Nat. Hazards Earth Syst. Sci. Discuss., 2, 207–259, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/207/2014/
doi:10.5194/nhessd-2-207-2014

Natural Hazards and Earth System Sciences
Discussions
Open Access

A decision-supporting methodology for assessing the sustainability of natural risk management strategies in urban areas

A. M. Edjossan-Sossou[1,2], O. Deck[1], M. Al Heib[2], and T. Verdel[1]

[1]Université de Lorraine, GeoRessources, UMR 7359, Ecole des Mines de Nancy, Campus Artem, CS 14234, Nancy Cedex, 54042, France
[2]INERIS Nancy, c/o Ecole des Mines de Nancy, Campus Artem, CS 14234, Nancy Cedex, 54042, France

Received: 5 December 2013 – Accepted: 17 December 2013 – Published: 14 January 2014

Correspondence to: A. M. Edjossan-Sossou (abla-mimi.edjossan-sossou@univ-lorraine.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This paper attempts to provide a decision support framework that can help risk managers in urban areas improve their decision-making processes related to sustainable management. Currently, risk management strategies should no longer be selected based primarily on economic and technical insight. Managers must address the sustainability of risk management by assessing the impacts of their decisions on the sustainable development of a given territory. These assessments require tools that allow ex ante comparisons of the effectiveness and the likely economic, social and ecological impacts of the alternative management strategies. Therefore, a methodological and operational framework was drafted and tested using a theoretical case study to illustrate its use, determine the most sustainable decision and identify its improvement trails.

1 Introduction

In this paper, we propose a framework to examine the sustainability of risk management measures. The capacity for risk response toward natural hazards exists within societies to different degrees. Various mechanisms like "land-use planning", "financial compensation and insurance", "awareness raising", "strengthening of early warning systems", and "structural enhancement of buildings" are some of strategies deployed to manage prevalent natural risks. However, not all responses are sustainable (Tompkins and Adger, 2004). Planners continue unsustainable practices because they do not sufficiently factor sustainability principles into their management decisions. Consequently, those decisions engender conflicts between economic and social/environmental interests or prove unacceptable under societal/ecological standards. A consistent use of this framework would improve the adequacy assessments used under different management strategies or combinations of strategies, using sustainability principles.

In recent years, cities have become extremely vulnerable to natural hazards (Hansson et al., 2008) due to the population density, activities, buildings and infrastructure in urban areas. Accordingly, the losses created by those hazards (e.g., earthquakes, floods, grassland fires, landslides) have become increasingly serious. These losses can compromise socio-economic development for years (Faber, 2010; Ni et al., 2010). Consequently, the management of risks due to natural hazards can be considered "*a specific element of sustainable development*" (Peltonen, 2006; Knott and Fox, 2010).

Therefore, one of the key challenges for cities is to reduce their economic, social and ecological vulnerability to natural hazards and to control those hazards because their future will depend on strategically planned risk management policies. However, the current approach adopted to manage natural risks only focuses on the financial and technical concerns and appears out-of-date. Critics argue that although this strategy may reduce losses in the short term, it has failed to meet this goal in the long term (Mileti, 1999) because natural risk is a complex problem that transcends technical and economic issues. This approach cannot address sustainability, and sustainability is an emerging issue in the risk management field. Therefore, establishing sustainable risk management practices has become necessary (Di Mauro et al., 2006). Accordingly, the traditional risk management approach has been rethought through efforts to integrate non-technical aspects such as socio-cultural, environmental, and governance-related issues (Wurbs, 1996; Putri and Rahmanti, 2010).

Addressing the sustainability of risk management activities (prevention, mitigation, response, and recovery) has gathered momentum, as indicated by the numerous initiatives or studies, and has been recognised by several nations and international organisations around the world (Mileti, 1999; Kundzewic, 2002; Galloway, 2004; Scottish Executive, 2005; Werritty, 2006; Agrawala, 2007).

Due to this focus on sustainable risk management, managers must be able to measure performance in this area because many studies indicate that sustainability assessment is required to increase the diffusion of sustainable activities and sectors. Therefore, to foster their efforts to shift toward this new approach, formal appraisal procedures must be introduced to the decision-making process, requiring "*the existence of tools, instruments, processes, and methodologies to measure performance in a con-*

NHESSD
2, 207–259, 2014

sistent manner with respect to pre-established standards, guidelines, factors, or other criteria" (Poveda and Lipsett, 2011).

Finding an accurate framework to assess the sustainability level of future and the existing decisions has become an important issue. A review of literature shows that some methodologies and tools are available to assist managers in the sustainable risk management field (Turner II et al., 2003; Freedman et al., 2004; Achet and Fleming, 2006; Kang et al., 2013). However, most of these tools are either specific to a hazard (mostly flood and coastal hazards; see McGahey et al., 2009), based on a mono-criterion approach, considering only one aspect of sustainability (e.g., Environmental Impact Assessment – EIA, Life Cycle Assessment – LCA, Social Impact Assessment – SIA, Cost-Benefit Analysis – CBA; see Singh et al., 2012), or do not provide specific criteria and/or indicators among the few methods that account for the different aspects of sustainability. At our knowledge, although these tools can guide sustainable risk management, none of them are general, integrated theoretical tools that provide the proper set of criteria and indicators for assessing the sustainability of natural risk management in urban areas (Kundzewicz, 2002).

The specific purpose of this paper is to support sustainable natural risk management by guiding the assessment of potential sustainability during management decisions. This proposal is within the scope of the INCERDD research project (prise en compte des INCERtitudes pour des Décisions Durables) that seeks to provide a methodology that accounts for the uncertainties within the sustainable decisions in urban areas. This paper proposes a methodological and applicative framework that is built from a review of the sustainability literature. This article is organised as follows: first, a conceptual framework of sustainable risk management is presented; the proposed methodology is then outlined; finally, a theoretical case study demonstrates its applicability.

NHESSD
2, 207–259, 2014

A. M. Edjossan-Sossou et al.

2 Definition and principles of sustainable risk management

While sustainability is becoming a central goal for policies in the risk management sector, there is no common or standard definition of sustainable risk management. Individuals may understand this concept differently. Even in the literature, definitions are scarce. Consequently, because studies of sustainable natural hazard management are usually flood-specific, we may first refer to the definition given by the Scottish National Technical Advisory Group on Flooding Issues (NTAG). Sustainable flood management is defined as a management that "*provides the maximum possible social and economic resilience against flooding, by protecting and working with the environment, in a way which is fair and affordable both now and in the future*" (Scottish Executive – NTAG, 2004). Sustainable risk management can be defined as the 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. This general definition is consistent with that adopted by this paper and proposed by Saunders (2010b): sustainable risk management "*ought to reduce, or at minimum not increase, community vulnerability and disaster recovery costs to levels that do not compromise other public objectives nor burden future generations*". This definition argues that in addition to ensuring risk prevention, mitigation or recovery, the additional consequences of implemented measures also require careful consideration within the complex economic, technological, political, social, and environmental urban aspects (Kenyon, 2007).

Therefore, this paper adheres to the principles guiding sustainable risk management processes that were proposed by Mileti (1999) regarding the key components for sustainable hazard mitigation: (1) maintaining and enhancing the environment; (2) maintaining and enhancing the quality of life; (3) fostering local resilience toward and responsibility for disasters; (4) recognising that vibrant local economies are essential; (5) identifying and ensuring inter- and intra-generational equality; and (6) adopting a consensus-building approach beginning at the local level through local participation.

NHESSD
2, 207–259, 2014

Specifically, any sustainable management measure requires an interdisciplinary analytical and operational approach that must be combined with a more flexible and participatory institutional framework and involve a wider range of stakeholders. This approach also requires better reversibility, common acceptance, and environmental friendliness (Kundzewicz, 2002). Furthermore, this approach considers the historical and institutional perspectives, as well as the socio-economic, environmental, and cultural aspects (Turner et al., 1999). Alternative strategies should focus on reducing natural hazard losses and contribute to the broader goal of sustainable development (Klijn et al., 2009).

The ultimate goal for every sustainable risk management process is to maximise the outcomes because the losses due to natural disasters increase due to human decisions and investments (Hansson et al., 2008). Consequently, this paper introduces a methodology based on an indicator-based tool for examining whether risk management strategies will point toward sustainability during the decision-making process.

3 Methodology for assessing the sustainability of risk management

As illustrated in Fig. 1, the standard approach to sustainable decision-making may be outlined as a sequential process with four major stages. Moreover, to support successful decisions regarding risk management needs, among other requirements, "*a common conceptual framework which seeks to understand and formalise the full range of issues that stakeholders may pose*" and "*a supporting methodological framework which is a translation of the conceptual framework into an analysis process containing tangible algorithms, methods and model interactions*" must be introduced (McGahey et al., 2009). Therefore, the suggested evaluation framework should represent the third stage, and its construction can be subdivided into three tasks: (1) selecting sets of criteria and indicators, (2) formulating a methodology to evaluate the sustainability performance, and (3) defining decision rules for selecting the most sustainable decision.

NHESSD
2, 207–259, 2014

The methodology followed in this paper is based on a literature review of the indicator-based approaches for sustainability assessment, as described below after specifying some methodological choices. These choices concern the relevant spatial and temporal scales considered during the sustainability assessment while using this tool.

3.1 Spatial and temporal scales

Spatial and temporal scales are very important when "*attempting to put sustainability into practice, or in gauging the level of sustainability*" (Ko, 2005).

The diverse spatial scales have different specific factors that influence the risk management decision process. According to Graymore et al. (2010), the current sustainability assessment methods used at the global, national and state scales are not entirely effective at fulfilling their goal, according to these spatial scales. The indicators are defined on the chosen spatial scale, and they capture only synoptic aspects for the scale on which they are applied. Therefore, this paper uses municipalities, which are a smaller urban spatial unit, as a meaningful or suitable scale that could lead to a more accurate framework and assist the further adaptation and application to the other spatial scales. The focus is on typical French communities with less than 2,000 people (INSEE)[1] and an average area of approximately 20 km^2.

Concerning the temporal orientation, this framework obeys a prospective logic because it is designed for *ex ante* assessments of decisions; it might be used to examine the sustainability of existing management measures. Because the consequences and impacts of decisions can vary over time, their sustainability must be assessed on different temporal scales. Some effects can occur immediately after implementing the decision or only after a longer or shorter interval. First, this paper argues that the temporal

[1] According to the INSEE (Institut National de la Statistique et des Etudes Economiques), the average population of the most of French communities is about 1750 inhabitants on 1 January 2008.

