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ENHANCING CLIMATE RESILIENCE OF HYDROPOWER INFRASTRUCTURE IN THE BLACK DRIM BASIN THROUGH NATURE-BASED SOLUTIONS

Abstract:

Climate changes in recent decades have led to an increase in hydro-meteorological hazards, posing increasing risks to hydropower infrastructure in mountainous river basins. In the Black Drim Basin, extreme precipitation, erosion, landslides, sediment transport, and debris accumulation threaten dam safety, functionality and operational reliability. This study investigates the applicability of Nature-based Solutions (NbS) as complementary measures to conventional engineering approaches for reducing hydro-meteorological risks within this hydropower system. A structured qualitative assessment framework is applied to characterize dominant hazard processes and identify potential ecosystem-based interventions. The proposed approach supports hybrid grey-green strategies as a sustainable pathway for long-term resilience and climate adaptation planning.

Keywords: hydro-meteorological hazards, nature-based solutions, hydropower infrastructure, climate resilience

Побољшање отпорности хидроенергетске инфраструктуре на климатске промјене у басену Црног Дрима кроз рјешења заснована на природи

Сажетак:

Климатске промјене у посљедњим деценијама довеле су до повећања хидрометеоролошких опасности и представљају све већи ризик за хидроенергетску инфраструктуру у планинским ријечним сливовима. У сливу Црног Дрима, екстремне падавине, ерозија, клизишта, транспорт седимента и отпада угрожавају безбједност и оперативну поузданост акумулације. Ова студија истражује примјењивост рјешења заснованих на природи као комплементарних мјера конвенционалним приступима за смањење хидрометеоролошких ризика у оквиру овог система. Примјењује се структурирани квалитативни оквир за процјену доминантних опасности и идентификовање потенцијалних интервенција заснованих на екосистему. Предложени приступ подржава хибридне сиво-зелене стратегије као одрживи пут за дугорочну отпорност хидроенергије и планирање климатских прилагођавања.

Кључне ријечи: хидрометеоролошке опасности, рјешења заснована на природи, хидроенергетска инфраструктура, климатска отпорност.

1. INTRODUCTION

Climate change is progressively altering precipitation regimes, leading to more frequent and intense droughts and extreme rainfall events across the Western Balkans. These changes are increasingly affecting critical infrastructure systems, particularly those located in mountainous catchments, such as concrete and earth-fill dams, bridges and hydropower systems. These assets are highly sensitive to hydro-meteorological hazards (HMHs), including flooding, erosion, sedimentation, landslides, and debris transport, which threaten their long-term performance, operational reliability and structural integrity [1], [2], [3]. Recent studies highlight that infrastructure networks are becoming increasingly exposed to multi-hazard and cascading effects, particularly in complex geomorphological environments where hydrological and geotechnical processes interact [2].

Under these evolving climatic conditions, conventional grey engineering solutions continue to serve as the dominant protective approach. While effective in providing immediate and localized protection, they often exhibit limited adaptability to non-stationary climate conditions, require continuous maintenance, and may result in negative environmental impacts [1], [3]. Moreover, purely engineered solutions may exhibit limited performance under extreme or compound hazard scenarios, emphasizing the need for more flexible and adaptive approaches [4]. In this context, Nature-based Solutions (NbS) have emerged as a complementary and sustainable strategy for enhancing infrastructure resilience. NbS utilize ecosystem functions to mitigate hydro-meteorological risks while simultaneously delivering co-benefits such as biodiversity enhancement, carbon sequestration, and improved ecosystem services [5], [6], [7].

Hydro-meteorological hazards represent nearly 90% of global disaster events in recent decades, resulting in substantial economic losses and long-term societal consequences [1], [8]. Climate change and the intensification of the hydrological cycle further amplify these risks, increasing both hazard frequency and magnitude [2], [3]. In mountainous river basins, these processes are often interconnected, leading to cascading effects such as erosion-induced landslides, sediment transport, and debris accumulation, which directly affect reservoir functionality and the operational reliability of hydropower systems [2], [9]. Consequently, infrastructure systems require adaptive, scalable, and evidence-based resilience strategies capable of addressing multi-hazard environments.

