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A comprehensive framework tool for performance assessment of NBS for hydro-meteorological risk management

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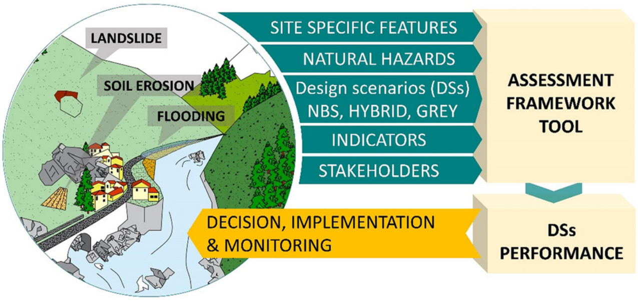
This paper describes an assessment framework tool to analyze the performance of nature-based solutions (NBS) for hydro-meteorological risk management. The tool is based on multi-criteria decision analysis within the context of NBSs, an umbrella concept currently in focus that promotes nature and provides ecological and socio-economic benefits. The proposed tool includes the selection and application of key performance indicators (KPIs) for the co-benefits and costs associated with the implementation of NBSs. To ensure high societal impact, the tool relies on a participatory approach. Stakeholder preferences are taken into account within the assessment process. As such, the assessment framework can be used as a design and selection tool for NBSs and other alternative measures, including grey and hybrid solutions. The proposed procedure can be adapted to the specific socio-environmental context and hydro-meteorological risk by tailoring the set of relevant KPIs. The assessment framework is useful for monitoring the implemented measures and to document their effectiveness. The methodology provides quantitative and transparent documentation of hydro-meteorological risk management processes, useful for decision- and policy-makers, and stakeholders dealing with NBS measures.

GRAPHICAL ABSTRACT



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Abbreviations: AF: assessment factor; BGI: Blue–Green Infrastructure; BMP: best management practice; BS: baseline scenario; CC: climate change; DRR: disaster risk reduction; DS: design scenario; EC: European Commission; EU: European Union; GI: green infrastructure; KPI: key performance indicator; LID: low impact development; LL: Living Lab; MCDA: multi-criteria decisional analysis; NBS: nature based solution; NGO: non-governmental organization; SFDRR: Sendai Framework Disaster Risk Reduction; SH: stakeholder; SUDS: Sustainable Urban Drainage System; UN: United Nations

Keywords: NBS; hydro-meteorological risk; disaster risk reduction; risk management; performance assessment; multi-criteria assessment

1. Introduction

The occurrence of extreme hydro-meteorological events such as floods, droughts, storm surges, landslides and the related damage and cost, is progressively increasing throughout Europe (McGregor, Ferro, and Stephenson 2005; Beniston 2007; Ritter *et al.* 2021; Wasko *et al.* 2021). Owing to the changing hydro-meteorological conditions and increasing land and water use, the damage induced by such water-related risks is continuously increasing (Intergovernmental Panel on Climate Change 2014).

In this context, given the high costs and the limited flexibility of traditional grey solutions for disaster risk reduction (DRR), alternative ecosystem-based measures and approaches are necessary. Interest from practitioners, policy makers and researchers is increasingly turning toward different practices and methodologies, such as Best Management Practices (BMPs, Du *et al.* 2019; Hudson *et al.* 2019), Low Impact Development Techniques (LID, D'Aniello *et al.* 2019; De Paola *et al.* 2018; Khadka *et al.* 2019; Pugliese *et al.* 2022; Shafique and Kim 2015), Sustainable Urban Drainage Systems (SUDS, Fryd, Dam, and Jensen 2012), Green Infrastructure (GI, Naumann *et al.* 2011), Blue–Green Infrastructure (Alves *et al.* 2020), Ecosystem-Based Adaptation (EbA, Secretariat of the Convention on Biological Diversity 2009), Ecological Restoration (e.g. Harris *et al.* 2006) and Ecosystem-Based Disaster Risk Reduction (Eco-DRR, Renaud, Nehren, and Sudmeier-Rieux 2016). Such methodologies allow dealing with different types of societal and environmental challenges, based on natural processes and ecosystems, and can be grouped under the more general concept of Nature-Based Solutions (NBSs) (Ruangpan *et al.* 2020; Cohen-Sachaman *et al.* 2016; Zingraff-Hamed *et al.* 2019). NBSs simultaneously provide economic, social, and environmental benefits and help build resilience as well as biodiversity (Maes and Jacobs 2015; European Commission 2020). These initiatives represent a positive and cost-efficient way of supporting DRR and adaptation to climate change (CC), while often providing significant co-benefits in terms of CC mitigation or human health, safety and well-being (Faivre *et al.* 2018). NBSs represent an effective alternative to technological strategies and involve managing systems using a comprehensive approach to sustain and potentially increase ecosystem services (Eggermont *et al.* 2015; Rowiński *et al.* 2018).

Although NBSs have proven to be effective for hydro-meteorological risk management (Sahani *et al.* 2019; Perosa, Gelhaus, *et al.* 2021; Kalantari *et al.* 2018; Debele *et al.* 2019), their uptake and level of acceptance are still limited. The need to overcome barriers related to the technical, social and cultural acceptance of NBSs for hydro-meteorological risk management calls for effective instruments for their performance assessment (Pugliese, Caroppi, *et al.* 2022). The selection, design and monitoring of NBSs entail quantitative methods capable of providing evidence of their effectiveness. Several frameworks have been recently proposed for the assessment of NBSs for different urban and environmental contexts (Liquete *et al.* 2016; Calliari, Staccione, and Mysiak 2019; EKLIPSE 2017; Raymond, Breil, *et al.* 2017; Rödl and Arlati 2022; Sowińska-Świerkosz and García 2021). Among them, Liquete *et al.* (2016) applied an MCA for the comprehensive assessment of water design projects in peri-urban areas affected by flooding and pollution phenomena. A structured procedure was proposed, composed of performance indicators and criteria, comparing a non-intervention scenario with both grey and green solutions and the pairwise comparison approach was applied to weight the criteria. The model was tested on the Gorla Maggiore (Italy) water park, according to an ex-post assessment to evaluate the benefits of an already implemented measure. The NBSs aimed at limiting the flooded areas, by improving the ecological status of the Olona River and fostering biodiversity and residents' livelihoods in the area. The ex-post analysis identified the green solution as the most effective alternative, despite the higher investment and construction costs. Indeed, the NBS measure returned multiple benefits for the stakeholders. In the frame of the Eklipse Project (EKLIPSE 2017), Raymond *et al.* (2017) developed a holistic framework for the design, implementation and monitoring of NBSs in urban areas, integrating the estimation of the effects on ecosystem services and the related co-benefits (or costs), based on multi-stakeholder involvement. It was based on four perspectives: (a) co-benefits for human health and well-being; (b) integrated environmental performance; (c) trade-offs and synergies to biodiversity, health or economy; (d) potentiality for citizens' involvement in governance and monitoring and 10 challenges. A set of indicators was collected, given the specific context of urban areas. A 7-stage procedure was developed guiding the NBS implementation. Nevertheless, the analytic procedure did not provide a quantitative estimation of the performance of the proposed scenario. Calliari, Staccione, and Mysiak (2019), consistent with the approaches of Liquete *et al.* (2016) and Raymond *et al.* (2017), built an integrated framework including economic, social and environmental effects of NBS implementation, by encouraging the multifunctional design of the interventions and defining univocal criteria to assess grey, hybrid and NBS solutions. Different from previous studies, the authors included a "climate-proofing" stage, aimed at estimating the effectiveness of the developed measures, under different climate scenarios. The framework was based on an adaptive structure for continuous monitoring, assessment and adaptation under different environmental and climate scenarios. Sowińska-Świerkosz and García (2021) developed a procedure, guided by performance questions, for the assessment of NBS effectiveness based on three main steps: (1) the definition of the project aim, issues, scale effects and thresholds of the problem; (2) the discharging of unfeasible solutions which do not comply with the site conditions and setting requirements; (3) the assessment of the performance questions. The framework was based on including performance indicators belonging to seven main aspects, namely stakeholder participation, policy and management capability, economic efficiency, synergies and trade-offs, adaptation to local conditions, performance in the long-term, adequate spatial scale. All these aspects were considered with the same level of importance to quantify NBS effectiveness, by assuring stakeholder involvement in the assessment, categorized into three different levels: micro-level actors (citizens), meso-level (employees of water agencies, municipal departments) and macro-level (regional and national authorities). Nevertheless, the framework was structured for the design of NBS scenarios, rather than for their ex-post evaluation. Rödl and Arlati (2022) provided a step-by-step procedure supporting users in the optimal selection of indicators from a plethora from the literature to estimate NBS effectiveness, given the specific context and aim of the research. The model was based on the H2020 CLEVER Cities Project (CLEVER Cities 2021). The procedure was based on 5 core steps, regarding the definition of assessment targets, the description of the assessed object, the selection of criteria and indicators, the related data collection to calculate the indicators and their assessment for NBS planning, design and implementation. Each step was characterized by targeted questions, useful to directly understand the aim of the activities. Spatial and temporal boundaries of the analysis should be properly marked in order to set the policies and the time horizon of the assessment. The approach was tested on three case studies in Europe (Hamburg, London and Milan) to evaluate the residents' social cohesion, wellbeing and security, resulting in a good flexibility to be adopted in different contexts.