NHESSD
2, 207–259, 2014

scale should involve the entire life or mission span of the risk management decisions. Second, planning those decisions within the context of sustainability entails planning beyond 50 or 100 yr (Saunders, 2010a), requiring plans for future generations. Indeed, the decisions "*should not only be taking short- and medium term into account but also the (very) long term, thus leading to more sustainable risk decisions*" (Genserik, 2012).

Building on the evidence that accounting for different temporal perspectives can improve the level of sustainability, this framework is intended to address the assessment as a continuum (ranging from the short to the long term) when predicting the variability of the sustainability over time. This tool should facilitate strategic planning within sustainable risk management in the long term while considering the dynamic behaviour of the factors that affect the sustainability over time, such as the expected territorial dynamic; this factor helps determine the future of the territory and establish risk management requirements. In the case study, only one time-scale assessment was undertaken. However, several time-scale assessments should be performed in practice to appraise the evolution of the sustainable strategies over time and to determine the most sustainable decision over time, thereby generating relevant sustainable decisions for the future.

3.2 Criteria identification and indicators selection

The main objective is to elaborate an indicator-based grid. Criteria and indicators can be selected using a top-down or a bottom-up approach (Franco and Montibeller, 2009; Weiland et al., 2011). Both approaches involve decomposing a complex decision into a hierarchical structure that represents the sustainability performance and is built from the input variables situated at the bottom level of the pyramid.

The top-down method is used to break down the sustainability concepts into dimensions, criteria and indicators. This deductive approach facilitates the following: the theoretical description of the objectives and the rigorous collection of the corresponding criteria and indicators from the literature. This approach should ensure that the correct conceptual information is retained with the common criteria and indicators of generic sustainability.

The bottom-up approach is used to select criteria and indicators that match the contextual requirements from the specific field whose sustainability will be assessed. This inductive approach is often rooted in the concerned field and aims to ensure that specific information related to the field at hand is accounted for. It starts with the identification of the potential consequences and effects of the field. Once the set of consequences and effects is defined, they can be grouped into indicators based on similarities. Indicators can then be grouped into criteria. Finally, the criteria can be grouped into objectives. The potential consequences and effects serve as benchmarks for the validation of which indicators and criteria are suitable to fulfil the sustainability concerns of the targeted field.

In this paper, a hybrid approach has been applied, complementarily combining bottom-up and top-down approaches. The process used to construct the assessment grid involves three steps.

The first step involves identifying the criteria based on the objectives of sustainable risk management. The top-down approach was applied to identify the appropriate criteria using a combination of the principles for sustainability assessment (Gibson et al., 2005; Gibson, 2006) and those for achieving sustainable risk management Mileti (1999). The following five criteria were proposed:

- **Technical and functional effectiveness** addresses the capability of measures to fulfil the primary function of risk management, providing protection against natural risks and reduce losses from those risks.

- **Economic sustainability** is used to obtain the most out of measures with fair economic outcomes (efficiency and affordability).

- **Social sustainability** addresses the social and societal aspects, such as the community benefit and fair distribution/contribution.

- **Environmental sustainability** assesses the implementation of measures relative to all species, habitats, and landscapes.
- **Institutional sustainability** addresses the issue of governance (norms, values, and practices).

The second step concerns the identification and selection of performance indicators that highlight the different aspects of sustainable natural risk management depicted by the five criteria. Sustainability indicators depend strongly on their target field. In this paper, they were suggested according to their ability to describe the pressures of risk management on territorial sustainability.

The bottom-up approach was exhaustively applied when inventorying the potential (direct and indirect, as well as tangible and intangible) effects and consequences (pros and cons) of risk management decisions over periods that are much longer than the lifetimes of the investments. For the natural risk management policies, the potential consequences could include a decrease/increase in casualties and disabilities (direct), a decrease/rise in economic activity (indirect), continuing damage to assets due to the residual[2] risk (tangible), impacts on human health or natural resources and functions (intangible), increased public awareness of local natural hazards (pros), or a transfer of risks to another area (cons). Furthermore, some policies may have positive future consequences, but their immediate consequences could be negative, or vice versa. For instance, the development level of a territory might be improved in the future, but there may be significant implementation costs on the short-term scale.

These potential effects have shown which parameters are important while assessing risk management decisions; these effects were explored to identify the relevant indicators. Once these effects and consequences were identified, a literature review was completed and a set of potential indicators was created according to their relevance

[2]The residual risk is the irreducible portion of the risk associated with the potential implementation of management solutions.

regarding the studied field and based on an overview of existing national and international sustainability assessment methodologies (Singh et al., 2012) and tools.

No specific indicators exist for evaluating the risk management that are universally or widely accepted (Carreño et al., 2007). Therefore, indicators were selected from various tools used to gauge sustainability: RST02 grid (France), "Boussole 21" grid (Belgium), International Urban Sustainability Indicators List (IUSIL), Reference Framework for European Sustainable Cities, Sustainable Transportation Performance Indicators (STPI), and risk management performance criteria proposed through the action framework led by the International Strategy for Disaster Reduction (ISDR).

Finally, using a collaborative and multi-disciplinary process, researchers involved in the INCERDD project shared their knowledge, experience and judgements to validate the set of the proposed indicators with regard to their relevance, applicability and other characteristics, such as measurability and accessibility to those without specific knowledge. Although it was difficult for every indicator to conform to all of these requirements, it was important that they complied as much as possible. For instance, some effects and aspects seem to be significant but remain difficult to assess, particularly regarding the social and institutional dimensions (Lekuthai and Vongvisessomjai, 2001 cited by Poulard et al., 2010). Because some of the indicators are related to intangible concerns (e.g., recreational value, quality of life), the analysis is very complex; these indicators are often assessed based on subjective assumptions. Subsequently, their estimation causes several problems, such as finding consensus on the parameters and how to measure these factors concretely.

The obtained sustainability assessment grid is constructed using a hierarchical structure that includes seventeen context-specific indicators. This grid is schematically depicted in Fig. 2 and assumes that the indicators[3] might include numerous sub-indicators called parameters that would enable their assessment. Parameters are the measurable or observable variables that describe the corresponding indicator (Bragança et

[3]The indicators are not necessarily split into parameters; some parameters might be split into sub-parameters.

NHESSD
2, 207–259, 2014

al., 2010). Parameters can be identified and selected on a case-by-case basis by relying on the distinctive characteristics of the territory and its prevailing sustainable development targets. Although the objective of this paper is to provide a more precise and defined framework to assess the sustainability of risk management initiatives, the parameters were informally selected. This choice might render the framework more flexible by allowing to users to propose better parameters depending on their view of sustainable development. An illustrative list of the parameters retained for the case study is available in Tables A1–A5.

These suggested indicators should be a reference for public institutions and the private sector when making sustainable natural risk management decisions. The suggested indicators are not exclusive and should be treated as indicative checklist of which issues to consider at a minimum when assessing possible solutions with a focus on sustainability. However, one of the challenges remains rendering the grid operational. To address this issue, the following subsection focuses on formulating a methodology to assess the sustainability performance using the grid.

3.3 Sustainability performance assessment

Once the indicators were selected, they needed to be quantified or qualified depending on the quantitative and qualitative nature of the related parameters. While quantitative parameters can be evaluated directly from the available data related to measured amounts; qualitative parameters are evaluated based on a comparison to a system of references, description, perception or judgement regarding their relative importance when accurate data are limited. The obtained qualifications can then be expressed within numerical codes or matrices.

As asserted by González et al. (2013), "*successful decision support tools provide information in a concise relevant format in order to inform decision-making processes*". To fulfil this objective, a sequenced, understandable and easy-to-use methodology should be used to evaluate different strategies during natural risk management. As-

NHESSD
2, 207–259, 2014

suming that the input data[4] of the methodology are the parameter values, the calculation process is organised as follows.

3.3.1 Estimation of the performances of strategies at the parameters level

The estimation is based on a relative approach that estimates the changes (consequences) resulting from the studied options. This process requires reference values to which each parameter value can be compared. Several values could be taken as reference:

- The desired level of sustainability value for each parameter should be included (van Cauwenbergh et al., 2007).
- The fixed thresholds may be expressed either as lower, higher or ranges of acceptable values that should not be exceeded (Wiek and Binder, 2005; Zahm et al., 2006). They may be normative values based on legal or scientific norms or expert judgements derived from observations related to the parameters.
- The parameter value of a reference policy is often the baseline policy; this action is the status quo or do-nothing alternative, assuming that no new measures are taken (Klijn et al., 2009).

For the quantitative parameters, this estimation consists of three steps. The first step includes the calculation describing the expected performance of a given option in the context of a specific parameter. The absolute values of the parameters are not used to reveal this performance; a comparison with reference values provides this information (Tugnoli et al., 2008). The variation relative to the baseline option or the distance

[4]The data sources (e.g., historical records, instrumental records, maps) and various methods/tools (e.g., physical and numerical models, existing mono-criterion sustainability assessment tools, expert judgements) might be used to generate input data. This framework does not indicate which methods/tools to use; the primary purpose is to generate the required input data.

NHESSD
2, 207–259, 2014

from the desired level of sustainability or the fixed threshold might be used (Acosta-Alba and van der Werf, 2011). Equation (1) can be used to assess whether the option is better/worse than the reference situation or contributes to/conflicts with the target/threshold regarding the considered parameter.

$$V_{\text{dif}}=V_{\text{opt}}-V_{\text{ref}} \tag{1}$$

where V_{dif}, V_{opt} and V_{ref} are the potential performance, the parameter value for the analysed option and the parameter value for the reference situation, respectively.

The second step involves in the calculation of the impact rate or the degree of convergence/compliance to the target/threshold (ImpR). This value represents the ratio[5] between the potential performance (V_{dif}) and the reference value (V_{ref}), as shown in Eq. (2). This step produces the relative impact values expressed as percentages and enables the relative values to be combined with several quantitative parameters that are no longer defined by their own specific measurement units. The normalisation of the potential performance reveals the magnitude of impacts in relation to the reference value for each parameter (Myllyviita et al., 2013).

$$\text{ImpR} = \frac{V_{\text{dif}}}{V_{\text{ref}}} \tag{2}$$

The third step consists of assigning a value score (ImpS) to each impact rate (ImpR) according to its level and its nature (advantage or disadvantage); this process generates ordinal numerical values, facilitating aggregations and simplifying the assessment process (Gafsi and Favreau, 2013). The scoring could be performed using a bidirectional[6]

[5] To simplify the calculations, when the reference value = 0, the following are true:
the value of the impact rate (ImpR) = 0 % when the alternative value = 0
the value of the impact rate = ±100 % when the alternative value ≠ 0.

