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Managing protection in torrential mountain watersheds: A new conceptual integrated decision-aiding framework

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In mountains, natural hazards such as torrential phenomena are damageable for elements at risk. Land use management policies depend on natural risk analysis and on its reduction by protective measures such as civil engineering structures (e.g. check dams, dikes) and forest. Managing these systems is thus needed to help land use planning. It is related to multidisciplinary decision-making problems, from technical effectiveness assess-ment of protective measures (structural, functional) to their socio-economic efficiency to reduce risk. Decision-aiding tools such as Cost-Benefit Analysis (CBA) have been recently introduced in mountain watersheds' management field. Nevertheless, traceability of involved expert reasoning is still missing such as the link between technical and socio-economic problems. This paper aims to show how decision-aiding tools can help to improve these aspects within an innovative integrated decision-aiding framework at the torrential watershed scale. Therefore, a brief overview of decision-aiding approaches, involving several theoretical frameworks, is provided. The integrated decision-aiding framework is then introduced. Finally, improvements are discussed showing that field applications are now needed.

1. Introduction

The torrential event on the 18th of June 2013, in the Central Pyrénées of France, caused two victims and severe damage on roads (almost 30 million euros), houses (13 destroyed such as on Fig. 1, 22 deteriorated), economic activities (destruction of 6 farm buildings, 2 other economic ones, and sites of 5 camping), and agricultural lands (loss of 60 ha) (Gallou et al., 2014; Duchêne, 2015). This is one of the most noteworthy examples of damages caused by torrents and torrential rivers in French mountainous areas such as in Grenoble (14/09/1219), Faucon-de-Barcelonnette (13/08/1876), Briançon (30/05/1856), Verdun (23/06/1875), Sainte-Foy-en-Tarentaise (16/09/1883), Saint-Gervais (12/07/1892), Voiron (05/06/1897), Modane (numerous debris flows during the 19th century, and more recently in 24/08/1987, 01/08/2014), Salau dans l'Ariège (05/10/1937, 27/10/1937, 08/11/1982), all the Pyrénées-Orientales department (14/10/1940), Pontamafrey (19/05/1965), Bourg-Saint-Maurice (24/07/1996), or Contamines-Montjoie (22/08/2005) (Givry and Peteuil, 2011). In fact, torrential phenomena, such as debris flows and torrential floods with bedload transport, propagate on steep slopes, faster and with more impact pressure on obstacles than flood plains phenomena. Their impact on humans and properties such as buildings, roads or industries may therefore be devastating.

In the field of natural phenomena, the risk R_{Ω} on a given territory is defined in Eq. (1) as the combination of two components: the hazard and the potential of damage in exposed area to this hazard analysed for each effect of the phenomenon (e.g. impact, scouring, overflowing for a torrential flood) (Tacnet et al., 2014).

For each type of phenomenon (e.g. debris flow), the hazard is characterized by the probability of occurrence $P(M_k)$of an event of magnitude (e.g. volume of debris flow) higher than a minimum established value M_k, and the spatial probability $P(X_{y_l}|M_k)$ of reaching a point X with an intensity y_l (e.g. depth of material deposit) (Corominas et al., 2013). Given the return period T_k, which is the mean time between two consecutive events with a magnitude above M_k, one has: $P(M_k) = 1 - 1/T_k$. In practice, experts consider several scenarios S_k, $k = 1, \ldots, K$, which are discrete evaluations of the magnitude M_k. Thus, the annual probability of occurrence of each scenario S_k is given by $P(S_k) = 1/T_k - 1/T_{k+1}$ (Bründl et al., 2009).

The potential of damage is defined by the combination of three components: the exposure of elements at risk, their vulnerability, and their value. The exposure rate $q(z_e, X_{y_l})$ is the probability of each

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Fig. 1. House destroyed by the Bastan flood on the 18th of June 2013 in Barèges, in the Hautes-Pyrénées (photo taken on the 03/07/2013, S. Carladous).

element at risk z_e, $e = 1, \ldots, \Omega$ being at the point X at the moment of the occurrence of the event. The vulnerability $V(z_e, y_l)$ is the potential damage rate of each element at risk z_e, $e = 1, \ldots, \Omega$, given intensity y_l. For quantitative analysis of risk R_Ω, a value $C(z_e)$ is given to each element at risk z_e, $e = 1, \ldots, \Omega$ (Corominas et al., 2013).

$$R_\Omega = \sum_{e=1}^{\Omega} q\left(z_e, X_{y_l}\right).\ C(z_e).\ \sum_{k=1}^{K} P(S_k).\ P\left(X_{y_l}|M_k\right).\ V(z_e, y_l) \tag{1}$$

If the risk is considered as too high, territorial managers will expect to reduce the risk to a socially acceptable level acting either on components of hazard which are $P(S_k)$and $P(X_{y_l}|M_k)$, or on components of potential of damage such as exposure and vulnerability (Leone et al., 2010).

1.1. From a problem of operational management to a problem of decision-making

Concerning risk management policies, the Ministry for Ecological and Inclusive Transition (MTES) is responsible for implementation of risk prevention actions on French national territory. Amongst these, structural measures, such as protective structures, aim to reduce hazard acting on the components of hazard. Several types of protective structures exist (e.g. torrent control structures, sediment traps, dikes) with specific functions and effects on torrential phenomena (Hübl et al., 2005). Torrent control structures, such as check dams to consolidate and stabilise the profile along the riverbed, limit departure of materials from bedload source areas. It helps to reduce the annual probability $P(S_k)$. Channelling a river by the construction of dikes avoids the river to flood in vulnerable areas, reducing therefore the spatial probability $P(X_{y_l}|M_k)$. Sediment traps retain a volume of materials to limit their transport and deposition in areas at risk here again through reduction of $P(X_{y_l}|M_k)$ (Fig. 2). Nature based solutions (NBS) such as forests, grass seeding, erosion control netting or wattles, are distinguished from civil engineering structural measures that they complement (Ecole Forestière, 1911).

Since the 19th century, the French government has initiated a policy to protect mountain areas against torrential phenomena, known as the Restoration and Conservation of Mountain Lands regulation framework (referred by RTM acronym in France standing for “Restauration des Terrains en Montagne”). As a consequence, more than 380,000 ha of lands have been acquired in mountains by French State mainly for reforestation. Approximately 100,000 so-called torrent control structures (rustic, masonry and concrete check dams) have been constructed on these areas (Messines du Sourbier, 1964) (Fig. 3). From the seventies,

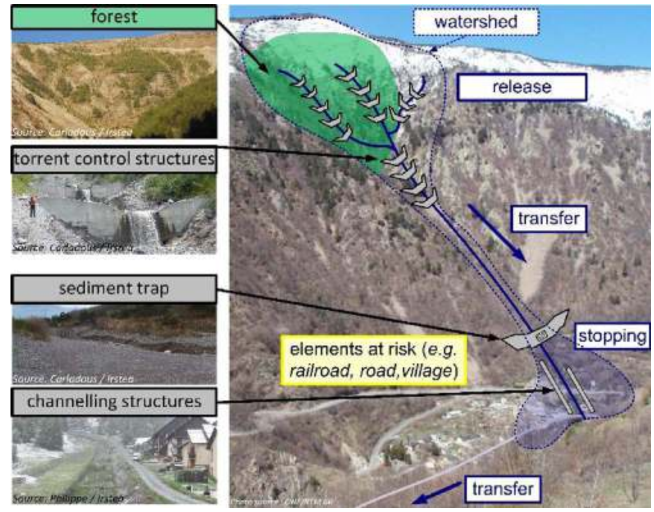

Fig. 2. Distribution of structural protection measures and their functions to mitigate torrential floods in a mountain watershed.
(adapted from Carladous et al. (2016a)

the protection expanded to include other phenomena such as snow avalanches (Brugnot and Cassayre, 2002). The French State, represented by its Ministry of Agriculture and Food (MAA), is nowadays the owner of all those protective structures implemented in state-owned RTM forests since the 19th century.

Their maintenance is needed to limit occurrence of structural damage over time. Building new structures in state-owned forests can also be needed to improve the protection effect on natural hazard components. Nowadays, these maintenance and investment works are managed by RTM services of the National Forestry Office (ONF) on behalf of the MAA, in state-owned RTM forests of mountain departments (Alps and Pyrénées). Therefore, the RTM database (BD-RTM) has been developed for almost 15 years to register old and more recent structures to be managed. The RTM technical officers regularly visit them and register their monitoring advice in this BD-RTM. The current version encloses approximately 21,000 protective structures against torrents, snow avalanches, and rock falls. Amongst the 17,000 protective structures against torrential phenomena presently registered, more than 93% are torrent control structures. Compared with the 100,000 torrent control structures registered in 1964, the number of registered structures has decreased to focus monitoring and maintenance actions on the most significant structures.

According to the national RTM activities report in 2011, the maintenance cost of structures in RTM forests was estimated at €12 million/year (€8 million in machinery use and €4 million in personnel costs). At the same time, protection needs have changed, with a decrease in the rural population and an increase in the tourist and peri-urban population (Brugnot and Cassayre, 2002). Two operational problems have emerged to keep on guaranteeing that (1) the level of protection offered by the existing structures is sufficient and (2) their maintenance fits with actual needs to make the best use of restricted budgets.

In order to answer these problems, natural hazard managers, and their assisting experts, seek to estimate the effectiveness of protective structures. Although this concept may seem essential to the process, it is often not formalised and contains several decision-making problems. Are the existing systems, degraded and impacted by destructive phenomena, able to structurally resist? Will they achieve their assigned functional objectives such as limiting erosion, overflows, etc.? Which strategy should be chosen to maintain, or sometimes increase, their effectiveness thanks to maintenance actions or new structures construction?

