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Evaluating the Sustainability of Longtime Operating Infrastructure for Romanian Flood Risk Protection

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Abstract: Flood protection infrastructures are crucial for enhancing the resilience of societies exposed to natural hazards. Newly designed infrastructures are evaluated for sustainability using a coherent and internationally recognized method defined by the International Hydropower Association (IHA). However, in operation, old structures require a different assessment approach. Different work proposes a modified IHA protocol, mHSAP, which identifies opportunities for improvement and develops a sustainability evaluation framework for existing infrastructures. This paper applies the modified protocol to evaluate the sustainability of two types of flood protection structures: a unique canal system for flood–drought protection of an urban area and a flood protection dike. The time of operation of these structures is over 250 years and over 50 years, respectively. The application of the modified framework demonstrates its advantages in identifying areas for improving flood protection structure operation while maintaining the structure's sustainability. It also illustrates how Romanian water boards can use such tools to facilitate collaboration between structure owners and stakeholders, allowing them to assess the risks and effects of flooding on society. Through these two examples from Romania, we also show that the mHSAP framework has the potential to actively support the fulfillment of the United Nations Agenda 2030 Sustainable Development Goals (SDGs). The results presented here show that this method can be further utilized by water board authorities to account for climate change effects, address related challenges in a coordinated and efficient manner, develop resilient flood management strategies, inform infrastructure investment decisions, and enhance collaboration among water management authorities.

Keywords: water resources engineering; mHSAP protocol; flood risk; improved water management; sustainable infrastructure; Romania

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1. Introduction

Floods are among the most frequent natural disasters worldwide, usually resulting from heavy rainfall. One of the essential flood risk protection elements is hydraulic structures, which play an essential role in protecting communities, infrastructure, and economies from the impacts of floods, especially in the context of climate change [1]. Their importance also extends to the broader UN-defined sustainable development goals (SDGs), such as contributing to water resource management, resilient infrastructure, sustainable cities, climate adaptation, and ecosystem protection. The construction, maintenance, and operation of hydraulic structures must be carefully done to continuously aim to address environmental and social impacts while being integrated within existing water management strategies. Such an approach enables hydraulic structures to support sustainable development and enhance resilience to flooding in a changing climate [2,3]. The analysis of the role of hydraulic structures for flood risk protection shows their alignment with multiple SDGs, such as SDG6, SDG11, SDG13, and SDG15.

Dikes and dams play a crucial role in achieving SDG6 (Clean Water and Sanitation) and SDG13 (Climate Action) by providing sustainable water resources management and flood protection and enhancing community resilience against climate-induced extreme weather events. Here, we can mention the example of dams and their corresponding reservoirs that provide clean water for various purposes while also fulfilling the function of flood control. In the case of SDG 11 (Sustainable Cities and Communities), hydraulic structures create safe and resilient cities because they reduce the risk and impact of urban flooding. Effective flood management is essential for protecting homes and public spaces. One of the most important SDGs in which hydraulic structures play an important role is SDG13 (Climate Action). Climate change is expected to increase the frequency and severity of extreme weather events, including floods. Hydraulic structures are important measures that help society adapt to the impacts of climate change, enhancing resilience.

While these systems have historically provided vital protection, they now face significant challenges due to climate change, increased urbanization, and evolving environmental standards.

Macioszek et al. (2022) [4] present innovative approaches to urban transportation within the context of smart cities. While primarily focused on transportation, the concepts discussed in this paper can be effectively applied to the realm of sustainable flood protection structures, such as dikes. The multidisciplinary approach of [4] aligns well with the complex nature of flood protection, which requires input from various fields, including engineering, hydrology, ecology, and urban planning. Just as smart cities leverage technology for energy-efficient transportation systems, flood protection infrastructure needs to incorporate smart technologies for real-time monitoring, early warning systems, and automated control mechanisms. This integration of technology would allow for more responsive and adaptive flood management strategies in the future.

Moreover, their daily operation and long-term management present certain challenges. These include environmental and social impacts, maintenance and certification for functioning, and integrated water management [5]. Large dams and corresponding reservoirs can affect the natural ecosystems (i.e., fish migration, sediments, and water quality). Therefore, the sustainable design and operation of structures are necessary in order to mitigate the ecosystem impacts [6]. During the construction of large infrastructure, communities might be displaced, which has a high social impact. In terms of maintenance for certification of functioning, the main challenges are the technical expertise of the ones employed to operate a structure and the investments needed for maintenance [7].

By effectively managing the above challenges, hydraulic structures can confirm their role in promoting sustainable development and play an important role in resilience against flooding, given the ongoing climate change [8,9].

In response to growing concerns over the environmental and social impacts of large infrastructure projects, the hydropower sector developed the Hydropower Sustainable Assessment Protocol (HSAP) in the early 2000s. This protocol, initiated by the International Hydropower Association (IHA), provides a standardized method to evaluate the sustainability of hydropower projects. This industry faced increasing questions over the environmental and social impacts their projects would have. The concerns included biodiversity loss, displacement of communities, and changes in water quality and flow regimes, leading to calls for more sustainable practices.

To address these challenges, the International Hydropower Association (IHA) initiated a multi-stakeholder process involving governments, financial institutions, non-governmental organizations (NGOs), and industry experts in an effort to create the tool that could guide the development and management of hydropower projects in a manner that balances economic, social, and environmental considerations [10]. The HSAP protocol was officially launched in 2010 after a decade of rigorous development and pilot testing. It was designed to be a voluntary, globally applicable assessment tool that provides a consistent and transparent way to measure and improve the sustainability performance of hydropower projects [11]. Several countries, like Zambia, France, New Zealand, and others, recognized the value of the protocol and applied it during the design and construction phase. However, the need for a similar assessment tool for existing flood protection structures became apparent, especially for those with long operational histories. While these systems have historically provided the needed protection, they now face significant challenges due to climate change, increased urbanization, and evolving environmental standards.

To address this gap, Popescu et al. (2024) [12] proposed a modified HSAP protocol (mHSAP) specifically adapted for assessing the sustainability of existing flood protection infrastructures. This innovative approach allows for the evaluation of various types of hydraulic structures, including canals, dikes, and levees, with a focus on identifying areas for improvement while maintaining operational sustainability. The application to these old and very old still operated structures involves conducting thorough environmental impact assessments, engaging stakeholders and addressing their concerns, and especially implementing best practices during operation and maintenance to minimize negative impacts and enhance the benefits of their use.