The conceptual evaluation of NbS applicability requires structured and integrative approaches that consider hazard characteristics, local conditions, infrastructure exposure and operational constraints. Recent frameworks emphasize the importance of multi-criteria and multi-scale approaches that integrate engineering and environmental dimensions [7], [9], [10]. Advances in monitoring technologies, such as satellite-based interferometry and structural health monitoring, further support the evaluation of infrastructure performance and NbS effectiveness over time [11]. However, the effectiveness of NbS remains highly site-specific and depends on local geomorphological, hydrological, ecological and operational conditions.

In this context, hybrid grey-green approaches, combining conventional engineering measures with NbS, have been increasingly recognized as a promising pathway toward climate-resilient infrastructure. Such integrated solutions enable the reliability of engineered systems to be complemented by the adaptability and long-term benefits of ecosystem-based interventions, providing improved performance under uncertain and changing climatic conditions [4], [10]. This approach is particularly relevant for complex infrastructure systems exposed to multiple hazards, where single-solution strategies are often insufficient.

This study applies a structured qualitative assessment framework across seven selected infrastructure locations within the Black Drim catchment, representing diverse asset typologies and hydro-meteorological hazard conditions. The assessment is conducted within the framework of the NATURE-DEMO project (HORIZON-MISS-2023-CLIMA-01-02, Grant No. 101157448), which aims to deploy, monitor and evaluate NbS performance across multiple demonstrator regions. The selected locations were identified in cooperation with the hydropower system operator based on observed hazard occurrence, operational relevance, accessibility and representativeness of different hazard typologies within the catchment. The applied approach builds upon the NbS classification and selection principles defined in the NATURE-DEMO catalogue [12], ensuring consistency in linking hazard types with appropriate ecosystem-based interventions. The multi-location assessment illustrates how NbS concepts may be adapted to varied infrastructure and geomorphological conditions within the hydropower system.

In this study, the seven selected sites include hydropower facilities, erosion processes and slope-sensitive structures exposed to varying combinations of hydro-meteorological threats. For each site, dominant hazard conditions and potentially exposed infrastructure elements are qualitatively identified with potentially applicable NbS measures. Furthermore, for one selected location, a preliminary implementation concept and site-specific SWOT analysis are presented as an illustrative example of NbS planning within the broader catchment assessment. By systematically linking hazard processes, infrastructure performance and ecosystem-based interventions, the study provides an integrated perspective on the application of NbS. The results contribute to supporting climate adaptation planning and the further development of quantitative, risk-informed NbS strategies for resilient infrastructure systems.

2. STUDY AREA AND PROBLEM DESCRIPTION

The Black Drim Hydroelectric System in North Macedonia includes the Shpilje and Globochica dams (Figure 1). It represents the largest hydroelectric power system in the Black Drim River basin and serves as a key source of electricity production for the western part of the country. The system relies on water inflows from both the Black Drim and Radika Rivers, whose hydrological regimes are increasingly influenced by climate variability and changing precipitation patterns.

Figure 1. Shpilje Dam (left) & Globochica Dam (right) (photography by author).

Climate change is causing more intense and unpredictable precipitation events in this region, leading to increasing hazards like erosion, landslides and floating waste transport (Figure 2, Figure 5). These processes can obstruct the intake tunnel, reduce reservoir capacity through sediment deposition, increase mechanical wear on equipment and interrupt hydropower production [13], [14]. In addition, slope instability and erosion processes may affect adjacent critical infrastructure assets, including access roads surrounding the facility.

A) Location 2

B) Location 3

C) Location 4

D) Location 5

Figure 2. Climate change induced hazards at Black Drim catchment area (photography by author).

The climate effects influence the intensity and frequency of drought and intense precipitation (rain/snowfall) events, which can further contribute to instabilities of hydropower production. Under extreme conditions, progressive soil disintegration, washouts, landslides and rockslides may also threaten the stability and operational safety of dam structure itself. Consequently, the Black Drim catchment represents a relevant case study for examining the practical application of NbS in reducing such hydro-meteorological hazards.