Despite the number of assessment frameworks available in the literature, tools addressing the implementation of NBSs at the river basin scale are lacking, since rural and mountainous areas have typically received less attention (Strout *et al.* 2021; Pugliese *et al.* 2020; Zhang, Zheng, and Chen 2019; Baills, Garcin, and Bernardie 2021). Rural and mountainous areas show specific hydro-meteorological and geographic conditions, complex geological features, as well as multiple hydro-meteorological hazards, including e.g. landslide, flooding and rockfall (Slaymaker 2010; Korup and Clague 2009; Allamano, Claps, and Laio 2009; Anderson *et al.* 2021). Such features amplify risks, especially under extreme weather events. The national DRR plans focus mainly on regions with the highest population density, which tend to be urban and/or coastal areas. The impacts of extreme hydro-meteorological events in mountain areas often affect entire river catchments. Some of the natural hazard-related disasters in urban and coastal areas, such as flooding, are due to processes and events such as flash floods and landslides that begin in hilly and mountainous regions higher up in the river basin (Zumpano *et al.* 2018). In addition, mountainous areas are particularly susceptible to CC and are often within protected areas due to their high biodiversity (Spehn, Rudmann-Maurer, and Körner 2012; Vaculisteanu, Niculita, and Margarint 2019). From the social and economic viewpoint, rural and mountainous areas present additional challenges linked to depopulation and underdevelopment (Ingold, Balsiger, and Hirschi 2010; Lampe 1983; Sarmiento 2006). Thus, NBSs for natural hazard risk management should not only address risk reduction but also provide targeted co-benefits to address the abovementioned challenges (Perosa, Fanger, *et al.* 2021).

Owing to the characteristic multi-functional structure of NBSs, Multi-Criteria Decision Analysis (MCDA) (Huang, Keisler, and Linkov 2011; Cinelli, Coles, and Kirwan 2014; Ahilan *et al.* 2018) is a suitable approach for assessing their performance. MCDA is typically used to address, in a structured way, the variety of co-benefits (and costs) associated with the implementation of a specific design scenario (Koschke *et al.* 2012; Kiker *et al.* 2005; Mendoza and Prabhu 2003; Alves *et al.* 2020). In this study, design scenario (DS) refers to the set of measures to be implemented for tackling the site-specific hydro-meteorological risks. MCDA can involve the stakeholders (SHs) through a Living Lab (LL) approach (Niitamo *et al.* 2016; Fohlmeister *et al.* 2018; Lupp *et al.* 2021). Specifically, MCDA can include weights to address how the relevance of some co-benefits (or costs) can significantly differ depending on the specific context and on the SHs' perception (Velasquez and Hester 2013; Koschke *et al.* 2012).

In this paper we describe a novel MCDA-based assessment framework tool designed to estimate the hydro-meteorological risk reduction, the co-benefits and the costs associated with the implementation of NBSs, grey and hybrid solutions. The assessment framework tool was developed within the EU-funded Horizon 2020 project PHUSICOS (https://phusicos.eu/). PHUSICOS aims to demonstrate the potential of NBSs in reducing the risk of extreme weather events in vulnerable areas such as rural mountain landscapes (Solheim *et al.* 2021; Baills, Garcin, and Bernardie 2021). The tool allows performance assessment at different stages of the NBSs' lifetime, from their selection and design to their implementation and monitoring (Pignalosa *et al.* 2022). The paper includes an example of the tool's application with reference to a simplified, hypothetical case study representative of conditions commonly found in mountainous areas. The proposed tool is intended to be used by professionals involved in multi-stakeholder and multi-disciplinary teams working in the planning, design, implementation, monitoring and evaluation of NBSs during the various stages of their life. Although the tool is designed for the analysis of risk mitigation measures in mountainous areas, it can be easily tailored to different environmental and social contexts.

2. The comprehensive assessment framework

The role of the proposed assessment framework tool in the hydro-meteorological risk management process is schematically depicted in Figure 1. Given a specific case study, presenting known hazards and characterized by its environmental, socio-economic, and ecological dimensions, a set of possible alternative DSs can be defined.

The MCDA-based assessment framework aims at quantifying the performance of the site-specific proposed DSs with reference to a set of key ecosystem services, benefits and costs, described by a set of Key Performance Indicators (KPI). Once the KPIs are measured (or modeled) for the different alternatives, the framework allows evaluating a score for each alternative, providing the quantitative estimation of the performance and

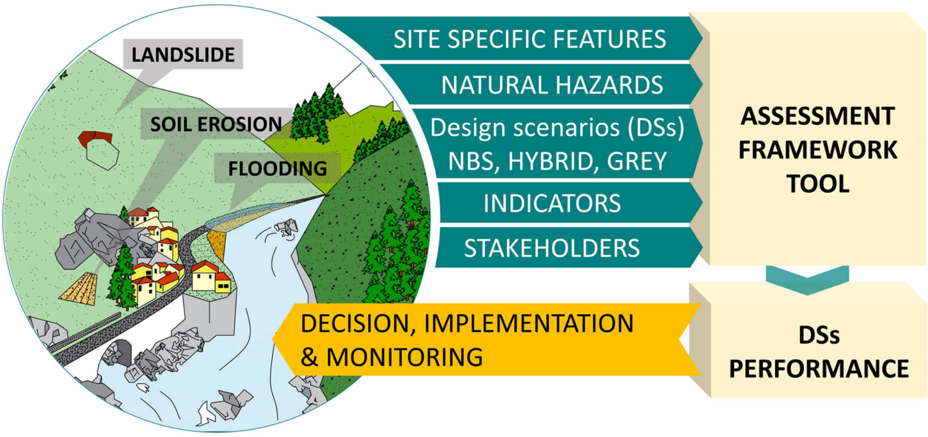

Figure 1. Conceptual scheme for the performance assessment of alternative design scenarios. Given a site of interest, based on the site-specific features, including the characteristic natural hazards and the socio economic context, it is possible to identify the viable alternative design scenarios (DS) for disaster risk reduction (NBS, hybrid and grey). Based on the site specific features and the alternative DSs, key performance indicators can be defined and relevant stakeholders can be identified. This information feeds the assessment framework tool, providing as outputs the quantitative assessment of the performance of the alternative DSs, providing, in turn, the elements for identifying the optimal alternative. The tool aids in the implementation and monitoring of the optimal alternative.