In this context, old infrastructure used for flood risk protection often includes a variety of structures and systems that have been in place for decades or even centuries. These can range from diversion canals and levees to dams and drainage systems. Levees, which are embankments built along rivers, are designed to prevent water from overflowing into populated areas. Diversion channels, where possible, help control the flow of rivers to reduce the risk of flooding downstream. While these structures have historically provided protection against flooding, many of them are now in need of significant upgrades or replacements to cope with modern-day challenges, such as increased rainfall due to climate change and urban development [13,14]. As a result, it is essential that these structures are frequently certified and inspected not only for their structural integrity but also for their sustainability. Ensuring that these systems are both robust and environmentally sustainable is important for maintaining long-term flood protection and adapting to evolving environmental conditions.

This article illustrates how old Romanian flood protection structures can be tested for sustainability by applying the mHSAP (modified HSAP) protocol. This study focuses on two specific structures: a diversion channel system of over 200 years old and a levee of over 50 years old, both designed for urban flood protection.

The application in this study of the mHSAP framework to the Romanian case studies offers several key advantages and innovations:

- It provides a tool for assessing the sustainability of flood protection structures that have been in operation for extended periods, some for over two centuries;
- It facilitates the identification of areas where operational improvements can be made while ensuring the continued sustainability of the structure;
- The framework promotes collaboration between structure owners, stakeholders, and water management authorities, encouraging a more integrated approach to flood protection;
- It aligns with and supports the fulfillment of multiple UN Sustainable Development Goals, particularly those related to water management and climate action;
- The mHSAP offers water board authorities a method to address climate change effects and related challenges in a coordinated and efficient manner.

The methodology and detailed case study descriptions are presented in Section 2, followed by results and discussion in Section 3. The final section of the article summarizes the main conclusions and implications of this research for sustainable flood protection management.

2. Materials and Methods

2.1. Overall Methodology

Launched in 2010 by IHA, the HSAP protocol provides an approach to evaluate hydropower projects across various sustainability dimensions. The need for the development of this protocol came as a response to the environmental and social risks (impacts on communities, population displacements) posed by hydropower, which is an important renewable source of energy. The HSAP is a globally recognized assessment tool [15,16] that was developed through collaboration among industry experts, environmental groups, financial institutions, and governmental organizations [17].

The assessment employs a scoring system to provide an overall sustainability evaluation, highlighting strengths and identifying areas for improvement. Each evaluated topic (criteria) is assigned a scoring system from 1 to 5, with higher scores indicating better sustainability practices and compliance with international norms. The scores are based on objective criteria, allowing assessors to identify strengths and weaknesses within projects and highlighting areas for improvement [18].

The criteria for evaluation are depicted for each project on a rosette with five ranking levels [11]. These levels range from low performance (value one) to the highest performance (value 5). Level three is identified as the baseline for sustainability. For an infrastructure project to be considered sustainable, it must attain at least level three or higher in all criteria.

The sustainability evaluation is conducted at various stages of a project's lifecycle: early stage (ES), preparation (P), implementation (I), and operation (O); each one of them is assessed across specific sustainability topics. These topics include biodiversity conservation, community impacts, water quality, resettlement, and labor practices, among others.

Early stages and preparation assess the project's initial planning and design, covering feasibility studies, environmental and social impact assessments, stakeholder engagement, and risk identification. It ensures that the groundwork for sustainability is established before construction begins. Implementation evaluates the construction process, including labor management, compliance with environmental standards, and the effectiveness of health and safety measures. It focuses on mitigating construction-related impacts on communities and ecosystems. Once the hydropower project is functional, the operation stage assesses its environmental management, water management, and contributions to local economies. It evaluates whether the project is adhering to its sustainability commitments and effectively managing operational impacts.

The 26 HSAP-defined criteria for sustainability assessment are summarized in Table 1, and a detailed description for each one of them can be found in [11].

In this study, Table 1 lists each evaluated criterion and indicates the stage of the structure's lifecycle in which it is used. The stages are denoted as ES, P, I, or O. Each criterion is assigned a code consisting of the stage letter followed by a number. If a criterion is not applicable to a particular stage, it is marked with "-" in the table, and the numbering for subsequent criteria is adjusted accordingly. There are 9 criteria for the early stage, 24 for preparation, 22 for implementation, and 20 for operation. Several criteria are applicable to more than one stage of the project lifecycle, as it is, for example, "Governance" (Table 1, aspect 25) or "Communication" (Table 1, aspect 14), which are relevant for three out of the four stages of a structure's lifecycle.

Whenever a project is evaluated, a rosetta is produced for each stage. A conceptual representation of these rosettas is given in Figure 1.

While the HSAP provides a comprehensive framework for evaluating hydropower projects, it does not address other domains, such as flood protection structures, nor does it specifically consider older, in-operation existing infrastructure. Recognizing the advantages of such structured evaluations, researchers have developed a modified HSAP (mHSAP) tailored for in-operation structures [12]. The mHSAP-adapted protocol is utilized in the present study, having the advantage of extending the benefits of sustainability assessment to flood management infrastructure for a very old time-standing structure and a relatively new one. Aspects like economic viability or social consideration (moving people because of new construction) are not part of the mHSAP or are defined differently, i.e., economic viability refers to the identification of improvements to ensure further flood protection.

Table 1. Evaluation criteria.

Sustainability Aspect		Sustainability Criteria	Stage of The Structure Life Cycle *				mHSAP Relevant Criteria **
Aspect	No		ES	P	I	O	
Technical	1	Siting and Design	ES1	P1	-	-	n.a
	2	Hydrological Resource	-	P2	-	O2	C
	3	Demonstrated Need and Strategic Fit	ES3	P3	-	-	n.a
	4	Infrastructure Safety	-	P4	I4	O4	C
	5	Asset Reliability and Efficiency	ES5	-	I5	O5	C
Environmental	6	Environmental and Social Impact Assessment and Management	ES6	P6	I6	O6	C
	7	Erosion and Sedimentation	-	P7	I7	O7	C
	8	Water Quality	-	P8	I8	O8	C
	9	Waste, Noise, and Air Quality	-	-	I9	-	n.a
	10	Reservoir Planning/Preparation and Filling/Management	-	P10	I10	O10	n.a
	11	Downstream Flow Regimes	-	P11	I11	O11	C
	12	Biodiversity and Invasive Species	ES12	P12	I12	O12	C
	13	Climate Change Mitigation and Resilience	-	P13	I13	O13	C
Social	14	Communications and Consultation	-	P14	I14	O14	C
	15	Project Benefits	-	P15	I15	O15	C
	16	Project-Affected Communities and Livelihoods	ES16	P16	I16	O16	n.a
	17	Cultural Heritage	-	P17	I17	O17	n.a
	18	Indigenous Peoples	-	P18	I18	O18	n.a
	19	Resettlement	-	P19	I19	O19	n.a
	20	Public Health	ES20	P20	I20	O20	C
	21	Labor and Working Conditions	-	P21	I21	O12	C
Economic	22	Financial Viability	ES22	P22	I22	O22	C
	23	Economic Viability	ES23	P23	-	-	C
	24	Procurement	-	P24	I24	-	n.a
	25	Governance	-	P25	I25	O25	C
	26	Integrated Project Management	-	P26	I26	-	C

* ES—early stage, P—preparation, I—implementation, O–operation, ** n.a.—not selected, C—selected criteria.

