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Research article

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ABSTRACT

Risk management measures (RMM) participate in the sustainability of cities and communities through the protection of these socio-eco-environmental systems against threatening events, and by ensuring system recovery. They include structural measures that are grey or green/blue solutions, or hybrid solutions combining the two former types. These measures can provide environmental and social co-benefits (e.g., improved biodiversity, recreational services) and disbenefits (e.g., the development of unwanted flora, concentrations of pollutants). The aim of this article is to provide an approach to assess and compare RMMs by considering these different dimensions. An application to three natural hazards – floods, coastal floods and wildfires – is proposed. The approach takes the form of a procedure to assess the co-benefits/disbenefits of the various RMMs and some technical specifications. It allows comparing the performances of one RMM against another and collectively discussing the choice of RMMs that takes into account a wide range of dimensions. The approach is based on the formulation of eight sustainability criteria and thirty-one indicators. The results were graphically displayed as several types of diagram: one radar chart per RMM, compiling all the indicators; one radar chart by type of risk studied (flood, wildfire and coastal flooding) based on averages of indicators per criterion; a table of the global score assigned to each RMM calculated with an arithmetic mean or a weighted mean. The approach relies on an interdisciplinary research team and involves end-users in a focus group for the validation step. This approach constitutes a transparent base for decision-making processes in the context of sustainable spatial planning against natural risks.

1. Introduction

Each year in the world, major natural and technological phenomena cause disasters with considerable damage to human life, property and ecosystems (MunichRe, 2021; United Nations/Department of Economic and Social Affairs, 2015). The year 2021 and summer 2022 were unfortunately no exception, with major flooding events in Europe (Belgium, Germany, Luxembourg, Netherlands), Pakistan, China and Australia as well as wildfires (mega-fires) and heatwaves worldwide (Algeria, Canada, France, Greece, USA). The literature acknowledges that the number and intensity of these dramatic events are expected to increase due to climate change (IPCC, 2021).

International interest in risk management activities has increased throughout the 20th century and early 2000s (Vigier et al., 2019), resulting in the definition of strategies such as the Hyogo and Sendai frameworks (United Nations/International Strategy for Disaster Reduction (UNISDR), 2005; United Nations/International Strategy for Disaster Reduction (UNISDR), 2015), and the European Flood Directive (European Parliament and Council, 2007). This concern about risk is also addressed in the 2030 Agenda for sustainable development (United Nations, 2015) and more specifically through the Sustainable Development Goal (SDG) #11 ("Make cities and human settlements inclusive, safe, resilient and sustainable") and one of its related topics: disaster risk reduction. Thus, policies concerning sustainable risk management are recent. The "Management of Aquatic Environments and Flood Prevention" (GEMAPI) competence in France (Vigier et al., 2019), "Making Space for Water", Planning Policy Statement 25 (PPS25), and the National Planning Policy Framework (NPPF) in the UK and "Room for the River" in the Netherlands

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(Chan et al., 2022), the Chinese "Sponge City Program" (Qi et al., 2020) are examples of such policies. In this paper, the definition of sustainable risk management given by Edjossan-Sossou et al. (2014) (p. 3210) is adopted: "minimisation of damage caused by natural hazards and/or the enhancement of resilience in both people and buildings toward these hazards to promote economic efficiency, social well-being and equity, as well as environmental improvements in the long term".

Moving towards sustainable risk assessment means that the classical process of risk assessment must be rethought, by integrating economic, social and environmental perspectives. This notably concerns the strategies and measures implemented to reduce and mitigate risks, and improve resilience (Curt and Tacnet, 2018). They are composed of structural (physical constructions) and non-structural (e.g., land-use, spatial planning, insurance, communication) measures. This article focuses on structural measures that are either grey (e.g., levees, pipes, use of mechanical means) infrastructures or solutions (GS) or green/blue, also called nature-based solutions (NBS) (e.g., green roofs, open detention basins). Hybrid solutions (HS) combine GS and NBS (e.g., multi-functional retention pond where both the built basin and the surrounding vegetation contribute to flood management). NBS are defined by the International Union for Conservation of Nature as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016). Ecosystem-based disaster risk reduction, defined as "the sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development" (Estrella and Saalismaa, 2013), is part of NBS.

Suitable risk management measures (RMM) participate in the sustainability of cities and communities through the protection of these socio-eco-environmental systems against threatening events and by ensuring system recovery (Sayers et al., 2013; Stephan et al., 2017; Titko and Ristvej, 2020). Moreover, the measure can provide co-benefits and multi-functionality (Figure 1 - not all advantages/disadvantages are represented) that balance different possibly conflicting interests (Alves et al., 2019; Hoang et al., 2018; McVittie et al., 2018; O'Donnell et al., 2020; van Veelen et al., 2015; Faivre et al., 2018). We chose to present only these aspects in Figure 1 as

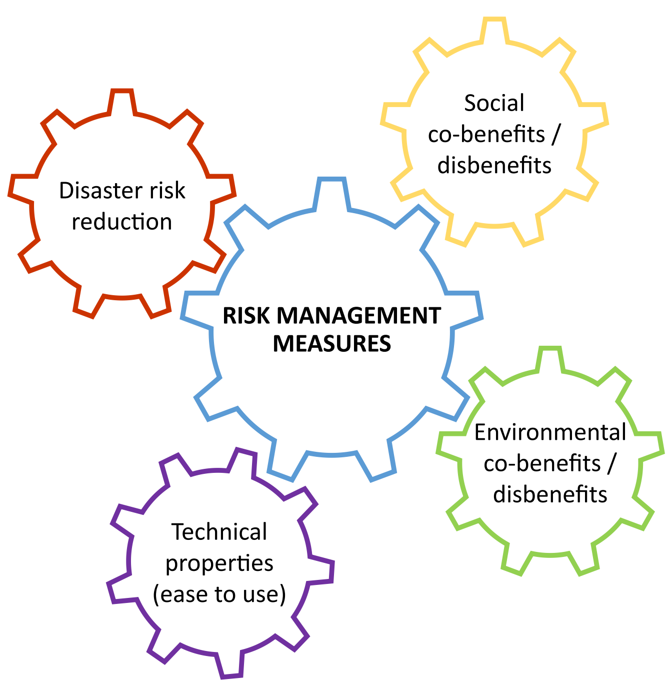

Figure 1. Contribution of risk reduction measures to disaster risk management and environmental and social benefits or disbenefits. Not all advantages/disadvantages are represented.

sustainability usually refers to economic (efficient use of resources), social (health, safety and quality of life), and environmental (preserve ecological assets or at least not deplete them) "pillars" (Bhinge et al., 2015; Nobanee et al., 2021; Sadollah et al., 2020). For instance, flood risk management can contribute to cultural services (cultural, intellectual and spiritual inspiration, recreational experiences), supporting services (soil quality, nutrient dispersal across floodplains), regulating services (climate mitigation, carbon sequestration, water quality and purification) and provisioning services (food, water, energy security) (Alves et al., 2019; Sayers et al., 2013). However, disbenefits can also arise from the measures (Hoang et al., 2018): for instance, pollutant concentrations, development of unwanted fauna, cutting of an existing green/blue belt, interruption of established uses, loss of biodiversity, allergenicity of the vegetation. Both NBS and GS, such as flood defense structures (van Veelen et al., 2015), can provide co-benefits and disbenefits. All of them have technical properties and notably related to ease to use (Figure 1).

Multi-functionality is usually little or not considered in decision-making processes concerning risk management (Alves et al., 2019; Dittrich et al., 2019; Ferrans et al., 2022; Viti et al., 2022). Traditionally, choices are made following assessments of safety performance, economic efficiency and suitability to the site, and they focus mainly on GS. Consequently, approaches are needed to integrate other elements such as social or environmental criteria to move towards sustainable perspectives. A literature analysis was carried out (See Appendix A1 for more details). We kept 116 references considered relevant for our study. Among them, 19 works deal with the assessment of multi-functionality, co-benefits or disbenefits brought by RMMs. They are listed in Table 1.

Thus, works dealing with the multi-functionality of RMMs are quite rare and mainly concern flood management, far ahead of other natural hazards such as droughts and landslides (Table 1); Edjossan-Sossou et al. (2014) developed a more versatile approach which they applied to GS for flood management; a recent EU Handbook deals with different natural hazards (European Commission, 2021). The works presented in Table 1 mainly focus on NBSs: 16 articles out of 19 deal with NBS while 6 of them focus on GS, or less frequently HS. Few articles consider several types of solution. Three aims can be distinguished in these works: the most common is the assessment of co-benefits and sustainability (15 articles) followed by the integration of the sustainable development criteria in risk management plans or control policies (4 articles), then by the enhancement of NBS acceptance (1 article).

