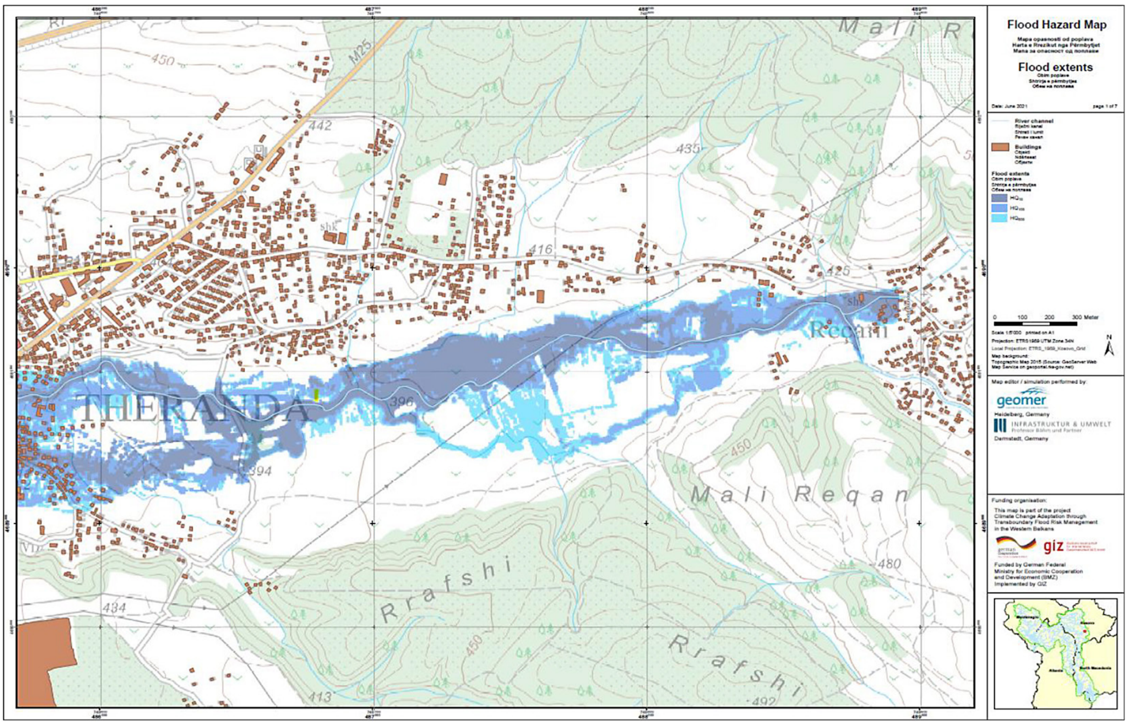

Figure 6. Flood Hazard Map HQ10, HQ100, HQ500 - Kosovo, Suhareka, Toplluha. Source: GIZ GmbH

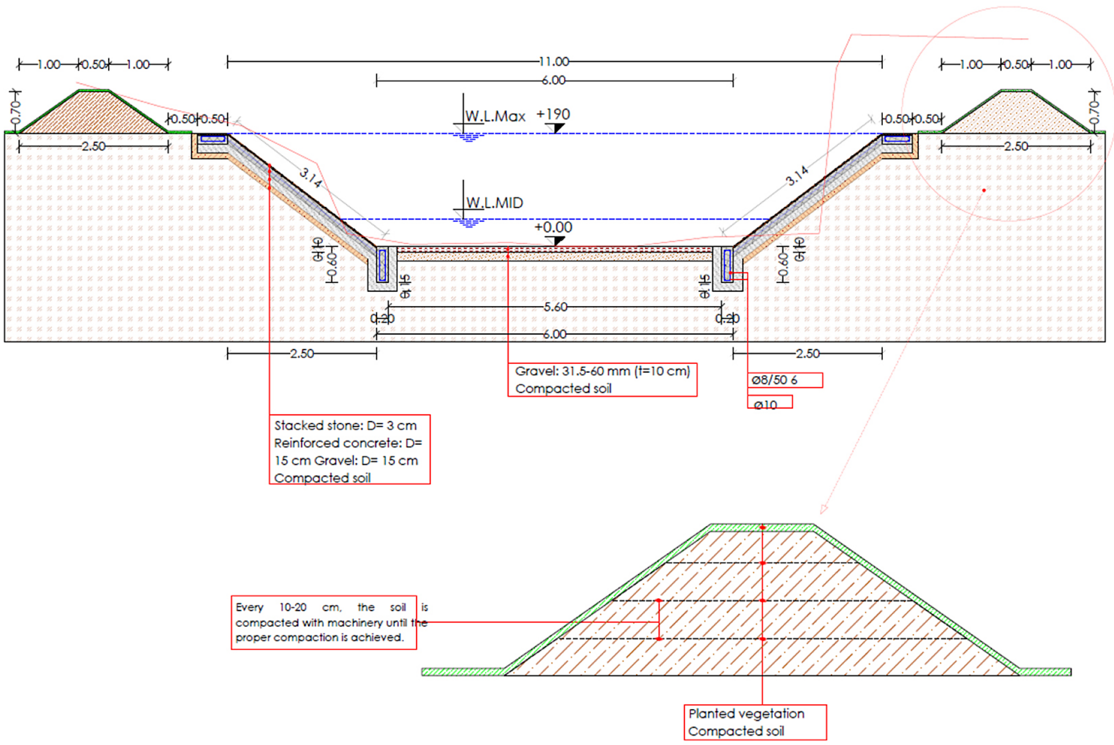

Figure 7. Transverse profile of the bed regulated by levees

By building the levees, we aim to positively influence the preservation of water quality, by preventing pollutants, including sediments that may contain toxic substances, from penetrating the water. Within the framework of our study, the levees are expected to be built from homogeneous material, soil, with the external covering made of vegetation, grass. The material will be provided by excavations in the river bed, guaranteeing the use of materials available in the area (Figure 7).

CONCLUSIONS

The lack of comprehensive data on climate change continues to pose a significant challenge to the accurate prediction of flood risk, leading to inaccurate assessments of protection needs and inadequate infrastructure to cope with extreme rainfall events.

From the hydraulic calculations carried out, the optimal dimensions of the regulated river profile have been obtained, based on the analysis of existing bed measurements for the 40 analyzed profiles. The dimensions of the river width (b = 2.5 m) and the slope of the banks (m = 2.5) have been adopted based on field measurements of these profiles. These dimensions have been used for the design and regulation of the river segment, ensuring efficient flow management and protection of the relevant area, in accordance with hydraulic and environmental requirements.

After an analysis of different options for regulating the banks of the Toplluha River, it has been concluded that reinforcing the banks with graded rock material and constructing levees constitute the most effective measures to address flood risk. These measures are sugested in the context of the damage caused by frequent floods to date and the potential impact of the lack of accurate data on flows and climate change. The regulation of the riverbed, accompanied by the construction of levees, is expected to have a positive impact on improving flood safety and protecting the area. These measures are designed to prevent potential floods, increase ecosystem resilience and ensure sustainable use of agricultural lands at risk from flooding. They will also contribute to the protection of water quality and the prevention of the infiltration of waste and sediments from soil erosion and agricultural activities.

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