The mHSAP method selects 17 out of the 26 criteria to evaluate very old flood protection structures. Their relevance to flood protection within the context of water resources is specifically detailed in column "mHSAP relevant criteria" of Table 1, where C stands for selected criteria.

It is important to mention that both HSAP and mHSAP are not certification schemes for sustainable projects or structures, nor do they replace environmental and social impact assessments required by national policies in a country. Instead, the sustainability assessments provide a snapshot of a structure's performance at a specific point in time (either in the design phase or in operation). These assessments are advised to be conducted by a team of accredited experts for HSAP or for the proposed mHSAP by flood risk protection experts. As this study focuses on Romanian case studies, the experts to asses old structures are the National Romanian Water Administration (ANAR). The experts visit the project site, review all relevant documents, conduct interviews with stakeholders and operators, and prepare a final report with the results of the assessment. The latter identifies gaps that need to be addressed, promoting continuous improvement in sustainability performance. It also facilitates dialogue among the stakeholders through the sharing of results.

Not all mHSAP criteria are applicable to every structure, as some may be irrelevant for a specific case under evaluation. For instance, water quality for drinking purposes is not pertinent if the water is not intended for consumption. However, even when a criterion is not evaluated due to its irrelevance, it is still listed in the report and corresponding rosetta, albeit without a score. This approach ensures comprehensive documentation and maintains consistency across assessments.

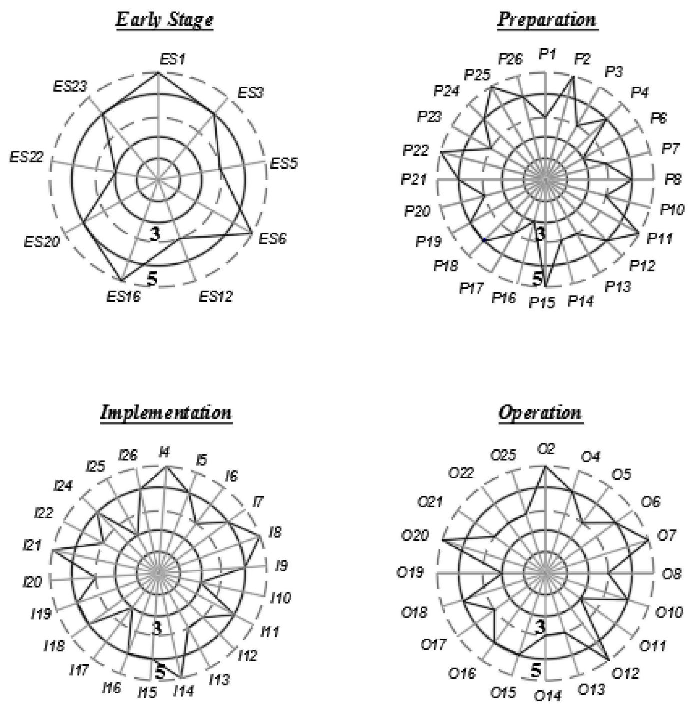

Figure 1. HSAP topics (as per Table 1) and example rosettas.

2.2. mHSAP Evaluation Criteria and Scoring

In this study, two structures were evaluated using the mHSAP protocol. The main aim of these structures is to protect two main cities in Romania from floods. The detailed significance of the selected criteria to assess the two structures for flood protection of the two Romanian cities are as follows:

- Hydrological resource (HR) assesses the understanding and management of water resources from short and long-term perspectives. This criterion is important for effective flood risk protection, ensuring that strategies are based on reliable and up-to-date hydrological data;
- Infrastructure safety (IS) addresses the safety of the evaluated infrastructure with all appurtenance works, aiming to protect lives, property, and communities from the potential consequences of structural failures;
- Asset reliability and efficiency (ARE) refers to the evaluation of how well the infrastructure under consideration is maintained and operated to ensure the functionality for which it was designed. This includes aspects such as regular maintenance schedules and performance monitoring;
- Environmental and social impact assessment and management (EIA) focuses on the management processes for environmental and social issues. The main goal is to explore if the negative environmental and social impacts associated with the existing structure are effectively managed by implementing measures for minimization, mitigation, compensation, and improvement, as well as fulfilling environmental and social commitments;
- Erosion and sedimentation (ES) focus on the responsible management of erosion and sedimentation issues related to the operation of hydrotechnical facilities. When such problems arise, they must be addressed because they are closely associated with infrastructure safety;

- Downstream flow regime (EF) refers to ensuring that rules and regulations regarding the defined environmental flow in the downstream are met. Current research addresses flood risk. Therefore, this criterion is not the most important. However, it was selected to be evaluated because one of the case studies fulfills both protection against floods and against droughts;
- Climate change mitigation and resilience (CCMR) normally looks at greenhouse emissions. In this research, this criterion looks at the role of the structure in climate change adaptation.
- Communication and consultation (CC) address the engagement with affected communities, governments, key institutions, partners, contractors, watershed residents, etc.;
- Project benefits (PB) address the additional benefits that can arise from a flood risk protection project beyond immediate flood prevention. The intent is that opportunities for broader benefits, such as recreational spaces and ecosystem restoration, are evaluated and implemented in collaboration with communities living around the infrastructure;
- Public health (PH) looks at whether the structures are affecting the public health in the area surrounding the structure;
- Labor and working conditions (LWC) investigate if there are safe, fair, and equitable working conditions for all employees and contractors;
- Financial viability (FV) addresses both access to finance and the flood risk structure operation has the capacity to generate the financial returns to achieve required financing measures to ensure project sustainability and manage flood risk effectively;
- Economic viability (EV) is different from financial viability, as it looks at the overall economic benefits of the flood protection structure for the society as a whole. It takes a broader societal perspective, looking at whether the economy and community benefits are enough to justify the cost of operating the structure;
- Governance (G) looks at the internal rules and processes governing the operation of the structure. It also looks at external governance, which involves the legal and regulatory framework within which the structure operates;
- Integrated project (IP) management addresses the ability of the owner's flood protection structure to ensure its operation in a sustainable manner.