guiding the choice among the DSs (Figure 1). In the assessment process, each DS is evaluated with reference to a Baseline Scenario (BS) describing the current situation, i.e. prior to the implementation of NBSs or other interventions.

In the following sections the structure of the framework, the selection of KPIs, their evaluation and aggregation, along with the scenario score calculation are described in detail. Finally, in Section 3, the application of the framework is illustrated with reference to a simplified case study.

2.1. Structure of the framework

A multi-dimensional hierarchic framework for NBSs, hybrid or grey DS assessment was created based on the systematic analysis of different sources of information. The analysis was carried out to identify the key ecosystem services and co-benefits, i.e. the relevant KPIs, suitable for the performance assessment of NBSs for hydro-meteorological risk reduction in rural and mountainous areas. A basic set of indicators was identified through the analysis of existing projects, networks and platforms (such as ICLEI, Sustainable Cities Platform, Oppla, Nature4Cites, NATURVATION, NAIAD, BiodivERsA, INSPIRATION, URBAN GreenUP, UNaLaB, URBINAT, CLEVER Cities, proGIreg, EdiCitNet, etc.) dealing with NBSs (Di Sabatino *et al.* 2020), the assessment of both the H2020 EKLIPSE Knowledge and Learning Mechanism on Biodiversity and Ecosystem Services (EKLIPSE 2017), and the latest standards for indicator definition on sustainable development (ISO 37120:2014 and ISO 37121:2017).

The assessment framework was built including the specific features of rural and mountainous areas in terms of hydro-meteorological hazards and socio-environmental conditions. In such areas, the hazards induced by CC, as well as exposure and vulnerability, show different characteristics in comparison with urban areas: i.e. no heat island effect; different hazard issues deriving from runoff; higher relevance of biodiversity conservation and maintenance of biogeochemical cycles, greater importance of agricultural, fishery and livestock resources. Moreover, from the social and economic viewpoint, these areas show specific challenges related to e.g. aging, depopulation, youth unemployment, poor services and spatial accessibility, for which NBSs can provide benefits and opportunities.

Within the assessment framework tool, the KPIs were identified using a top-down procedure. Building upon the assessment frameworks proposed by Raymond *et al.* (2017) and Liquete *et al.* (2016), 5 different macro-areas of co-benefits and costs, referred to as ambits, were defined. Each ambit includes the indicators suitable to evaluate the performance of the DS toward one of the following specific aspects:

1. Verify the DS performance towards risk reduction;
2. Assess the technical and economic feasibility of the DS;
3. Assess the effects of the DS on the environment;
4. Identify potential positive and negative implications of the DS on the society;
5. Assess the effects of the DS on the local economy.

The 5 ambits were respectively labeled as (1) Risk Reduction; (2) Technical and Feasibility Aspects; (3) Environment and Ecosystems; (4) Society; (5) Local Economy. For each ambit, sub-categories, defined as criteria, covering the most relevant elements of the corresponding ambit, were categorized, as described in Table 1. Then, specific sub-criteria were identified, as summarized in Table 2.

For each sub-criterion, one or more KPIs were identified. Within this paper we propose a set of ∼100 indicators to be used in the application of the assessment framework following the indications of Section 2.1.1. The list, reported in the online supplemental material section, includes KPIs suitable for the assessment of NBS, hybrid and grey measures for hydro-meteorological risk management in rural and mountainous areas. The framework matrix, whose structure is sketched in Table 3, represents the core of the assessment framework tool. The matrix has as many rows as the number of indicators and 13 columns. Specifically, columns 1, 2 and 3 report the ambit, the criterion and the sub-criterion to which the indicator belongs, respectively. Column 4 contains the indicator's name. The remaining columns display different types of indicator information, useful for their further characterization and for performing targeted analyses, as described in detail hereafter. For each indicator the following properties were specified:

- Metric (Mt, column 5) details the unit of measurement of the indicator.
- Typology (Tp, column 6) describes the type of data needed for characterizing the indicator, i.e. qualitative (QL), quantitative (QT) or semi-quantitative (S-QT).
- Direction ($\rightleftarrows$, column 7) indicates whether the indicator should be maximized (max) or minimized (min) at the optimum.
- Source (S, column 8) gives information about the source of the data needed for the characterization of the indicator, including survey (SV), modeling (M), Living Lab (LL), geographic information system (G), statistical data (SD) and sampling (SM).

Finally, the last 5 columns of the matrix (Table 3) include attributes useful for creating different sub-sets of indicators to be used to carry out specific analyses. These attributes, as detailed below, specify the role played by the indicator in the evaluation process, its temporal scale, and the agreement with specific sustainable development goals.

Owing to their nature, not all the indicators can be defined for both the BS and the DS. Thus, the attribute Δ (Column 9) is set either equal to Δ when the indicator can

Table 1. Scheme of ambits and criteria of the hierarchic comprehensive framework assessment tool.

Ambit	Criterion
Risk Reduction	Hazard
	Exposure
	Vulnerability
Technical and Feasibility Aspects	Technical Feasibility
Environment and Ecosystems	Water
	Soil
	Vegetation
	Green Infrastructure
Society	Quality of Life
	Community Involvement and Governance
	Landscape and Heritage
Local Economy	Revitalization of Marginal Areas
	Local Economy Reinforcement

Table 2. Scheme of criteria and sub-criteria of the hierarchic comprehensive framework assessment tool.

Criterion	Sub-criterion
Hazard	Landslide Risk Resilience
	Flooding Risk Resilience
	Snow Avalanche Risk Resilience
	Drought Risk Resilience
Exposure	Potential Areas Exposed to Risks
	Potential Population Exposed to Risks
	Potential Species Exposed to Risks
	Potential Buildings Exposed to Risks
	Potential Infrastructures Exposed to Risks
Vulnerability	Potential Population Vulnerable to Risks
	Potential Economic Effects due to Risks
	Potential Infrastructures Vulnerable to Risks
Technical Feasibility	Cost-Benefit Analysis of the Intervention
	Application of Suitable Materials and Technologies
Water	Biodiversity Provision
	River Quality
	Water Quality
Soil	Belowground C Sequestration
	Physical Resilience
	Fertility
	Biodiversity Provision
Vegetation	Aboveground C Sequestration
	Biodiversity Provision and Threats
	Soil Protection
	Wildfire Risk Mitigation
Green Infrastructure	Landscape Connectivity
Quality of Life	Leisure and Connections Increasing
	Social Justice
	Ageing Contrast
Community Involvement and Governance	Participatory Processes and Partnerships
Landscape and Heritage	Identity
	Heritage Accessibility
	Landscape Perception
Revitalization of Marginal Areas	Promotion of Local Socio-Economic Development of Marginal Areas
Local Economy Reinforcement	New Areas for Traditional Resources
	Enhancement of Local Socio-Economic Activities

be evaluated at the BS and compared to the one evaluated for the DS or 0 elsewhere. In the evaluation process, the magnitude of benefits deriving from the DS, namely the effectiveness (E), the economic and technical feasibility (F), the ability to induce co-benefits (CB) and the effects toward site resilience (R) are considered. Therefore, each indicator is labeled with one or more Assessment Factors (AF, column 10), indicating the role of the indicator toward the abovementioned aspects. By creating subsets of indicators sharing the same AF targeted analyses of the DS toward specific topics can be performed.