[6] The plus and minus signs indicate whether the studied option has a positive or negative incidence compared to the reference.

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

Likert-type scale whose range captures the perceived sensitivity of the parameters. The higher the range of the scale[7], the more sensitive the parameters are. Therefore, using different rating scales might be possible during the same assessment. In this situation, the assessors should ensure a link between the scales, thus facilitating the subsequent calculations.

Using the same range might be possible; however, the length must be adjusted according to the sensitivity of the parameters. For instance, when handling a more sensitive parameter, instead of using a fixed length between two consecutive scores, a different length could be applied from one score to another.

- For a very high impact, $\text{ImpR} > 0.75$ (low sensitivity) or $\text{ImpR} > 0.3$ (high sensitivity)
- high impact: $0.75 \geq \text{ImpR} > 0.5$ (low) or $0.3 \geq \text{ImpR} > 0.2$ (high)
- medium impact: $0.5 \geq \text{ImpR} > 0.25$ (low) or $0.2 \geq \text{ImpR} > 0.1$ (high)
- low impact: $0.25 \geq \text{ImpR} > 0$ (low) or $0.1 \geq \text{ImpR} > 0$ (high)
- nil impact: $\text{ImpR} = 0$ (low or high sensitivity)

For the methodology, a nine-point graded scale was chosen for all of the parameters. This scale is shown in Table 1 and was also applied to the indicators and criteria.

When a quantitative impact assessment is impossible[8], a qualitative assessment might be conducted using various methods based on expert judgements, subjective information, scientific, or legal references. When utilising qualitative data, ordinal scales are routinely for conversion into numbers. Therefore, the qualitative parameters can be scored using the fully described level of the estimated impact through the impact

[7]The number used for the scale points is derived from a percentile value for the impact rate; this value might be 9 (fixed length of 25 %), 11 (length of 20 %), or 21 (for 10 %). The scoring scale depends on the context of the study and might influence the overall sustainability rating.

[8]This situation occurs for some of the parameters for the selected indicators.

NHESSD
2, 207–259, 2014

assessment matrices. Regarding the adopted nine-point scale, the matrix shown in Table 2 was proposed for assessing the qualitative impacts within the developed framework. The scores are assigned based on a −4 to +4 scale, referring to the quantitative impact scores scale presented above (Table 1).

As for the quantitative parameters, impact assessment matrices could also capture the sensitivity of parameters. Table 3 shows an example of a possible interaction matrix between impact level and parameter sensitivity.

Once the impact scores for parameters have been quantified, they are aggregated to obtain a composite index that summarizes the performance of each indicator. Aggregation involves joining many individual values to form a more cohesive and concise value. When assessing sustainability, aggregation may occur in sequential stages to gather the performances of the parameters and obtain the performances of the indicators; the latter are then combined to obtain the criteria indexes.

3.3.2 Aggregation of the parameters

There exist many aggregating methods (for example, weighted sum, weighted arithmetic mean, weighted product, weighted geometric mean, non-compensatory outranking methods like multiple criteria decision analysis approach) and there is a lack of objective criteria for adopting an appropriate one (Zhou et al., 2006). However, the two most commonly used aggregating methods for constructing the composite indexes are weighted arithmetic and weighted geometric means (Juwana et al., 2012). The core difference between these methods is that the geometric approach takes into account the differences in the sub-indexes, while the arithmetic aggregation do not do so and therefore create perfect compensability among all sub-indexes.

The aggregation of the impact scores for the parameters with those for the synthetic indicators reduces the amount of information provided to the decision-makers, thereby simplifying the comparison of the performances of the evaluated alternatives and facilitating the ranking process. In this paper, this aggregation was achieved using the weighted arithmetic mean of the impact scores related to each indicator. This method was chosen because, in contrast to the weighted geometric mean, sub-indexes do not have to be strictly positive. The use of geometric method under the proposed scheme needs to transform all impact scores for parameters into positive values. Since this methodology is tailored to public use, the aggregation of sub-indexes should be kept as clear as possible. In this sense, the weighted arithmetic mean that is simple and easy to understand was chosen, although it assumes that there is complete compensation among the performances of the parameters/indicators.

The calculation for the indicator performance index (IPI) is shown in Eq. (3) (where x_i = weight of the parameter i).

$$\mathrm{IPI} = \frac{\sum x_i \cdot \mathrm{ImpS}_i}{\sum x_i} \tag{3}$$

Parameters are weighted according to their relevance and setting the weight of each parameter is inconvenient. The weighting is critical because the weight of parameters is essentially a value judgment that depends on the context of the risk management project, the sustainability priorities of the territory and the relative importance of each parameter within the composite indicator value. Higher weights are assigned to the most important parameters (Bragança et al., 2007). However, when information regarding the preference of parameter or indicator over another is unavailable, assigning equal weights seems to be the norm (Zhou et al., 2007). Therefore, while using this framework, the decision-makers must assign weights to the parameters or indicators that account for the specific needs and societal preferences of the territory.

To avoid subjectivity, the IPIs in the case study are calculated based on an unweighted average, except for the two indicators related to the "*environmental sustainability*" criterion; weighting values for these indicators are available from various environmental rating systems. The environmental parameters are weighted in this paper to demonstrate that this methodology can accommodate weighted values. The weightings used in this paper for the environmental parameters are consultative. For the indicator named "*impact on the environmental vulnerability*", the weights may be provided by

NHESSD
2, 207–259, 2014

the "Territorial Coherence Scheme" (schema de coherence territorial – SCOT) based on the prioritized environmental issues for the given territory. The SCOT is a French document describing urbanism that allows municipalities in a given territory to remain consistent in their policies between various areas to achieve sustainability. This document integrates an environmental diagnostic and an impact assessment regarding environment to underline and rank the stakes.

Parameters related to "*environmental impacts*" can be aggregated using the weights provided by environmental rating systems, such as the "Leadership in Energy & Environmental Design" (LEED) system, while analysing structural alternatives. LEED is a scoring system developed by the US Green Building Council to evaluate the environmental friendliness of buildings.

3.3.3 Aggregation of the indicators

After the IPIs are estimated, they are aggregated to form the criterion performance index (CPI). The scheme for calculating CPIs is similar to that mentioned above for evaluating the IPIs.

Similarly, the aggregation is based on equally weighted values. Theoretically, indicators should have the same importance; even when there is total compensation, aggregation occurs within a specific dimension. Nonetheless, while assessing the options within this framework, users could attribute different weights to the indicators when calculating the CPI, as outlined in Eq. (4) (where k_j indicates the weight of the indicator j).

$$\mathrm{CPI} = \frac{\sum k_j \cdot \mathrm{IPI}_j}{\sum k_j} \tag{4}$$

The results from aggregating the IPIs might reveal the sustainability performance for all five specific sustainability criteria, thus enabling comparisons between the different measures within each criterion. The most sustainable option for the desired goals

NHESSD
2, 207–259, 2014

must then be selected. Therefore, the fulfilment of the sustainability goals should be interpreted.

3.3.4 Comparative assessment of alternative options

To capture the interactions between the contributions of the criteria toward sustainability, the results are graphically displayed. Graphical representations are a useful starting point (Gomiero and Giampietro, 2005) during the comparative assessment because they provide a global performance overview for the alternative strategies in the context of the sustainability goals through the sustainable profiles. This general overview clearly displays the performance of the options at the level of each criterion.

In the proposed framework, the five CPIs were plotted onto a five-axis spider-gram illustrating the trade-offs (Fig. 3). As previously mentioned (Sect. 3.3.1), the CPIs are scored from −4 to 4 for each target. These indexes are mapped over axes, beginning at the interior and moving outward (the external limit denotes increasing level of sustainability). They are drawn relative to the adopted reference situation (target, thresholds or baseline strategy): the 0 level of the scale corresponds to the minimum sustainability level according to the reference and represents the component points of the reference graph.

Negative impacts are located inside the referential situation graph while positive ones are on the external side. Therefore, identifying which criteria perform better/worse or fall short/exceed the target/threshold is easy. A bigger diagram indicates than an option is more sustainable.

Moreover, this type of graphical representation facilitates comparisons between two or more options, matching the basic goal of this paper, which is to propose a tool to assess and compare one or more option.

After the sustainability profile for the options is visualised, the decision rules must be assigned to guide the selection of the most sustainable options and propose understandable and transparent justifications for these decisions. The CPIs will rank the options according to the different decision rules; these rules reflect the diverse visions of sustainable development. The alternative options during ranking may vary depending on the compromises made between the different aspects of sustainability. To handle the trade-offs between the sustainability criteria, some rules have been proposed for decision-making regarding sustainability assessment (Gibson et al., 2005). No specific decision rules have been established within this assessment framework. This feature is studied in the case study to demonstrate the potential variability in the option rankings in accordance with the adopted decision rules, possibly producing options that are ranked differently between rules. The decision-makers using this framework must choose the appropriate rule or combination of rules from the following possibilities.

Rule 1: maximum net gains

This rule delivers the most sustainable option based on the levels of cumulative contribution from each criterion toward global sustainability, selecting the option that offers the most positive net effects. The performance of the options toward sustainability might be estimated as follows:

(a) Calculating a composite index of sustainability

The CPIs are collapsed into a composite index. To remain consistent with the indicators and the criteria performance calculation scheme, the sustainability performance index (SPI) is a weighted average obtained using the following formula (5):

$$\mathrm{SPI} = \frac{\sum w_n \cdot \mathrm{CPI}_n}{\sum w_n} \quad (5)$$

where w_n = weight of criterion n and CPI_n = performance of criterion n.

To remain consistent with sustainability principles, equal importance would be ideally assigned to the CPIs during the sustainability performance assessment. However, because this framework aims to be generic, decision-makers could ap-

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

ply different weights, depending on their territorial specificities and sustainable development priorities.

In this type of composite index, a criterion could compensate for the lower performance of another criterion. Theoretically, when the five dimensions are equal, they cannot be substituted for one another. Further, the required similarities in the performance of all five sustainability dimensions seem too optimistic. Imagining a natural risk management decision that can simultaneously minimise all negative effects is difficult. Therefore, each criterion should be required to deliver net gains that positively contribute to the risk management sustainability.

(b) Computing the sustainability profile area

The options could be ranked according to the size of their sustainability profile. The sustainability profile ratio (SPR) could be calculated by dividing the sustainability coverage area of the option by that of the reference situation, as defined by Eq. (6), for a nine-point scale.

$$\mathrm{SPR} = \frac{1}{80} \cdot (a \cdot b + b \cdot c + c \cdot d + d \cdot e + e \cdot a) \tag{6}$$

where a, b, c, d and e are the lengths of the axes relative to the performance of each criterion.