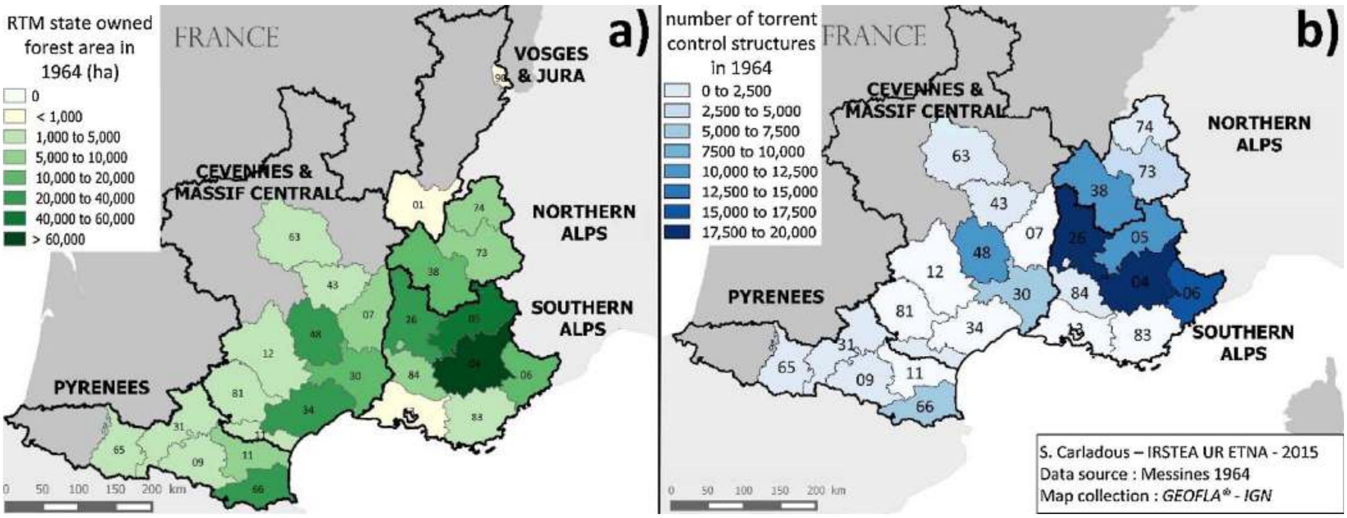

Fig. 3. Geographical distribution in 1964 in 25 departments showing a) RTM state-owned forest surface areas and b) torrent control measures. (adapted from Carladous et al. (2016b)

1.2. A multi-scale, multi-component decision-making problem based on imperfect information

In watersheds, the objective of structural measures is to protect elements at risk exposed to phenomena. Structures with a common technical function are grouped into devices. In this way, three different systems at different scales are interlinked (Fig. 4). (i) The watershed with elements at risk comprises the elements at risk, the phenomena release, propagation and stopping areas, as well as all the protective measures whose role is to protect against them. (ii) The device consists of a set of structures with the same function in a given geographical area of the watershed. (iii) The structure provides a technical function which, coupled with that of other structures, allows the device to ensure its function.

At each scale, the design of protection systems must ensure that the expected function is properly executed while resisting structurally to pressure. A structure's effectiveness is evaluated according to its design and construction.

The process of functional design and structural dimensioning is known (Deymier et al., 1995; Suda and Rudolf-Miklau, 2010) but it is based on hypotheses that are not always formalised or available. There are different forms of imperfection regarding topographic, geotechnical and hydraulic required knowledge. Inconsistency is about the conflict between several sources of information. Imprecision corresponds to information insufficiency: the "true" value is bounded through lower and upper interval values. Incompleteness is about the lack or partial availability of information. Uncertainty relates to the relation between the real state and its assessment for the same situation (Smets, 1997). General term of uncertainty includes aleatory and epistemic uncertainty. The former results from a random behaviour on the object assessed: it is represented through objective probability. The latter results from a lack of knowledge on the system (Tacnet et al., 2014).

Furthermore, the functional and structural effectiveness of protective structures in service decreases over time. Indeed, materials naturally degrade implying that their structural resistance progressively reduces. Moreover, protective structures are located in torrents and are exposed to very damageable natural phenomena (e.g. snow avalanches, rock falls, debris flows). As a consequence, effectiveness assessment requires that structures are inspected on a regular basis. Since weaknesses associated to these structures are known (Suda, 2009), status indicators are deducted from them to help perform the assessment. These indicators are evaluated under difficult conditions (dangerous

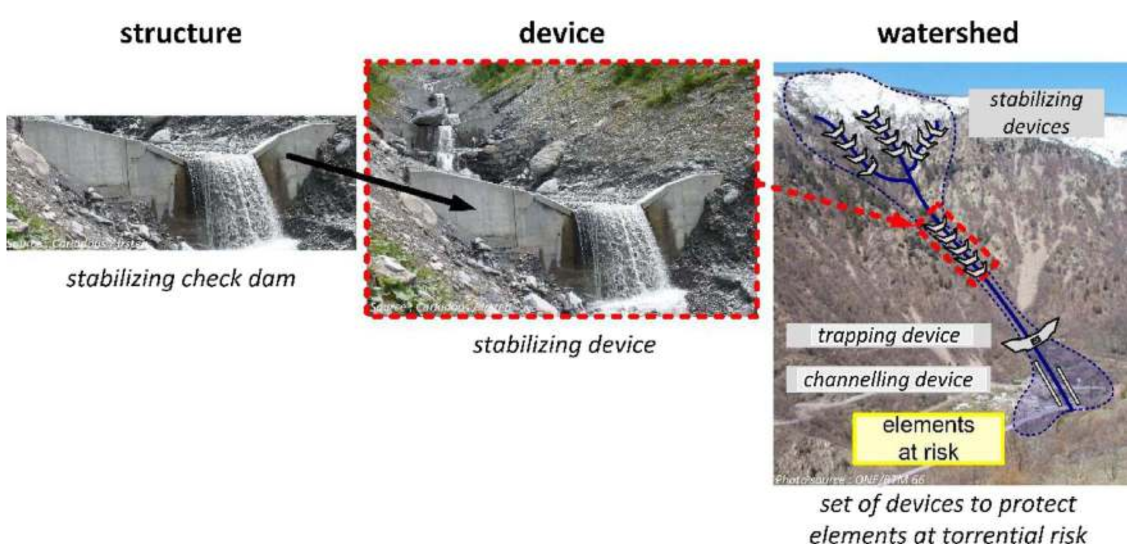

Fig. 4. The three scales of torrent control measures. (adapted from Carladous et al. (2014)

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locations, difficult access) and is therefore mainly based on visual observations, which are imprecise and qualitative poor data. Moreover, the incorporation of this evaluation in the effectiveness assessment is based on an expert opinion (Suda, 2013), and the traceability of this process of incorporation is limited. In order to help managers of the previously presented area of structures in their decision-making, an effectiveness assessment should also include the socio-economic component of risk reduction (Tacnet et al., 2014). To do so, the cost-benefit analysis (CBA) is the most used method to help decide which actions of protection should be implemented, for example as performed in Switzerland by way of the data program EconoMe® (Bründl et al., 2009). Management decisions for torrent control structures are therefore multicomponent and relate to structural, functional and socio-economic issues.

Based on an economic efficiency assessment, the evaluation of the socio-economic component is based on risk reduction and cost of associated measures. Eventually, effectiveness assessment depends on the risk assessment taking into account the protection measures' effect.

At this stage, a first issue of CBA is that risk quantification is limited to tangible damage (CGDD, 2014), while other intangible damage (human health, environmental goods, etc.) are not considered. A second issue is that the quantification of torrential risk reduction is based on the assumption of random behaviour. This supposes sufficient knowledge of the phenomenon's physics to represent this behaviour (Woo, 1999). In the torrential domain, this knowledge is very limited (Chambon and Laigle, 2013, p. 201).

Thus, managers of torrent control structures are in charge of decision-making and are confronted with the difficult integration of multiple scales and components within a context of imperfect information and natural hazards management. To do this, specific methods are needed to: (i) structure the effectiveness assessment problem taking into account the different scales and components; (ii) perform decision-aiding by considering the various forms of imperfection and the unequally reliable multiple sources; (iii) integrate the expertise process into a multi-scale decision aiding process.

The objective of this article is to show how the use of new decision-aiding methods may be integrated into a formalised framework of analysis through the conceptual description of this analytical framework. This article does not aim at detailing mathematical aspects of such methods or at showing the real application of these individual methods on different sub-problems as already done elsewhere (Carladous et al., 2015, 2016c). Under this assumption, the Section 2 introduces the methods, didactically, without detailing calculation-intensive aspects but by justifying choices made. The Section 3 presents the integrated analytical framework pointing out integration of decision-aiding methods within a complex, multi-scale and multi-component decision-aiding framework. The Section 4 discusses this analytical framework by identifying remaining developments to be performed as well as expected practical applications.

2. Methods: mathematical tools at the service of the decision-aiding process

Methods that are used shall contribute to structure multi-scale decision-making problems, to take into account various dimensions of risk mitigation, and to make decisions based on imperfect information. Thus, we describe successively the general principles of decision-aiding, dependability methods and the theoretical frameworks of propagation of the various forms of information-related imperfections in the decision-aiding process.

2.1. Multi-criteria decision-aiding in an uncertain context

Decision-making consists in discriminating several potential alternatives in a defined set, according to three types of problems (Roy, 1985): i) choosing the best alternative, ii) sorting alternatives by assigning them to predefined classes, iii) classifying alternatives according to an order of preference. For example, this may correspond to different cases: (i) the choice of the best protection solution at watershed level, (ii) the evaluation of the effectiveness of structures or devices at different levels of effectiveness (zero, low, medium, strong), and iii) grading different devices from the most effective to the least effective.

2.1.1. Formalising the decision-making problem: alternatives, criteria, scenarios

In order to do so, several criteria must be considered. These criteria are more or less important to each decision-maker. Furthermore, each alternative is assessed according to each criterion while considering the decision-maker's preferences.