Exposure of the dams and catchment basin to climate threats can lead to two main repercussions: (a) reduction or halt of power production and (b) cut-off of transportation routes for the nearby population. In this study, NbS measures such as afforestation, vegetation-based slope stabilization, bioengineering techniques and sediment control interventions are considered as potential approaches for reducing erosion, landslide susceptibility, debris transport and surface runoff. These measures may contribute to improving slope stability, reducing sediment inflow toward reservoirs and supporting the long-term resilience of the critical infrastructure assets and the nearby transport network. The proposed NbS may also provide environmental co-benefits, including ecosystem restoration, biodiversity enhancement and improved water retention capacity. The approach supports the integration of conventional grey engineering measures with ecosystem-based strategies within climate adaptation planning for critical infrastructure systems.

3. HAZARD IDENTIFICATION AND SITE-SPECIFIC NBS SELECTION

The scope of the study is focused on the conceptual identification and matching of NbS measures with dominant hazard processes. Hazard identification was performed through a combination of field observations, review of existing technical documentation, historical information provided by the operator and expert judgement of the multidisciplinary project team. The assessment considered the dominant hydro-meteorological and geomorphological processes affecting the selected locations, including erosion, landslides, rockfall, sediment transport, debris accumulation, and wildfire exposure.

3.1. DESCRIPTION OF THE LOCATIONS WITHIN THE BLACK DRIM HYDROPOWER SYSTEM

Within the Black Drim hydropower system, seven representative locations have been identified for targeted assessment (Figure 3). These locations reflect different hazard typologies, critical infrastructure assets, geographical management zones and operational responsibilities. The selected sites illustrate the diversity of hydro-meteorological risks affecting the catchment area and provide a basis for evaluating the potential applicability of NbS.

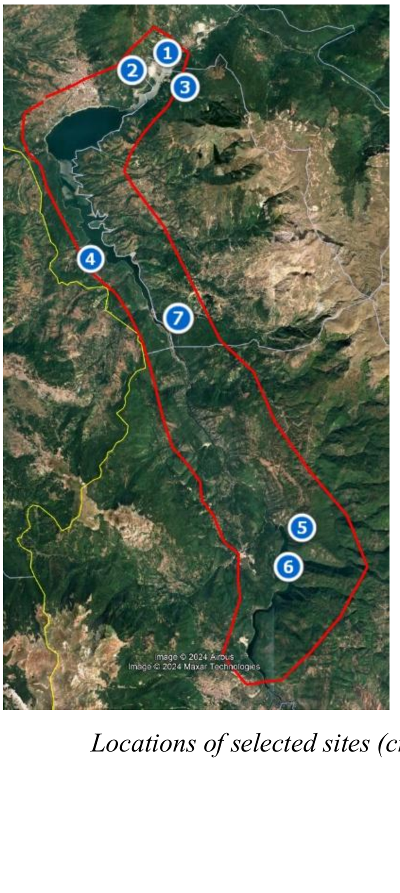

Figure 3. Locations of selected sites (created by author).

3.1.1. Location 1

Location 1 comprises reservoir-adjacent slopes exposed to erosion, landslides and rockfall processes (Figure 4). The steep terrain surrounding the accumulation is highly sensitive to intense precipitation, snowmelt, and surface runoff, which accelerate soil detachment and sediment transport. Progressive slope instability increases the risk of mass movements entering the reservoir, contributing to sedimentation and potential localized wave generation and sediment influx that may affect nearby hydraulic structures and reservoir operation.

Figure 4. View of Location 1 (photography by author).

The primary infrastructure assets at risk include reservoir banks, access roads and nearby hydropower-related facilities. Geographically, this site represents a slope-reservoir interaction zone where geomorphological processes directly influence storage capacity and operational safety. Without stabilization measures, continued erosion may reduce reservoir volume and compromise long-term functionality.

Grey engineering measures have been undertaken in the past by installing concrete frame retaining structures - Herkulice - at two separate positions along the slope. Due to lack of maintenance and aging of the structures, their function is limited.

3.1.2. Location 2

Location 2 is characterized by sediment deposition and chemically abrasive processes affecting reinforced concrete structural elements, including bridge components (Figure 2a). Fluvial transport of suspended and dissolved materials, including gypsum-rich sediments, can lead to abrasion, deposition and long-term material degradation.

The critical assets at risk include bridge columns and foundations, reservoir structures and hydraulic elements exposed to fluctuating water levels. This site functions as a hydraulic-structural interface zone, where both geomorphological and chemical processes influence infrastructure durability. Progressive sedimentation further reduces effective reservoir capacity, affecting flood control and hydropower efficiency.