With a nine-point scale, CPIs range from −4 to +4. Thus, the calculations proceeded by considering the five triangles defined by the axes of the diagram and adding +4 to the value of each CPI so that the length of each arm of the star described by the criteria can be measured from the centre of the diagram where the indexes value is equal to −4. Consequently, for the reference situation, the value of the five lengths equals 4.

The central angle of each of the five triangles is one-fifth of 360° (72°) and the formula used to estimate the sustainability area (SA) of a diagram is as follows:

$$\mathrm{SA} = \frac{1}{2} \cdot (a \cdot b + b \cdot c + c \cdot d + d \cdot e + e \cdot a) \cdot \sin(72^\circ) \tag{7}$$

NHESSD
2, 207–259, 2014

Using the Eq. (7), the SA of the reference situation equals to $40 \cdot \sin(72^{\circ})$ and Eq. (6) is obtained by dividing the sustainability area of the option by that of the reference situation.

However, the rankings provided by the multi-criteria spider-gram cumulative surface area method might be biased by the arbitrary order of the criteria (Dias and Domingues, 2014).

Rule 2: maximum positive performances

To avoid compensation effects among the dimensions due to aggregation, the sustainability of the options could be judged by analysing the criterion performance indexes individually. This rule focuses on positive criterion performance indexes, and the ranking could follow two distinct and complementary lines of thought. Therefore, the most sustainable option will be one of the following:

- the option with the highest number of positive performance indexes or
- the option that scores best on the most aspects of sustainability or has more of the performance indexes.

Rule 3: minimum adverse performances

The application of this rule focuses avoided the negative performances of the options relative to the reference. When using this rule, the ranking is based on negative indexes and the less sustainable option is the one with the lowest index.

Rule 4: fixed performance range or threshold

This rule ranks the options based on their ability to belong to a given "sustainability range" (minimum and/or maximum threshold values) for each criterion. The "sustainability range" is the largest interval in which a criterion performance index contributes to

NHESSD
2, 207–259, 2014

the global situation in accordance with local sustainable development. This range defines the desirable or tolerable limits of sustainability. The lower boundary is the most important because it is the minimum performance required to contribute to the sustainability. The most sustainable option is the one with the highest number of criterion performance indexes within the "sustainability ranges".

This framework is a preliminary attempt to elaborate a method for sustainability assessments regarding natural risk management decisions. The applicability of this method can be demonstrated using a case study that illustrates the use of the framework and offers improvements to it.

4 Case study

To test this methodological framework, we refer to a theoretical case based on virtual data. This case was designed to be as close as possible to a real case study. First, using the virtual data will help us keep the approach to sustainability assessment generic. Sitzenfrei et al., (2010) explained why this type of case study is used: "*Because of the specific boundary conditions and system properties of each single case study, it is problematic to generalize and transfer the results to other systems. Therefore the application of virtual case studies to test measures, approaches or models is a well suited and known technique*". Using this type of case study also overcomes the possibility of missing data. Therefore, this case study is suitable because we do not have any empirical or real data.

Consequently, the theoretical case study was built in the following manner. The study is conducted in a fictive French municipality containing approximately 2000 inhabitants within 20 km^2; the risk under management was not related to any natural hazard. In this study, only one punctual assessment on the temporal scale was carried out. This assessment was a snapshot at a single point time for the middle term through a 10 or

15 yr prediction[9]. The time span chosen for the temporal scale was not entirely arbitrary. The middle term should carefully balance the short- and long-term results. The short term is too early to assess the sustainability of a risk management decision, and the long term generates more uncertainty because the future is inherently uncertain.

The chosen reference situation should be the baseline policy. Therefore, we designed four strategies: a "do-nothing" strategy as the current management policy and three alternative strategies. Alternative 1 consists of willingly adjusting buildings to accommodate the hazard to the municipality; the citizens are supposed to fund this strategy. Alternative 2 consists of a valorisation or exploitation of the hazard prone area considering the long-term character of natural hazards and betting that the advantages would overcome the disadvantages; the local government is supposed to fund this strategy. Alternative 3 is the construction of management infrastructure by local authorities using public funding to reduce the level of the hazard. These strategies are supposed to have different characteristics while remaining identical in terms of technical complexity during implementation. The potential consequences have been reviewed to determine the most sustainable strategy.

For this assessment, imaginary data were assigned to each parameter (without any engagement or preference). Table 4 presents an extract of the worksheet (for the entire data set, see Tables A1–A5). In this table, each parameter was assigned three values (low, average and high) to capture its possible range; these values cannot be estimated as single values due to the uncertainty inherent to long-term estimations. Equal weights have been assigned to the parameters[10], indicators and criteria, except for the parameters related to "environmental sustainability"; these parameters were weighted

[9]This prediction should provide the following: alternative levels of vulnerability based on the future population and other factors in the territory; losses from future risks based on the current decisions (such as land-use and building codes); and impacts on and changes in the aspects of sustainability (economic vitality, ecological quality and social equity).

[10]In this paper, some parameters, particularly those of "Social sustainability", are split into sub-parameters that should have equal weighting within the parameters.

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

differently by relying on the weights provided by the SCOT of "Grand Clermont" (MEDDTL, 2011) and LEED 2009 (see Poveda and Lipsett, 2011).

5 Results and discussion

The first part of this section describes the aspects that could strongly influence the results of future real-case studies. The second portion contains the results of the case study.

5.1 Variability of the results

This case study exhibits some important sources of variability: the input data uncertainty and the impact score scale.

Sustainability assessments require precise data, but no long-term predictions are without uncertainty. These predictions could gain could uncertainty from various sources (e.g., assumptions, data, methods, models) that affect the decision-making process. The content in Table 4 demonstrates the potential incidence of uncertainty. The results of the calculation for the "economic sustainability" performance index using the lower, average and upper values from the ranges of the parameters within this table are presented in Table 5. These results show how the ranking of the alternatives could vary according to the values. The potential range of the performance of alternative 2 lies within that of alternative 1. These results suggest that alternatives 1 and 2 might score equally. An uncertainty analysis is necessary to improve the sustainability assessment. However, the core purpose of this paper is not to address uncertainty; further work will be conducted to address this issue. Therefore, the case study was carried out using only one set of data that was assumed to contain the average values for the parameters (see Tables A1–A5).

The values in Table 4 demonstrate the importance of the scale used to assign the impact scores. For instance, when using the average values for the parameters, the

NHESSD
2, 207–259, 2014

impact rates (calculated using Eq. 2) of alternatives 1 and 3 regarding the total annual cost are −19 % and −9 %, respectively. Based on the nine-point bidirectional scale (length of 25 %) adopted in this paper, both impact scores equal −1, while a twenty-one-point scale (length of 10 %) will assign an impact score of −2 to alternative 1 and an impact score of −1 to alternative 3. Ceiling effects should be considered due to the specifics of the study case. The use of an eleven- or twenty-one-point scale might provide more precise results than the nine-point-scale, even if performing the calculation using the latter scale is much easier.

5.2 Options ranking

The results from this application are the scored criteria assigned to each alternative. Table 7 presents the obtained CPIs, the ranking of each strategy against each criterion and the sustainability profiles.

No option has technical, economic, social and institutional unsustainability. Regarding those criteria, the results show an overall improvement in the performance compared to the reference. Regarding "Environmental sustainability", alternatives 2 and 3 are predicted not to be environmentally friendly, whereas alternative 3 will contribute the most to reducing environmental vulnerability. Figure 4 visually compares the performances of the assessed alternatives.

An analysis based solely on the techno-economic performances indicates that alternative 3 seems to be optimal. The options ranked based on the "Technical and functional effectiveness" and "Economic sustainability" criteria (obtained by combining the indexes values of the two criteria) from best to worst is as follows: 1st = alternative 3, 2nd = alternative 2 and 3rd = alternative 1. In the traditional approach, where risk management is focused on techno-economic feasibility, the decision to invest in alternative 3 might be the most promising.

For the integrated decision-making perspective, the rankings that depend on the different decision rules are summarised in Table 6. These results illustrate that the most sustainable solution is most likely alternative 3 and that the least sustainable option is alternative 2, according to the weighted parameters and indicators. Based on the six ranking possibilities, alternative 3 ranks 1st four times and ranks 2nd twice, while alternative 2 ranks 2nd twice and 3rd four times. By ranking 1st two times and 2nd four times, alternative 1 seems to be less interesting than alternative 3 but more attractive than alternative 2.

Therefore, appraising the options that rely on sustainable development objectives affects the ranking by comparing them based only on technical and economic criteria: 1st = alternative 3, 2nd = alternative 2 and 3rd = alternative 1 (for a techno-economic assessment) vs. 1st = alternative 3, 2nd = alternative 1 and 3rd = alternative 2 (for a sustainability assessment). Using sustainability targets when making risk management decisions can refine an assessment.

The case study accounts for some features that are not often considered during the existing natural risk management processes. The findings reveal that the developed framework can provide an excellent informational resource about indicators and criteria that is optimised for each possible management strategy. The results can also highlight the shortfalls in each case. Therefore, based on this supportive analysis tool, decision-makers could compare the sustainability performance of the identified strategies and choose the most sustainable one. They could also monitor the progress toward sustainability or their failure to meet sustainability goals.

Though the case study ensures the reliability of the framework, this method must be applied to more realistic and precise case studies (including various hazards and strategies) to detect any foreseeable difficulties, limits or threats to its validity. These tests will be performed in the future using real data. This application should be the first step toward appraising the ability of the tool to accommodate any type of natural hazard.

As recognised by Helming et al., (2011), "*it is fair to say that no methodological framework for ex ante impact assessment will ever manage to comprehensively capture the complex relationships between changes in policy [. . .] and the resulting changes in social, economic, and environmental systems*". No tool will ever be able to capture and reflect every possible impact of a decision or an action. Therefore, this tool does not provide a "set of best parameters, indicators and criteria"; it instead provides a formal and credible set that might be used to support decision-making processes. This method introduces a methodology prototype that proposes simple calculations through an accessible conceptual approach. These calculations should be appropriate for managing natural risks and transferable to any other country.

Decision-making for a sustainable risk management policy depends on the distinctive characteristics of each case study. Because the decision-makers weight the parameters, indicators and criteria, the results cannot remain the same when the aggregation framework changes. For a given territory with the same data, sustainability appraisals are liable to evolve because the weights are assigned based on value judgments. In the future and to enhance the robustness of the tool, the variance introduced by the weighting changes regarding the sustainability performance should be subjected to a sensitivity analysis.