In summary, none of these studies considers both the assessment of co-benefits and disbenefits regardless of the natural hazard and the type of measure (HS, GS and NBS). Therefore, new methodologies and tools that assess the multi-functionality of NBS, HS and GS and integrate it in decision-support systems should be developed. RMMs are necessarily implemented locally and therefore need to be decided upon in consultation with local decision-makers. Consequently, the aim of the article is to propose an approach to assist them in this decision-making process, concentrating on environmental and social criteria for NBS, HS and GS. Moreover, our approach deals with various natural hazards (floods, coastal floods and wildfires) and types of RMM (NBS, GS and HS). We chose to focus on these issues (various hazards, various types of RMM), as there is no published method that meets these requirements (Table 1). It takes the form of a procedure to assess the co-benefits/disbenefits of the various RMMs, including environmental and social issues. It allows comparing the performances of one measure against another and thus helps in the decision-making process.

2. Methodology

2.1. Methodology steps

Considering the wide range of co-benefits or disbenefits and the types of hazards considered, the process to develop a procedure to assess the co-benefits/disbenefits of the various RMMs requires interdisciplinary approaches (Edjossan-Sossou et al., 2014; O'Donnell et al., 2020).

Table 1. Literature review – works dealing with multi-functionality of RMM (at least environmental and social criteria) – NBS: Nature-Based Solution, GS: Grey Solution, HS: Hybrid Solution, SUDS: Sustainable Urban Drainage Systems - * other impacts are studied in this reference.

Aim	Reference	Theme	Hazard	RMM	Limits
Assess	(Alves et al., 2018a)	Select green and grey infrastructure to reduce flood risk and increase co-benefits	Flood	NBS – GS	Limited to Flood
	(Alves et al., 2018b)	Combine co-benefits and stakeholders perceptions	Flood	NBS	Limited to Flood and NBS
	(Alves et al., 2019)	Assess the co-benefits of green-blue-grey infrastructure	Flood	NBS – GS	Limited to Flood
	(Andersson-Sköld and Nyberg, 2016)	Assess the effectiveness and sustainability of risk reduction measures	Flood Landslide	GS	Limited to GS
	(Bana e Costa et al., 2004)	Evaluate flood control measures	Flood	GS – HS	Limited to Flood
	(Dittrich et al., 2019)	Analyse a climate change adaptation measure to reduce flood risk	Flood	NBS	Limited to Flood
	(Beceiro et al., 2022)	Assess the contribution of NBS to urban resilience	Flood	NBS	Limited to Flood and NBS
	(Edjossan-Sossou et al., 2014)	Assess the sustainability of natural risk management strategies	Various types of hazards	GS	Limited to GS
	(Hoang et al., 2018)	Evaluate the multiple benefits of urban flood management practices	Flood	NBS	Limited to Flood and NBS
	(European Commission, 2021)*	Evaluate the (social, environmental, economic) impacts of NBS	Natural hazards	NBS	Limited to NBS
	(Lähde et al., 2019)	Assess alternative design scenarios involving SUDS elements	Stormwater	NBS	Limited to Stormwater and NBS
	(O'Donnell et al., 2020)	Evaluate the benefits of Green-Blue Infrastructure	Flood Stormwater	NBS	Limited to Stormwater and NBS
	(Ossa-Moreno et al., 2017)	Economic analysis of benefits of SUDS	Flood Stormwater	NBS	Limited to Stormwater and NBS
	(Wójcik-Madej and Sowińska-Świerkosz, 2022)	Assess the capacity of NBS to address societal and environmental challenges	Flood	NBS	Limited to Flood and NBS
	(Yang and Zhang, 2021)	Assess the performance of grey and green strategies for SUDS development	Flood	NBS - GS	Limited to Flood
Incorporate	(Vincent et al., 2017)	Include Ecosystems Services Benefits in SUDS	Flood Stormwater	NBS	Limited to NBS
	(Banihabib et al., 2019)	Incorporate the sustainable development criteria in risk management plans	Flood	GS	Limited to Flood and GS
	(Brouwer and van Ek, 2004)	Integrate ecological, economic and social impact assessment of alternative control policies	Flood	NBS	Limited to Flood and NBS
	(European Commission, 2021)*	Evaluate the (social, environmental, economic) impacts of NBS	Natural hazards	NBS	Limited to NBS
Accept	(Giordano et al., 2020)	Enhance NBS acceptance	Flood Drough	NBS	Limited to NBS

Moreover, participatory approaches are interesting as they involve stakeholders and more precisely the future final end-users in the developments. The stakeholders actively participate in the analysis of the developments and their validation. These interactions allow better understanding and consideration of the different points of view, preferences and suitability of the tools developed. In this work, we developed a participatory approach "involving" stakeholders in the sense of the definition given by the Canadian Environmental Assessment Agency (Canadian Environmental Assessment Agency, 2008): it includes opportunities for dialogue with the interested parties and the focus is ensuring the developed method reflects, as much as possible, the consideration of input, interests, issues and concerns of stakeholders.

The approach is based on the formulation of sustainability criteria and indicators such as those described in recently developed studies (Alves et al., 2018a, 2018b, 2019; Andersson-Sköld and Nyberg, 2016; Edjossan-Sossou et al., 2014; McVittie et al., 2018; European Commission, 2021). Here, the indicators must be suitable for all types of natural risk and all types of solution. The methodology comprises five main steps summarized in Figure 2 (S1, S2a, S2b, S2c, S3). All of them involved an interdisciplinary research team with 5 experts in decision-support, risk, ecology, geography, urban planning and psychology that shared their knowledge and experience to identify and build criteria and indicators. The role of each of them is presented in Table 2: depending on the tasks to be carried out, they had a leading or participating role, in line with their specialty.

2.2. Inventory of types of RMM

First, a literature review made it possible to compile an inventory of all types of RMM (S1 - Figure 2): GS, NBS and HS. It was under the responsibility of the risk engineer belonging to the expert group. The sources of the survey were miscellaneous: scientific and technical literature as well as practical achievements in different countries and municipalities. Appendix A2 presents (i) the queries made for the literature search and the keywords used to identified the websites of interest and the technical reports, (ii) the publications (articles, reports, websites) kept for the analysis, (iii) the list of references used for the analysis. RMMs were classified according to the technical functions they fulfilled (e.g., for flood RMM: "Store (and potentially move) water"; "Collect and move water"; "Increase or maintain the infiltration capacity of soils" for flood management measures). These functions were identified thanks to functional analysis (EN 1325-1, 2014) that allows to describe the functioning of a system and identify the functions offered by this system to satisfy the needs of its user (Ferrer et al., 2018). For example, store water, collect and move the water, increase of maintain the infiltration capacity of the soil are examples of technical functions performed by flood RMM. Moreover, the review allowed identifying examples of co-benefits and disbenefits that will permit defining criteria and indicators (S2a and S2b - Figure 2).

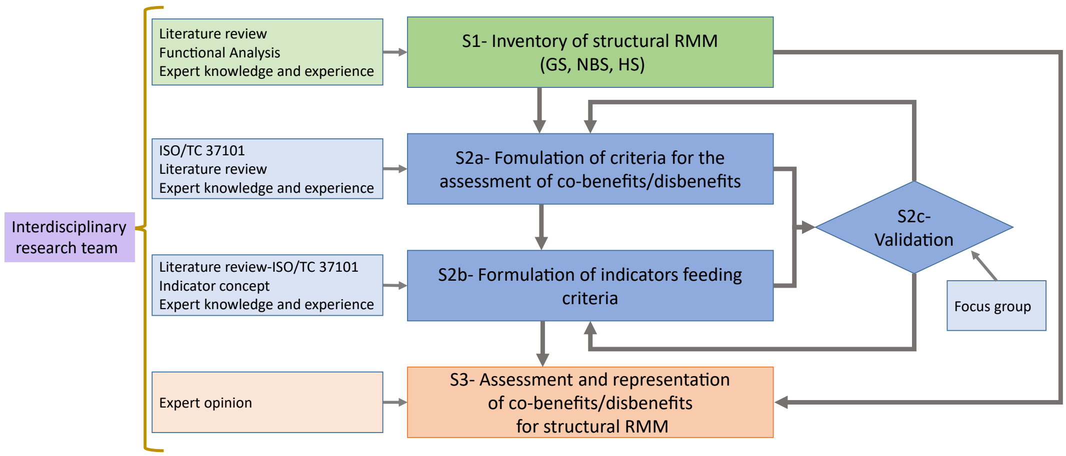

Figure 2. Methodology steps for the assessment of co-benefits and disbenefits provided by Grey Solutions (GS), Nature-Based Solutions (NBS) and Hybrid Solutions (HS).

2.3. Formulation of indicators and criteria

To formulate criteria and indicators, several sessions dedicated to knowledge gathering and formalization were carried out involving the members of the interdisciplinary team. An animator specialized in decision-support prepared the sessions (e.g. redaction of documents discussed during the session), organized the debates during the session and compiled the results, which were presented at the beginning of the following session. The discussions were collective: the objective was to define the consensus list of criteria and indicators and then give a consensus description of each indicator.