The timescale of the effects of a DS varies depending on the type of KPI. For example, the effects of a reforestation intervention on soil erosion will be tangible after

Table 3. Structure of the framework matrix.

Ambit	Criterion	Sub-criterion	Indicator	Mt	Tp	⇄	S	Δ	AF	TS	SFDRR	UNDSG
Risk Reduction	Hazard	Flooding Risk Resilience	Peak Flow	m^3/s	QT	min	M	Δ	R	ST	–	13
			Total Runoff Volume	m^3	QT	min	M/SV	Δ	R	ST	–	13
			Flooded Area	ha	QT	min	M/SV	Δ	R	ST	–	13
		…	…	…	…	…	…	…	…	…	…	…
	…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…
Society	Landscape and Heritage	Landscape Perception	Viewshed	km^2	QT	max	G	Δ	CB	ST	–	3
			Scenic Sites and Landmarks Created	nr.	QT	max	M/G	–	CB	ST	–	3
			Scenic Paths Created	km	QT	max	M/G	–	CB	ST	–	3
		…	…	…	…	…	…	…	…	…	…	…
	…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…

several years, while a slope terracing will be effective immediately after its implementation. This consideration leads to the definition of a Time-Scale parameter (TS, column 11) characterizing each KPI. Consistent with Raymond *et al.*'s (2017) approach, the following timescale is considered: short-term (ST, within 5 years), medium-term (MT, 5-10 years) and long-term (LT, over 10 years). Extracting subsets of indicators all characterized by the same TS factor allows DS performance analysis for a specific temporal horizon.

Finally, for each KPI, two additional attributes are set, namely the SFDRR (column 12) and the UNSDG (column 13), to set the agreement of the indicator to one or more targets of the Sendai Framework for Disaster Risk Reduction (SFDRR, Aitsi-Selmi *et al.* 2015) and the UN Sustainable Development Goals (UNSDG, United Nations 2017), respectively. Values attained by these attributes correspond to the target number and goal number of the SFDRR and the UNSDG lists, respectively.

2.1.1. Case-specific tailored matrices

For each specific case study, the number and type of indicators should be accurately selected. This operation leads to the definition of a sub-set of indicators to be used for the analysis. The choice of the KPIs should account for:

- The relevancy of the indicator to the specific case study; for example, in a flood-prone area indicators for landslide risk are not relevant and should be discarded;
- The sensitivity of the indicators to the changes provoked by the DS implementation;
- The possibility of measuring and monitoring the indicator (data availability), at both the BS and the DSs;
- The aim and the accuracy of the analysis.

The resulting matrix is, thus, a tailored matrix and should be considered as the actual set of indicators to be used for the analysis. Consistent with the hierarchic structure defined by ambits, criteria and sub-criteria, new or different indicators can be included in agreement with the site-specific hazards and features. The definition of indicators can be carried out relying on specialized literature (Shah *et al.* 2020; Dumitru and Wendling 2021).

2.1.2. Framework application for NBS implementation and monitoring

The proposed tool allows the comprehensive and quantitative estimation of the performance of the considered DS through the calculation of a DS score. The DS score can be used to provide solid and quantitative evidence of the performance of the DS and can be applied to different decision-making contexts. With reference to a typical measure for DRR (NBS, grey or hybrid), two stages can be distinguished by dividing the life of the DS in an *ex-ante stage* (i.e. before its implementation), and an *ex-post stage* (i.e. during the monitoring activities, after its implementation). The performance analysis can be carried out with the proposed framework at the two different stages (Table 4) by modifying the framework tool and carefully selecting the type and number of indicators, according to the aim and the accuracy of the analysis.

Table 4. Framework matrix to be used in the ex-ante and ex-post stage.

Stage of the assessment	Aim of the assessment	Assessment tool
Ex-ante	Preliminary, quick assessment of different design scenarios (NBS, grey, hybrid)	Simplified matrix
	Assessment of a specific design scenario at demonstration site before the implementation	Simplified or extended matrix
Ex-post	Targeted assessment of the implemented design scenario toward specific goals	Assessment factor matrix
	Detailed performance assessment of the implemented design scenario	Extended matrix

In the *ex-ante* stage, a preliminary assessment can be performed for a quick evaluation and selection of the suitable alternatives. At this stage, the use of a simplified matrix is suggested. A simplified matrix can be created by opportunely selecting at least one indicator (from the most relevant ones for the considered DS) for each criterion. If greater detail is required, the simplified matrix can be derived by extracting one indicator for each sub-criterion. Once the most suitable alternatives are identified, a more accurate assessment is generally needed and can be performed referring to the extended matrix (including a larger set of measurable indicators). Otherwise, if a lower level of detail is sufficient, a simplified matrix can be adopted.

In the *ex-post stage*, a detailed performance assessment of the implemented scenario is generally needed (e.g. for providing an evidence base for policy decisions, or monitoring purposes). In this case, the use of the extended matrix is recommended and the final score is provided in comparison with the BS. In the *ex-post stage*, a quick assessment of implemented scenarios on specific topics (the timescale, agreement with the UN Sustainable Development Goals, compliance with the targets of the SFDRR) can also be performed by considering the assessment factor matrix. In this case, KPIs are selected depending on the attributes included in columns 9–13 of the framework matrix.

2.2. Normalization, weighting and aggregation of KPIs

For each alternative DS, the selected KPIs have to be estimated. The assessment procedure allows measurement of the performance of each specific DS in comparison with the BS. Once the performance of each DS is evaluated, a comparison between the available alternatives can be carried out, providing relevant outcomes for decision makers and stakeholders. The performance of each DS is achieved by a total score obtained by progressively summing up the values attained by the KPIs, through a procedure consistent with the hierarchical structure of the framework. The evaluation of the DS score is described in the following sub-sections.

2.2.1. Indicator normalization

Owing to the different nature of the indicators (different metrics, qualitative vs. quantitative, etc.), the DS score can be evaluated only by considering normalized indicators. Given a set of n alternative DSs K_i, with $i = 1, \dots, n$, to be analyzed with respect to a set of n_I indicators $I_{j,i}$, with $j = 1, \dots, n_I$, following Koschke *et al.* (2012), the values attained by indicators at each DS can be normalized to a dimensionless relative scale from 0 to 100 using Equations (1) and (2):

$$\bar{I}_{j,i} = 100 \cdot \left(\frac{I_{j,i} - I_{j\min}}{I_{j\max} - I_{j\min}} \right) \tag{1}$$

$$\bar{I}_{j,i} = 100 \cdot \left(\frac{I_{j\max} - I_{j,i}}{I_{j\max} - I_{j\min}} \right) \tag{2}$$

where:

- $\bar{I}_{j,i}$ is the normalized value of the indicator $I_{j,i}$, i.e. the indicator I_j evaluated for the K_i DS;
- $I_{j\max}$ ($I_{j\min}$) is the maximum (minimum) value achieved by the indicator I_j evaluated at the BS.