Although uncertainty is not the focus of this paper, it is interesting to analyse the impact of the estimated performance range on sustainability profile. Figure 5 presents the shape of the possible "Economic sustainability" indexes of alternative 1, which has the largest interval for this criterion (Table 5). The space for the predicted values is situated between the first and the third graphs along the "Economic sustainability" axis, demonstrating that decisions can vary between these two endpoints and can potentially include the value ranges of other options. Therefore, wider index ranges generate more uncertainty.

Ex ante sustainability assessments, as well as territorial dynamics and various forecasts, contain several assumptions. Nevertheless, these assumptions are unable to reflect the long-term characteristics of hazardous events or effects of the planned decisions because, as noted by Zhu et al., (2011), "*the future is inherently uncertain, all exercises about the future are facing and should cope with great uncertainty*". As a strategic appraisal, the sustainability assessment needs to address the inevitable uncertainties introduced during the formulation and implementation processes for the

NHESSD
2, 207–259, 2014

decisions: uncertainty analysis should be an integral phase of the sustainability assessment. In the specific context of risk management, this perspective is confirmed by Olbrich et al. (2009), who argue that "*any meaningful assessment of sustainability of risk management strategies faces issues on a fundamental level: the necessity to address uncertainty about the system dynamics in the criterion used for the assessment*". Therefore, developing methodological approaches that can handle uncertainty and examine its effects on the results of a study is critical. Further INCERDD project work is being conducted to develop a framework that accounts for uncertainty within a risk management policy-making process that is geared toward sustainable decisions.

6 Conclusions

Accounting for sustainability issues is currently a fundamental aspect of any decision when identifying the objectives and indicators that are used to monitor the effects of that decision. During the risk management decision process, when sustainability requirements are included, the chosen strategies would be technically, economically and environmentally efficient while enhancing the societal and institutional benefits.

This paper defined a comprehensive and structured methodology for sustainability assessments regarding natural risk management options in urban areas. It has provided an indicator-based tool that includes the technical/operational, and economic considerations, and the social, environmental, and institutional effects of risk management activities. Of the three common pillars of sustainable development, the technical performance and institutional dimensions have been added to appreciate the holistic nature of sustainable natural risk management in urban areas.

By providing information regarding the sustainability performance of urban natural risk management activities, this framework should respond more objectively to the following questions: "Is sustainable risk management in a given municipality achievable?" and "What is the best way to attain this achievement?" This capability has been tested using an imaginary case study, providing results that must be validated.

NHESSD
2, 207–259, 2014

This methodological framework should contribute to the sustainability of natural risk management decisions. However, the approach has only been tested using a theoretical case with virtual data, leaving it far from being a fully operational and consensual tool. This method does take a step forward in the field of natural and anthropogenic risk management by structuring the process that leads to decisions regarding the sustainability assessments. Although this tool is tailored to the specific field requirements of risk management, it has potential applicability to any type of decision after some revisions, particularly those that involve the indicators of the "Technical and functional effectiveness" criterion, before being used in different fields. This decision support tool could promote a systematic and coherent sustainability assessment for decisions throughout their entire life cycle.

Acknowledgements. The authors would like to acknowledge the National Research Agency (Agence Nationale de la Recherche – ANR) for funding the research (INCERDD project) leading to this paper.

References

Achet, S. H. and Fleming, B.: A watershed management framework for mountain areas: Lessons from 25 yr watershed conservation in Nepal, J. Environ. Plann. Man., 49, 5, 675–694, 2006.

Acosta-Alba, I. and van der Werf, H. M. G.: The use of reference values in indicator-based methods for the environmental assessment of agricultural systems, Sustainability, 3, 424–442, 2011.

Agrawala, S. (Ed.): Climate change in the European Alps: Adapting winter tourism and natural hazards management, Organization for Economic Co-operation and Development (OECD) Publishing, Paris, France, 127 pp., 2007.

Bragança, L., Mateus, R., and Koukkari, H.: Perspectives of building sustainability assessment, in: Portugal SB07 – Sustainable Construction, Materials and Practices, Challenge of the Industry for the New Millennium, edited by: Bragança, L., Pinheiro, M., Jalali, S., Mateus, R., Amoêda, R., and Guedes, M. C., IOS Press, Amsterdam, 356–365, 2007.

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

Bragança, L., Mateus, R., and Koukkari, H.: Building sustainability assessment, Sustainability, 2, 2010–2023, 2010.
Carreño, M. L., Cardona, O. D., and Barbat, A. H.: A disaster risk management performance index, Nat. Hazards, 41, 1–20, 2007.
Di Mauro, C., Bouchon, S., Carpignano, A., Golia, E., and Peressin, S.: Definition of multi-risk maps at regional level as management tool: Experience gained by civil protection authorities of Piemonte region, Proceedings of the 5th Conference on Risk Assessment and Management in the Civil and Industrial Settlements, 17–19 October 2006, Pisa, Italy, 12 pp., available at: http://conference.ing.unipi.it/vgr2006/archivio/Archivio/2006/Articoli/700196.pdf, 2006.
Dias, L. C. and Domingues, A. R.: On multi-criteria sustainability assessment: spider-gram surface and dependence biases, Appl. Energ., 113, 159–163, 2014.
Faber, M. H.: Critical issues in the management of catastrophic and global risks, Proceedings of the International Symposium on Reliability Engineering and Risk Management, 13 pp., 2010.
Franco, L. A. and Montibeller, G.: Problem structuring for multi-criteria decision analysis interventions, Working paper OR 09–115, 25 pp., available at: http://www.lse.ac.uk/management/documents/WP-09-115.pdf, 2009.
Freedman, P. L., Nemura, A. D., and Dilks, D. W.: Viewing total maximum daily loads as a process, not a singular value: adaptive watershed management, J. Environ. Eng.-ASCE, 130, 695–702, 2004.
Gafsi, M. and Favreau, J. L.: Indicator-based method for assessing organic farming sustainability, in: Methods and Procedures for Building Sustainable Farming Systems, Application in the European Context, edited by: Marta-Costa, A. A. and Soares da Silva, E. L. D. G., Springer, 175–187, 2013.
Galloway, G.: Integrated flood management case study – USA: Flood management – Mississippi river, The Associated Programme on Flood Management, Geneva, Switzerland, 12 pp., available at: http://www.apfm.info/publications/casestudies/cs_usa_mississippi_full.pdf, 2004.
Genserik, R.: Integrating risk and sustainability: a holistic and integrated framework for optimizing the risk decision and expertise rad (ORDER), Disaster Advances, 5, 25–32, 2012.
Gibson, R. B.: Sustainability assessment: basic components of a practical approach, Impact Assessment and Project Appraisal, 24, 170–182, 2006.

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

Gibson, R. B., Hassan, S., Holtz, S., Tansey, J., and Whitelaw, G.: Sustainability Assessment: Criteria and Processes, Earthscan Publishers, London, 254 pp., 2005.
Gomiero, T. and Giampietro, M.: Graphic tools for data representation in integrated analysis of farming systems, International Journal of Global Environmental Issues, 5/4, 264–301, 2005.
González, A., Donnelly, A., Jones, M., Chrysoulakis, N., and Lopes, M.: A decision-support system for sustainable urban metabolism in Europe, Environ. Impact Asses., 38, 109–119, 2013.
Graymore, M. L. M., Sipe, N. G., and Rickson, R. E.: Sustaining human carrying capacity: a tool for regional sustainability assessment, Ecol. Econ., 69, 459–468, 2010.
Hansson, M., Danielson, M., and Ekenberg, L.: A framework for evaluation of flood management strategies, J. Environ. Manage., 86, 465–480, 2008.
Helming, K., Diehl, K., Kuhlman, T., Jansson, T., Verburg, P. H., Bakker, M., Perez-Soba, M., Jones, L., Johannes Verkerk, P., Tabbush, P., Breton Morris, J., Drillet, Z., Farrington, J., LeMouël, P., Zagame, P., Stuczynski, T., Siebelec, G., and Wiggering, H.: Ex ante impact assessment of policies affecting land use – Part B: Application of the analytical framework, Ecol. Soc., 16, 23 pp., available at: http://www.ecologyandsociety.org/vol16/iss1/art29/), 2011.
Juwana, I., Muttil, N., and Perera, B. J. C.: Indicator-based water sustainability assessment – A review, Sci. Total. Environ., 438, 357–371, 2012.
Kang, M. G., Jeong, H. S., Lee, J. H., and Kang, B. S.: Assessing national flood management using a sustainable flood management framework, Water policy, 15, 418–434, 2013.
Kenyon, W.: Evaluating flood risk management options in Scotland: a participant-led multi-criteria approach, Ecol. Econ., 64, 70–81, 2007.
Klijn, F., de Bruijn, K., McGahey, C., Mens, M., and Wolfert, H.: Towards sustainable flood risk management: On methods for design and assessment of strategic alternatives exemplified on the Schelde Estuary, FLOODsite project report, Executive summary, 30 pp., available at: http://www.floodsite.net/html/partner_area/project_docs/T14_08_02_sustainable_flood_risk_management_Schelde_ExecSum_V1_2_P01.pdf, 2009.
Knott, G. and Fox, A.: A model of sustainable risk management, The magazine of the emergency planning society, 62, 38–42, 2010.
Ko, T. G.: Development of a tourism sustainability assessment procedure: a conceptual approach, Tourism Manage., 26, 431–445, 2005.
Kundzewicz, Z. W.: Non-structural flood protection and sustainability, Water Int., 27, 3–13, 2002.