Criteria for the assessment of co-benefits and disbenefits were formulated (S2a) using the objectives listed in the ISO/TC 37101 Standard (ISO/TC 37101, 2016). Indeed, this standard which deals with "Sustainable development in communities - Management system for sustainable development - Requirements with guidance for use" offers communities a framework for structuring a sustainable development policy. Consequently, we consider it particularly relevant for this study. Indeed, as no approach is proposed in the literature to study both co-benefits and disbenefits regardless of the natural hazard and the type of measure (HS, GS and NBS), we chose to use this standard that gives a reliable framework and that concretely, proposes a set of "sustainable development goals" that we have considered as criteria. Other criteria stemmed from the literature (Table 1). These criteria referred to, on the one hand, environmental and social co-benefits or disbenefits and, on the other hand, the ability of the RMM to manage the risk (main function of the RMM) and its ease of use (e.g., ease of maintenance or monitoring).

Table 2. Contribution of the group of specialists.

	Leader	Participants
Inventory of structural RMM (GS, NBS, HS)	Risk engineer	Researchers in Ecology, Geography, Urban planning
Formulation of criteria for the assessment of co-benefits/disbenefits	Decision-support researcher	Researchers in Ecology, Geography, Psychology, and Urban planning, Risk engineer
Formulation of indicators feeding criteria	Decision-support researcher	Researchers in Ecology, Geography, Psychology, and Urban planning, Risk engineer
Validation	Psychology researcher – Geography researcher	Researchers in Ecology and Urban planning, Risk engineer
Assessment and representation of co-benefits/disbenefits for structural RMM	Decision-support researcher – Risk engineer	Researchers in Ecology Geography, Psychology, and Urban planning

Indicators that fed the criteria were then defined (S2b) by the research team, according to three sources: (i) the benefits and disbenefits of RMMs (identified in S1) from environmental and social standpoints; (ii) "examples" given for each "sustainable development goal" in the ISO/TC 37101 Standard; (iii) expert knowledge and experience. Indicators were formalized in grids comprising the following fields: name, definition, assessment scale with milestones (Curt et al., 2010; Talon et al., 2014). All the indicators were assessed on a qualitative scale comprising at least 2 values. +1 expresses strengthening of sustainability through benefits; -1 reveals the degradation of sustainability through disbenefits; the value 0 is assigned when no impact is expected when using the RMM (it provides neither co-benefits nor disbenefits). As some indicators are binary *i.e.* the RMM does or does not present the property (the RMM is or is not multifunctional), the value 0 was not used for the whole set of indicators. For instance, for the indicator "Social permeability": assuming the RMM favours co-habitations, co-uses, co-sharing of spaces, integrative practices, citizen participation (for example, appropriation by associations, sports sessions on the site), the indicator score is +1; if the RMM degrades co-habitation, co-use, co-sharing of spaces, integrative practices, citizen participation, then the indicator score is -1; if the RMM does not affect co-habitation, co-use, co-sharing of spaces, integrative practices, citizen participation, then the indicator is assessed as 0. This type of formulation allows the use of indicators in different contexts (i.e. for flood, wildfire, etc.; GS, NBS or HS) and geographic locations (i.e. according to its location and from an environmental point of view, a classical retention pond does or does not disconnect an existing green or blue belt and consequently does or does not degrade the restoration and improvement of the ecological connection).

2.4. Validation process

We propose an interdisciplinary, participatory approach that involves the end-users for the validation step. It was led by the researchers in psychology and in geography. A focus group composed of seven potential operational French end-users was then organized (S2c - Figure 2). They belonged to regional or local public authorities (DREAL, DDTM, Métropole Aix Marseille Provence, SDIS, services techniques et service de gestion des risques Vitrolles, Conservatoire du Littoral). The civil servants had expertise in different sectors including risk management, environment management, environmental protection, rescue services, and urban planning. This offered the advantage of gathering diverse beneficiaries who could perceive co-benefits and disbenefits differently from each other. The objectives of this session were (i) to collect the interest of the participants in, and their ability to appropriate, the approach; (ii) to integrate stakeholders' views and values; and (iii) to verify and, if necessary, modify the list of criteria and indicators as well as their formalization grid. The

Table 3. Flood RMMs classified following technical functions and types of solution.

Technical functions	Inventoried RMMs	GS	NBS	HS
Store water through specific structures and potentially move the water	Levee	X		
	Retention pond: Open pond; Underground facility; Infiltration well	X		
	Multifunctional retention pond: Dry basin; wet basin			X
	Green roof – Green wall		X	
	Bioretention (rain garden)		X	
	Above-ground or underground storage at gutter outlets	X		
	Dynamic flood control – Flood expansion zone		X	
Collect and move the water	Rainwater network	X		
	Swale		X	
Increase or maintain the infiltration capacity of the soil	Soil moisture control		X	
	Intervention on soil structure		X	
	Preservation or intervention on soil compaction		X	
	Soil drainage: Infiltration trench with drainage			X
	Pervious pavement			X
	Increase vegetation cover on the land		X	
	Agricultural development: Terrace cultivation; Ploughing perpendicular to the slope of the land – Installation of Fascines and dense hedges		X	

discussions were based on documents stemming from steps S2a and S2b. Once the session was over, the criteria and indicators were considered validated. The criteria and indicators are versatile: they can apply whatever the risk and the type of RMM considered.

2.5. Graphical representations

Finally (S3 - Figure 2), the indicators were used to characterize the different RMMs identified during S1. The elements given as references in the indicator grids supported the assessment. Indicators were assessed on the basis of expert opinion. The results were graphically displayed as several types of diagram:

- one radar chart per RMM, compiling all the indicators;
- one radar chart by type of risk studied (flood, wildfire and coastal flooding) based on averages of indicators per criterion;
- a table of the global score assigned to each RMM calculated with an arithmetic mean or a weighted mean: e.g., indicators relating to the protection against risk have a weight of 10; those relating to the environmental and social criteria have a weight of 5 and those relating to the technical criteria have a weight of 2. Weights can be elicited from experts using methods such as the Analytic Hierarchy Process (Saaty, 1982).

The figures allow comparing several RMMs, taking into account the context in which they are implemented and discussing collectively the choice of RMMs that takes into account a wide range of dimensions.

3. Results

3.1. Inventory of structural RMMs (flood, wildfire, coastal flooding)

Many RMMs are available for a given risk: for instance, for flood management, it is possible to implement open retention basins or vegetated facades, drain soil, etc. Following the functional analysis, we classified the measures according to three technical functions. For flood management (Table 3), we distinguished: storing water using specific structures and possibly move it; collecting and moving the water; increasing or maintaining the infiltration capacity of soil. For wildfire management (Table 4), we defined four functions: keeping the landscape open; increasing the capacity of forests to cope with the crisis; preparing for firefighting; managing the wildland-urban interface. For coastal flood (Table 5), three functions were defined: reducing wave energy; maintaining and increasing the shoreline; developing a calm zone behind the beach.

The RMMs are of different types for the three hazards considered (Tables 3, 4, and 5): NBS such as rain gardens or green roofs, or grey such as retention ponds or stormwater networks, or hybrid such as multifunctional retention ponds. Some RMMs may have several functions. For instance, swales, evacuate water while ensuring its storage and infiltration. Another example is multifunctional dry basins, which are temporarily submersible green spaces allowing the infiltration of rainwater but they can also be used, outside the flood period, as playgrounds or sports areas. For a given RMM, only the major function is shown in the tables.

Table 4. Wildfire RMMs classified according to technical functions and types of solution.

Technical functions	Inventoried RMMs	GS	NBS	HS
Keep the landscape open	Mechanical clearing	X		
	Silvopastoral clearing (grazing)		X	
	Controlled burning			X
	Removing biomass from the forest		X	
Increase the capacity of the forest to cope with the crisis	Improvement of resistance and resilience capacity by changing types of species		X	
	Improvement of resistance and resilience capacity by changing species distribution		X	
	Assisting species migration		X	
Preparing for firefighting	Storing water in forest massifs	X		
	Easy access to the forest/open tracks	X		
Manage the wildland-urban interface	Designing a safety buffer zone or contact areas between forest and houses		X	
	Consideration of the role of ornamental vegetation at the interface		X	

Table 5. Coastal flood RMMs classified according to technical functions and types of solution.