Each alternative may have different consequences according to events that may occur (Chateauneuf et al., 2006), which are called states of the nature or scenarios. In the case of natural phenomena, which is our issue here, these scenarios are generally established in a discrete way (Bründl et al., 2009). According to aggregated knowledge from all scenarios, one defines decision problems in a certain, risky, ignorant or uncertain environment in order to compare alternatives (Abdellaoui and Gonzales, 2006; Tacnet and Dezert, 2011). In the case of an uncertain environment, the consequence of the alternative depends on the scenario whose knowledge is characterized by epistemic uncertainty, which corresponds to our field of application in the torrential domain. The status of this knowledge is defined by a degree of belief.

The framework of rational decision theory is traditionally used for decision-aiding purposes (Von Neumann and Morgenstern, 1944; Yager, 2008). To do so, the subjective probabilities introduced by De Finetti (1937) are used while respecting the axiomatic of Savage (1954). The optimal solution can thus be established: this is currently practiced in the field of natural hazards by applying CBA. However, one observes several restrictions. i) The decision-making problem is not established within its decision framework (Tsoukiàs, 2006). ii) Only monetary criteria are taken into account (CGDD, 2014). (iii) Numerous studies in the field of cognitive science and psychology have shown that decision-makers' true behaviour did not respect the axioms of Savage (Arrow, 1951; Allais, 1953; Luce, 1956): decisions are not always rational and optimization has limits in practice.

2.1.2. Problem formulation aiding and incorporation of potentially contradictory criteria

Even though the theoretical framework of rational decision is used in practice, its restrictions require the support of other methods such as multi-criteria decision-aiding methods (MCDM). They do not only allow us to consider several criteria in order to compare different alternatives, but they are also part of the constructive approaches viewed by Tsoukiàs (2006), which are based upon the four stages of the decision-making process: 1) context description, 2) problem formulation, 3) modelling, 4) validation.

In MCDM modelling, the importance of each criterion can be represented by a weight (between 0 and 1). On the one hand, total preorder MCDM such as analytic hierarchy process (AHP) (Saaty, 1980), or techniques for order preference by similarity to an Ideal Solution (TOPSIS) by Lai et al. (1994), allow evaluating a single criterion of synthesis. On the other hand, methods of pseudo-order by outranking such as those in the Electre series (Roy, 1985) or the Prométhée series (Brans et al., 1984) introduce a form of imperfection in the structure of the decision-maker's preferences.

2.2. Systemic modelling and functional analysis

Criteria have to be identified at the very beginning of the process. For the socio-economic component, they are cost and risk reduction criteria while taking into account different units of potential damage.

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The analysis of technical components is based upon a systemic approach. Each system element is a component (Birnbaum, 1968). As a result coming from the industrial world, systemic modelling of dependability has already been applied to physical systems such as hydraulic flood protection structures using the Application of Professional Techniques method (APTE) originally introduced by de la Bretesche (2000) (Serre et al., 2007). This method needs, however, to be adapted in a new way to protection structures against torrential phenomena and to the associated multi-scale context.

Each structure is a system. Functional analysis methods are based on three successive stages. 1) The structural analysis defines the boundaries of the system and breaks it down into different components. 2) The external functional analysis (EFA) identifies the system in its environment while establishing its main functions (MF), which are actions of the system between two elements of the environment, and its constraint functions (CF), which result from reaction of the system to constraints coming from elements of the environment. 3) The internal functional analysis (IFA) identifies the technical functions of the different components.

After the descriptive functional analysis, the process failure mode and effects analysis (FMEA) provides the analysis of hydraulic structures (AFNOR, 2006) in two phases. (1) Process FMEA establishes failure modes caused by the design process and/or the system set-up process. (2) Product FMEA analyses the causes and effects of system failure when the system is operating.

2.3. Taking into account imperfect information from several sources

Decision-aiding methods must take into consideration the imperfection of information which impact assessments of indicators, criteria and consequences but also knowledge of the states of nature. For that purpose, probabilities are generally used but they only represent the stochastic component of the process. The representation of different forms of imperfection, but also the combination of several sources according to their level of reliability, are identified limits (Tacnet et al., 2014).

The theory of fuzzy sets makes it possible to represent the vagueness of language (Zadeh, 1965). The theory of possibilities relates to imprecision and uncertainty (Zadeh, 1978). Evidential Reasoning, derived from the theory of belief functions (Shafer, 1976), considers different forms, including epistemic uncertainty and ignorance. Within this theoretical framework, the frame of discernment regroups all potential decisions corresponding to single hypothesis. Knowledge about the evaluation is represented by a mass function (a mass is attributed to each element of the power-set of frame of discernment). Shafer's (1976) initial theoretical framework was grounded on the hypothesis of mutually exclusive and exhaustive frame of discernment decision elements. With recent theoretical developments such as Smarandache and Dezert's Plausible and Paradoxical Reasoning Theory (Smarandache and Dezert, 2004, 2006, 2009, 2015), this hypothesis is not necessary.

Faced with a multi-criteria decision problem, Tacnet (2009) proposed to differentiate the imperfection of a criterion's measure from its transformation within a common evaluation framework, according to linguistic labels. In this way he combines the three formalisms in order to evaluate each criterion according to a mass function for a predetermined frame of discernment.

For the decision-aiding, evaluation of indicators or criteria must be combined in the same way as information from several heterogeneous sources, which may be unequally reliable. One of the main interests of Evidential Reasoning is to propose a framework for combining information from several sources, considered more or less reliable or more or less important (Smarandache, 2010). For this purpose, it relies on the discounting of sources according to a coefficient of reliability, or importance for the criteria, followed by the use of a fusion rule. Dempster's original rule (Shafer, 1976) is the most commonly used but has been the subject of many debates within the scientific community since Zadeh (1979). Amongst all the existing fusion rules, the proportional conflict redistribution fusion rule No. 6 (PCR6) developed by Martin and Osswald (2006) is finally considered to be the most efficient (Smarandache and Dezert, 2009) (Vol. 3). Since this rule is non-associative, it is however harder to implement than the Dempster's original rule.

For a given frame of discernment, a single mass function is obtained after combining several mass functions from heterogeneous and unequally reliable sources. The final decision consists in choosing an element from the frame of discernment. Shafer (1976) initially proposed to decide according to a pessimistic attitude based on the calculation of the credibility function or an optimistic attitude based on the function of plausibility. Between these two extreme attitudes, compromise attitudes are established by a subjective probability function such as, for example, Smets and Kennes' pignistic probability.

Several multi-criteria decision aiding methods (MCDM) based on Evidential Reasoning were therefore developed in order to improve traditional MCDM. For multi-criteria sorting problems, the Evidential Reasoning for Multi Criteria Decision Analysis method (ER-MCDA) (Tacnet et al., 2010; Dezert et al., 2010) develops hierarchical multi-criteria analysis (AHP), taking into account the imperfect evaluation of each criterion, produced from several sources. The four belief-function-based methods TOPSIS, denoted BF-TOPSIS series, improve the grading of alternatives, and thus the choice, by being sturdier than traditional methods when confronted with rank reversal phenomena (Dezert et al., 2016).[1]

In order to sort alternatives and choose the best in an uncertain environment, the Ordered Weighted Averaging (OWA) method was originally proposed by Yager (2008). Its principle is simple but it is based on the choice of the decision-maker's attitude. Its development by Tacnet and Dezert (2011) and then Han et al. (2012) led to the Fuzzy Cautious OWA with Evidence Reasoning (FCOWA-ER) method. It uses the theory of fuzzy sets and frees itself from the subjective definition of the decision-maker's attitude with better computational performances.

Carladous (2017) shows that MCDM and decision-aiding methods in an uncertain environment based on Evidential Reasoning can be associated in order to sort, grade and/or choose alternatives on the base of several criteria evaluated in an imperfect manner within a context of epistemic uncertainty regarding the knowledge of scenarios. The association of FCOWA-ER with ER-MCDA helps to sort alternatives considering ignorance on several scenarios. The ER-MCDA-Rank methodology developed by Carladous (2017) helps to grade and to choose alternatives considering imperfect evaluation of criteria. As a consequence, the association of FCOWA-ER with ER-MCDA-Rank helps to grade and to choose alternatives considering this imperfect assessment but also imperfect knowledge on scenarios.

2.4. Synthesis of main advantages and limits of current methods

Previous sections introduced decision-aiding methods and systemic modelling which can contribute to formalize a multi-scale problem in a constructive approach.

The application of methodological steps of the systemic modelling is limited in order to answer the problems identified in Section 1.2: the multi-scale processing is not formalised, the socio-economic component remains to be taken into account, and the overall evaluation of the system's performance from the individual evaluations for each failure mode is needed. As a consequence, the methodology introduced in the Section 3 will aim at going beyond those limits: they will be applied to different scales of systems (structures and devices); the socio-economic component will be taken into account when applied within the framework of an integrated analysis.

[1] Given a grading for a set of alternatives, adding a new alternative changes the previous alternatives' ordering.

Table 1
Comparison of decision-aiding methods previously introduced.

Methods	1	2	3	Imperfect information considered		
				4	5	6
CBA	g, c	no	no	no	no	uncertainty (subjective probabilities)
AHP	g, c	yes	yes	no	no	no
TOPSIS	g, c	no	yes	no	no	no
Electre series	s, g, c	yes	yes	yes	no	no
Prométhée series	s, g, c	yes	yes	yes	no	no
ER-MCDA	s	yes	yes	yes	yes	no
BF-TOPSIS series	g+, c	no	yes	no	no	no
ER-MCDA-Rank	g+, c	yes	yes	yes	yes	no
OWA, FCOWA-ER	g, c	no	no	no	no	ignorance, epistemic
FCOWA-ER + ER-MCDA	s	yes	yes	yes	yes	uncertainty
FCOWA-ER + ER-MCDA-Rank	g+, c	yes	yes	yes	yes	

(column 1: type of problem with the choice between s = sorting, g = grading, g+ = grading with a better robustness to rank reversal phenomena, c = choice; column 2: is it a constructive approach?; column 3: are several criteria considered?; column 4: is imperfect information considered for the structure of DM's preferences?; column 5: is imperfect information considered for criteria assessment?; column 6: what is the knowledge on scenarios which is considered?