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

Lekuthai, A. and Vongvisessomjai, S.: Intangible flood damage quantification, Water Resour. Manag., 15, 343–362, 2001.
McGahey, C., Sayers, P., Mens, M., Luther, J., and Schanze, J.: An approach to planning for sustainable flood risk management in the long-term (supported by prototype tools), FLOODsite project report, Executive summary, 16 pp., available at: http://www.floodsite.net/html/partner_area/project_docs/T18_07_03_Task_18_Executive_Summary_V2_0_P01.pdf, 2009.
Mdaghri, Z. A.: Intégration de la pensée cycle de vie aux études d'impacts: Cas du site minier Raglan, Ph.D. thesis, Université de Montréal, Canada, 243 pp., 2008.
Mileti, D.: Disasters by Design: A Reassessment of Natural Hazards in the United States, The Joseph Henry Press, Washington, D. C., 376 pp., 1999.
Ministère de l'Écologie, du Développement durable, des Transports et du Logement (MEDDTL): Service de l'économie, de l'évaluation et de l'intégration du développement durable: Fiche exemple 12: Hiérarchisation et territorialisation des enjeux, 5 pp., available at: http://www.developpement-durable.gouv.fr/IMG/pdf/F12_MEDDTL_Fiches_Guide_Ev_Env_Doc_Urba_BD_nov2011.pdf, 2011.
Myllyviita, T., Leskinen, P., and Seppälä, J.: Impact of normalisation, elicitation technique and background information on panel weighting results in life cycle assessment, Int. J. Life Cycle Ass., 1–10, doi:10.1007/s11367-013-0645-6, 2013.
Ni, J., Sun, L., Li, T., Huang, Z., and Borthwick, A. G. L.: Assessment of flooding impacts in terms of sustainability in mainland China, J. Environ. Manage., 910, 1930–1942, 2010.
Olbrich, R., Quaas, M. F., and Baumgärtner S.: Sustainable use of ecosystem services under multiple risks – A survey of commercial cattle farmers in semi-arid rangelands in Namibia, Working Paper Series in Economics, N°137, Leuphana University of Lüneburg, Germany, 24 pp., 2009.
Peltonen, L.: Recommendations for a risk mitigation oriented European spatial Policy, in: Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, edited by: Schmidt-Thomé, P., Geological Survey of Finland, Special paper 42, 153–167, 2006.
Poulard, C., Lafont, M., Lenar-Matyas, A., and Łapuszek, M.: Flood mitigation designs with respect to river ecosystem functions – A problem oriented conceptual framework, Ecol. Eng., 36, 69–77, 2010.

Poveda, C. A. and Lipsett, M. G.: A review of sustainability assessment and sustainability/environmental rating systems and credit weighting tools, Journal of Sustainable Development, 4, 36–55, 2011.
Putri, P. W. and Rahmanti, A. S.: Jakarta Waterscape: From structuring water to 21st century hybrid nature? Nakhara, Journal of Environmental Design and Planning, 59–74, available at: http://berkota.files.wordpress.com/2011/12/putri-and-sari-nakhara-06.pdf, 2010.
Saunders, W.: How long is your piece of string – Are current planning timeframes for natural hazards long enough? Paper presented at the Planning pathway to the future, 20–23 April, Christchurch, New Zealand, 6 pp., available at: http://www.planning.org.nz/Folder?Action=View%20File&Folder_id=185&File=Saunders.pdf, 2010a.
Saunders, W.: Sustainable urban design for natural hazard risk reduction, Proceedings of New Zealand Sustainable Building Conference: SB10 – Innovation and transformation, 26–28 May 2010, Te Papa, Wellington, New Zealand, 11 pp., available at: http://www.branz.co.nz/cms_show_download.php?id=499b83c7139b64f02c5f62d3ee76cbac5fef0d5f, 2010b.
Scottish Executive: National Technical Advisory Group on Flooding Issues – NTGA: Sustainable flood management sub-group report, Report for 23 September 2004 NTGA Meeting, 21 pp., available at: http://www.scotland.gov.uk/Resource/Doc/1223/0007095.pdf, 2004.
Scottish Executive: Sustainable flood management pilot study (Final report), MWH and Jacobs Babtie, Edinburgh, UK, 57 pp., available at: http://www.scotland.gov.uk/Resource/Doc/1223/0020971.PDF, 2005.
Singh, R. K., Murty, H. R., Gupta, S. K., and Dikshit, A. K.: An overview of sustainability assessment methodologies, Ecol. Indic., 15, 281–299, 2012.
Sitzenfrei, R., Fach, S., Kinzel, H., and Rauch, W.: A multi-layer cellular automata approach for algorithmic generation of virtual case studies: VIBe, Water Sci. Technol., 61, 37–45, 2010.
Tompkins, E. L. and Adger, W. N.: Does adaptive management of natural resources enhance resilience to climate change?, Ecol. Soc., 14 pp., available at: http://www.ecologyandsociety.org/vol9/iss2/art10, 2004.
Tugnoli, A., Landucci, G., and Cozzani, V.: Sustainability assessment of hydrogen production by steam reforming, Int. J. Hydrogen Energ., 336, 4345–4357, 2008.
Turner II, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A., and

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

Schiller, A.: A framework for vulnerability analysis in sustainability science, P. Natl. Acad. Sci. USA, 1004, 8074–8079, 2003.
Turner, R. K., Adger, W. N., Crooks, S., Lorenzoni, I., and Ledoux, L.: Sustainable coastal resources management: principles and practice, Nat. Resour. Forum, 23, 275–286, 1999.
Van Cauwenbergh, N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Garcia Cidad, V., Hermy, M., Mathijs, E., Muys, B., Reijnders, J., Sauvenier, X., Valckx, J., Vanclooster, M., Van der Veken, B., Wauters, E., and Peeters, A.: SAFE – A hierarchical framework for assessing the sustainability of agricultural systems, Agr. Ecosyst. Environ., 120, 229–242, 2007.
Weiland, U., Kindler, A., Banzhaf, E., Ebert, A., and Reyes-Paecke, S.: Indicators for sustainable land use management in Santiago de Chile, Ecol. Indic., 11, 1074–1083, 2011.
Werritty, A.: Sustainable flood management: oxymoron or new paradigm?, Area, 38, 16–23, 2006.
Wiek, A. and Binder, C.: Solution spaces for decision-making – A sustainability assessment tool for city-regions, Environ. Impact Asses., 25, 589–608, 2005.
Wurbs, R. A.: Optimal sizing of flood damage reduction measures based on economic efficiency, Int. J. Water Resour. D., 12, 5–16, 1996.
Zahm, F., Viaux, P., Girardin, P., Vilain, L., and Mouchet, C.: Farm sustainability assessment using the IDEA Method: From the concept of farm sustainability to the case studies on French farms, in: From Common Principles to Common Practices, Proceedings and Outputs of the 1st Symposium of the International Forum on Assessing Sustainability in Agriculture (INFASA), edited by: Häni, F. J., Pintér, L., and Herren, H. R., International Institute of Sustainable Development and Swiss College of Agriculture, Bern, 77–110, 2006.
Zhou, P., Ang, B. W., and Poh, K. L.: Comparing aggregating methods for constructing the composite environmental index: an objective measure, Ecol. Econ., 59, 305–311, 2006.
Zhou, P., Ang, B. W., and Poh, K. L.: A mathematical programming approach to constructing composite indicators, Ecol. Econ., 62, 291–297, 2007.
Zhu, Z., Bai, H., Xu, H., and Zhu, T.: An inquiry into the potential of scenario analysis for dealing with uncertainty in strategic environmental assessment in China, Environ. Impact Asses., 31, 538–548, 2011.
Zihri, G.: Risques liés aux ouvrages souterrains: Constitution d'une échelle de dommages, Ph.D. thesis, Ecole des Mines de Nancy, France, 226 pp., 2004.

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

Table 1. Quantitative impact scores for the type of impact.

Impact rate (ImpR) value range	Positive impact	Impact score (ImpS)	Negative impact	Impact score (ImpS)
ImpR > 0.75	Very high advantage	+4	Very high disadvantage	−4
0.75 ≥ ImpR > 0.5	High advantage	+3	High disadvantage	−3
0.5 ≥ ImpR > 0.25	Medium advantage	+2	Medium disadvantage	−2
0.25 ≥ ImpR > 0	Low advantage	+1	Low disadvantage	−1
ImpR = 0	Nil impact		Nil impact	

Source: authors.

NHESSD
2, 207–259, 2014

Table 2. Quantitative impact scores based on the level of impact.

Impact level	Impact score (ImpS) Positive impact	Negative impact
Negligible impact [a]	0	0
Low impact	+1	−1
Medium impact	+2	−2
High impact	+3	−3
Very high impact	+4	−4

[a] Negligible impact is an impact expected not to occur.
Source: authors inspired by the work of Zihri (2004) and Mdaghri (2008).

NHESSD
2, 207–259, 2014

Table 3. Examples of the impact scores based on the sensitivity of the parameters.

	Sensitivity of the parameter: Low to Medium				Medium to High				High to Very High			
	Impact level				Impact level				Impact level			
	Low	Medium	High	Very High	Low	Medium	High	Very High	Low	Medium	High	Very High
Impact level based on sensitivity	Low	Med.	High	Very High	Med.	High	Very High	Very High	High	Very High	Very High	Very High
Impact score (ImpS)	±1	±2	±3	±4	±2	±3	±4	±4	±3	±4	±4	±4

Source: authors.

NHESSD
2, 207–259, 2014

Table 4. Extract of the "economic sustainability" criterion from the worksheet.

Indicators	Parameters	Do-nothing	Altern. 1	Altern. 2	Altern. 3
Total annual costs	–	3 700 000–4 000 000 (**3 850 000**)	4 350 000–4 850 000 **(4 600 000)**	6 500 000–8,500 000 **(7 500 000)**	4 000 000–4,400 000 **(4 200 000)**
Impact on the economic vulnerability (expected annual avoided damage)	–	2 800 000–4 200 000 **(3 500 000)**	4 500 000–5 900 000 **(5 200 000)**	8 500 000–16 500 000 **(12 500 000)**	6 000 000–10 000 000 **(8 000 000)**
Creation or endangerment of economic opportunities	GDP per capita	1650–1670 **(1660)**	1700–1800 **(1750)**	1900–2300 **(2100)**	1800–1900 **(1850)**
	Number of expected new jobs	600–800 **(700)**	650–750 **(700)**	900–1300 **(1100)**	800–1200 **(1000)**
	Unemployment rate	12–16 **(14)**	9–19 **(14)**	9–11 **(10)**	10–16 **(13)**
	Total number of enterprises	140–180 **(160)**	150–210 **(180)**	200–300 **(250)**	180–220 **(200)**
	Annual turnover of economic activities	560 000–600 000 **(580 000)**	715 000–745 000 **(730 000)**	920 000–990 000 **(955 000)**	765 000–800 000 **(782 500)**

Averaged values are in brackets.
Source: authors.

NHESSD
2, 207–259, 2014

Table 5. Estimated ranges of the "economic sustainability" indexes.

Calculation with:	Altern. 1	Altern. 2	Altern. 3
Lower values	1.07	0.6	**1.53**
Average values	0.6	0.87	**1.47**
Higher values	0.4	0.87	**1.4**

Source: authors.