All criteria are evaluated qualitatively for best practices, which for in operating flood risk protection refers to proactive maintenance, real-time monitoring, and adaptive planning to ensure reliability and responsiveness [14]; regular inspections, automated monitoring, and clear emergency procedures enable swift and efficient actions during flood events [19]; collaborative planning with local authorities, community engagement, and transparent communication promote public awareness and readiness. Climate resilience is built by adjusting protocols based on predictive models and climate data while maintaining environmental flows to protect ecosystems [20]. Detailed record-keeping, well-trained personnel, and sufficient funding for upkeep and improvements further reinforce the flood risk protection structure's ability to safeguard communities against evolving flood risks.

For each criterion, the assessment score is on a scale from 1 to 5, depending on the above-defined best sustainability practices for flood risk structures:

- Score 1 shows poor performance, with significant gaps in sustainability measures;
- Score 2 is similar to score 1, but it shows only one significant gap, not several;
- Score 3 reflects good practice, meeting basic compliance with international standards. At level 3, the assessment includes the key considerations most relevant to flood risk, but it maintains a predominantly flood risk-focused perspective, placing greater emphasis on identifying impacts and risks rather than exploring potential opportunities. Potential opportunities include the integration of natural flood management methods, such as the creation of green spaces, improved water management for agriculture, and collaborative initiatives with communities to increase awareness and preparedness;
- Score 4 is given when the structure has adequate and effective management, operation, and perspective beyond level 3 and has only a few gaps in the interrelationships amongst relevant sustainability issues;

- Score 5 represents proven best practices where the project demonstrates leadership in sustainability.

The methodological approach for determining the scoring of each criterion in this sustainability assessment follows a comprehensive process outlined in Figure 2. This process begins with the identification of key evaluation areas for each criterion based on their previously established significance. Customized questionnaires are then developed for interviews with structure owners, environmental specialists (where available), and identified local stakeholders. During these interviews, the availability of documents necessary for the sustainable operation of the structure is assessed. Following the interviews, a qualitative analysis is conducted, considering the range of responses provided. The study team then assigns scores to each criterion based on predefined scoring levels detailed in Table 2, producing a comprehensive report and a rosetta to summarize the findings. The final step involves sharing results with the structure owner and providing suggestions and recommendations for improvement. It is important to note that the evaluated structures were not legally obligated to implement the report's recommendations. The decision to utilize the findings and implement changes remains at the discretion of the structure owners.

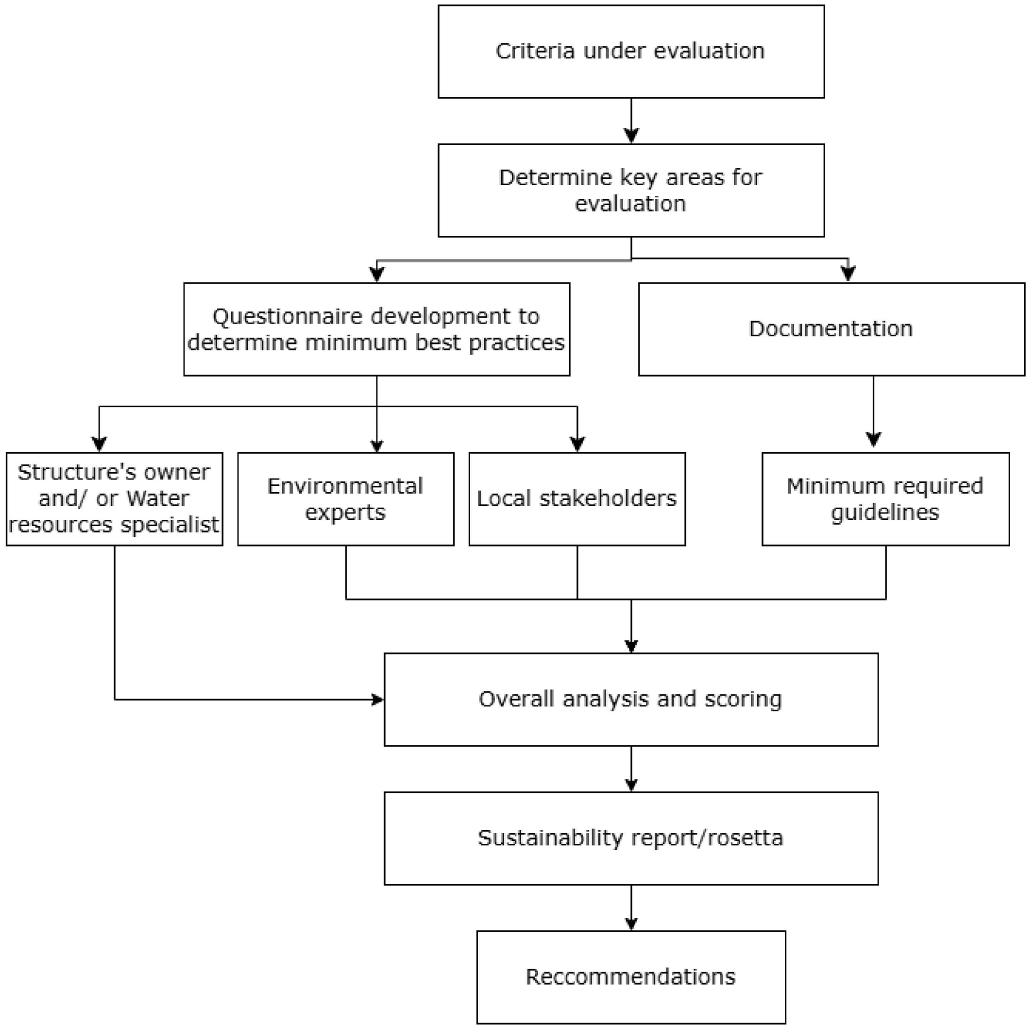

Figure 2. Performed step-by-step mHSAP methodology to determine the scoring of each analyzed criterion.

This methodology ensures a thorough and systematic approach to assessing the sustainability of the evaluated structures while also recognizing the voluntary nature of implementing the resulting recommendations.

To evaluate all selected mHSAP criteria, the authors conducted face-to-face interviews with Romanian Waters (the structures' owners), reviewed available documentation, and examined Romanian norms for operational structures. Examples of built questionnaires for the three types of questionnaires used in the interviews and the type of checked documentation are given in Table 2 for the HS and/or CCRM criteria.