The different types of decision-aiding methods have been presented through several examples. Table 1 synthesizes main aspects allowing to compare them. The CBA method is the most used method in natural hazard context to decide the best action to implement, considering economic aspects. To take into account several criteria without monetary valuation step, the AHP method is the multi-criteria decision-aiding method the most frequently practiced in many fields. Nevertheless, the TOPSIS method was recently used to compare several protective structures according to their functional state (Cortes Arevalo et al., 2017). As shown in Table 1, recent developments based on Evidential Reasoning help to go further taking into account several types of imperfect information which arise to model the structure of the DM's preferences, to assess criteria, and to express knowledge on scenarios. Thus, those advanced methods answer to problems expressed in the Section 1.2, and they have been chosen to be included in the methodological framework developed in the Section 3.

3. A new integrated framework to assist the management of torrent control structures

In light of the methods previously introduced, the following methodological framework was chosen and will be detailed in this Section 3:

- Stage 1 – The effectiveness concept is first specified. A systemic approach makes it possible to break down the problem into sub-problems according to different components of effectiveness and scales of protection measures. Functional analysis and failure mode analysis are used to help extract indicators and effectiveness criteria at the scale of each system;
- Stage 2 – Each decision-making sub-problem is formulated for each scale and component;
- Stage 3 – The modelling of each decision-making sub-problem is proposed according to MCDM based on Evidential Reasoning;
- Stage 4 – Effectiveness assessment according to the different sub-problems identified are integrated at the scale of the watershed.

3.1. Multi-scale systemic break down of the decision-making problem

After having formalised the effectiveness aspect, the systemic approach helps to formalize the break down according to different scales

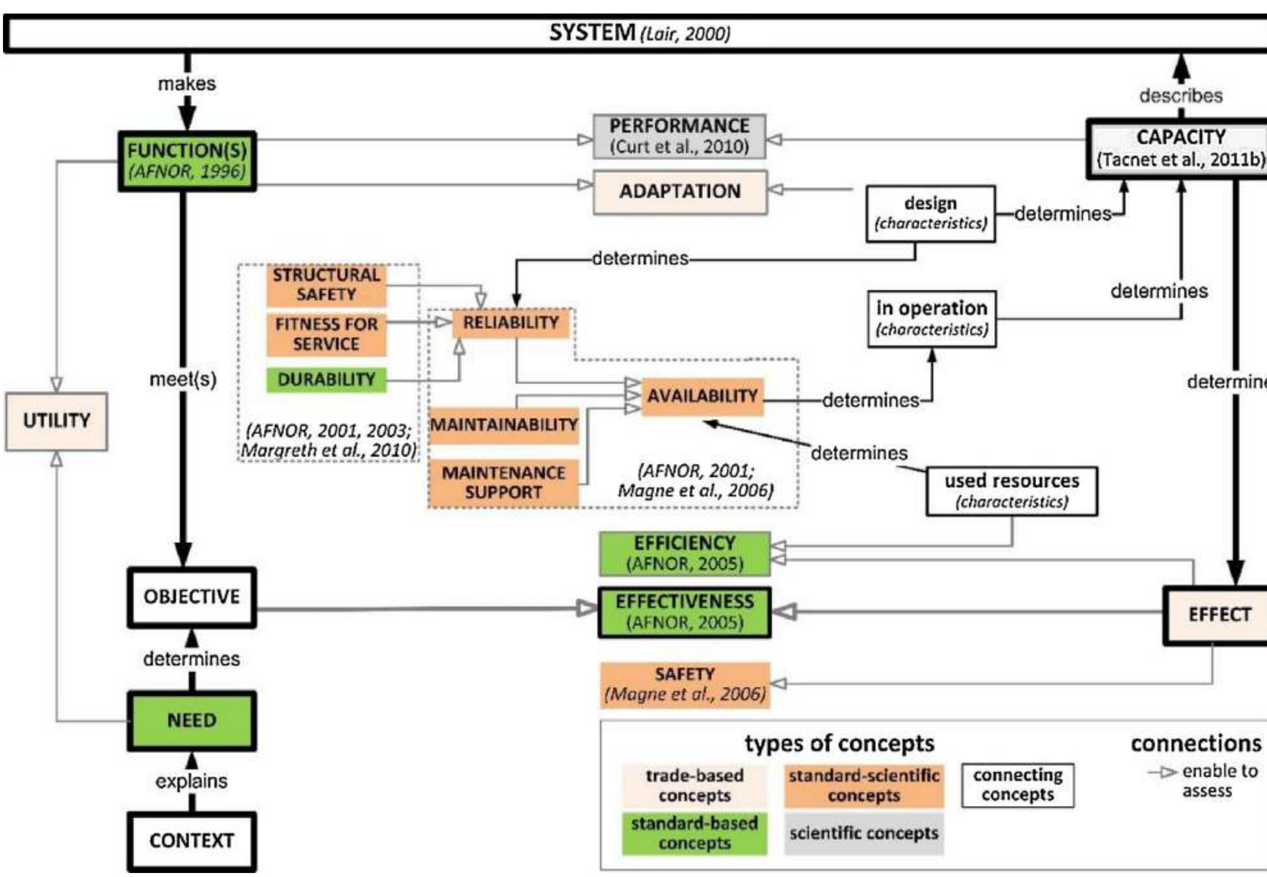

Fig. 5. Conceptual effectiveness diagram.

described in Fig. 4 (structure, device, watershed). The decision-aiding approach allows considering that decision-making sub-problems may be formulated for each of these scales.

3.1.1. Stage 1a: conceptual formalization

The conceptual diagram in Fig. 5 formalizes the effectiveness concept: it identifies concepts, establishes interrelations and specifies information sources. We distinguish five types of concepts:

- trade-based concepts: the definitions come from the BD-RTM, the Austrian and Swiss guides (Suda, 2009, 2013; Suda and Rudolf-Miklau, 2010; Frei et al., 2012; Margreth and Romang, 2010);
- standard-based concepts: definitions come from existing standards and regulations (AFNOR, 1996, 2001, 2003, 2005, 2011);
- scientific concepts: definitions come from scientific publications (Villemeur, 1988; Magne and Vasseur, 2006; Curt et al., 2010; Tacnet et al., 2011);
- standard-scientific concepts: definitions from standards and scientific writings complete each other;
- connecting concepts: they connect the previous concepts.

For each function considered, the effectiveness analysis is based on the comparison between the technical capacity of a system and the objective assigned to it. In order to perform effectiveness assessment, one must therefore identify the system, its function, the targeted objective and its capacity.

To make a decision, the consideration of the cost (used resources) compared to the technical capacity brings us to the assessment of efficiency.

3.1.2. Stage 1b: multi-scale structural analysis

Three scales of torrent control measures are to be considered:

- micro: the structure is the highest scale of the considered system;
- meso: the device is the intermediary scale;
- macro: the watershed is the lowest scale.

For each scale, the structural analysis allows to outline the system and to identify its components which are numbered (Fig. 6). Torrent control devices and structures have different functions (Piton, 2016). In state-owned RTM forests, Carladous (2017) shows that the function of consolidation and stabilization of torrents (Fig. 4) is the most common. It has been chosen for illustration purposes.

As shown in Fig. 6, the "structure" system (micro) is a classical check dam divided into 18 components: 6 below the spillway, 6 below the left hedge, and 6 below the right hedge. Several check dams are components of the "device" system (meso): numbers *1* to *m* are structures from downstream to upstream and numbers *10* to *m0* are respective upstream channels. Each device is itself a component of the "watershed" system (macro), which is defined without involving elements at risk. Indeed, the watershed is divided into homogeneous geomorphological and hydraulic units which contributes to torrential hazard. Those components are numbered from downstream to upstream: 1–9 for series-connected components along the main river, followed by numbers 0–9 for components in parallel. Red components (1, 2, 3, 5, 6, 9, 13, and 23 in Fig. 6) correspond to geomorphological units with devices, allowing to assess their local effect on hazard. Green components are units without any device.

3.1.3. Stage 1c: multi-scale functional analysis

Tables 2 and 3 are results of the external functional analysis applied to structure and device scales. Table 4 is an excerpt of the functional analysis table, result of the internal functional analysis, for a device. It shows that the "structures" (micro) system's service functions (main and constraint functions) are its technical functions as a component of the "device" (meso) system.

3.1.4. Stage 1d: extraction of effectiveness multi-scale evaluation criteria

Several failure modes may affect as well a system as a structure (Table 5).

The performance according to each failure mode is considered as an assessment criterion for the global system effectiveness. Simplified performance assessment criteria given each of these modes are extracted. For a practical use, they correspond to field measurements. They are specified by number, name, assessment unit, scale of assessment, given a description and examples (Curt et al., 2010) which is an improvement in comparison to current practices. This stage is carried out at structure and device scales (Fig. 7). Thanks to this approach, specialists have a common detailed framework for their regular visit of inspection in order to assess the current state of the structures and devices according to structural and functional effectiveness evaluation criteria.

The aim is to assess effectiveness which is related to objectives. Thus, each criterion scale is defined according to a referent objective. For instance, the criterion g_7 is assessed comparing volume in erosion with objective volume initially given to be stabilized. Moreover, as explained in introduction part, natural hazard analysis is based on definition of several scenarios S_k, $k = 1, \ldots, K$. Structural and functional effectiveness assessment at micro and meso scales depends on scenarios that affect individual structures and devices. That is why assessment of criteria is implemented for several scenarios as illustrated in Fig. 7, for criterion g_1.

3.1.5. Stage 2: multi-scale formulation of decision problems

Evaluation scales for a device's capacity and effect have been established in Carladous et al. (2016a). In the same way, evaluation criteria are established at the scale of structures. The effectiveness of each torrent control system is thus evaluated by comparing targeted capacity with actual system capacity. Efficiency assessment is performed by comparing expected results in terms of capacity with necessary resources. On the other hand, safety cannot be evaluated without considering the consequences and therefore the effects.