NHESSD
2, 207–259, 2014

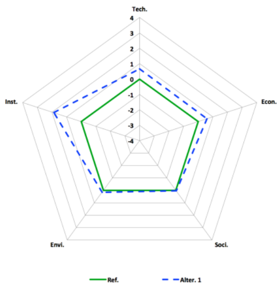
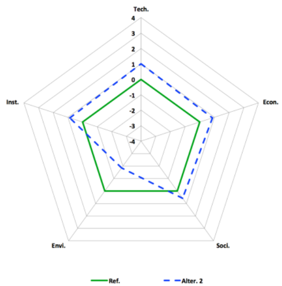
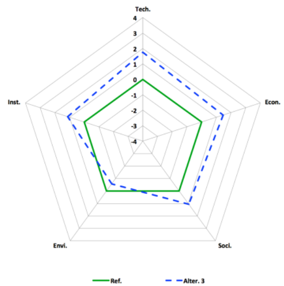
Table 6. Options ranking based on the decision rules.

	1st	2nd	3rd
Composite index of sustainability	Alter. 3 (SPI = 0.97)	Alter. 1 (SPI = 0.67)	Alter. 2 (SPI = 0.3)
Sustainability profile ratio	Alter. 3 (SPR = 1.52[a])	Alter. 1 (SPR = 1.37[a])	Alter. 2 (SPR = 1.15[a])
Highest number of positive performance indexes	Alter. 1 (5 indexes > 0)	Alter. 2 Alter 3 (4 indexes > 0)	–
Highest number of best performance indexes	Alter. 3 (3 best indexes)	Alter. 1 (2 best indexes)	Alter. 2 (0 best index)
Minimum adverse performances	Alter. 1 (No negative index)	Alter. 3 ($CPI_{Env} = -0.57$)	Alter. 2 ($CPI_{Env} = -1.8$)
Fixed performance threshold. For example: criteria performance indexes ≥ 1	Alter. 3 (3 indexes ≥ 1)	Alter. 1 Alter. 2 (1 index ≥ 1)	–

[a] Values obtained by preserving the order of the criteria on the graph for all of the options.
Source: authors.

NHESSD
2, 207–259, 2014

Table 7. Sustainability assessment data.

	Alternative 1	Alternative 2	Alternative 3
Technical and functional effectiveness	0.67 (3rd)	1.00 (2nd)	**1.75** (1st)
Economic sustainability	0.60 (3rd)	0.87 (2nd)	**1.47** (1st)
Social sustainability	0.05 (3rd)	0.58 (2nd)	**1.06** (1st)
Environmental sustainability	**0.16** (1st)	−1.84 (3rd)	−0.57 (2nd)
Institutional sustainability	**1.88** (1st)	0.88 (3rd)	1.13 (2nd)
Sustainability profile			

Source: authors.

NHESSD
2, 207–259, 2014

Table A1. Technical and functional effectiveness.

Indicators	Parameters (units)	Do-nothing	Alter. 1	Alter. 2	Alter. 3
Impact on the hazard	Magnitude or intensity (variable units)	4.5	4.5	4.5	2
	Share of the surface of a municipality in a hazardous area (%)	28	28	33	21
Impact on structural vulnerability	Percentage of community buildings within the hazard prone area (%)	19	19	27	15
	The mean robustness of community buildings against hazards (#, 1 to 4) [a]	3.5	2.5	2.5	3.5
	Percentage of buildings within the hazard prone area with sensitive elements (%) [b]	74	35	50	70
	Percentage of buildings with protective gear within the hazard prone area (%)	13	21	18	13
Creation or exacerbation of risks on the given territory or elsewhere	Magnitude or intensity of each type of generated or exacerbated hazard (variable units)	0.5	0.5	0.2	0.1
	Share of the municipality affected by each type of generated or exacerbated hazard (%)	6	6	2.8	1.5
	Vulnerability index related to each type of generated or exacerbated hazard depending on the type of land use (#) [c]	2	2	1	1

[a] 1 = very high robustness to hazard; 2 = high robustness to hazard; 3 = moderate robustness to hazard; 4 = low robustness to hazard.
[b] Heating system, electrical system, fuel tanks, etc.
[c] 0 = no vulnerability; 1 = fallow land; 2 = agricultural area; 3 = ecological interest area; 4 = commercial and residential area.

NHESSD
2, 207–259, 2014

Table A2. Economic sustainability.

Indicators	Parameters (units)	Do-nothing	Alter. 1	Alter. 2	Alter. 3
Total annual costs (€)	–	3 850 000	4 600 000	7 500 000	4 200 000
Impact on economic vulnerability	Average annual avoided damage[a] (€)	3 500 000	5 200 000	12 500 000	8 000 000
Creation or endangerment of economic opportunities	GDP per capita (€)	1660	1750	2100	1850
	Total number of jobs (#)	700	700	1100	1000
	Unemployment rate (%)	14	14	10	13
	Total number of enterprises (#)	160	180	250	200
	Annual turnover of economic activities (€)	580 000	730 000	955 000	782 500

[a] Amount of annual expected damage costs that will be reduced due to the management strategy.

NHESSD
2, 207–259, 2014

Table A3. Social sustainability.

Indicators	Parameters (units)	Do-nothing	Alter. 1	Alter. 2	Alter. 3
Impact on social vulnerability	Percentage of community inhabitants within the hazard prone area (%)	27	27	33	20
	Proportion of sensitive [a] and disabled persons among endangered inhabitants (%)	25	21	25	17
	Share of the establishments open to the public within the hazard prone area [b] (%)	12	12	12	8
	Warning system (#, 1 or 2) [c]	1	2	2	1
	Resilience	–	–	–	–
	1 – Number of people working in emergency services (#)	150	150	185	150
	2 – Accommodation capacity (shelters) for evacuation outside the hazard prone area (# of persons)	250	250	3,200	250
	3 – Recovery time (# of days)	3	2	3	1
Social acceptability	Implementation constraints	–	–	–	–
	1 – Aesthetic integration into the landscape (#) [d]	2	2	1	1
	2 – Sound level (#, 1 or 2) [e]	1	1	2	2
	3 – Completion time (#, 1 to 4) [f]	1	1	4	3
	4 – Distance from residents (km)	2.9	0	5.3	3.6
	5 – Economic value of land use conflicts (€)	600 000	600 000	440 000	650 000
	Direct contribution to existing issues	–	–	–	–
	1 – New housing units (#)	40	40	150	40
	2 – Local employment creation (#)	20	25	50	35
	3 – Direct economic benefits (€)	1 300 000	1 680 000	2 500 000	2 000 000
	Willingness of stakeholders to support implementation constraints: scored according to opinion polls (#, −4 to 4) [g]			−2	3
	Degree of compliance to the preferential representation by stakeholders regarding the best risk management decision (#, 1 to 4) [h]	2	1	2	3
Equity/social cohesion	Socioeconomic equity	–	–	–	–
	1 – Difference between per capita public expenditures for the upper (richest income) and lower (poorest income) social groups (€)	120	81	153	57
	2 – Difference between the share of income dedicated to risk management expenditures for the lower and upper social groups (%) [i]	8	13	8	8
	Socio-spatial equity	–	–	–	–
	1 – Difference between the total expenditures per capita in vulnerable and non-vulnerable areas (€)	243	308	243	215
	2 – Average individual income within the potentially exposed areas (€per capita)	1370	1330	1405	1370
	3 – Share of the wealthy households in potentially exposed areas or likely to be affected (%) [j]	10	10	13	8
	4 – Difference between the comparative social risk index for the lower and upper social groups (%) [k]	27	27	24	27

NHESSD
2, 207–259, 2014

A. M. Edjossan-Sossou et al.

Table A3. Continued.

Indicators	Parameters (units)	Do-nothing	Alter. 1	Alter. 2	Alter. 3
Quality of life	Average travel time to work per capita (min)	17	17	10	15
	Average travel distance to work per capita (km)	1.3	1.3	0.9	1.1
	Average travel time for amenities [l] per capita (min)	9	9	4	5
	Average travel distance for amenities per capita (km)	0.8	0.8	0.6	0.7
	Number of amenities per 1,000 inhabitants (#)	9	9	13	11
	Urban and suburban green space (landscape) per capita (m^2)	27	27	30	21
Territorial identity	Share of non-native residents (%) [m]	13	11	22	17
	Share of residents in isolated houses (%) [n]	7	7	8	7
	Number of heritage and cultural sites within the potentially exposed areas (#)	5	5	3	2
	Annual visits to heritage/cultural sites (#)	32 700	32 700	41 500	37 200
	Potential impacts on the tourism sector (%) [o]	8.3	8.3	7.1	6
	Number of members of cultural promotional organisations per 1000 inhabitants (#)	113	113	128	150

[a] Inhabitants under 5 and over 65 yr of age.
[b] Hospitals, nurseries, schools, homes for elderly people, camp sites, buildings directly involved in crisis management.
[c] Having a warning system reduces the vulnerability: 1 = no warning system; 2 = warning system exists.
[d] Scattered state (bad integration) = 0; gathered state (acceptable integration) = 1; not concerned or full integration into the landscape = 2[e] Sound below the hearing threshold = 1; sound over the hearing threshold = 2[f] Not concerned = 1 Duration in days = 1; weeks = 2; months = 3; years = 4[g] When the views are mostly disputed: −4 = contested over 75 %; −3 = contested from 50 to 75 %; −2 = contested from 25 to 50 %; −1 = contested from 0 to 25 %. When the views are mainly supported: 4 = supported over 75 %; −3 = supported from 50 to 75 %; −2 = supported from 25 to 50 %; −1 = supported from 0 to 25 %. When the majority of the views are undecided: 0.
[h] Based on the overall satisfaction of stakeholders: 1 = 0–25 % of satisfactory opinion concerning the ability of project to respond to their risk management concerns; 2 = 25–50 %; 3 = 50–75 %; 4 = over 75 %.
[i] Financial contribution = (total household expenditures for risk management)/(social group average income).
[j] Wealthy households are better equipped to respond to hazards.
[k] The comparative social risk index indicates the degree of socio-spatial inequality; it calculates the proportion of people in a given social group at risk compared to the total population at risk.
[l] Public amenities, banks, nursery, stores, parks, health care centres, etc.
[m] They were not born in the municipality, or they do not have their cultural and familial roots in the municipality.
[n] The lower the dispersion of residential localisations, the stronger the territorial cultural identity is.
[o] Share of hotel beds capacity lost.

NHESSD
2, 207–259, 2014

Table A4. Environmental sustainability.