3.1.3. Location 3

Location 3 includes a mountainous road segment of an international road corridor exposed to landslides, rockfall and progressive slope deformation (Figure 2b). Intense rainfall, rapid snowmelt, and surface runoff destabilize slope materials, particularly in areas affected by deforestation or inadequate drainage systems.

The main infrastructure assets at risk are road embankments, pavement structures, retaining elements and drainage systems. This zone represents a transport infrastructure management area where slope instability may lead to traffic disruption, economic losses and safety risks. Recurrent mass movement processes may gradually reduce the structural reliability of road infrastructure and increase maintenance demands.

3.1.4. Location 4

Location 4 corresponds to areas within the reservoir influenced by fluvial sediment transport from the adjacent mountain and underwater erosion processes (Figure 2c). During high-flow events, significant quantities of sediment are transported into the reservoir, leading to progressive deposition.

The affected infrastructure includes the reservoir storage system. Sediment accumulation reduces effective storage volume, decreases reservoir regulation efficiency and may reduce turbine operational performance through increased sediment abrasion and intake obstruction. This location represents a hydrological management zone where catchment-scale processes directly affect operational performance.

3.1.5. Location 5

Location 5 is situated at the vicinity of Globochica Dam and is primarily exposed to rockslide, landslide and slope instability hazards (Figure 2d). Steep rock formations adjacent to hydraulic structures present a risk of block detachment and potential obstruction of spillway discharge capacity.

The critical asset at risk is the spillway system, which plays a fundamental role in flood regulation and dam safety. Obstruction during extreme hydrological events could significantly increase overtopping risk and hydraulic loading on the dam structure. This area represents a dam safety management zone where slope stability is directly linked to hydraulic reliability.

In the past, retaining walls and protective wire meshing were implemented on the lower steeper slope surface that partially solved the erosive processes. However, recent evaluations have identified the upper slope as a significant hazard for the operational reliability of the hydropower system due to its influence on the operational capacity of the dam and the adjacent infrastructure assets.

3.1.6. Location 6

Location 6 is characterized by debris flow processes transporting sand, woody material and anthropogenic waste toward the reservoir during intense rainfall events. Steep upstream catchment areas combined with deforestation and uncontrolled land use increase debris yield.

The main assets at risk include spillways, intake structures and mechanical components of the hydropower system. Debris accumulation may obstruct intake and spillway flow paths, reduce turbine performance and increase mechanical wear. This location represents a dynamic catchment–hydropower interface zone where upstream processes directly impact infrastructure safety and efficiency.

Figure 5. View of Location 6 (photography by author).

3.1.7. Location 7

Location 7 comprises the high-voltage transmission line corridor within the Black Drim hydropower system, representing a critical component of the regional energy supply network. This infrastructure is exposed primarily to climatological and meteorological hazards, including blizzards, cold waves, strong winds, and wildfires.

During winter periods, intense snowfall combined with strong winds can lead to ice accretion on conductors and towers. Ice loading increases tensile forces in cables and structural demand in pylons, potentially resulting in mechanical damage, conductor sagging or even collapse in extreme cases. Cold waves further exacerbate material brittleness and may affect structural connections and foundation performance, particularly in mountainous terrain where temperature gradients are significant. In contrast, summer months present elevated wildfire risk due to prolonged droughts, high temperatures and dense vegetation in the corridor zone. Wildfires can damage tower foundations, compromise steel elements through thermal exposure and reduce insulation performance of conductors. Additionally, vegetation encroachment increases the probability of flashovers and short circuits during wind events. Strong winds and storms pose an additional hazard by inducing dynamic loading on towers and conductors, increasing the risk of structural instability or progressive failure along the line.

From a geographical management perspective, Location 7 represents a linear infrastructure zone crossing forested and mountainous areas, where hazard exposure varies significantly along the corridor. The interaction between climatic extremes and surrounding vegetation makes this location particularly sensitive to compound hazard scenarios.

3.2. CONCEPTUAL HAZARD MAPPING AND NBS SELECTION

Table 1 provides a structured overview of the relationship between identified hydro-meteorological hazards and a portfolio of potential NbS applicable across different locations within the Black Drim system. Rather than prescribing a single intervention per hazard, the table illustrates the diversity and flexibility of ecosystem-based measures that can be considered depending on local conditions and implementation feasibility.