The detailed results and discussion of each criterion's evaluation are presented in Section 3 of this study.

Table 2. Interview topics and questions used for scoring flood protection structures.

Interviewed/ Checked Documentation	Topics Addressed	Questions
Water Resource Specialists:	Hydrological Data and Analysis	1. What hydrological data sources were used for the project's design? (e.g., historical flow records, seasonal and annual variability studies) 2. What scenarios are considered regarding water availability during drought and/or flood conditions?
	Monitoring and Adaptive Management	3. What hydrological monitoring systems are currently in place? Are there automated systems or manual checks? 4. How frequently are hydrological data reviewed and reported? 5. Have any unexpected hydrological changes been observed since you operated the structure?
	Climate Change and Future Resilience	6. How does the structure documentation account for potential climate change impacts on hydrology? 7. Are there contingency plans in place for extreme events (e.g., prolonged droughts, severe floods)?
Environmental Experts	Ecosystem Impacts:	1. How are ecological needs, such as seasonal flows for fish spawning or maintaining wetland habitats, considered in the flow management plan? 2. What studies have been conducted to understand how changes in flow affect local biodiversity?
	Cumulative Impacts	3. Are there other water-intensive projects in the basin? How is cumulative impact considered in hydrological planning?
	Community engagement	4. Have downstream communities expressed concerns regarding water flows due to structure functioning? Are these addressed? If yes, how? 5. Are there mechanisms in place for communities to report issues related to water availability or quality?
Local stakeholders	Water availability	1. Have there been any changes in water availability or quality due to the structure's existence? 2. Have there been instances when, due to structure operation, there were water restrictions that impacted water use?
	Environmental Flows	3. Are you aware of any efforts the project makes to ensure river health or environmental flows? Are these measures adequate from your perspective?
	Communication and solution of issues	4. Are there mechanisms in place for communities to report issues related to water availability or quality? 5. Are discussions with owners of the structure taking place?

Table 2. *Cont.*

Interviewed/ Checked Documentation	Topics Addressed	Questions
Documents availability	Hydrological Studies and Flow Data	- Historical Flow Records: Data showing historical water levels and flow patterns over time, including seasonal and annual variability. - Flow Forecasting Models: Models predicting future water availability under various climate scenarios. - Flood and Drought Management Plans: Protocols for managing high and low flow events, particularly in relation to downstream impacts.
	Monitoring and Reporting Protocols	- Hydrological Monitoring Plans: Documentation on systems and frequencies for flow and quality monitoring, including the use of any sensors or automated systems. - Annual Hydrological Reports: Reports summarizing flow data, - Incident Reports: Records of any significant hydrological events (e.g., droughts, floods) and the structure's operation for it.
	Climate adaptation and resilience plans	- Climate Change Impact Assessments: Studies addressing how changing climate patterns could impact the availability of flow and structure's function - Adaptation Strategies: Plans outlining how the structure would respond to anticipated climate-related changes to hydrology.
	Stakeholder engagement	- Consultation Records: Meeting minutes or records from engagements with communities and other stakeholders concerning the structure's operation with the purpose of flood protection. - Complaints and Resolution Records: Documentation of any concerns raised by stakeholders related to the operation of the structure and how these were resolved.

2.3. Study Areas

In Romania, historical records indicate that floods account for the majority of disasters, impacting property, infrastructure, human safety, and economic activities [20,21]. Romania's flood risk strategy is comprehensive, tackling the dual challenges of aging infrastructure and the opportunities offered by new developments. By integrating traditional engineering methods with modern technologies and natural solutions, the country seeks to boost its flood resilience, safeguard communities, and support economic growth. This multi-faceted approach includes upgrading old levees, diversion channels, dams, and drainage systems to meet contemporary standards, ensuring they can handle increased rainfall and extreme weather events driven by climate change [22].

One of the most important policies regarding flood risk is the European Flood Directive, which requires that old structures are assessed regularly, not only for safety but also for sustainability [23]. In this context, Romania is constantly applying and revising its regulatory frameworks to ensure that all flood risk management activities adhere to safety and environmental standards [24,25].

A tool for prioritizing which flood protection structures need improvement is beneficial not only to Romanian Waters but also to all stakeholders involved. Therefore, two old structures were selected for evaluation with mHSAP.

2.3.1. The Timis–Bega Canal System

The transboundary Timis–Bega basin (Figure 2), located mainly in the Banat region of Romania, has a long history of recurrent flooding events. Significant flood events have occurred periodically in the last century, with the highest flow rate recorded at approximately 1600 m^3/s in May 1912. The most recent major flood, in 2005, peaked at 1200 m^3/s but lasted longer, resulting in a greater overall flood volume. Factors contributing to the frequent occurrence of floods in this area include inadequate natural drainage due to the flat topography, climate conditions, and hydrological characteristics [26,27].

Over the past few centuries, various technological measures have been implemented to mitigate both drought and flood hazards in the Timis–Bega region. The Timiș–Bega Canal System is the most crucial infrastructure for protecting the city of Timișoara. It regulates the water flow of the Timiș and Bega rivers to mitigate flood risks and safeguard the city. Additional flood protection measures include developing canal networks, constructing diversion dikes and temporary (non-permanent) reservoirs, and correcting river tracks and levees [28,29], all presented schematically in Figure 3.

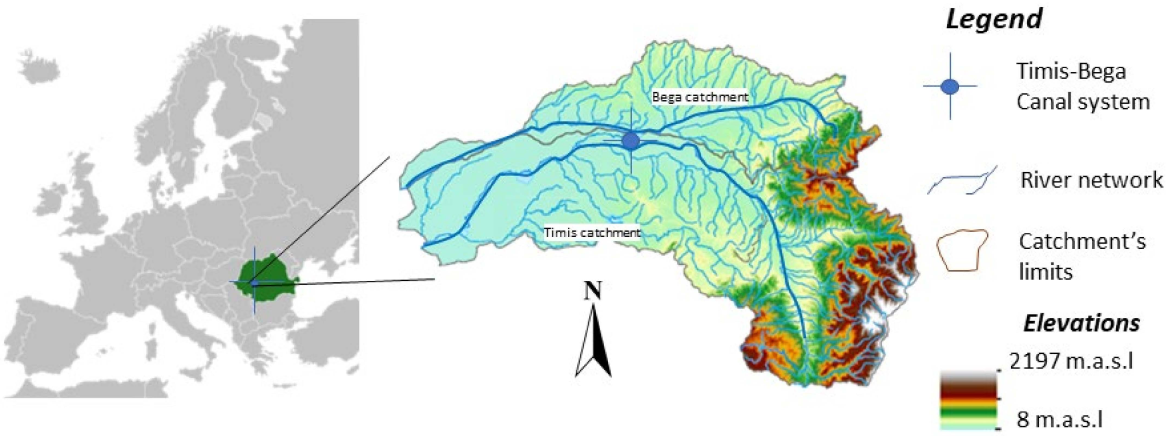

Figure 3. The Timis–Bega catchment.