At this stage, the different system scales (micro, meso, macro) have been identified. The conceptual diagram (Fig. 5) has determined concepts pertaining to the effectiveness assessment. Functions, associated objectives and means of capacity and effect assessment have been specified (Carladous et al., 2016a) for the different scales of control systems. An evaluation process, broken down and sequential, is thus established in Fig. 8.

This sequential analysis identifies components and scales of systems upon which intermediary decisions are based (levels of): utility? adaptation? effectiveness? significance? safety? efficiency?

Actions of maintenance on structures are performed in order to modify their capacity, and at the same time, the capacity of the device and that of the at-risk watershed control system. For each system scale, with or without maintenance, and each concept to be assessed, the issue may be sorting or grading to choose. Let us take a few examples:

1. To which utility label belong "watershed" protection systems?
2. To which class of adaptation belong protective devices?
3. How do we grade devices in a watershed according to importance?
4. Which structures are the most effective? If we have predefined classes, the problem is the sorting. Without classes, the problem is the grading.
5. Which action increases the effectiveness of a device the most?
6. Which is the most efficient action in a watershed?

3.1.6. Stage 3: decision-aiding methods for each problem

The analysis of each decision-making problem depends on the analysis of several criteria of which the assessment is imperfect and performed in an uncertain environment. Decision-aiding methods grounded on Evidential Reasoning as previously introduced are used to answer each of these problems (Carladous et al., 2015, 2016c), as

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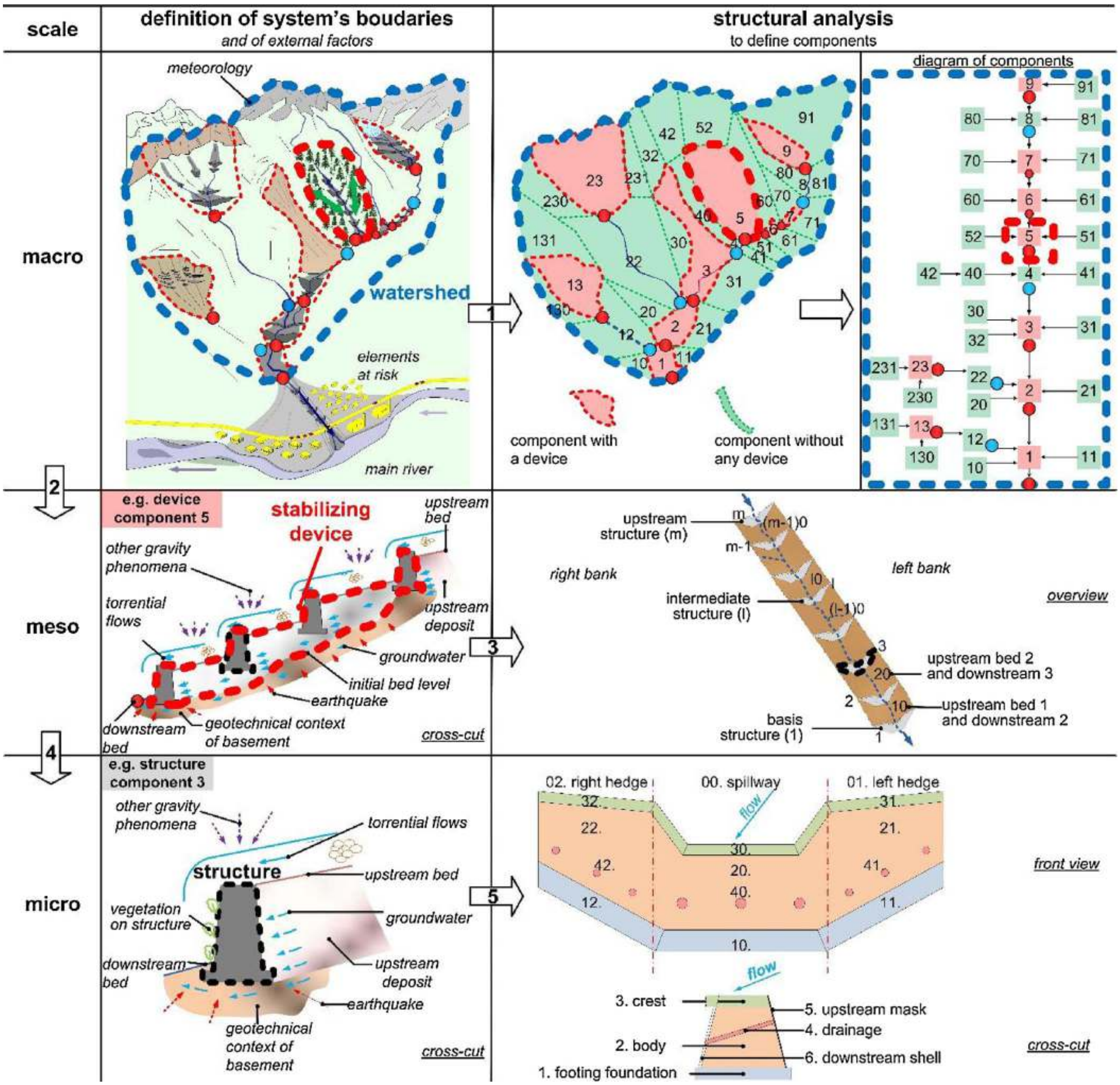

Fig. 6. Multi-scale structural analysis. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

shown in Fig. 9.

3.2. Stage 4: integrating multiple decisions at the scale of the watershed

The effectiveness analysis must be integrated in the macro-scale of the watershed. To allow operational analysis, one needs to establish a spatialized and sequential process (Fig. 10). First, systems are sorted, from macro scale to micro scale, to help the operational definition of analysis priorities (Phase 1). Then, priority systems' effectiveness is evaluated, knowing that evaluation at micro-scale conditions the one at macro scale (phase 2). The last step is effectiveness assessment of maintenance actions on existing systems, or of construction of new systems (phase 3).

3.2.1. Phase 1: preliminary multi-scale sorting (Fig. 11)

Stage 1.1. – macro scale: In order to determine the watersheds with the highest potential of damage, the ER-MCDA method allows to sort watersheds according to initial damage assessment labels (zero, weak, medium, strong). Watersheds in the "zero" category are not further analysed. Watersheds in categories "strong", "medium" and "weak" are respectively analysed according to the priority ranking 1, 2 and 3.

Stage 1.2. – macro scale: Watersheds (of priority 1 then 2 then 3) are sorted according to the objective which is the level of residual damage considered acceptable by the decision-maker. It may be zero according to a conservative hypothesis.

Stages 2.1. and 2.2. – meso scale: Devices are sorted according to their level of importance. In the same way as for the macro scale, the ER-MCDA method is used to eliminate devices graded as "zero" importance (no expected damage reduction) and to grade others according to analytical priority ranks.

Stage 2.3. – meso scale: Only adapted devices are kept. The device's design characteristics are compared to its functions to analyse their

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Table 2
Service functions of a torrent control device with stabilization function.

Service functions	N°	Definition
Main Functions (MF)	MF1	to ensure the transit of torrential flows towards downstream bed
	MF2	to ensure the transit of torrential flows to stabilise longitudinal profile of initial bed
	MF3	to direct torrential flows to limit lateral bank erosion and to enable development of vegetation
Constraint Functions (CF)	CF8	to resist geotechnical context of basement
	CF9	to resist torrential flows
	CF10	to take into account groundwater
	CF11	to resist vegetation
	CF12	to resist other gravity phenomena (snow avalanches, rock falls, etc.)
	CF13	to resist earthquake
	CF14	to stabilise upstream bed
	CF15	to resist loads due to upstream deposit
	CF16	a) to resist loads from banks b) to anchor within upstream banks
	CF17	to resist loads due to upstream slopes
	CF18	to be founded on downstream bed
	CF19	to direct flows considering stability of downstream banks
	CF20	a) to stabilise bed b) to resist loads due to fixed bed
	CF21	a) to resist loads due to lateral banks b) to anchor within lateral banks c) to store materials from lateral banks
	CF20	a) to resist loads due to lateral slopes b) to store materials from lateral slopes

Table 3
Service functions of a torrent control structure with stabilization function.

Service functions	N°	Definition
Main Functions (MF)	MF1	to change torrential flows to enable upstream deposit of materials
	MF2	to ensure the transit of torrential flows coming from upstream bed, without impact on downstream lateral banks
Constraint Functions (CF)	CF3	to resist geotechnical context of basement
	CF4	to resist torrential flows
	CF5	to take into account groundwater
	CF6	to resist vegetation on structure
	CF7	to resist other gravity phenomena (snow avalanches, rock falls, etc.)
	CF8	to resist earthquake
	CF9	to resist loads due to upstream deposit
	CF10	a) to resist loads due to upstream banks (on the structure) b) to anchor within upstream banks (on the structure)
	CF11	to resist loads due to upstream slopes
	CF12	to be founded on downstream bed
	CF13	to consider downstream structure for direction and foundation
	CF14	to be based on downstream banks

adaptation.

Stage 3.1. – micro scale: Only useful structures are kept. The approach is qualitative: the structure's actual functions are compared to those expected.

Stage 3.2. – micro scale: Structures are sorted according to their level of importance. By way of multiple-scale analysis of failure modes, one may analyse the relative likelihood of structure failure to the likelihood of device failure, for a given failure mode.

Stage 3.3. – micro scale: According to the same principle as in stage 2, only adapted structures are kept.

The socio-economic approach is involved during the phase 1 at stages 1.1., 1.2 and 1.3 to assess initial damage, to help the decision-maker to decide what the objective of maximal damage to reach thanks to protective measures is, and to assess residual damage taking into account effect of protective measures.

3.2.2. Phase 2: from technical effectiveness to damage reduction effectiveness (Fig. 12)

The previous phase 1 allowed choosing structures, devices and watersheds for which a multi-scale assessment of the effectiveness of protection measures must be performed.