Technical functions	Inventoried RMMs	GS	NBS	HS
Reduce wave energy	Reducing wave energy before it reaches the coast: breakwaters, floating breakwaters, perforated caisson dikes	X		
	Reducing wave energy before it reaches the coast: Geotextile tubes			X
	Reducing wave energy before it reaches the coast: bottom vegetation, artificial reefs		X	
	Attenuating wave energy at the coastline: hydraulic piles	X		
	Attenuating wave energy at the shoreline: beach re-profiling		X	
	Attenuating wave energy at the shoreline: Covering the beach with plant debris		X	
Maintain and increase the shoreline	Fixing the coastline with structures: dykes, gabions, riprap groynes	X		
	Fixing the coastline with structures: geotextile tube groynes, drainage and "dewatering" systems, geotextile tubes to stabilise the dune belt			X
	Recharging the shoreline with materials: significant increase of the beach area, sediment bridging systems, "ganivelles" (permeable wooden barriers), net barriers, soil vegetation		X	
	Recharging the shoreline with materials: soil vegetation		X	
Develop a calm zone behind the beach	Channel over-visitation with “ganivelles”		X	
	Strategic retreat of the coastline		X	

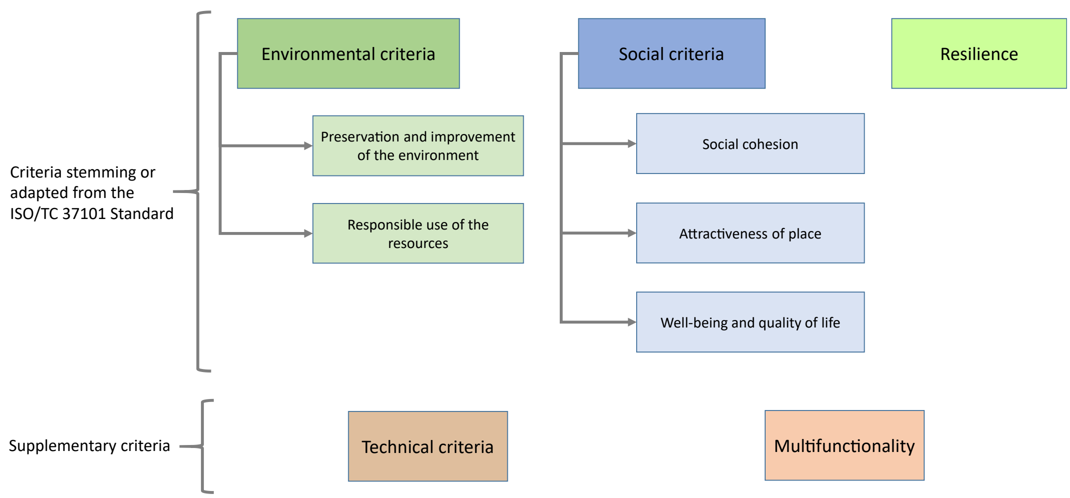

Figure 3. Criteria used to analyse co-benefits/disbenefits.

This type of structure can be associated with the following impacts:

- environmental co-benefits: the effective depollution of rainwater by the decantation of particles; increasing the infiltration capacity of water towards the groundwater;
- social co-benefits: multiple land-use; landscape integration; development of new reception areas for the public, etc.
- social disbenefits: concentration of pollutants carried out by rainwater (leaching) in play areas.

These positive and negative impacts were then used to formulate indicators and notably their assessment scale.

3.2. Definition of criteria to assess the co-benefits/disbenefits of RMMs

The following eight criteria were defined (Figure 3):

- Four stemming directly from "sustainable development goals" described in the ISO/TC 37101 Standard: Resilience; Preservation and improvement of the environment; Responsible use of resources; Social cohesion;
- Two adapted from "sustainable development goals" described in the standard to best match with our objectives: Attractiveness of place (“Attractiveness” in the Standard); Well-being and Quality of life (“Well-being”);
- Two added for the specific purposes of the study: Multi-functionality (the measure has at least another use in addition to risk management); Technical specifications for the phases of building and maintenance (Andersson-Sköld and Nyberg, 2016; Bana e Costa et al., 2004).

All the objectives of the ISO/TC 37101 Standard have been kept and supplementary ones added (Figure 3). The eight criteria cover environmental (Preservation and improvement of the environment; Responsible use of resources), social (Attractiveness of place, Social cohesion, Well-being and Quality of life), and technical issues, multi-functionality and resilience *i.e.* five main themes.

3.3. Formulation of indicators and validation

Criteria are established using indicators based on the positive and negative, environmental and social impacts identified during the RMM inventory and the examples provided for each goal in the ISO/TC 37101 Standard. Table 6 shows an example for the indicators relating to the Attractiveness of a place. Some indicators are constructed from the aggregation of two examples given in the standard (Sense of place - Sense of identity) or are specified (“Attachment to place” instead of “Place”). The culture item appears twice in the Standard, in the goals Attractiveness and Social Cohesion. We chose to keep the indicator Culture only in the Social cohesion criterion.

Table 6. Generation of indicators from examples given in the ISO/TC 37101 Standard - Illustration for the Attractiveness/Attractiveness of place.

Goal: Attractiveness Examples given in ISO/TC 37101 Standard	Criteria: Attractiveness of the place Indicators
Sense of place Sense of identity	Sense of place – Sense of identity
Place	Attachment to place
Interest of citizens and other interested parties e.g., investors	Interest of citizens and other interested stakeholders e.g., investors – use made of place
Culture	

Thirty-one indicators were formalised for the eight criteria for assessing the sustainability of structural risk management measures (Table 7 – a full presentation of the indicators is provided in Appendix B). Environmental and social indicators were validated by members of local and regional authorities during the focus group. Technical indicators stem from the literature and expert knowledge. Compared to the initial list produced in step S2b, 42% of the indicators were confirmed in their formulation, 27% were slightly modified and 31% underwent major changes.

Slight modifications entailed, for example, grouping two indicators judged similar (e.g., “creativity” and “culture” becoming “Creativity – Recreation” or “attachment to place” and “feeling of identity” becoming “Sense of place – Sense of Identity”) or just to add one word. Major changes either covered new dimensions (e.g., “to use land better” can be not to use it all – the indicator name was changed from “land use improvement” to “Land-use”), or proposed to specify concepts (e.g., the detail “anticipation” became “forecast” and “prevention”). Another major modification was to insist on the local aspect, as the measures are situated locally. Finally, the group proposed to integrate the capacity of the measure to stimulate civic participation, which was esteemed very important. It is now part of the definition of two indicators (Interest of citizens and other stakeholders – Use made of the place; Social Permeability).

In the general discussion following the evaluation of the measures by the focus group, its members proposed to improve the description of the indicators by adding examples to the definitions, to make them more concrete (Table 8).

Finally, 31 indicators were broken down as follows (Table 7):

- 1 for “Multi-functionality”
- 4 for “Resilience”
- 2 for “Attractiveness of place”
- 5 for “Social cohesion”
- 5 for “Well-being and quality of life”
- 2 for “Responsible use of resources”
- 4 for “Preservation and enhancement of the environment”
- 8 for “Technical specifications”

Indicators are divided according to four properties: their ability to manage risk (e.g., preparing to change to increase risk awareness -

Table 7. List of the indicators associated with a criterion – Properties characterized: ability to manage risk; ease to use; co-benefits-disbenefits (X–S: social co- and disbenefits; X – E: environmental co- and disbenefits).

Criterion	Indicator (code)	Ability to manage risk	Ease to use	Co- and Disbenefits
Multi-functionality	Multifunctional property (M1)			X
Resilience	Anticipation – Hazard performance (RE1)	X		
	Recovery from shocks and events (RE2)	X		
	Preparing for change to increase risk awareness (RE3)	X		
	Preparing for change towards more sustainable practices (RE4)			X–S
Attractiveness of place	Sense of place – Sense of identity (A1)			X–S
	Interest of citizens and other stakeholders – Use made of the place (A2)			X–S
Social cohesion	Accessibility (S1)			X–S
	Social permeability (S2)			X–S
	Equity - Reduction of inequalities (S3)			X–S
	Integration (S4)			X–S
	Social Mobility (S5)			X–S
Well-being and Quality of life	Creativity – Recreation (W1)			X–S
	Education – Training (W2)			X–S
	Landscaping (W3)			X–S
	Liveable city (W4)			X–S
	Sense of security (W5)			X–S
Responsible use of resources	Improvement of land-use (RU1)			X - E
	Reduction, reuse and recycling of materials - Sustainable production (RU2)			X - E
Preservation and improvement of the environment	Improving environmental performance (P1)			X - E
	Protection, restoration and enhancement of biological diversity and ecosystem services (P2)			X - E
	Restoration and enhancement of connectivity (P3)			X - E
	Health risks (P4)			X - E
Technical specifications	Ease of monitoring (technical means) (T1)		X	
	Ease of maintenance (technical means) (T2)		X	
	Ease of monitoring (know-how) (T3)		X	
	Ease of maintenance (know-how) (T4)		X	
	Lifespan (T5)		X	
	Health and safety (T6)		X	
	Vandalism – Theft (T7)		X	
	Legal constraint (T8)		X	

Table 8. Definition and assessment scale for three examples of indicator.

Criterion	Indicator Name	Indicator Definition and Assessment Scale
Attractiveness of place	Sense of place – Sense of identity	Ability of the RMM to influence the sense of place or identity +1: the RMM strengthens the sense of place or identity *For instance, the use of particular architecture, materials (e.g., local), old or traditional know-how to build the RMM, or the presence of an RMM considered as a man-made or natural heritage can contribute to increasing and preserving the sense of identity or the place* 0: the RMM have no effects on the sense of place or identity -1: the RMM degrade the sense of place or identity. *If the RMM replaces another infrastructure or natural environment that was a marker of the place or identity*
Preservation and improvement of the environment	Restoration and improvement of ecological connection	Ability of the RMM to act on the restoration or improvement of the ecological connection +1: the RMM strengthens the restoration and improvement of the ecological connection *For instance, the RMM creates a green or blue belt.* 0: the RMM have no effects on the restoration and improvement of the ecological connection -1: the RMM degrades the restoration and improvement of the ecological connection *For instance, the RMM disconnects an existing green or blue belt*
Preservation and improvement of the environment	Health risks	Ability of the RMM to have effects on the environment; the effects are expressed in the quality of water, air, soil and health +1: the RMM lowers health risks *For instance, the RMM efficiently depollutes rainwater by decanting particles; the RMM creates a cool island.* 0: the RMM has no effects on health risks -1: the RMM strengthens health risks *For example, the RMM traps undesirable components (heavy metal, toxic residues) in playgrounds, leading to the possible concentration of pollutants; the RMM allows the development of undesirable fauna (mosquitoes, rats, etc.)*

Table 7) and ease to use (e.g., ease of maintenance - Table 7) or whether they generate environmental/social co-benefits or disbenefits (e.g., improving environmental performance -Table 7).