The choice between Equations (1) and (2) is made by considering the direction of the indicator, as specified by the attribute ($\rightleftarrows$) in column 7 of the assessment framework tool (Table 3). If I_j identifies a variable that has to be maximized at the optimum (for example, considering the landslide risk resilience, the safety factor). Equation (1) should be adopted. In such a way the normalized performance indicator can provide information about the magnitude of the improvement (if positive) or the worsening (if negative) of the indicator $I_{j,i}$ (describing a benefit or a detrimental effect) induced by the implementation of a given DS relative to the BS.

Once the normalized indicators are evaluated, the overall DS score is calculated. In the score evaluation process, a multi-level weighting scheme is adopted to account for the preferences of the SHs involved in the process. Indeed, depending on the typology of the SHs and on the local conditions, some co-benefits or costs, and in turn some indicators, criteria or ambits, can assume a relatively higher or lower importance in the assessment. Consequently, a multi-level weighting scheme is adopted, as described in Section 2.2.3.

2.2.2. *Design scenario score evaluation*

The overall score for each DS can be evaluated following a hierarchic procedure, consistent with the structure of the framework. The score evaluation is schematically depicted in Figure 2 showing the progressive aggregative procedure from the bottom level (indicator score) to the top level (scenario score).

The DS score is evaluated by progressively calculating:

I. The indicator score (Equation 3);
II. The criterion score (Equation 4);
III. The ambit score (Equation 5);
IV. The DS score (Equation 6).

Recalling that the alternative DSs all share a common set of n_I indicators, grouped in n_C criteria and n_A ambits, the overall score R^i for the ith DS can be evaluated according to the procedure described in the following. The score is evaluated at each level, consistent with the framework hierarchic structure, and later aggregated,

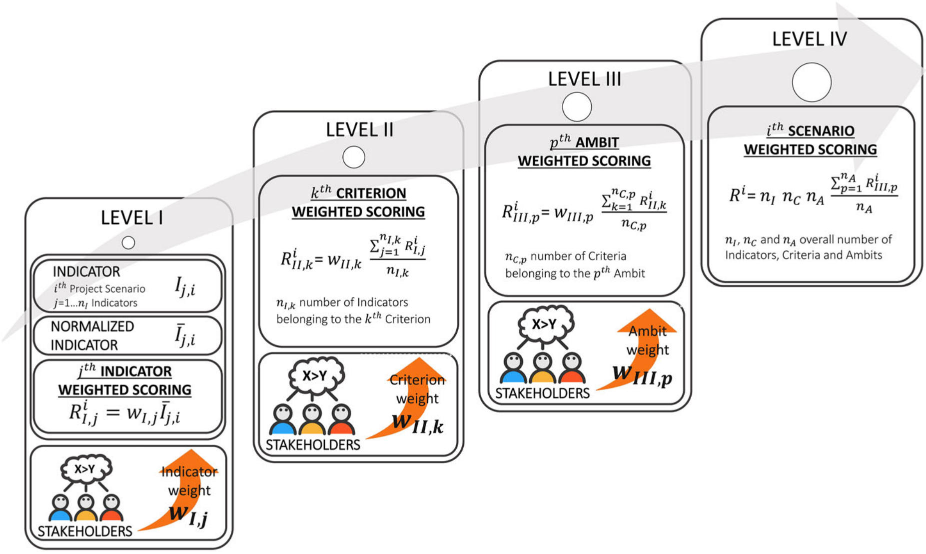

Figure 2. Design scenario score evaluation process.

averaged and weighted (w being the considered level weight) for providing the upper-level score.

- Level I: The weighted score $R^i_{I,j}$ of the jth normalized indicator $\bar{I}_{j,i}$ can be evaluated as:

$$R^i_{I,j} = w_{I,j} \cdot \bar{I}_{j,i} \tag{3}$$

- Level II: The weighted score $R^i_{II,k}$ of the kth criterion, composed by $n_{I,k}$ indicators, can be evaluated as:

$$R^i_{II,k} = w_{II,k} \cdot \frac{\sum_{j=1}^{n_{I,k}} R^i_{I,j}}{n_{I,k}} \tag{4}$$

- Level III: The weighted score $R^i_{III,p}$ of the pth ambit, composed by $n_{C,p}$ criteria, can be evaluated as:

$$R^i_{III,p} = w_{III,p} \cdot \frac{\sum_{k=1}^{n_{C,p}} R^i_{II,k}}{n_{C,p}} \tag{5}$$

- Level IV: finally, the overall scenario score R^i, composed by n_A ambits, can be evaluated as:

$$R^i = n_I \cdot n_C \cdot n_A \cdot \frac{\sum_{p=1}^{n_A} R^i_{III,p}}{n_A} \tag{6}$$

with $\sum_{J=1}^{n_I} w_{I,j}=1$, $\sum_{k=1}^{n_C} w_{II,k}=1$, $\sum_{p=1}^{n_A} w_{III,p}=1$ and n_I represents the total number of indicators, n_C the total number of criteria and n_A the total number of ambits. At each level, the corresponding weight is applied, and the score is averaged with respect to the number of elements, to provide scores regardless of the quantity of indicators, criteria and ambits. The final design scenario score R^i is conceptually analogous to the score of a normalized indicator. Indeed, it is evaluated by progressively averaging the sum of normalized indicators. The final multiplication by the quantity of indicators, criteria and ambits algebraically simplifies the application of weights, resulting in a score R^i ranging from 0 to 100.

The multi-level scoring can provide useful insights into the performance of each alternative DS. Comparing criterion and ambit scores can be useful to evaluate the performance of the DS, aiding in the communication and dissemination of the assessment results. The final scenario score R^i provides the quantitative measurement of the DS overall performance and can be used for identifying the optimal alternative, as well as monitoring the performance of the implemented DS over time.

2.2.3. Weight definition

The weights adopted in the framework tool were defined considering two different approaches: (1) Likert categories (Cohen, Manion, and Morrison 2017), and (2) equal weights. In the first weighting procedure, SHs or experts can be asked to state their preferences referring to a Likert Scale of 1 (“not at all important to me”) to 5 (“very important to me”) categories. As a result, the relative weight of each object can be estimated in comparison to any other. Weights can be obtained by surveying the SHs with *ad hoc* questionnaires (an example is reported in Table 5), using an LL approach (Lupp *et al.* 2021; Du *et al.* 2019; Zingraff-Hamed *et al.* 2019). Each participant will be asked to provide additional information to clarify their role within the process. After the stakeholders have stated their preferences, the weights can be normalized and used in the scoring procedure. An example of the questionnaire used for ranking the ambits is reported in Table 5. Analogous surveys can be used for ranking indicators and criteria. In practice, due to the large number of indicators considered in the application of the framework and the difficulties encountered by non-technical SHs in assigning weights on detailed aspects, the adoption of uniform weights tends to be the most viable approach for indicators.