Stages 1.1. and 2.1. – micro and meso scales: For each scale, evaluation criteria are formalised by way of a functional analysis and then failure modes. If the objective is effectiveness evaluation according to qualitative labels (zero, weak, medium, strong), the ER-MCDA method is applied to aggregate their imperfect evaluation. The FCOWA-ER method is associated to the ER-MCDA method to grade the systems (a device's structures or a watershed's devices) according to their level of effectiveness.

Stage 2.2. – meso scale: evaluation of the device's actual capacity by comparing the level of functional effectiveness from the previous stage with the device's expected capacity.

Stage 2.3. – from meso scale to macro scale: effectiveness assessment in terms of damage reduction. To do so, actual capacity helps to evaluate the true effect on scenarios at the scale of the watershed. This stage is based on expert analysis of scenarios for which we have uncertain knowledge.

Stage 3.1. – macro scale: evaluation of damage reduction for all the devices in a watershed. Stages 1.1–2.3 allow evaluation of each device's effectiveness. Overall damage reduction obtained from the set of devices may now be evaluated. Decision-aiding in an uncertain context based on the FCOWA-ER method provides for damage analysis in an uncertain environment. By using the ER-MCDA method, one may evaluate watersheds according to qualitative labels that correspond to the effectiveness of damage-reduction control systems. When associated with the BF-TOPSIS method (also called ERMCDA-Rank by Carladous (2017)), one may use this effectiveness for grading purposes.

Stage 3.2. – macro scale: safety verification at the scale of a watershed while making sure that the level of residual damage does not exceed the level of initial damage for each of the considered scenarios.

3.2.3. Phase 3: multi-scale evaluation of control actions in order to keep the most efficient (Fig. 13)

If the effectiveness of existing control measures is considered insufficient in phase 2, several actions (maintenance, new constructions) may be proposed at different scales (micro, meso, macro). Their evaluation depends on the comparison between at the one hand, the situation with the proposed action, and at the other hand, the initial situation with no action taken. Phase 2 allows evaluation in an initial situation. Phase 3 is based on a new evaluation, according to the same stages as in phase 2, but by including actions in the consideration.

The actions we compare are the alternatives to distinguish. The best action is the one with highest efficiency: it provides the best benefit at the smallest possible cost. Thus, benefit and cost are the criteria on which decisions are based.

Stages 1.1, 2.1 and 3.1 – multi-scale definition of actions to compare. One may consider different actions at different scales:

- at the micro scale of a structure and the meso scale of a device, the benefit of an action is the function's increased technical effectiveness;
- at macro scale of a watershed, with existing protective measures, the benefit from actions such as construction of new devices or maintenance of existing devices, is the reduction of residual damage and increased safety;
- at macro scale of a watershed, without existing protective measures,

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Table 4
Excerpt from the Functional Analysis table of a stabilization device, for the structure (component) number 3 (as shown in Fig. 3).

N° comp.	Technical Functions (TF)		MF/CF given scale	
	N°	definition	structure	device
3	TF5-6.1	to ensure the transit of torrential flows coming from upstream bed towards downstream bed	MF2	MF1
	TF5-6.2	to direct torrential flows towards downstream structure spillway, without impact on downstream lateral banks	MF2/CF13	MF3
	TF5-6.3	to ensure groundwater transit from upstream bed towards downstream bed	CF5	CF10
	TF7.1	to change torrential flows coming from upstream bed to enable deposit above initial bed	MF1	MF2/MF4/MF6/MF7
	TF7.2	to ensure the transport of a part of bedload from upstream bed towards downstream bed during torrential flood events	MF1	MF1/MF7

Table 5
Failure modes of a consolidation/stabilization structure.

Structural fracture	Functional failure
1. by lateral pushing	1. by lateral bypassing
2. by sliding	2. by bad downstream direction
3. by lateral scouring	3. by too low bed level stabilization
4. by axial pushing	
5. by settling	
6. by toe scouring	
7. by earthquake	

the benefit from each action is the reduction of initial damage made possible by this action.

Stages 1.2, 2.2 – multi-criteria decision aiding in an uncertain context. The problem of multi-criteria decision-aiding is formalised at each scale in an uncertain context, based on predefined criteria. Multi-criteria decision-aiding methods (MCDM) in an uncertain context based on Evidential Reasoning are applicable. The application of ER-MCDA followed by FCOWA-ER allows to grade actions carried out on a structure or on a device. The application of FCOWA-ER followed by ER-MCDA Rank allows to grade actions in a watershed with elements at risk.

4. Discussion

This article has first addressed the analysis of the effectiveness of protective measures which has become a central issue in the management of torrential hazards in mountain areas, and, secondly, the difficult problems it poses in matters of decision-making. The overall problem has consisted in integrating multiple scales and components into a process of decision-making analysis within a context of imperfect information and management of natural hazards. This work contributes to decision-making analysis by integrating several scales, several components and advanced decision-making methods.

4.1. Contribution to the decision-making process

Contributions to the decision-making process have consisted in the explanation of an ambiguous problem and in the structuring and formulation of a multi-scale decision-making problem. These developments have been applied to the problem of evaluating torrent control measures according to scales of structures (micro), devices (meso) and watersheds with elements at risk (macro).

The innovative adaptation of functional safety methods to this multi-scale context has made it possible to break down the problem in a systemic way: a structure is the component of a device, the device itself the component of a watershed. After having identified failure modes, a simplified approach, in accordance with current practices, determined in a direct way representative criteria for each failure mode. Such a generic approach had never been elaborated for this application context. However, the structuration of the multi-scale decision-making problem, clearly pointed out the importance of a key concept based on the change of scales. But, its evaluation remains difficult to obtain. The importance is many-faceted since specific to each failure mode. One may therefore consider its evaluation as a multi-criteria evaluation problem. Multi-criteria decision-aiding methods are therefore possible candidates to help evaluating the importance according to qualitative labels.

Based on the multi-scale construction above, we were able to formulate decision-making problems in an independent way according to issues related to sorting, grading or choice: for instance, to which utility label belongs each control device? how do we grade structures according to their effectiveness level? which is the most efficient action in a watershed with at-risk elements? This was a necessary pre-requirement to their modelling and processing.

4.2. A holistic approach for risk analysis and integration

In order to reduce the risk, protective measures have an effect on the phenomenon to reduce the hazard. Their effectiveness is defined in relation to the risk reduction they provide for. But, the consideration of protective measures and their ageing over time is not formalised, nor traced in the risk reduction analysis. A holistic approach has been elaborated in order to formalize their integration to the analytic process. In this way, it contributes to the methodological development of natural hazard analysis. Another important aspect would be to consider change of hazard potential over time in relation with global climate change.

The developed integrated approach replaces protective measures at the core of risk analysis. It merges technical and socio-economic approaches. The measure must perform functions at each of these scales. The execution of these technical functions allow for risk reduction. The effectiveness is thus evaluated according to technical (structural, functional) and socio-economic components. Assessment of the two types of effectiveness is carried out according to independent processes. The developed integrated approach formalizes a multi-scale process of analysis which connects the components between them. First of all, the socio-economic objective determines the technical objective. Then, the assessment of the technical objective's effectiveness determines the assessment of socio-economic consequences in terms of damage reduction.

Even though effectiveness assessment in the proposed approach is at the core of the analysis, it is not propagated. Indeed, the effective propagation of failure consequences is not carried out from one scale to the other, given that failure scenarios are not established. One may consider the multi-scale adaptation of the bow-tie risk analysis framework (Zwingelstein, 1996) to define failure scenarios. Considering the failure of the "top event", this framework both uses the Fault Tree Analysis (FTA) to establish the top event tree's initiating events and the Event Tree Analysis (ETA) to analyse the potential consequences of the top event. Each initiating event connected with the top event is a failure

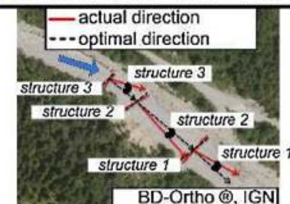
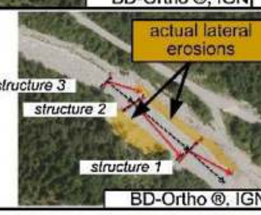
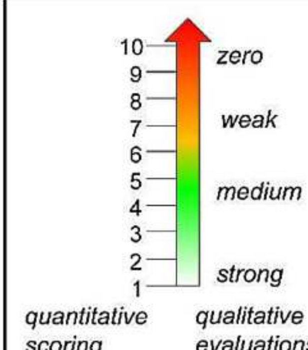
functional failure mode	criteria g_j	evaluation scale	description	example
1. by lateral scouring / bypassing of structures	g_1 spillway size	rate (%) $X_1=[0\%,100\%]$	**rate** between: - **hydraulic capacity Q_{cap}** of the smallest spillway amongst all device's structures; - **flow evaluation Q_k** for a scenario S_k	
	g_2 structures' direction	angle of deflection (°) $X_2=[0°,90°]$	**mean angles of deflection** for all device's structures	*top view* 
	g_7 actual lateral erosion	rate (%) $X_7=[0\%,100\%]$	**rate** between: - **volume** provided by actual lateral **erosions**; - **objective volume** of lateral stabilization	*top view* 
2. by too low bed level stabilization	g_3 longitudinal setting-up of structures	meters (m)	**mean height difference** between: - **actual** crest level; - **optimal** crest level.	
3. by fracture of structures	g_4 structural effectiveness of the most significant structures	structural stability level $X_4=[1;10]$	**quantitative transformation** from a qualitative evaluation and vice versa	
	g_5 structural effectiveness of other structures			
	g_6 actual longitudinal erosion	rate (%) $X_6=[0\%,100\%]$	**rate** between: - **bed length with** actual longitudinal **incision;** - **objective bed length** of longitudinal stabilization.	*downstream view* 

Fig. 7. Effectiveness evaluation criteria for a consolidation/stabilization device.

scenario for which several consequences must be analysed. In this paper, failure modes have been established for each system scale. Considering them as the different top events, adaptation of the bow-tie framework to the multi-scale context would imply establishing the link between each top event consequences at micro scale (structure) and top event tree's initiation event at meso scale (device) for each failure mode.