Each indicator is described by a definition. Table 8 gives three examples. The other indicator descriptions can be found in Appendix B.

3.4. Assessment and representation of co- and disbenefits of RMMs

The last step leads to characterizing the different RMMs using the proposed indicators. Three types of tool and associated use are presented below; these tools give more or less detailed results. All address the comparison of several RMMs for floods, wildfires and coastal floods, regarding co- and disbenefits, their ability to manage the risk and their ease of use. They allow supporting the choice of solutions to implement, following the objectives of the planning: for example, favoring social co-benefits or choosing the measure that is the easiest to implement.

First, graphical representations like radar charts are proposed for each RMM (full set of indicators for social, environmental, or technical criteria) for flood (Figure 4), wildfire (Figure 5) and coastal flood (Figure 6) RMMs. This type of diagram allows comparing the RMM with each other at the indicator level, offering thus a detailed overview. For the sake of understanding, the indicators are separated into two groups (multi-functionality, environmental criteria and social criteria; ability to manage risk and ease to use) leading to two diagrams per RMM. For a given RMM, most of the indicators are context-dependent, such as shown in Table 8 with the indicator "Restoration and improvement of the ecological connection": for instance, a levee may or may not intersect a green and blue belt. In the results presented in Figure 4, it was considered

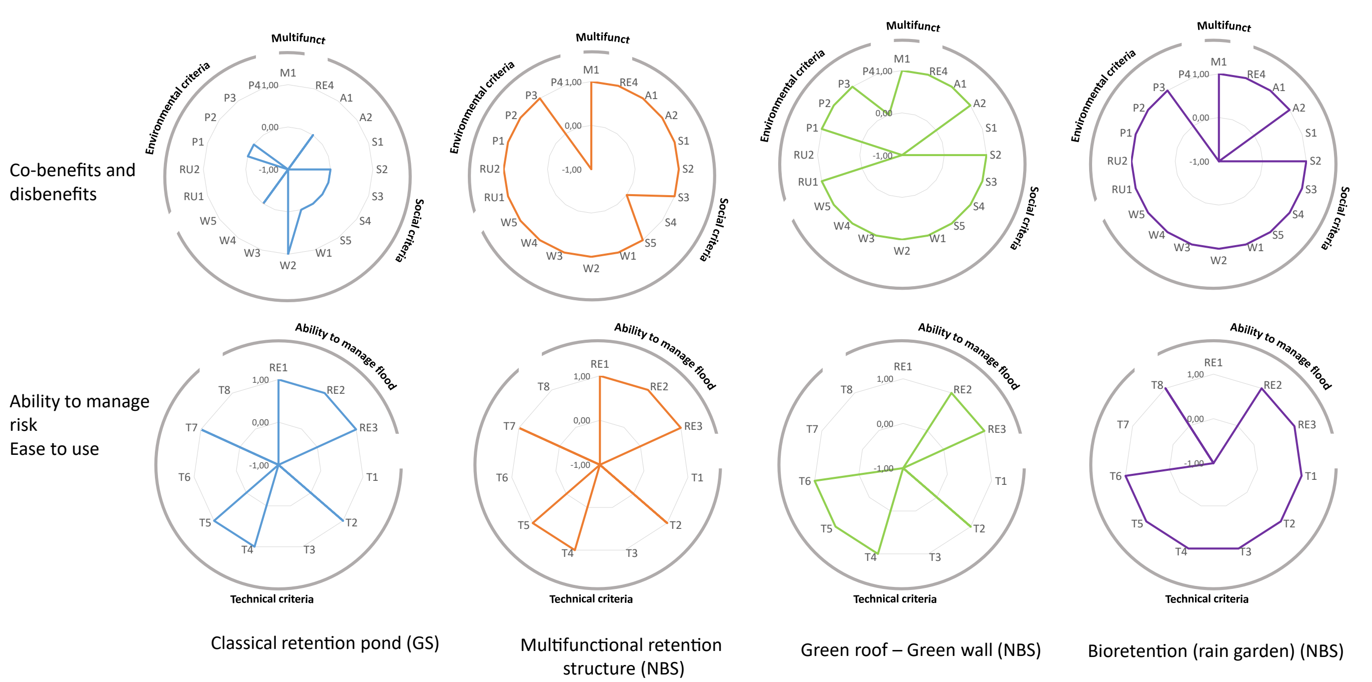

Figure 4. Comparison of co-benefits/disbenefits and ability to manage/use to use for four flood RMMs.

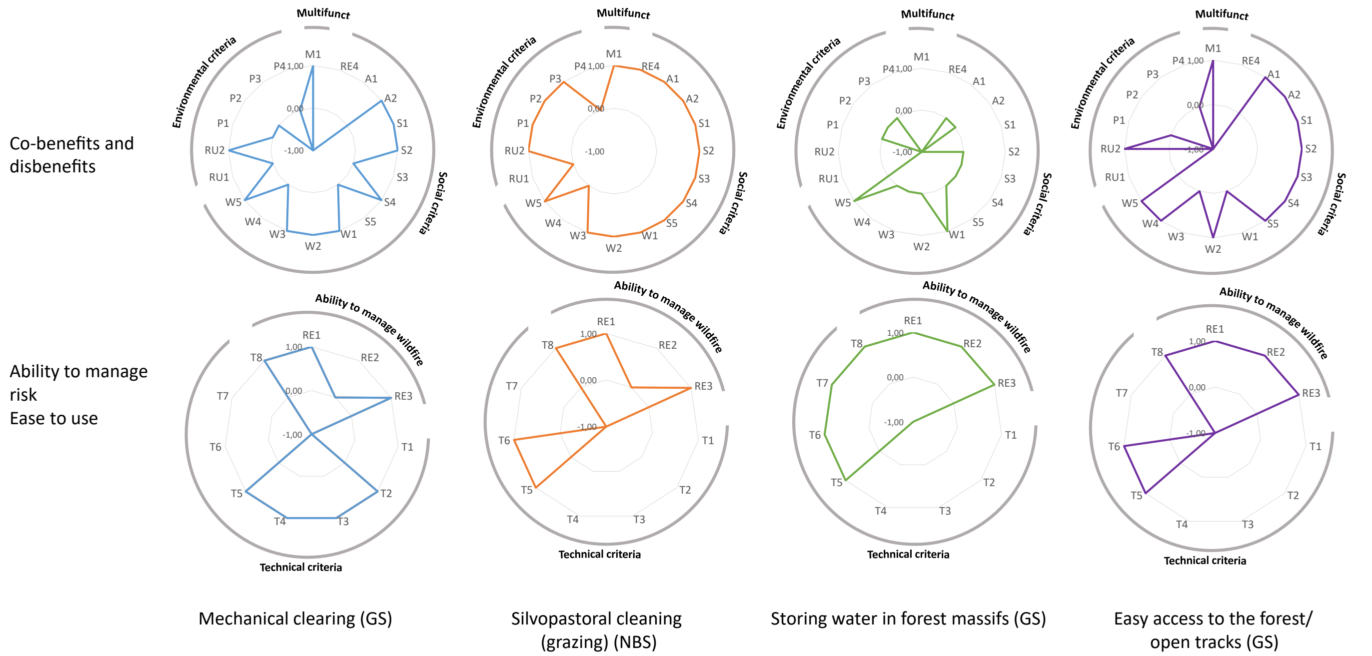

Figure 5. Comparison of co-benefits/disbenefits and ability to manage/use for four wildfire RMMs.

that, in the context studied (e.g. geographical area #1 in City1), the classical retention pond degrades the restoration and improvement of the ecological connection because it disconnects an existing green or blue belt (P3 indicator assesses as -1). With another geographic implantation (e.g. geographical area #2 in City1), the assessment could be 0, if the classical retention pond is placed outside an existing green or blue belt and is known to have no effect on the restoration or improvement of the ecological connection. This relies on the territory knowledge of the practitioners.

Conversely, multi-functionality property (M1) is considered as context-free and inherent to the RMM: for instance, rainwater networks are not multifunctional, contrary to green roofs.

The second tool provides a more synthetic view of environmental and social criteria, ability to manage risk and ease to use, which makes it easier to compare the RMMs with each other. The four scores are obtained by calculating the average of the indicators assigned to each property (Table 7 and Figures 4, 5, and 6).