The Timiș–Bega Canal system, built in 1757, consists of one gated gravity-based water flow diversion channel connecting the Bega to the Timiș River at Topolovăț, and the other a diversion channel connecting the Timiș with the Bega at Coștei, where there is a dam on Timis (see Figure 3).

During droughts in the Bega River, water from the Timiș River flows towards the Bega, ensuring a water supply to Timișoara. Conversely, when the Bega River experiences flooding, water is diverted to the Timiș River to protect the city from flood risk. Figure 4 shows a view of the canal at Topolovat, at the gate (a), and downstream of the gate (b).

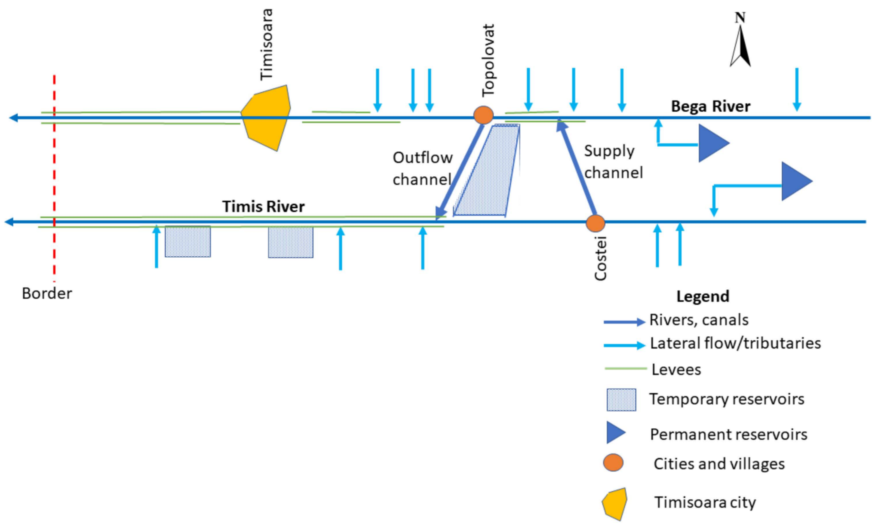

Figure 4. The flood protection measures along Timis–Bega, with a highlight of the protection canal system.

The flood protection works are owned by the National Administration "Romanian Waters", and the operating unit is the Banat Water Basin Administration.

2.3.2. The Deva City Dike Protection System

Deva, a city situated in the Hunedoara County of Romania, is known for its rich history and cultural significance. However, like many other regions and cities in Romania, Deva has not been immune to natural disasters, particularly floods [30,31]. The Mureş River forms the northern boundary of the city of Deva over a length of approximately 5 km. The Mureș River basin, partially represented in Figure 5, is surrounded by hills, making the city prone to heavy rainfall and subsequent river overflow. Historical records indicate that Deva has experienced multiple flooding events, with some of the most notable occurring in the 20th and early 21st centuries. One of the earliest recorded significant floods in Deva occurred in 1910, causing substantial damage to infrastructure and houses. The floodwaters, driven by intense rainfall, led to the overflowing of the Mureș River, inundating large parts of the city. In the 1970s, Deva was subjected to another series of floods. The 1970 flood, assessed at a 1% probability, caused significant damage, affecting buildings, economic units, institutions, and agricultural lands within the city of Deva. This event highlighted the need for better flood management and the construction of protective barriers [32]. Therefore, the "Flood Protection of the City of Deva" project was developed and implemented between 1975 and 1977.

(a) (b)

Figure 5. Timis–Bega Canal system at Topolovat; (**a**) At the Topolovat gate and (**b**) downstream of the gate.

The key components of Deva's flood protection strategy mitigating the impact of future floods are the dams and reservoirs on the Mureș River (Figure 6) and the reinforcement of riverbanks with levees [33]. Structurally, the flood protection closest to Deva city consists of an earth dike, with an average height of 5 m, a crest width of 4 m, and a sealing system featuring a clay core. It consists of two sections with a total length of approximately 8.8 km. The levee is situated on the left bank of the Mureş River and aims to protect the city of Deva from floods caused by the overflow of the river (Figure 7). There are two sections of the dike: Section 1, approximately 2.5 km long, which serves as a backwater dike, and Section 2, which is a longitudinal dike equipped with a berm. Figure 8 shows an overview of the dike.

The flood protection works are owned by the National Administration "Romanian Waters", and the operating unit is the Mureş Water Basin Administration, Hunedoara Water Management System.

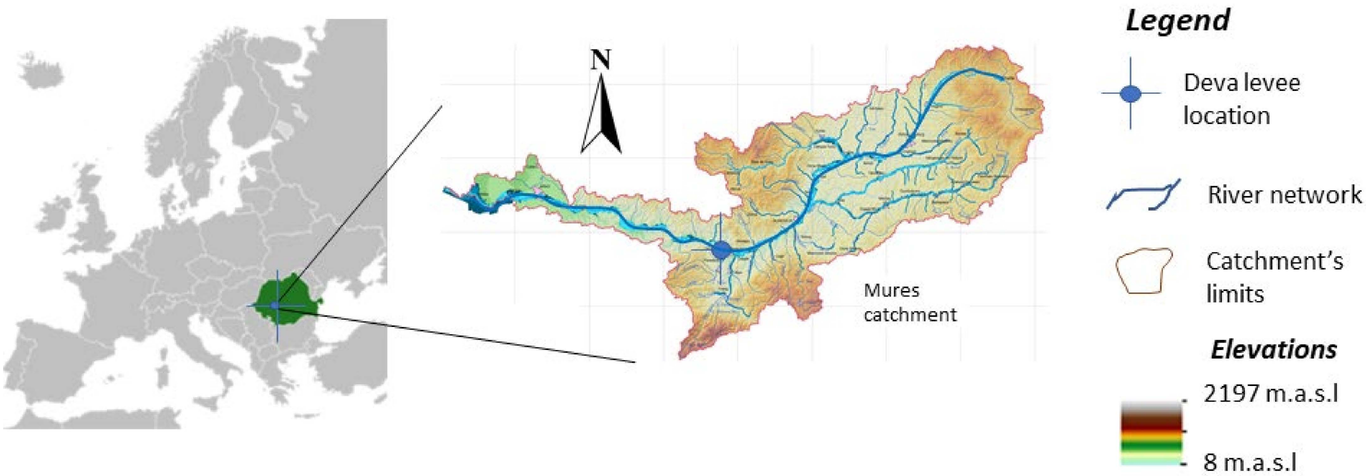

Figure 6. The Mures catchment.