The proposed NbS measures were selected based on the hazard-specific applicability principles defined within the NATURE-DEMO NbS catalogue [12] and the systematic framework proposed by Kuschel et al. [9]. The selection comprises a comprehensive set of 74 NbS with the potential to mitigate the specific hazard types defined in the project's classification system via an extensive NbS-hazard matrix. The approach emphasizes the relationship between hazard processes, site characteristics and the intended protective function of each intervention.

Table 1. Summary table with description of the 7 identified locations within the Black Drim catchment area and the possible NbS types

Locations	NH	Possible NbS types w/ full name and code
Location 1	Sheet erosion and rill erosion	Terracing – slope shaping (SE1) Vegetated biodegradable erosion control mats and blankets (SWB3) Afforestation and reforestation (FW1)
	Large rockfall (d>25-100 cm)	Avalanche mounds (SE3) Terracing (SE1) Afforestation and reforestation (FW1)
	Debris flow	Live fencing (SWB6) Terracing – slope shaping (SE1)
	Landslides <2m depth	Terracing – slope shaping (SE1) Afforestation and reforestation (FW1)
	Fluvial sediment transport	Afforestation and reforestation (FW1)
	Small rockfall (d<25 cm)	Avalanche mounds (SE3) Terracing – slope shaping (SE1) Afforestation and reforestation (FW1)
Location 2	Sheet erosion and rill erosion	Terracing – slope shaping (SE1) Vegetated biodegradable erosion control mats and blankets (SWB3) Afforestation and reforestation (FW1)
	Soil slope deformation and soil creep	Terracing – slope shaping (SE1) Vegetated log/stone barriers and live/rock check dams (SWB19)
	Small rockfall (d<25 cm)	Terracing – slope shaping (SE1) Afforestation and reforestation (FW1) Vegetated log/stone barriers and live/rock check dams (SWB19)
Location 3	Landslides >10m depth	Terracing – slope shaping (SE1)

		Vegetated biodegradable erosion control mats and blankets (SWB3)
	Large rockfall (d>25-100 cm)	Avalanche mounds (SE3) Vegetated biodegradable erosion control mats and blankets (SWB3)
	Sheet erosion and rill erosion	Vegetated biodegradable erosion control mats and blankets (SWB3) Afforestation and reforestation (FW1)
	Small rockfall (d<25 cm)	Terracing – slope shaping (SE1) Vegetated biodegradable erosion control mats and blankets (SWB3)
Location 4	Debris flow (volumetric sediment concentration > 40%)	Brush mattress (SWB17) Vegetated crib wall – fascine-based design (SWB15)
	Soil slope deformation and soil creep	Vegetated biodegradable erosion control mats and blankets (SWB3) Afforestation and reforestation (FW1)
	Fluvial sediment transport	Vegetated biodegradable erosion control mats and blankets (SWB3) Live fencing – for slope engineering (SWB6)
Location 5	Sheet erosion and rill erosion	Vegetated biodegradable erosion control mats and blankets (SWB3) Vegetated biodegradable erosion control meshes (SWB2) Afforestation and reforestation (FW1) Hydro-and mulch seeding (SWB1)
	Large rockfall (d>25-100 cm)	Terracing – slope shaping (SE1) Reinforced soil and earth packs – vegetated (SE5) Vegetated log/stone barriers and live/rock check dams (SWB19) Afforestation and reforestation (FW1)
	Fluvial sediment transport	Vegetated crib wall – layer-based design (SWB15) Live staking (SWB5) Live layered techniques (SWB8)
	Small rockfall (d<25 cm)	Terracing – slope shaping (SE1) Vegetated log/stone barriers and live/rock check dams (SWB19) Afforestation and reforestation (FW1)
Location 6	Debris flow (volumetric sediment concentration > 40%)	Groynes – vegetated (RW6)
Location 7	Wildfire (forest fire or bush fire)	Firebreaks and firestrips (FW6)
	Extreme cold temperatures (cold wave)	Protection forest management (FW2)
	Sheet erosion and rill erosion	Vegetated biodegradable erosion control mats and blankets (SWB3)

A single hazard type can often be addressed through multiple NbS approaches. For instance, erosion-related processes may be mitigated through slope terracing, vegetated erosion control mats, hydro- and mulch seeding, afforestation, or various bioengineering techniques. The selection among these measures depends on several site-specific factors, including slope gradient, soil characteristics, hydrological regime, construction accessibility, maintenance requirements, and the level of stabilization needed. In steeper and more unstable environments, bioengineering measures may be combined with structural elements such as vegetated barriers or crib walls, while in less critical conditions vegetation-based stabilization alone may be sufficient.