In the second weighting procedure, weights are deduced assuming uniform distributed importance between the objects. Thus, weights are all equal to $1/W$, where W is the number of considered objects. The two methods can be adopted concurrently; for example, weights for ambits and criteria defined using the Likert scale can be combined with uniform weights for indicators.

Table 5. Example of questionnaire for ambit weights definition to be proposed to stakeholders.

Ambit	Description	1	2	3	4	5
Risk Reduction	Verify the NBSs/Hybrid Solutions Performances and their Effectiveness with respect to Risk Reduction					●
Technical and Feasibility Aspects	Evaluate the Technical and Economic Feasibility Aspects (Affordability)				●	
Environment and Ecosystems	Assess the beneficial role on the Environment and Ecosystems					●
Society	Identify positive Co-Benefits and potentially undesirable side-effects on the Society		●			
Local Economy	Assess the effects of the NBSs/Hybrid Solutions on the Local Economy	●				

3. Framework application: an exemplified case study

In this section, the application of the assessment framework tool is shown with reference to an exemplified case study characterized by the features, in terms of hazards, socio-economic and ecological context, typically found in mountainous areas. Natural hazards typically characterizing mountainous areas, together with environmental, and socio-economic conditions typically found in such settings were considered for the case study definition. The context is that of a small upstream catchment where extreme rain events and uncontrolled surface run-off induce slope instabilities and the saturation of natural waterways, provoking diffuse landslide and flood events. The local economy is mainly driven by agriculture and small enterprises operating in the agro-tourism sector. Owing to the widespread emigration of young people, the local population shows a relatively high average age.

To address the hydro-meteorological hazards occurring in the area, two alternative DSs are considered:

a. An NBS DS, for which flood and landslide risk reduction is achieved through the implementation of stormwater detention ponds, a floodable park, and the installation of vegetated timber cribs;
b. A hybrid DS, consisting of river channel re-naturalization and the design of a concrete detention tank to limit the occurrence of flooding, along with the installation of extensive vegetative timber cribs.

In the NBS DS, the stormwater detention ponds and the floodable park allow the storage of part of the flood volume during flooding events (Harrell and Ranjithan 2003; Miguez, Raupp, and Veról 2019; Moura, Pellegrino, and Martins 2016). The vegetated timber cribs work as retaining structures, improving slope stability and limiting the occurrence of landslides (Acharya 2018). In the hybrid DS, the river channel re-naturalization represents an effective practice to improve flood protection while inducing ecological benefits (Ahilan *et al.* 2018). Moreover, it can contribute to preventing erosion processes. The concrete detention tank allows limiting both the peak flow and the total runoff volume during extreme events, by first storing a water volume and then releasing it depending on the conveyance capacity of the receiving watercourse.

The assessment framework matrix was tailored by selecting the KPIs suitable for evaluating the effectiveness of the two DSs. 33 KPIs were estimated, referring to three scenarios: (1) the BS; (2) the NBS scenario; (3) the hybrid scenario. Both the DSs potentially induce environmental and socio-economic co-benefits. Indeed, they both improve the soil and vegetation factors by increasing chemical protection, the diversity of plant species and the vegetation cover. Moreover, the NBS scenario improves the landscape connectivity and the social quality of life, promoting participatory processes and increasing local identity. From the economic viewpoint, both scenarios improve the development of marginal areas. Given the implementation of the planned NBSs and grey interventions, both scenarios limit the area available for traditional activities (e.g. agriculture, fishing).

The selected KPIs, as summarized in Table 6, cover all the 5 ambits, 13 criteria and 21 sub-criteria. The indicators reported in Table 6 are normalized with respect to the BS, consistent with Equations (1) and (2).

To account for the potential different perceptions of co-benefits and interests in DS implementation, four different SHs were simulated: (a) a neutral stakeholder,

Table 6. Framework matrix for the exemplified case study.

Ambit	Criterion	Sub-criterion	Indicator	NBSs scenario	Hybrid scenario
Risk Reduction	Hazard	Landslide Risk Resilience	Occurred landslide area	30.58	70.25
			Velocity of Occurred Landslide	2.88	31.78
		Flooding Risk Resilience	Peak Flow	29.69	52.38
			Total Runoff Volume	26.18	61.17
			Flooded Area	4.76	6.30
	Exposure	Potential Areas Exposed to Risks	Urban/Residential Areas	10.70	13.28
			Productive Areas	−15.59	−13.44
		Potential Population Exposed to Risks	Inhabitants	11.52	25.83
			Commuters	11.51	33.73
			Elderly, Children, Disabled	11.40	25.42
		Potential Buildings Exposed to Risks	Housing	8.71	28.41
		Potential Infrastructures Exposed to Risks	Road	9.44	40.99
	Vulnerability	Potential Population Vulnerable to Risks	Population	35.40	60.97
Technical and Feasibility Aspects	Technical Feasibility	Cost-Benefit Analysis of the Intervention	Initial Costs	15.59	18.78
			Maintenance Costs	24.63	20.03
			Avoided Costs	15.26	18.32
		Application of Suitable Materials and Technologies	Material and Techniques Used Coherence	100.00	0.00
Environment and Ecosystems	Water	Water Quality	Physical and Chemical Parameters	25.00	0.00
	Soil	Carbon Sequestration in Soil	Decomposition Rate	56.00	30.00
	Vegetation	Structural Diversity	Woody vegetation cover	15.16	15.16
			Total vegetation cover	30.93	30.93
		Stages of Forest Stand Development	Number of diameter classes	50.00	25.00
		Green Infrastructure	Hanski Connectivity Index	14.29	0.00
	Green Infrastructure	Functional Diversity	Diversity of Functional Groups	37.50	12.50

(*Continued*)

Table 6. (*Continued*).

Ambit	Criterion	Sub-criterion	Indicator	NBSs scenario	Hybrid scenario
Society	Quality of Life	Leisure and Connections Increasing	New Areas for Recreational Use and Cultural Events	5.66	0.00
			Different Activities allowed in New Recreational Areas	57.14	0.00
			New Pedestrian and Cycle Paths	27.00	0.00
	Community Involvement and Governance	Participatory Processes and Partnerships	Citizens involved	25.00	21.25
	Landscape and Heritage	Identity	Traditional Events Organized in the New Areas	10.00	0.00
		Landscape Perception	Scenic Sites and Landmark created	10.00	0.00
Local Economy	Revitalization of Marginal Areas	Promotion of Local Socio-Economic Development of Marginal Areas	New Employment in the Tourism Sector	33.33	20.00
	Local Economy Reinforcement	Enhancement of Local Socio-Economic Activities	New Areas Made Available for Traditional Activities (Agriculture, Livestock, Fishing, etc.)	−74.25	−74.25
			Forest Area Planted	4.83	4.83

presenting no specific preference toward the effects of the DS implementation; (b) a technical stakeholder, mainly interested in risk reduction and economic feasibility aspects; (c) a political stakeholder, mostly interested in the socio-economic benefits for local communities; (d) an environmental stakeholder, considering the environmental implications of the DS implementation to be more important. Tables 7 and 8 summarize the weights of SHs for ambits and criteria, respectively.

Table 7. Ambit weights.

	Stakeholder				
Ambit	Neutral	Technical	Political	Environmental	Average
Risk Reduction	3	5	2	3	3.3
Technical and Feasibility Aspects	3	4	3	2	3.0
Environment and Ecosystems	3	3	2	5	3.3
Society	3	1	5	4	3.3
Local Economy	3	2	5	3	3.3

Table 8. Criterion weights.