Figure 7 shows the score obtained by the four types of RMM presented in Figures 4, 5, and 6, respectively for flood (Figure 7a), wildfire (Figure 7b) and coastal flooding (Figure 7c). The individual protection level of NBS can be lower, and they must be multiplied to be effective at the urban scale (numerous green roofs or rain gardens, for example). However, at their level, they contribute to protection. Conversely, the mechanical (GS) and silvopastoral (NBS) clearing present the same level

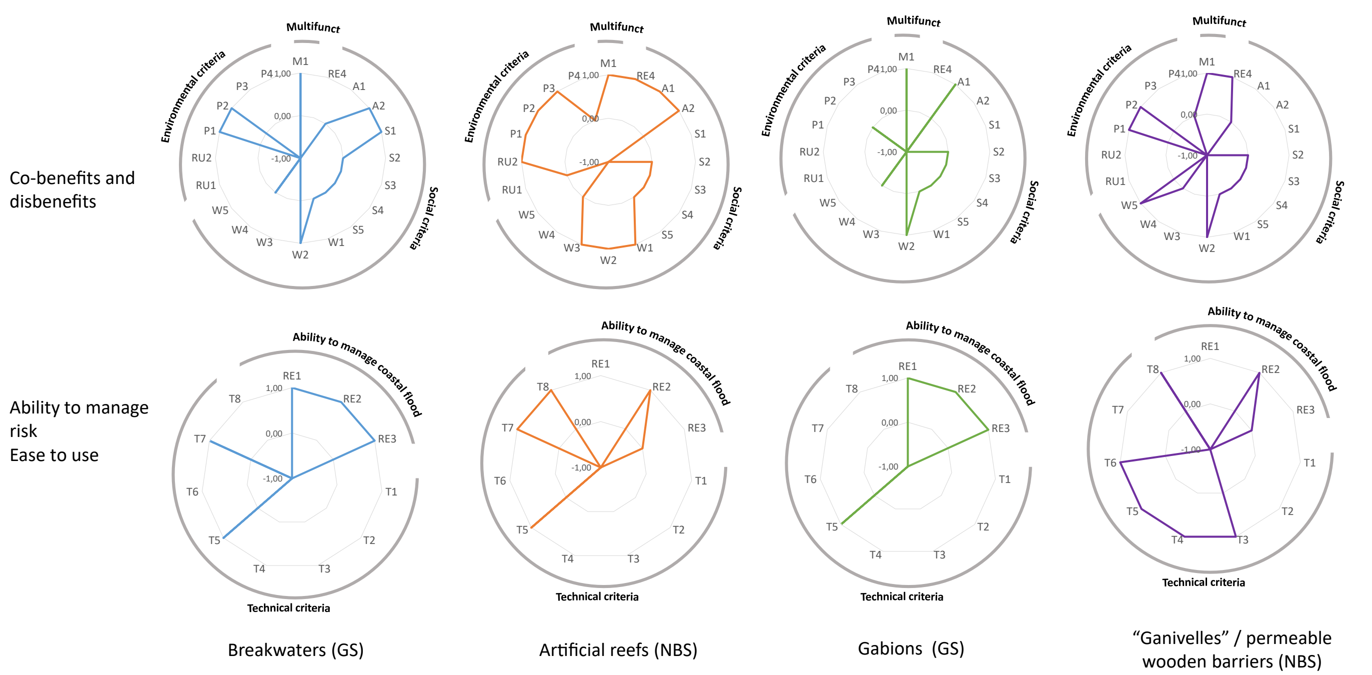

Figure 6. Comparison of co-benefits/disbenefits and ability to manage/use for four coastal flood RMMs.

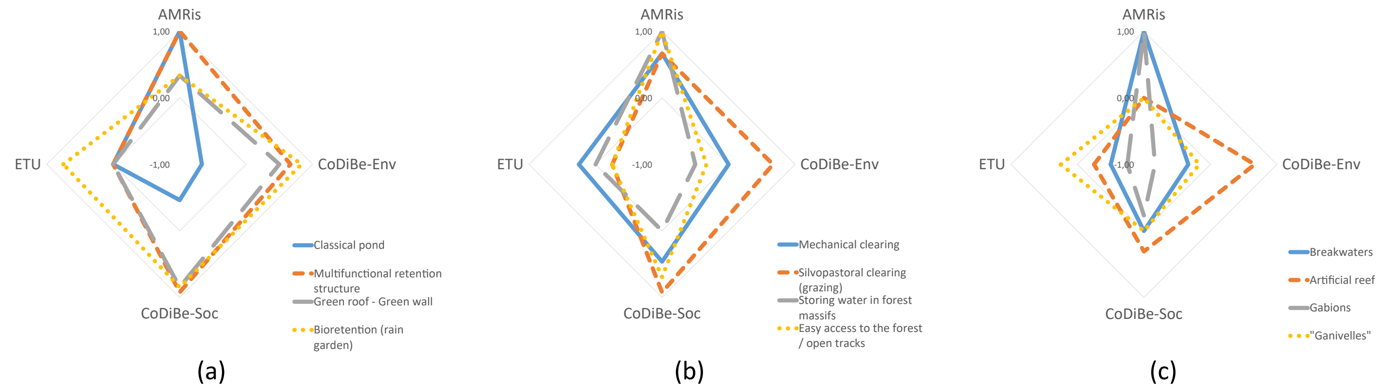

Figure 7. Comparison of aggregated criteria - AMRis/Ability to manage risk; CoDiBe-Env/Environmental Co- and Disbenefits; CoDiBe-Soc/Social Co- and Disbenefits; ETU: Ease to use – (a): flood measures; (b): wildfire measures; (c): coastal flood measures.

of protection against wildfire. Moreover, NBS offer more co-benefits from both social and environmental standpoints whatever the hazard considered, leading to multifunctional solutions. GS, NBS and HS can require significant know-how (for instance, the sylvopastoral clearing requires knowledge of husbandry and herd management practices, monitoring of the health status of the animals). At a defined level of protection, users can thus choose between several RMMs according to environmental and social criteria or ease to use.

Finally, this approach can be further refined (third tool) by associating weights to the indicators. This allows highlighting certain criteria. Table 9 presents the calculation of the score obtained by calculating (i) the arithmetic mean of the 4 scores (AMRis/Ability to manage risk; CoDiBe-Env/Environmental Co- and Disbenefits; CoDiBe-Soc/Social Co- and Disbenefits; ETU: Ease to use) for the wildfire hazard (results concerning flood and coastal flooding hazard can be found in Appendix C) and (ii) two weighted means. For the first one, the emphasis is put on environmental and social co- and disbenefits (weight for CoDiBe-Env/wCoDiBe-Env = wCoDiBe-Soc = 5 and wETU = 2); for the second one, the emphasis is put on ease to use (wCoDiBe-Env = wCoDiBe-Soc = 2 and wETU = 5); in both cases, the weight of the criterion defining the ability to protect has been set at 10 (wAMRis = 10). As shown by the scores, the ranking of RMMs differs following the criteria preferred: for instance, if the "ease to use" property is considered as more important than the environmental and social criteria, then the track opening (score = 0,50) is preferred over the sylvopastoralism clearing (score = 0,45) (Table 9). Conversely, if the "ease to use" property is considered as less important than the environmental and social criteria, then the sylvopastoralism clearing (score = 0,64) is preferred over the track opening (score = 0,51).

However, a single solution is rarely possible. In particular, in a context of climate change (IPCC, 2021) that tends to increase the intensity, duration and variability of natural hazards, these challenges can be overcome by all types of solutions, each with its own advantages and disadvantages. This militates in favour of combining GS and NBS that complement each other, leading to hybrid and multifunctional protection systems. This is in line with the results of Alves et al. (2019) and Sayers et al. (2013). Thus, compromises must be made between the different RMMs, considering the local environmental, economic, cultural, climatic contexts in particular. Indeed, not all solutions can be applied everywhere in urban areas: an analysis of local characteristics (types of potential sites and number) should be carried out in order to identify possible areas for implementing particular types of RMMs such as that performed in Alves et al. (2018b).

4. Discussion

4.1. *What advantages are provided by the approach developed?*

As seen in the introduction, few works have dealt with the issue of characterising the co-benefits/disbenefits of MMR. Moreover, these mainly consider NBS (Alves et al., 2018b; Beceiro et al., 2022; Brouwer and van Ek, 2004; Dittrich et al., 2019; European Commission, 2021; Giordano et al., 2020; Hoang et al., 2018; Lähde et al., 2019; O'Donnell et al., 2020; Ossa-Moreno et al., 2017; Vincent et al., 2017; Wójcik-Madej and Sowińska-Świerkosz, 2022), or NBS and GS (Alves et al., 2018a, 2019; Yang and Zhang, 2021). NBS are the subject of many works and recently two manuals have been published, one in the United States (Bridges et al., 2021) and the other in Europe (European Commission, 2021). We claim that the main strengths and contributions of the proposed approach in comparison to the literature are threefold: it analyses co-benefits and disbenefits gathered as eight criteria and five themes (Figure 3), it can be used for various types of RMM (GS, NBS or hybrid), and for different natural hazards (floods, wildfires and coastal floods were studied in particular, but the method can be applied to others). It can be applied to RMMs already implemented for improving an existing protection system or when planning new projects. It provides a basis for collective discussion on the choice of RMMs to be implemented, through three types of tool. This procedure allows building a transparent base for the decision-making processes in the context of sustainable spatial planning against natural risks. It relies on 31 indicators which is the same number as for the European Handbook (European Commission, 2021), when considering a green flood barrier (pp. 201–202). Several representation tools were proposed to support the exchanges between

Table 9. Global scores (without and with criteria weighting) for wildfire RMMs.