Similarly, certain NbS interventions can simultaneously contribute to mitigating several hazard types. Afforestation and reforestation, for example, improve root reinforcement, reduce surface runoff, and enhance soil cohesion. As a result, these measures can reduce sheet erosion, shallow landslides, and sediment transport at the same time. Terracing and slope reshaping also reduce slope inclination and runoff velocity, indirectly lowering the potential for debris mobilization. This multifunctionality highlights the systemic nature of NbS, where interventions address interconnected geomorphological processes rather than isolated hazards.

Importantly, the variability observed across the different locations reflects the context-dependent nature of NbS implementation. Topographical constraints, proximity to critical infrastructure, ecological considerations, accessibility, and maintenance requirements all influence the feasibility of specific measures. In steep or spatially constrained environments, bioengineering approaches may be more appropriate than large-scale earthworks, while sediment transport within river channels may require flow-regulating and bank-stabilization interventions. Consequently, the selection of NbS measures is not determined solely by hazard type but rather by the interaction between hazard characteristics, site conditions, and practical implementation constraints.

The proposed NbS measures represent preliminary portfolio of potentially applicable interventions for the identified hazard conditions. Prioritization of measures in future project phases should include detailed geotechnical investigations, hydraulic analyses, constructability assessment, economic evaluation and long-term monitoring considerations.

4. IMPLEMENTATION CONSIDERATIONS AND PRACTICAL CHALLENGES

4.1. IMPLEMENTATION PLAN

This study presents an implementation concept for Location 5 as an example location, where slope instability and rockfall hazards present significant risks to hydropower operation and dam safety. The proposed NbS measures focus primarily on afforestation and reforestation and vegetation-based slope stabilization interventions aimed at reducing erosion, mitigating shallow slope instability and limiting rockfall susceptibility affecting the adjacent hydraulic infrastructure. These interventions aim to restore degraded vegetation cover and provide new plants within the catchment area, particularly within erosion-prone areas and drainage corridors contributing to sediment transport and surface runoff. The approach builds upon recommendations and concepts previously discussed among the main stakeholder, i.e. the hydropower system operator and aligns with earlier technical evaluations addressing long-term slope stability and sediment control in the vicinity of the dam infrastructure.

Implementation begins with a detailed site survey to identify priority zones based on slope inclination, soil condition, existing vegetation and proximity to critical infrastructure assets. The first phase involves soil preparation through hydro- and mulch seeding to support vegetation establishment and reduce surface soil displacement caused by runoff. Native tree and shrub species are proposed to ensure strong anchorage and water regulation and to complement the existing trees that already fulfil their function as rockfall and landslide protective barriers (Figure 6). Seedlings will be planted in staggered patterns following the natural topography to maximize root interlocking and minimize surface runoff.

Figure 6. The role of the existing trees as rockfall protective NbS (photography by author).

Maintenance and monitoring are integrated into long-term dam management activities, including periodic inspections of vegetation survival, root development, erosion intensity and slope stability indicators. Adaptive management allows replanting or reinforcement in zones where vegetation fails to establish. To further reduce debris flow and rock detachment, vegetated buffer strips and live staking can be established along critical slope lines. Periodic drone-based surveys may also support monitoring of vegetation development and evolving slope conditions over time.

4.2. SWOT ANALYSIS

Due to the operational importance of the spillway system and the elevated slope instability conditions at Location 5, a preliminary implementation concept and site-specific SWOT analysis were developed for this location as an illustrative example of NbS planning within the broader catchment assessment. The proximity of the unstable slope to critical hydraulic infrastructure makes this location particularly relevant for evaluating the applicability of vegetation-based stabilization and hybrid grey–green protection measures.