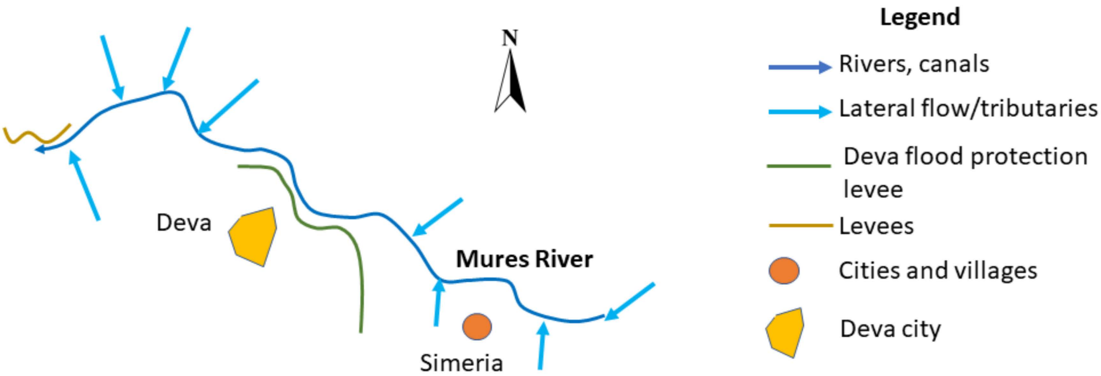

Figure 7. Schematic of flood protection levee near Deva city.

Figure 8. View of Deva flood protection levee.

3. Results and Discussion

For each of the case studies, an mHSAP evaluation was carried out by conducting interviews with operators of the structures, with the Romanian Waters Authority, and with visits onsite to evaluate the status of the structures. Several stakeholders who benefit from the existence of these structures have been contacted, and an open discussion about the benefits of the structures took place. The scoring values used for assessment were based on the best practices level for the specific evaluated criterion, as presented in Section 2.2.

The scores obtained for each of the case studies are presented in Table 3 and represented as rosettas in Figure 9.

Table 3. The scoring values for the studied cases.

Sustainability Aspect	mHSAP Considered Sustainability Criteria	Scoring Level *	
		The Timis Bega Canal System	The Deva Levee
Technical	Hydrological Resource (HR)	4	n.e.
	Infrastructure Safety (IS)	5	3
	Asset Reliability and Efficiency (ARE)	n.e.	3
Environmental	Environmental and Social Impact Assessment (EIA) and Management	3	4
	Erosion and Sedimentation (ES)	2	3
	Water Quality (WQ)	n.e	n.e.
	Downstream Flow Regimes (EF)	5	n.e.
	Biodiversity and Invasive Species (BIS)	n.e	n.e.
	Climate Change Mitigation and Resilience (CCMR)	2	2
Social	Communications and Consultation (CC)	2	3
	Project Benefits (PB)	n.e	4
	Public Health (PH)	5	5
	Labor and Working Conditions (LWC)	4	4
Economic	Financial viability	n.e	4
	Economic viability	n.e	4
	Governance (G)	3	3
	Integrated Project Management (IPM)	3	2

* n.e—not evaluated.

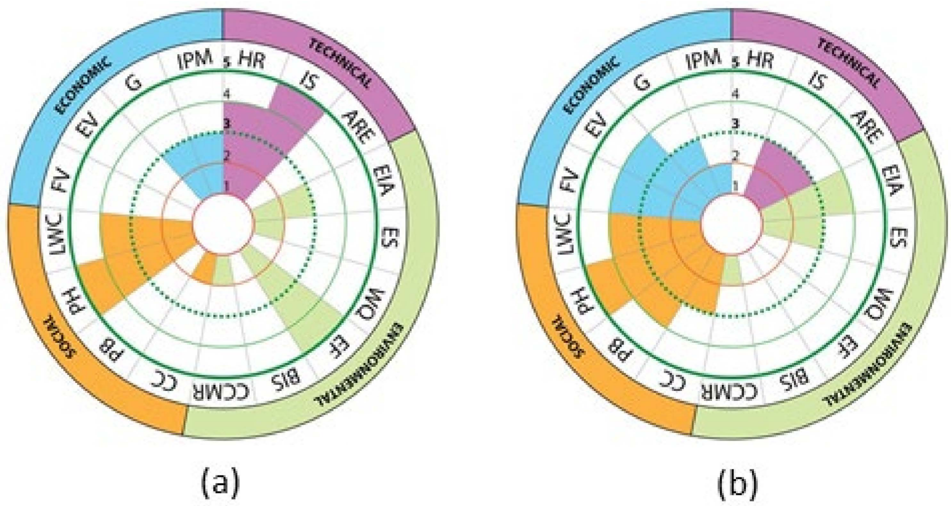

Figure 9. The rosetta of (**a**) Timis–Bega Canal and (**b**) Deva levee.

The results and discussion are further presented in detail for the most important aspects related to an old in-operation structure.

3.1. Hydrological Regime

The Hydrological Regime (HR) scoring for the Timis–Bega canal system (TBS) was 4, indicating a good level of information availability. A comprehensive series of data sources are accessible at Water Administration Banat, ABA Banat, providing detailed inflow hydrographs and rainfall analysis for the Timis–Bega River. The region benefits from a dense hydrographic measuring station network that delivers timely information complemented by prognosis and synthetic hydrographs. This robust data collection system enables effective monitoring and management of the canal system.

Despite the wealth of information available, there are areas for potential improvement. Studies correlating measured water levels with discharge values would be a valuable addition to the existing data set, especially in light of climate change challenges. Such studies could provide more accurate predictions of water behavior under various scenarios, enhancing the system's adaptive capacity. It is important to mention that while estimations of future climate change scenarios are available at the national central level, there is a lack of localized projections at the local administration level. Developing these local climate models could significantly improve long-term planning and risk management for the TBS.