Global Score	Mechanical clearing	Silvopastoral clearing	Storing water in forest massifs	Easy access to the forest/open tracks
Without weighting	0,34	0,50	0,13	0,28
With weighting (wAMRis = 10 - wETU = 5 - wCoDiBe-Env = 2 - wCoDiBe-Soc = 2)	0,47	0,45	0,47	0,50
With weighting (wAMRis = 10 - wETU = 2 - wCoDiBe-Env = 5 - wCoDiBe-Soc = 5)	0,43	0,64	0,34	0,51

stakeholders. The results are transferable to other territories and countries notably because they rely on elements present in the ISO/TC 37101 standard, which has an international scope.

The methodological framework integrates a participatory approach involving researchers and operational stakeholders. An analysis of works presented in Table 1 shows that:

- several of these studies do not take collaborative or participative aspects into account (Alves et al., 2019; Bana e Costa et al., 2004; Banihabib et al., 2019; Brouwer and van Ek, 2004; Dittrich et al., 2019; Edjossan-Sossou et al., 2014; Hoang et al., 2018; Lähde et al., 2019; Vincent et al., 2017; Wójcik-Madej and Sowińska-Świerkosz, 2022);
- some involve stakeholders in some steps (Alves et al., 2018a; Beceiro et al., 2022; O'Donnell et al., 2020; Yang and Zhang, 2021);
- some adopt a collaborative approach (Alves et al., 2018b; Andersson-Sköld and Nyberg, 2016; Giordano et al., 2020; Ossa-Moreno et al., 2017).

Thus, evaluation methods based on truly collaborative approaches are quite rare in our context. This is in line with the conclusion of Giordano et al. (2020) and Ferrans et al. (2022). Indeed, it allows integrating stakeholders' perceptions and points of view in the study. In this work, the interest and ease of use of the approach were confirmed by the members of the focus group. First, they found that the discussion group created a bridge between researchers and stakeholders. Second, they stated that the approach was useful for comparing measures and exchanging with inhabitants; it could be considered at different decision-making levels (e.g., local, regional) and different times (*i.e.* pre- and post-decision).

4.2. What improvements can be made?

To date, the results have been shared with a group of local and regional public authorities, with a focus on supporting reflection and decision-making. This leads to the emergence of two perspectives. The first aims at opening the participatory approach to other stakeholders: this was suggested during the focus group to integrate, for instance, funding bodies or associations that can have specific interests. The second is to communicate about the various RMMs, and their co-benefits/disbenefits to the general public. This can raise public awareness, preparation for natural hazards, and improve public understanding of the decision-making process. Approaches as willingness-to-pay can assess the involvement of communities (Haque et al., 2022).

The aim of the method is to provide useful information on the co-benefits and disbenefits of RMMs to decision-makers. It also supports their reflection in terms of choice of RMMs in a territory, in particular giving insights on which RMMs most promote environmental or social issues, or which are the simplest to implement or maintain. To complete the analysis, economic criteria assessed through the costs associated with RMM building, monitoring and maintenance should be considered. Currently, to our knowledge, the works by Alves et al. (2019) are alone in addressing this issue with five different types of RMM (green roofs, pervious pavements, rainwater barrels, open detention basins and pipes). The E.U. handbook presents a very high number of indicators specific to NBS (European Commission, 2021): it would be relevant to see their interest and usability for other types of RMM (GS, HS).

An extension to other combinations of RMM seems relevant. There is no single integrated approach at present to achieve this: some works have already proposed methods that go in this direction but none of them appears suitable. They are based mainly on three approaches: arithmetic associated with a spatial representation via a Geographical Information System (e.g., Hoang et al. (2018); O'Donnell et al. (2020)); Cost-Benefit Analysis (CBA) that monetises all the inputs (e.g., Alves et al. (2019); Ossa-Moreno et al. (2017); Vincent et al. (2017)) or Multi-Criteria Analysis (MCA) that permits combining criteria of various types (qualitative/quantitative) (e.g. (Alves et al., 2019; Banihabib et al., 2019; Biswal et al., 2022; Edjossan-Sossou et al., 2020; Johnson and Geisendorf, 2019; Turkelboom et al., 2021)). Finally, integrated approaches are possible, for instance CBA and MCA (e.g., Brouwer and van Ek (2004)). In other fields, notably in supply chains, optimization methods have been employed (e.g., Bhinge et al. (2015)). The availability of the data used to assess the indicators and their nature (qualitative/quantitative – monetized or not) is one of the criteria that guides the choice for one or the other approach. Moreover, their quality and notably uncertainties must be considered. Several works have dealt with this issue: for example, Edjossan-Sossou et al. (2020) developed a fuzzy multi-criteria decision-making approach. As a perspective, a tool based on the indicators described here and covering all these dimensions in a clearly defined and locally applicable form might prove helpful to adapt to these changing circumstances.

5. Conclusion

The number of areas highly exposed to several natural or technological hazards is increasing due to several factors (urban sprawl; shorter distances between inhabited and industrial areas; a larger number of infrastructures and their interrelations; changes in the amplitudes, frequencies and spatial distribution of hazards due to climate change) (Curt, 2021). Communities must implement strategies to cope with all the hazards that threaten them, knowing that interactions occur during multi-risk events. This can entail the management of conflicts between economic, environmental and/or social criteria. Our method goes in this direction, allowing comparing several RMMs, taking into account the context in which they are implemented and discussing collectively the choice of RMMs considering a wide range of dimensions. Several types of representation (radar chart for each RMM; radar chart for a given risk compiling several RMMs; global score by RMM using weighting of criteria) are proposed to stakeholders, providing them individual views and allowing comparisons in a set of solutions. This is intended to help them make wise choices relative to the land-use planning and sustainable risk management.

Declarations

Author contribution statement

Corinne Curt; Alexandra Schleyer-Lindenmann: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Pascal Di Maiolo; Anne Tricot: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Aurélie Arnaud; Thomas Curt; Nelly Parès; Franck Taillandier: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest statement

The authors declare no competing interests.

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References

Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., Sanchez, A., 2019. Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. J. Environ. Manag. 239, 244–254.

Alves, A., Gersonius, B., Sanchez, A., Vojinovic, Z., Kapelan, Z., 2018a. Multi-criteria approach for selection of green and grey infrastructure to reduce flood risk and increase CO-benefits. Water Resour. Manag. 32, 2505–2522.

Alves, A., Patiño Gómez, J., Vojinovic, Z., Sánchez, A., Weesakul, S., 2018b. Combining Co-benefits and stakeholders perceptions into green infrastructure selection for flood risk reduction. Environments 5, 29.

Andersson-Sköld, Y., Nyberg, L., 2016. Effective and sustainable flood and landslide risk reduction measures: an investigation of two assessment frameworks. Int. J. Disas. Risk Sci. 7, 374–392.

Bana E Costa, C.A., Antão Da Silva, P., Nunes Correia, F., 2004. Multicriteria evaluation of flood control measures: the case of ribeira do livramento. Water Resour. Manag. 18, 263–283. WARM.0000043163.19531.6a.

Banihabib, M.E., Chitsaz, N., Randhir, T.O., 2019. Non-compensatory decision model for incorporating the sustainable development criteria in flood risk management plans. SN Appl. Sci. 2 (6).

Beceiro, P., Brito, R.S., Galvão, A., 2022. Assessment of the contribution of Nature-Based Solutions (NBS) to urban resilience: application to the case study of Porto. Ecol. Eng. 175, 106489.

Bhinge, R., Moser, R., Moser, E., Lanza, G., Dornfeld, D., 2015. Sustainability optimization for global supply chain decision-making. Proc. CIRP 26, 323–328.

Biswal, B.K., Bolan, N., Zhu, Y.-G., Balasubramanian, R., 2022. Nature-based Systems (NbS) for mitigation of stormwater and air pollution in urban areas: a review. Resour. Conserv. Recycl. 186, 106578.

Bridges, T.S., King, J.K., Simm, J.D., Beck, M.W., Collins, G., Lodder, Q., Mohan, R.K., 2021. International Guidelines on Natural and Nature-Based Features for Flood Risk Management. Vicksburg, MS. U.S. Army Engineer Research and Development Center.

Brouwer, R., Van Ek, R., 2004. Integrated ecological, economic and social impact assessment of alternative flood control policies in The Netherlands. Ecol. Econ. 50, 1–21.

CANADIAN ENVIRONMENTAL ASSESSMENT AGENCY, 2008. A Guide for Meaningful Public Participation in Environmental Assessments under the canadian Environmental Assessment Act.