The integrated approach shows effectiveness assessment at different scales but its multi-temporal effectiveness assessment is not formalised. It is established at the moment of regular visits of inspection by RTM specialists who assess effectiveness criteria according to their evaluation scale (Fig. 7). A prospective analysis is then requested for an analysis in a given space of time, as in the Austrian practice (Suda, 2009). The formalization of relationships between these different temporal assessments has not been done yet. Integration of the temporal dimension is in fact linked to various indicators of reliability, maintainability and availability of a system's dependability (Mortureux, 2001). The formalization of this type of analysis in the context of torrential control measures is envisaged.

All this methodological framework has not been entirely applied to

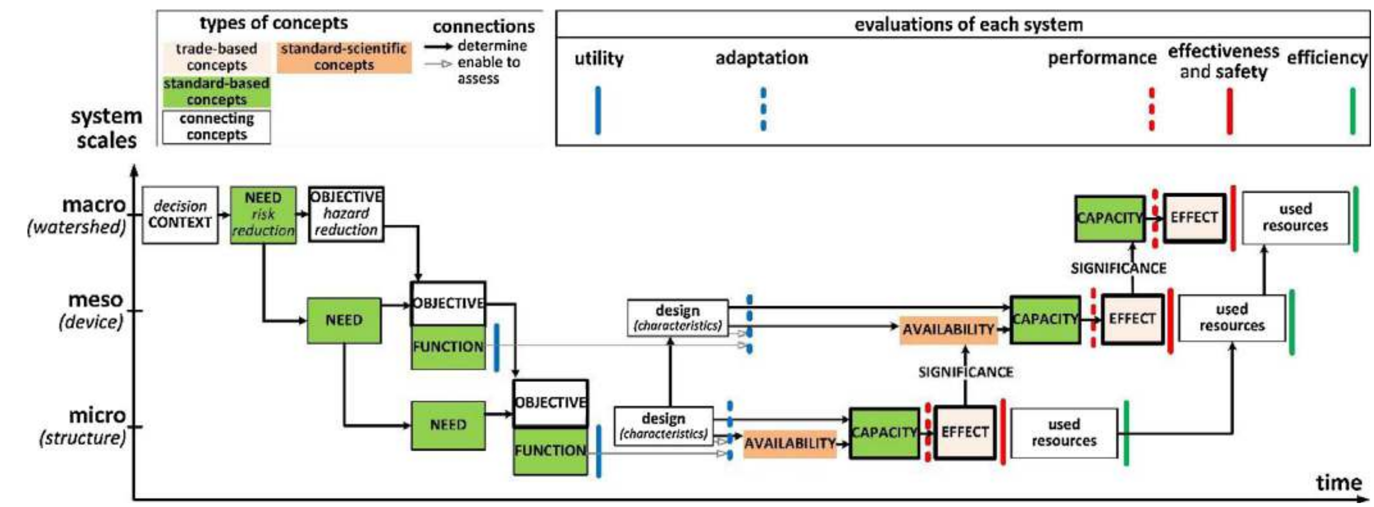


Fig. 8. The definition of objectives and functions, then capacity and effect evaluation allow a sequential, multi-scale and multi-dimensional effectiveness evaluation.

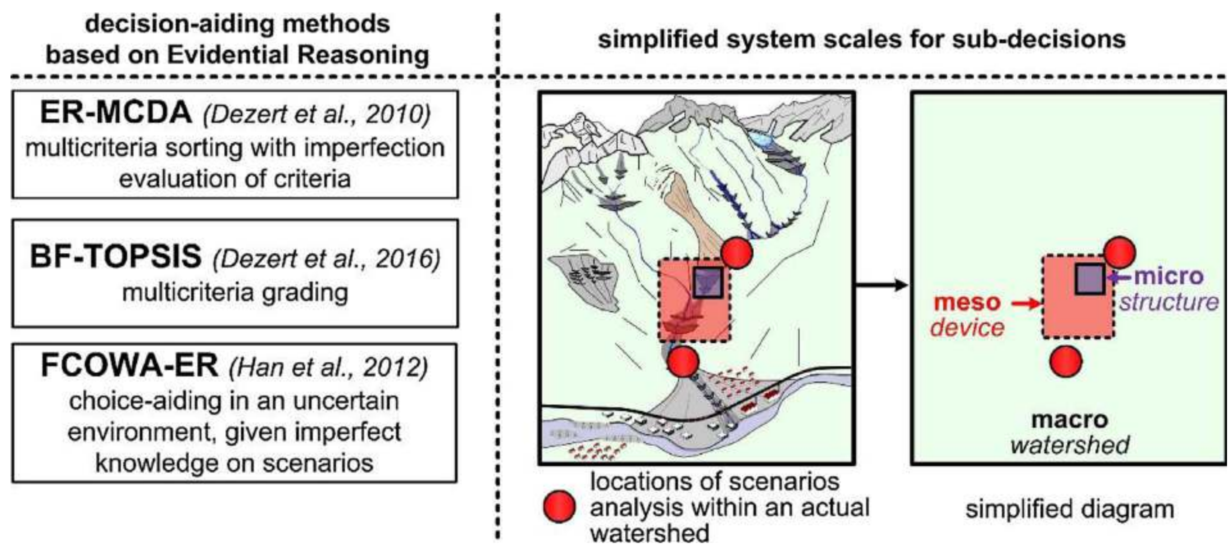


Fig. 9. Multi-scale modelling principle of decision-aiding problems and methods that can be used. .

an actual study site. Nevertheless, the stages 1–3 have been applied to different real examples, showing the practical interest and feasibility of application of decision-aiding methods to each system scale. The conceptual framework adds the inclusion stage 4 which is needed for a global decision. Its development is a key step for practical application. Indeed, Risk Watershed Studies are made by RTM specialists on study sites to help to decide priorities of structure maintenance at the watershed scale. Nevertheless, they miss some conceptual key points to help them to organize their analysis. Moreover, aiding the decision without hiding all imperfection of used information is also a practical challenge. Our future task, while difficult, will consist in progressively transferring this approach towards the practice in order to test it on a study case. The main stages of this transfer will consist in i) conceptual explanation, ii) decision-making process description, iii) decision-aiding methods implementation to each system scale, iv) integration of imperfect information in the analysis process.

5. Conclusion

The issue of effectiveness evaluation of protection measures against natural hazards in mountains is not new. It was addressed in the 1970s. The application of cost-benefit analysis (CBA) to this context was considered up to the 2000s (Brochot et al., 2003). Its development was abandoned in France for torrential floods at a time when it was considered for liquid floods (Grelot, 2004). The problem of consideration of numerous parameters and the evaluation in the field of torrential phenomena where knowledge is very limited are amongst the reasons to this abandonment.

The present work proposes an alternative. Considering that lack of information is part of the expert process, the expert approves hypotheses and corresponding choices. The proposed work considers and accepts imperfections but suggest objectifying them.

Considering all the complexity of the process in the elaboration of an integrated assessment approach of the effectiveness of protective measures seemed particularly interesting to us. The developed methodology links technical approaches and decision-aiding methods, assessment of technical effectiveness and risk analysis, something that, paradoxically, had never been addressed before.

In this work, we have used substantially complex methods in relation to practices. Different approaches may, however, be applied and compared at each stage of the methodology with simplified or detailed identification of criteria, different methods of incorporation considering or not the imperfection of criteria assessment, several sources of information and epistemic uncertainty to the knowledge of natural phenomena. The difference from actual practices lies in the fact of controlling the complexity of tools and then identifying elements of

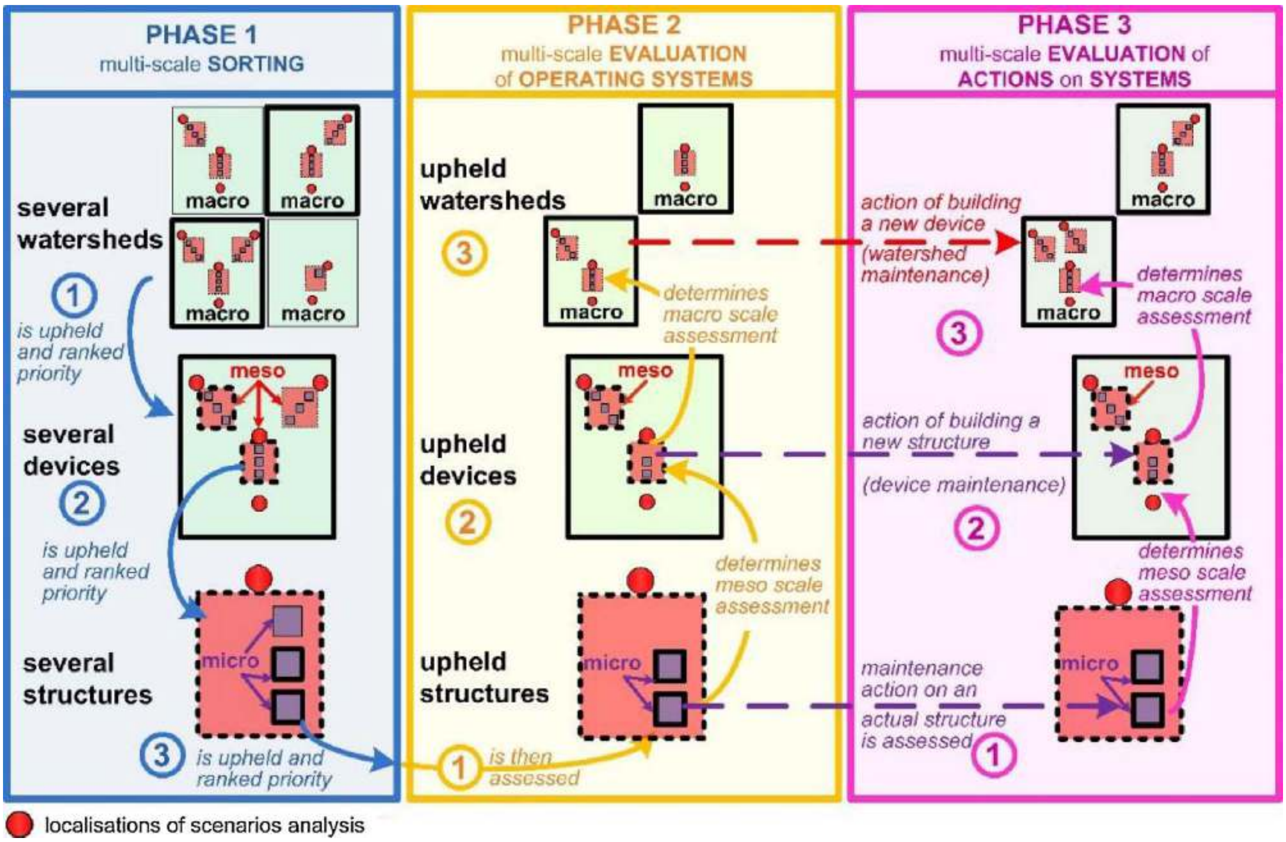


Fig. 10. Multi-scale principle of integrated methodology.