	Stakeholder				
Criterion	Neutral	Technical	Political	Environmental	Average
Hazard	3	5	3	2	3.3
Exposure	3	4	3	2	3.0
Vulnerability	3	4	2	3	3.0
Technical Feasibility	3	3	4	3	3.3
Water	3	2	3	5	3.3
Soil	3	3	5	4	3.8
Vegetation	3	1	4	4	3.0
Green Infrastructure	3	3	5	3	3.0
Biodiversity	3	2	3	5	3.3
Quality of Life	3	3	4	4	3.5
Community Involvement and Governance	3	3	5	4	3.8
Landscape and Heritage	3	2	4	4	3.3
Revitalization of Marginal Areas	3	2	4	4	3.3
Local Economy Reinforcement	3	4	5	3	3.8

The scoring procedure described in Section 2.2.2 was applied to assess the overall effectiveness of two DSs. In the score evaluation, the average weights are used. In this example, to show the potential of the tool and the effects of SHs on the outcomes, the analysis was carried out independently for each group of SHs. Figure 3 is used to discuss the comparison between the two DSs and the effects of SHs on the outcomes. Figure 3(a,c) summarizes the ambit score (Equation 5) for the two DSs evaluated for the different SHs. The same results are indicated in the plots of Figure 3(b,d).

For the NBS scenario, comparable scores were observed for each ambit between the neutral and political SHs (Figure 3a,b). The application of the weights of the technical and environmental SHs resulted in higher scores for Risk Reduction and Environmental and Ecosystems ambits, respectively. The Local Economy ambit obtained negative

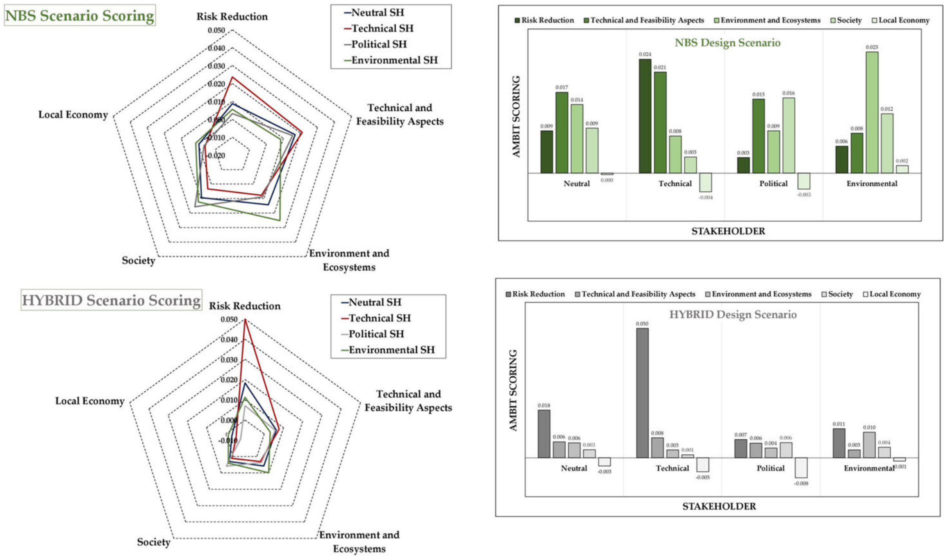

Figure 3. Ambit score for NBSs and hybrid design scenario for different SHs.

scores when the neutral, technical and political SHs were considered. This result is due to the reduction of the areas available for traditional activities caused by the implementation of the DSs. The use of the weights provided by the environmental SH resulted in a score for the Local Economy Reinforcement criterion lower than that of the Revitalization of Marginal Areas criterion. Consequently, for the NBS DS, the Local Economy ambit achieved a score greater than zero. In Figure 3(c,d), for the hybrid scenario, the greatest difference between ambit scores was observed when considering the weights provided by the technical SH. This was due to the higher effectiveness of the concrete detention tank for flood risk reduction in comparison with the detention ponds. The plots of Figure 3 represent an effective way for describing the output of the framework.

The comparison of criterion scores (Equation 4) resulting from the different SHs is plotted in Figure 4(a,b) for the NBSs and the hybrid DS, respectively. The higher scores for Hazard and Vulnerability criteria were achieved when considering the technical SH for both the NBSs and the hybrid scenarios. However, for the hybrid solution, the scores for these criteria were about three times higher than those for the NBS DS. The highest scores for the Biodiversity and Soil criteria were achieved by considering the Environmental SH.

As observed in Figure 3 in terms of ambit score, for all the SHs the Local Economy Reinforcement criterion obtained negative scores because of the reduction in areas available for traditional activities.

The comparison of the scores for the two DSs is shown in Figure 5. The results obtained with the averaged weights are included. The NBS scenario was the preferable alternative when the weights provided by the neutral, political and environmental SHs were used. Indeed, showing greater environmental and socio-economic co-benefits, the NBS scenario achieved the higher score, although the relevant benefit, in terms of risk reduction ambit, was provided by the grey solution.

This can be ascribed to the potential of the NBS DS to provide risk reduction while inducing environmental and socio-economic co-benefits (Gerwien 2020). The NBS scenario score was twice the hybrid one for both the neutral and the environmental SHs. The NBS DS score was six times higher than that of the hybrid DS when considering the political SH. This effect was due to the significantly greater socio-economic co-benefits provided by the NBS scenario, which were considered highly important by the political SH. By contrast, when using the weights provided by the technical SH, the two DSs achieved comparable scores, with the hybrid DS achieving a slightly higher score. For the hybrid

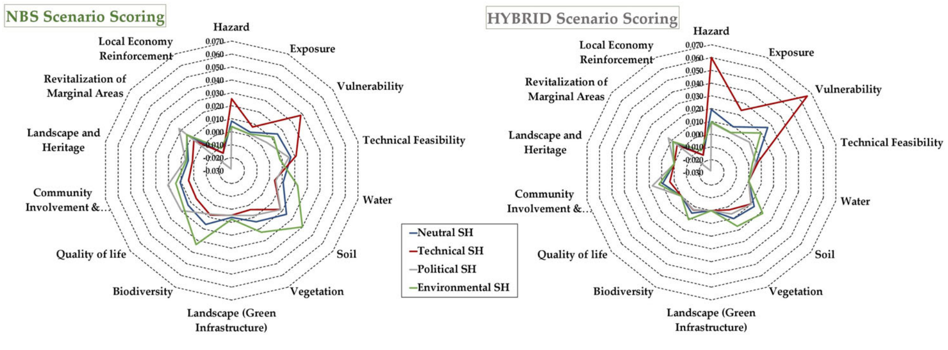

Figure 4. Ambit score for NBSs and hybrid design scenario for different stakeholders.

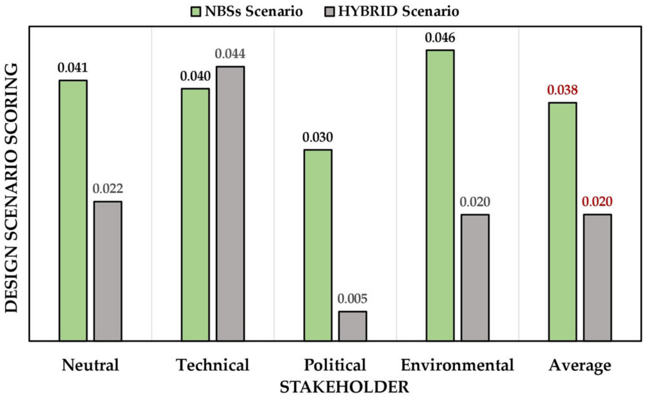

Figure 5. Comparison between the score for the NBS and the hybrid DS.