Chan, F.K.S., Yang, L.E., Mitchell, G., Wright, N., Guan, M., Lu, X., Wang, Z., Montz, B., Adekola, O., 2022. Comparison of sustainable flood risk management by four countries – the United Kingdom, The Netherlands, the United States, and Japan – and the implications for Asian coastal megacities. Nat. Hazards Earth Syst. Sci. 22, 2567–2588.

COHEN-SHACHAM, E., JANZEN, C., MAGINNIS, S., WALTERS, G. (Eds.), 2016. *Nature-based Solutions to Address Global Societal Challenges* Gland. IUCN, Switzerland.

Curt, C., 2021. Multirisk: what trends in recent works? – a bibliometric analysis. Sci. Total Environ. 763, 142951.

Curt, C., Peyras, L., Boissier, D., 2010. A knowledge formalization and aggregation-based method for the assessment of dam performance. Comput. Aided Civ. Infrastruct. Eng. 25, 171–184.

Curt, C., Tacnet, J.-M., 2018. Resilience of critical infrastructures: review and analysis of current approaches. Risk Anal. 38, 2441–2458, 10.1111/risa.13166.

Dittrich, R., Ball, T., Wreford, A., Moran, D., Spray, C.J., 2019. A cost-benefit analysis of afforestation as a climate change adaptation measure to reduce flood risk. J. Flood Risk Manag. 12, e12482.

Edjossan-Sossou, A.M., Deck, O., Al Heib, M., Verdel, T., 2014. A decision-support methodology for assessing the sustainability of natural risk management strategies in urban areas. Nat. Hazards Earth Syst. Sci. 14, 3207–3230.

Edjossan-Sossou, A.M., Galvez, D., Deck, O., Al Heib, M., Verdel, T., Dupont, L., Chery, O., Camargo, M., Morel, L., 2020. Sustainable risk management strategy selection using a fuzzy multi-criteria decision approach. Int. J. Disaster Risk Reduc. 45.

EN 1325-1, 2014. Value Management - Vocabulary - Terms and Definitions.

Estrella, M., Saalismaa, N., 2013. Ecosystem-based disaster risk reduction (Eco-DRR): an overview. In: RENAUD, G., -R., K.S., ESTRELLA, M. (Eds.), The Role of Ecosystems in Disaster Risk Reduction. United Nations University Press.

EUROPEAN COMMISSION, 2021. Evaluating the Impact of Nature-Based Solutions.

European Parliament And Council, 2007. Directive 2007/60/EC on the Assessment and Management of Flood Risks.

Faivre, N., Sgobbi, A., Happaerts, S., Raynal, J., Schmidt, L., 2018. Translating the Sendai Framework into action: the EU approach to ecosystem-based disaster risk reduction. Int. J. Disaster Risk Reduc. 32, 4–10.

Ferrans, P., Torres, M.N., Temprano, J., Rodríguez Sánchez, J.P., 2022. Sustainable Urban Drainage System (SUDS) modeling supporting decision-making: a systematic quantitative review. Sci. Total Environ. 806, 150447.

Ferrer, L., Curt, C., Tacnet, J.M., 2018. Analysis of a risk prevention document using dependability techniques: a first step towards an effectiveness model. Nat. Hazards Earth Syst. Sci. 18, 1201–1221.

Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., Nanu, F., 2020. Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. Sci. Total Environ. 713, 136552.

Haque, M.N., Saroar, M., Fattah, M.A., Morshed, S.R., 2022. Environmental benefits of blue ecosystem services and residents' willingness to pay in Khulna city, Bangladesh. Heliyon 8.

Hoang, L., Fenner, R.A., Skenderian, M., 2018. A conceptual approach for evaluating the multiple benefits of urban flood management practices. J. Flood Risk Manag. 11, S943–S959.

IPCC, 2021. Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

ISO/TC 37101, 2016. Sustainable Development in Communities - Management System for Sustainable Development - Requirements with Guidance for Use.

Johnson, D., Geisendorf, S., 2019. Are neighborhood-level SUDS worth it? An assessment of the economic value of sustainable urban drainage system scenarios using cost-benefit analyses. Ecol. Econ. 158, 194–205.

Lähde, E., Khadka, A., Tahvonen, O., Kokkonen, T., 2019. Can we really have it all?—designing multifunctionality with sustainable urban drainage system elements. Sustainability 11, 1854.

Mcvittie, A., Cole, L., Wreford, A., Sgobbi, A., Yordi, B., 2018. Ecosystem-based solutions for disaster risk reduction: lessons from European applications of ecosystem-based adaptation measures. Int. J. Disaster Risk Reduc. 32, 42–54.

MUNICHRE, 2021 [Online]. [Accessed]. https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html.

Nobanee, H., Al Hamadi, F.Y., Abdulaziz, F.A., Abukarsh, L.S., Alqahtani, A.F., Alsubaey, S.K., Alqahtani, S.M., Almansoori, H.A., 2021. A bibliometric analysis of sustainability and risk management. Sustainability 13, 3277.

O'Donnell, E.C., Thorne, C.R., Yeakley, J.A., Chan, F.K.S., 2020. Sustainable flood risk and stormwater management in blue-green cities; an interdisciplinary case study in portland, Oregon. J. Am. Water Resour. Assoc. 56, 757–775.

Ossa-Moreno, J., Smith, K.M., Mijic, A., 2017. Economic analysis of wider benefits to facilitate SuDS uptake in London, UK. Sustain. Cities Soc. 28, 411–419.

Qi, Y., Chan, F.K.S., Thorne, C., O'Donnell, E., Quagliolo, C., Comino, E., Pezzoli, A., Li, L., Griffiths, J., Sang, Y., Feng, M., 2020. Addressing challenges of urban water management in Chinese sponge cities via nature-based solutions. Water 12, 2788.

Saaty, T.L., 1982. Decision-Making for Leaders : the Analytical Hierarchy Process for Decisions in a Complex Word. Life-time learning publications, Belmont, CA, 94002 USA.

Sadollah, A., Nasir, M., Geem, Z.W., 2020. Sustainability and optimization: from conceptual fundamentals to applications. Sustainability 12, 2027.

Sayers, P., Yuanyuan, L., Galloway, G., Penning-Rowsell, E., Fuxin, S., Kang, W., Yiwei, C., Quesne, T.L., 2013. Flood Risk Management: A Strategic Approach. Asian Development Bank, GIWP, UNESCO and WWF-UK.

Stephan, C., Norf, C., Fekete, A., 2017. How "sustainable" are post-disaster measures? Lessons to Be learned a decade after the 2004 tsunami in the Indian ocean. Int. J. Disas. Risk Sci. 8, 33–45.

Talon, A., Curt, C., Boissier, D., 2014. Performance assessment based on evidence theory and fuzzy logic: application to building and dam performance. J. Comput. Civ. Eng. 28, 124–133.

Titko, M., Ristvej, J., 2020. Assessing importance of disaster preparedness factors for sustainable disaster risk management: the case of the Slovak republic. Sustainability 12, 9121.

Turkelboom, F., Demeyer, R., Vranken, L., de Becker, P., Raymaekers, F., de Smet, L., 2021. How does a nature-based solution for flood control compare to a technical solution? Case study evidence from Belgium. Ambio 50, 1431–1445.

UNITED NATIONS, 2015. Transforming Our World: the 2030 Agenda for Sustainable Development.

UNITED NATIONS/DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, 2015. Risks of Exposure and Vulnerability to Natural Disasters at the City Level: A Global Overview.

UNITED NATIONS/INTERNATIONAL STRATEGY FOR DISASTER REDUCTION (UNISDR), 2005. Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters - Extract from the Final Report of the World Conference on Disaster Reduction. Kobe, Hyogo, Japan.

UNITED NATIONS/INTERNATIONAL STRATEGY FOR DISASTER REDUCTION (UNISDR), 2015. Sendai Framework for Disaster Risk Reduction 2015-2030. Sendai, Japan.

Van Veelen, P., Voorendt, M., Van der Zwet, C., 2015. Design challenges of multifunctional flood defences: a comparative approach to assess spatial and structural integration. Res. Urban. Ser. 3, 275–292.

Vigier, E., Curt, C., Curt, T., Arnaud, A., Dubois, J., 2019. Joint analysis of environmental and risk policies: methodology and application to the French case. Environ. Sci. Pol. 101, 63–71.

Vincent, S.U., Radhakrishnan, M., Hayde, L., Pathirana, A., 2017. Enhancing the economic value of large investments in sustainable drainage systems (SuDS) through inclusion of ecosystems services benefits. Water 9, 841.

Viti, M., Löwe, R., Sørup, H.J.D., Rasmussen, M., Arnbjerg-Nielsen, K., Mcknight, U.S., 2022. Knowledge gaps and future research needs for assessing the non-market benefits of Nature-Based Solutions and Nature-Based Solution-like strategies. Sci. Total Environ. 841, 156636.

Wójcik-Madej, J., Sowińska-Świerkosz, B., 2022. Pre-existing interventions as NBS candidates to address societal challenges. Sustainability 14, 9609.

Yang, W., Zhang, J., 2021. Assessing the performance of gray and green strategies for sustainable urban drainage system development: a multi-criteria decision-making analysis. J. Clean. Prod. 293, 126191.