stages	formalism: alternatives A_i	formalism: criteria g_j	decision-aiding: data acquisition	decision-aiding: problem	decision-aiding: methods	decision-making
1 — 1.1	A_i = a watershed	initial damages (X_j unit)	- intensity maps - potential damages for different types of elements at risk	watersheds sorting given damages level	methods combination: FCOWA-ER + ER-MCDA	damages in A_i → priority of analysis zero → no further analysis weak → priority 3 watersheds medium → priority 2 watersheds strong → priority 1 watersheds
1.2	priority ranked watersheds	objective of maximal damages (X_j unit)	- given by the decision-maker		rule - if initial damages are lower than damages with devices - otherwise	→ watersheds with no useful protection → watersheds with useful protection
2 — 2.1, 2.2	A_i = a device	significance to reduce damages (X_j unit)	- structural analysis : capacity et hazard reduction analysis given design elements ↓ - residual damages given design elements	devices sorting given their significance to establish priority ranking	methods combination: FCOWA-ER + ER-MCDA	significance of A_i → priority of analysis zero → no useful devices weak → priority 3 devices medium → priority 2 devices strong → priority 1 devices
2.3	priority ranked devices	adaptation	- comparison with design standards	devices sorting given their adaptation	rule - if design is no consistent with function - otherwise	→ inadequate device → adequate device
3 — 3.1, 3.2	A_i = a structure	significance	- internal functional analysis of the device ↓ - failure mode analysis	strutures sorting given their significance	rule - if given function is no consistent with technical function - otherwise	significance of A_i zero → no useful structures weak → secondary structures medium → essential structures strong → principal structures
3.3	priority ranked structures	adaptation	- comparison with design standards	structures sorting given their adaptation	rule - if design is no consistent with function - otherwise	→ inadequate structure → adequate structure

Fig. 11. Phase 1–multi-scale sorting: use of systemic modelling, rules of decision-making and multi-criteria decision-aiding in an uncertain environment in order to help decisions at each stage.

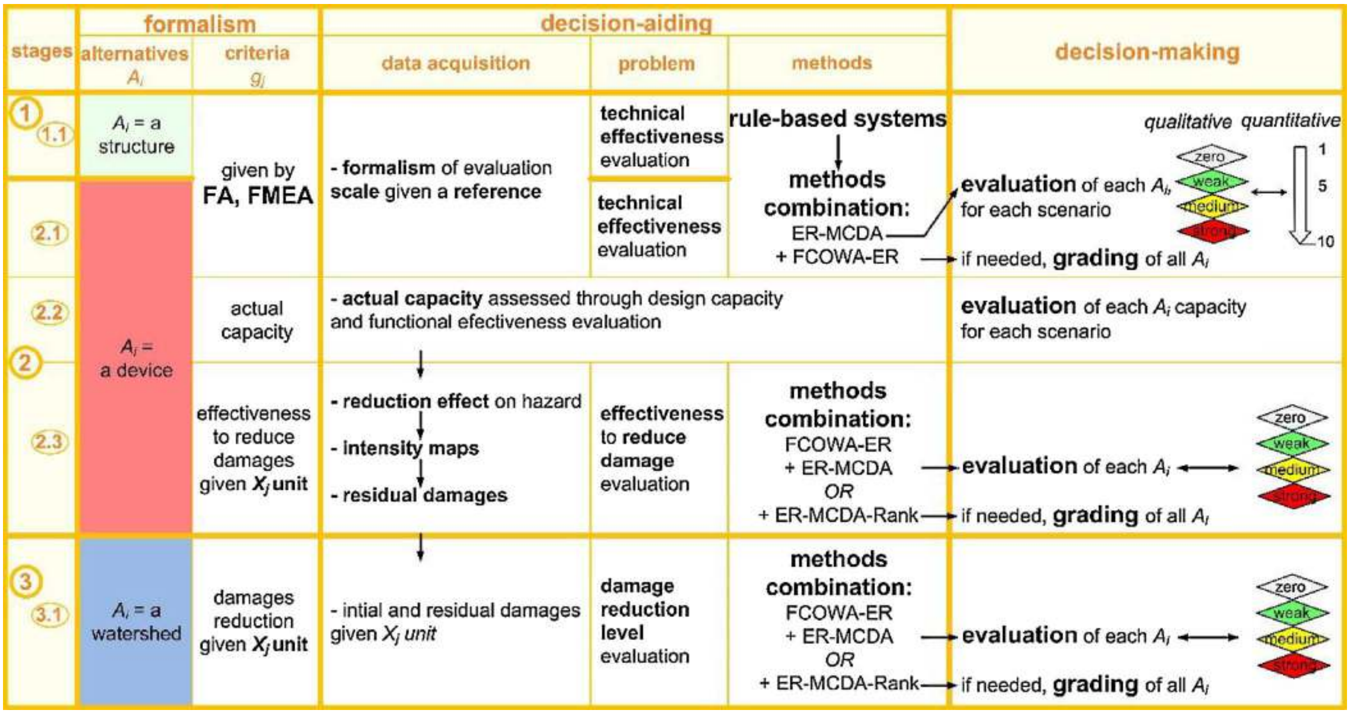


Fig. 12. Phase 2–multi-scale assessment of effectiveness supported by multi-criteria decision-aiding in an uncertain environment.

simplification.

So, after having dealt with the problem in its entirety and according to all its complexity, the decisive prospect of this work will be to gradually transfer these tools to practice by recognizing that "simplicity is the ultimate sophistication" (Leonardo da Vinci).

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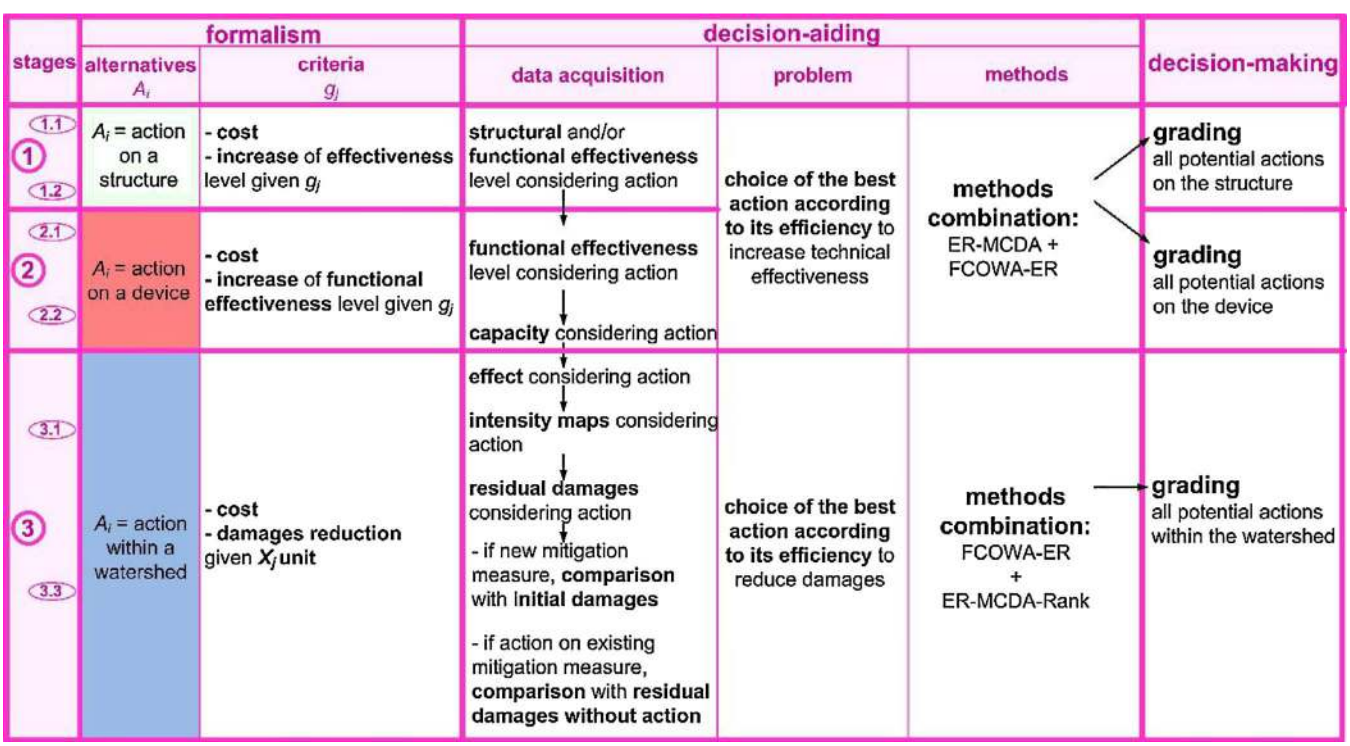

Fig. 13. Phase 3–multi-criteria and multi-scale decision-aiding in an uncertain context in order to grade potential control actions.

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