DS, the lower socio-economic co-benefits were compensated by the higher effectiveness of the measures in terms of landslide and flooding risk reduction. Considering the average weights, the score for the NBS scenario was about twice that of the hybrid DS, indicating the greatest potential for NBSs in inducing environmental and socio-economic co-benefits.

Figures 3–5 illustrate the outcomes of the proposed tool and can be used for quantitatively comparing different DSs. As observed from this example, the weighting methods can significantly affect the outcomes, highlighting the pivotal role of the LL in the reliable performance assessment of DSs. In the application of the tool, averaged weights should be used.

4. Discussion

In this section, the main strengths and shortcomings of the assessment framework tool are summarized and discussed. The proposed methodology can be easily adapted to different sites and NBS projects. Indeed, the type of indicators and the hierarchic structure of the framework can be adjusted for different socio-environmental contexts and hazards. The non-rigid structure of the tool allows adding, replacing or deleting indicators, respecting the hierarchic structure defined through ambits, criteria and sub-criteria. Additional or different indicators can be selected from specialized handbooks and literature to tailor the framework to specific environmental and social contexts (Shah *et al.* 2020; Dumitru and Wendling 2021).

The ambit-criterion-sub-criterion classification allows the user to systematically analyze the types of costs and co-benefits associated with the DS. The reliable evaluation of the performance of a given DS would benefit from the largest possible set of indicators, well distributed among the different ambits. This is a critical aspect of the entire assessment process. A large amount of data is generally needed for running the tool. In many circumstances data are not available or cannot be easily collected. Consequently, the number and type of indicators should be modified accordingly. However, the score evaluation procedure proposed in the framework tends to limit the potential biases induced by different quantities of indicators for different criteria and ambits. Specifically, when limited data are available, the procedure can be significantly affected by the type and the quantity of selected indicators. Thus, the selection of suitable indicators should be first disclosed by verifying the suitability of their estimation in the different scenarios.

A further shortcoming is the results' dependency on the weighting stage. To limit bias and increase the robustness of weighting, the grouping and involvement of stakeholders can couple the Living Lab approach with proactive territory ventures to promote socio-institutional motions and increase the awareness of stakeholders, perfecting their perceptions (Giordano *et al.* 2020).

The main strength of the proposed tool, in comparison with existing analogous assessment frameworks (Calliari, Staccione, and Mysiak 2019; Koschke *et al.* 2012; Liquete *et al.* 2016) and traditional MCDA and cost-benefit analysis, relies on the possibility for carrying out the assessment for different stages of the life of the DS. The tool can be used to monitor the effectiveness of the implemented DS over time (*ex-post*) but it can also be used as a design tool, aiding in the selection of NBS measures and comparing the predicted performance with alternative measures (*ex-ante*). Depending on the aim and the accuracy of the assessment, the tool can be modified by reducing the number of indicators, thus obtaining a simplified matrix. A reduced matrix can also be attained by selecting the indicators based on 5 different attributes. The analysis of the performance at different timescales, or with reference to the agreement with specific sustainable development goals is feasible. Different from other frameworks (e.g. Calliari, Staccione, and Mysiak 2019), the proposed assessment tool does not integrate backcasting (Quist 2007; Dreborg 1996) but, rather, is designed to guide the selection among a set of pre-defined viable alternatives. In the context of NBSs for hydro-meteorological risk management, the set of possible alternative measures is typically defined a-priori and relies on engineering-based approaches.

As typically observed for NBS measures, a certain benefit induced by NBS implementation can produce cascade effects, in turn inducing additional co-benefits, correlated among each other. The degree of correlation between different co-benefits or costs, and in turn between indicators, affects the performance assessment procedure, with the risk of overestimating the importance of certain benefits relative to others. The presence of correlation between indicators sets a limit on the reliability of the framework outcomes. The degree of correlation between indicators cannot easily be estimated and is not included, at this stage, within the assessment process. Possible improvement can be achieved by taking into account the correlations between indicators. This can be included by modifying the weighting strategy, decreasing the importance, i.e. the weight, of correlated indicators, without the need to alter the score evaluation procedure.

For the application of such a comprehensive tool, a variety of expertise is required, including e.g. engineering, ecology and environmental sciences, social sciences, landscape and urban planning. This should be carefully taken into consideration when arranging the team working on the framework. In addition, the proposed framework allows the involvement of SHs in the assessment process. The weighting methodology and indicator aggregation allows consideration of the SH perceptions and preferences over indicators, criteria and ambits. Specifically using, for example, an LL approach, SHs can be surveyed and can provide feedback on the relative importance of costs and co-benefits associated with the specific DS. The weighting procedure significantly influences the framework outputs and should be carefully carried out, with specific attention from facilitators to possible inequalities in terms of pressure and relevance among the SHs. Owing to the large number of indicators considered in this type of analysis, uniform weighting is usually considered at the first level, using the LL outputs for the second and third weighting levels (criteria and ambits, Figure 2).

The framework tool can provide a quantitative and repeatable measurement of the performance of NBS, hybrid and grey DSs. The outputs can be used by policy and decision makers for providing evidence of the effectiveness of the considered measures. To this aim, results should be displayed in a clear way to effectively reach a wide audience, including local communities, NGOs, and other relevant stakeholders.

5. Concluding remarks

This paper describes a comprehensive framework tool designed for the performance assessment of NBS, grey and hybrid measures for hydro-meteorological risk management. A multi-dimensional hierarchic framework for DS assessment was built based on the knowledge gained from the main NBS projects, network and platforms, and using the latest standards and literature as a starting point. The identification of the key co-benefits and ecosystem services related to DS implementation led to the definition of a set of KPIs to be adopted within the evaluation process. The defined indicators are sorted and collected under three hierarchically ordered categories (ambits, criteria and sub-criteria), to systematically assess the multiple co-benefits induced by NBSs. A list of KPIs for NBSs in rural and mountainous areas, as defined in the framework of the PHUSICOS project, is included in the supporting information associated with this manuscript. The tool was designed to account for stakeholder preferences via a multi-level weighting scheme of indicators, criteria and ambits. The resulting weighting scheme is effective and simple to use, while fostering the participation of SHs in the process.

In Section 3, the application of the methodology to an exemplified case study representative of typical conditions of mountainous areas is described. Two different DSs are considered in the application of the framework: an NBS and a hybrid one. The resulting procedure was effective for quantitatively comparing multiple DSs in a participative way, i.e. taking into account the SH preferences. The application of the framework highlighted the sensitivity of the tool to the weighting scheme. The methodology allowed accounting for the SH preferences but, on the other hand, highlighted possible biases induced by imbalances and inequalities among the SHs. This suggests that the tool should be applied in combination with an LL approach for managing and driving the involvement of the SHs in the DS definition and implementation. The combination with the LL approach is expected to foster the connection between local community and the DSs to be implemented. The proposed framework represents a useful tool to be used by professionals involved in multi-stakeholder and multi-disciplinary teams working in the planning, design, implementation, monitoring and evaluation of NBSs during the various stages of their life.

Disclosure statement

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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