In contrast, the Hydrological Regime analysis for the Deva levee (DL) was conducted at the level of the Mures catchment rather than specifically for the 8 km long dike. This broader approach, while providing a general understanding of the hydrological conditions, may not capture the nuanced hydrological dynamics directly affecting the levee. A more focused analysis of the immediate area of the DL could provide valuable insights for its management and maintenance.

3.2. Infrastructure Safety and Maintenance

Regarding infrastructure safety, the TBS demonstrates exemplary practices. It is very well documented and maintained, reflecting a proactive approach to infrastructure management. This level of attention not only ensures the current effectiveness of the system but also facilitates informed decision-making for future improvements or adaptations.

The Deva levee presents a more complex picture. Visual inspection indicates that the dike is well maintained, suggesting regular upkeep and attention to surface-level issues. However, there are notable gaps in the available documentation. The absence of records regarding calculations of structural strength raises concerns about the long-term stability and resilience of the levee. Furthermore, the expert evaluation, which is required for assessing the overall condition and safety of such structures, has only been conducted for a portion of the dike. This partial evaluation leaves uncertainties about the condition of the entire structure.

3.3. Erosion and Sedimentation Management

The erosion and sedimentation management for the DL is primarily conducted through regular visual inspections. Reports from these inspections do not indicate any significant problems, suggesting good maintenance practices for the dike. However, there is room for improvement, particularly in the implementation of advanced monitoring technologies. The introduction of sensors for dike erosion during flood events could significantly enhance the real-time monitoring capabilities and early warning systems.

In contrast, the TBS scores are lower in this aspect. The best practice is not yet achieved due to limitations in measurement techniques. Currently, measurements of solid flow are only conducted for suspended flow, neglecting the dragged flow. This limitation is attributed to a lack of appropriate programs and technology. To improve this score and overall management, investments in advanced measurement technologies and methodologies are necessary.

3.4. Climate Change

Climate change emerges as a criterion requiring significant improvement for both the TBS and DL. While both structures have demonstrated resilience during past devastating floods with very high discharge values, there is a notable lack of forward-looking climate change studies. At present, clear climate change estimations for the analyzed cases are not available, nor are there any measurements of gas emissions from these structures. This gap in climate-related data and projections represents a critical area for improvement to ensure the long-term sustainability and adaptability of these flood protection systems.

3.5. Communication and Stakeholder Engagement

The communication and consultancy aspects of both structures show room for improvement. While there are established communication policies and procedures, given by rules and regulations at the country level and at ANAR, the two structure's owners primarily send hazard announcements. Stakeholder involvement lacks a structured, planned approach. This area requires significant enhancement to ensure comprehensive community engagement and transparency in flood protection management. Despite these shortcomings, other social aspects of sustainability are well achieved and documented, adhering to national policies and European Union regulations.

3.6. Integrated Project (Structures) Management

In terms of IPM, the Banat administration demonstrates good management practices for the TBS. Regular certification processes are in place, including tests on gate operations and water flow management. The canals are well-maintained, reflecting a proactive approach to infrastructure maintenance.

The DL structure, while possessing the Romanian Water authorization for functioning, lacks several technical and environmental evaluations at the national level. This gap in comprehensive assessments potentially compromises the long-term sustainability and effectiveness of the levee system.

3.7. Recommendations

Based on the present analysis, several key recommendations emerge:

- Develop localized climate change projections for both the TBS and DL areas;
- Conduct comprehensive structural strength calculations for the entire length of the DL;
- Extend expert evaluations to cover the full extent of the DL;
- Implement studies correlating water levels with discharge values for the TBS, considering climate change scenarios;
- Standardize documentation and evaluation processes across all old and new flood protection infrastructures to ensure consistent, high-quality management practices;
- Erosion monitoring is important, particularly for the DL. In order to determine the type of erosion [34] and the effect of potential remediation solutions for erosion [35], it is advised that specialized knowledge is developed at ANAR. Moreover, investment in advanced technologies for monitoring is required;
- Enhance solid flow measurement capabilities for the TBS, including dragged flow measurements;
- Develop and implement a structured stakeholder engagement plan for both TBS and DL.

By addressing these points, both the Timis–Bega Canal System and the Deva Levee can be better prepared to face future challenges, ensuring their continued effectiveness in flood protection while adhering to principles of sustainability and resilience. This comprehensive approach to infrastructure management will not only enhance the safety of local communities but also contribute to the broader goals of sustainable water resource management in the face of climate change and increasing urbanization.

4. Conclusions

The current analysis shows that there are many tools available that can be used to assess a flood risk long-term operated structure for sustainability. All findings are useful and potentially can support water decision-making, leading to more resilient and sustainable water resource management.

Conducting a sustainable analysis of old infrastructure for flood risk mitigation is very important. This process helps identify both the strengths and weaknesses of existing structures, ensuring they meet current safety and performance standards [36]. Such analysis often reveals potential vulnerabilities and areas that require immediate attention, not only at the structural level but also at the governance level. By highlighting these critical aspects, decision-makers can prioritize interventions and allocate resources more effectively, enhancing the overall resilience of flood protection systems.

Given the historical importance of the Timis–Bega canal system, these evaluations provide valuable insights into the cultural significance of the infrastructure, guiding preservation efforts. They ensure that, while modernizing to meet contemporary flood protection needs, the historical integrity and cultural heritage of the infrastructure are maintained. This balance between modernization and preservation is crucial for maintaining the cultural identity of regions while ensuring the safety and well-being of communities.

It is worth noting that a new innovative method has been employed for evaluating extremely old flood risk structures. While the method itself is not entirely new, its application to these historical flood protection systems represents a novel approach. This methodology adapts existing sustainability assessment frameworks to the unique challenges posed by aging flood protection infrastructure, providing a more nuanced and comprehensive evaluation of these critical systems.

The implementation of the approach presented here allows for a more detailed understanding of how these historical structures perform against modern sustainability criteria. The method takes into account not only the structural integrity and flood protection capabilities but also factors such as environmental impact, social benefits, and long-term economic viability. This holistic assessment provides decision-makers with a more complete picture of the infrastructure's current state and future potential, enabling more informed and sustainable management decisions.

By utilizing this innovative, adapted methodology, we can bridge the gap between historical flood protection practices and contemporary sustainability requirements. This approach not only helps preserve valuable cultural heritage but also ensures that these structures continue to provide effective flood protection in a changing climate and in an increasingly urban environment.

Studies, like the one carried out during this research, can help determine necessary updates to the structures, such that, in time, the maintenance costs are reduced and the environmental impact is minimized while still serving the flood risk mitigation purpose for which they have been designed.

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