4.2.1. Strengths

The proposed implementation area at Location 5 corresponds to a clearly identified operational and safety-related problem affecting the Globochica Dam spillway and adjacent hydraulic infrastructure. Existing vegetation on portions of the slope already contributes partially to erosion reduction and localized rockfall mitigation, indicating favorable conditions for additional vegetation-based stabilization measures. Cooperation between research institutions and the hydropower operator ensures access to site-specific technical information, previous slope evaluations and operational observations, facilitating implementation planning and future monitoring activities. Furthermore, clearly defined ownership and administrative conditions at the site support the feasibility of future intervention works at the site.

4.2.2. Weaknesses

Challenges associated with Location 5 include the limited availability of technical NbS data and lack of previous local experience with vegetation-based stabilization measures on steep rock slopes directly above spillway infrastructure. The terrain configuration and narrow access paths significantly constrain transportation of materials, implementation logistics, and safe access for personnel. In addition, long-term monitoring data for vegetation-based stabilization measures within the catchment area are scarce, creating uncertainty regarding long-term maintenance requirements and protective effectiveness under extreme hydro-meteorological conditions. Additionally, there is limited experience among local stakeholders with both the maintenance and the long-term monitoring of NbS solutions.

4.2.3. Opportunities

Location 5 provides an opportunity to demonstrate the applicability of hybrid grey-green stabilization approaches within an operational hydropower environment exposed to hydro-meteorological hazards. Due to the direct interaction between the unstable slope and the spillway infrastructure, the site offers valuable conditions for evaluating how vegetation-based measures may complement conventional engineering protection systems. The implementation and monitoring of NbS measures at this site may contribute to the development of practical knowledge regarding vegetation-based slope stabilization in similar sites. The study also presents opportunities to attract additional resources for further enhancement and scaling-up of NbS implementation. The implemented NbS is expected to reduce risks affecting critical hydropower infrastructure, while also providing visibility of NbS benefits within a real operational context.

4.2.4. Threats

The steep and partially unstable terrain directly above the spillway structure increases implementation complexity and limits safe access for personnel, machinery, and equipment during both construction and maintenance activities. The geomorphological conditions of the site may also reduce the effectiveness of vegetation establishment in certain highly eroded or exposed rock sections. Adverse weather conditions, including intense rainfall and prolonged drought periods, may further affect vegetation survival and long-term slope stabilization performance. Delays associated with procurement procedures and the selection of specialized contractors may also affect implementation timelines. In addition, the challenging geomorphological conditions may increase project costs and require continuous long-term maintenance and monitoring efforts to ensure sustained protective performance.

5. CONCLUSIONS

This study highlights the increasing exposure of hydropower infrastructure in the Black Drin Basin to climate-induced hydro-meteorological hazards, including extreme precipitation, erosion, landslides, sediment transport and debris accumulation. These processes pose significant risks to dam safety, reservoir functionality, spillway operation and the long-term operational reliability of the hydropower infrastructure system.

The qualitative assessment presented in this study illustrates the potential applicability of NbS as complementary measures to conventional engineering approaches within mountainous hydropower environments exposed to multiple interconnected hazards. The results demonstrate that different hazard processes may be addressed through multiple NbS approaches, while individual NbS measures may simultaneously contribute to mitigating several hazard types. Measures such as afforestation, vegetation-based slope stabilization, erosion control techniques, terracing, and bioengineering interventions may contribute to reducing erosion, shallow landslide susceptibility, debris mobilization and sediment transport while also providing environmental co-benefits related to ecosystem restoration and water retention.

The study further confirms the strongly site-specific and context-dependent nature of NbS implementation, where topographical conditions, hydrological regime, accessibility constraints, proximity to critical infrastructure, and maintenance requirements influence the feasibility and suitability of different interventions.The implementation concept and SWOT analysis developed for Location 5 additionally illustrate the practical challenges associated with applying NbS measures on steep and operationally sensitive slopes directly above critical spillway infrastructure.

Overall, the study supports the integration of NbS into climate adaptation and infrastructure resilience planning for hydropower systems exposed to complex hydro-meteorological hazards. By linking dominant hazard processes with site-specific ecosystem-based interventions, the study contributes to the development of practical qualitative approaches for improving the resilience of critical hydropower infrastructure under changing climate conditions. Future work should include detailed geotechnical and hydraulic investigations, constructability assessment, long-term monitoring, economic evaluation, and quantitative performance analysis in order to support evidence-based design approaches and broader implementation of NbS strategies in similar mountainous river basin environments.

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