Indicators	Parameters (units)	Do-nothing	Alter. 1	Alter. 2	Alter. 3
Impact on environmental vulnerability	Landscape within the hazardous area (km^2)	2.4	2.4	2.4	1.6
	Specially protected areas within the hazard prone area (km^2)				
	Potentially endangered natural areas (km^2)	1.3	1.3	1.5	0.9
	Endangered species within the hazard prone area (# or %)	4	4	4	5
	Potentially endangered urban green spaces (km^2)	0.5	0.5	0.5	0.5
	Water bodies whose integrity is potentially impacted by the hazard (km^2)	0.8	0.8	1.6	0.6
	Drinking water catchment and pumping stations potentially impacted by the hazard ($m^3 d^{-1}$)	1525	1400	1525	1050
	Sewage treatment plants potentially impacted by the hazard ($m^3 d^{-1}$, BOD5 or PE)	2300	2300	2450	2100
	Solid waste treatment plants potentially impacted by the hazard (t/day)	5500	5160	5830	5600
	Solid waste potentially produced by the disaster related to the hazard (t)	56	40	49	40
	Plants using substances that are potentially dangerous to the environment within the hazard prone area (#)	6	6	6	3
	Polluted sites and soils within the hazard prone area (# or km^2)	0.6	0.6	0.6	0.6
Environmental impacts	Global warming: greenhouse gas emissions (kg CO_2 – eq)	2.4	2.7	6.5	3.9
	Eutrophication (kg PO_4 – eq)	4.7	4.7	5	8.8
	Photochemical smog (t C_2H_2 – eq)	1.8	1.2	3.9	3.2
	Human toxicity (kg 1,4-DichloroBenzene – eq or DALY)	6.2	6.1	8.5	6.4
	Land transformation and use ($km^2 yr^{-1}$)	1.1	1.1	1.6	2
	Terrestrial and aquatic eco-toxicity (kg 1,4-DichloroBenzene – eq)	3.5	3.8	6.1	3.1
	Acidification (kg SO_2 – eq)	3.3	3.3	3.3	3.3
	Water resource depletion (m^3)	5.4	6.2	8.3	5.4
	Fossil fuel and abiotic resource depletion (MJ or kg Sb – eq)	2.7	2.5	5.3	3.2
	Particulates (kg PM_{10})	2.1	1.9	5.7	5.1

NHESSD
2, 207–259, 2014

Table A5. Institutional sustainability.

Indicators	Parameters (units)	Do-nothing	Alter. 1	Alter. 2	Alter. 3
Flexibility/Reversibility (#, 1 to 4) [a]	–	1	3	3	4
Public participation in risk management process	Information/Transparency: share of stakeholders that have a correct understanding of the option details including the possible impacts and envisaged mitigation measures (%)	36	60	28	59
	Consultation: share of stakeholders that consider this project consensual (mutual recognition of interests) (%)	27	55	27	20
Compatibility with the territory sustainable development policies (#, −2 to 2) [b]	–	1	2	2	1
Territorial coherence (#, −2 to 2) [b]	–	- 1	2	0	- 1

[a] 1 = technically impossible; 2 = partial removal with high decommissioning costs/efforts; 3 = partial removal with low decommissioning costs/efforts or full removal with high decommissioning costs/efforts; 4 = full removal with low decommissioning costs/efforts.
[b] −2 = conflict of aims; −1 = mainly negative contribution with some supportive aspects; 0 = neutral impacts to the sustainable development priorities; 1 = compatible with some aims conflicting with sustainable development policies objectives; 2 = highly compatible.

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

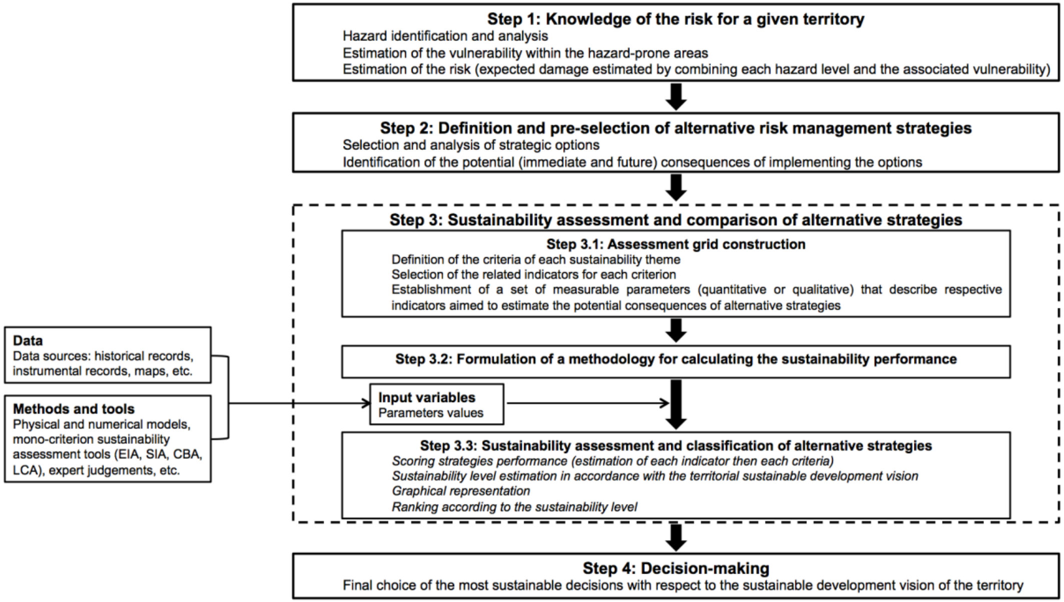


Fig. 1. Theoretical overview of the decision-making process for sustainable risk management (source: authors).

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

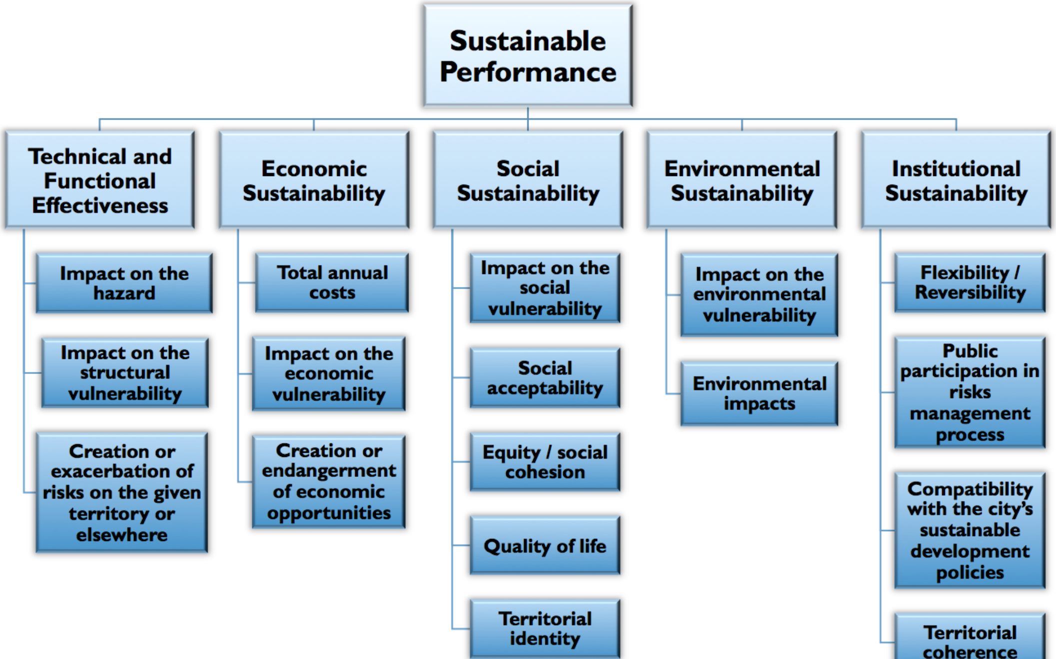


Fig. 2. Hierarchical structure of the sustainability assessment grid (source: authors).

NHESSD
2, 207–259, 2014

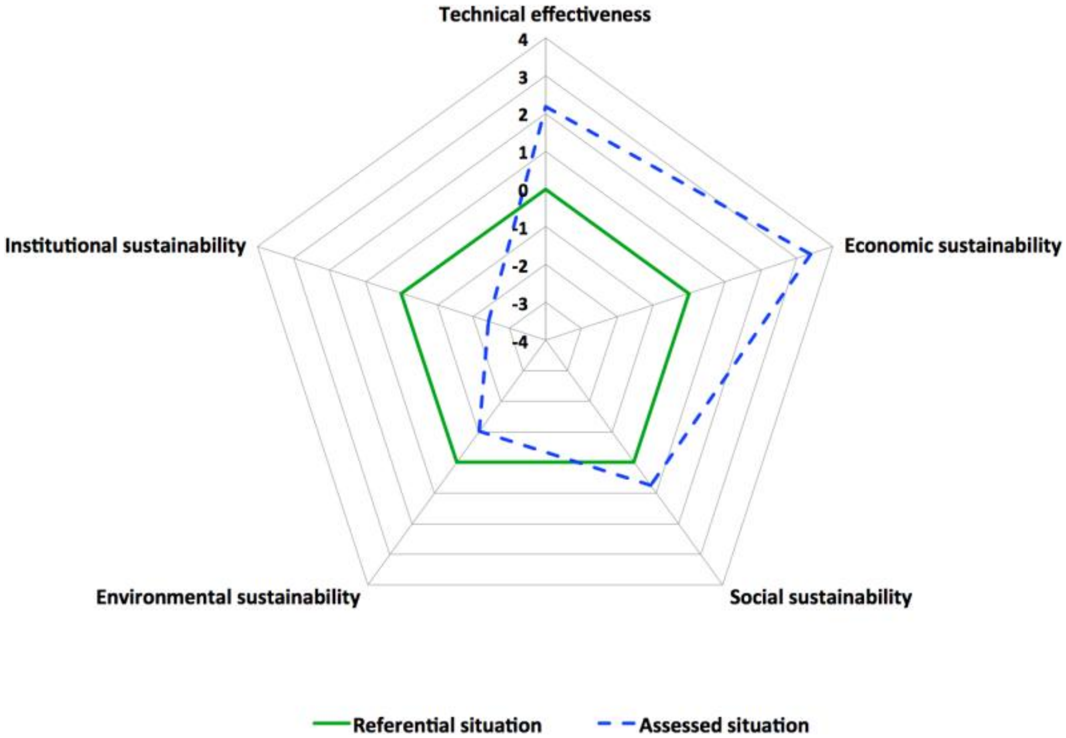


Fig. 3. General spatial representation of the sustainability profile (source: authors).

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

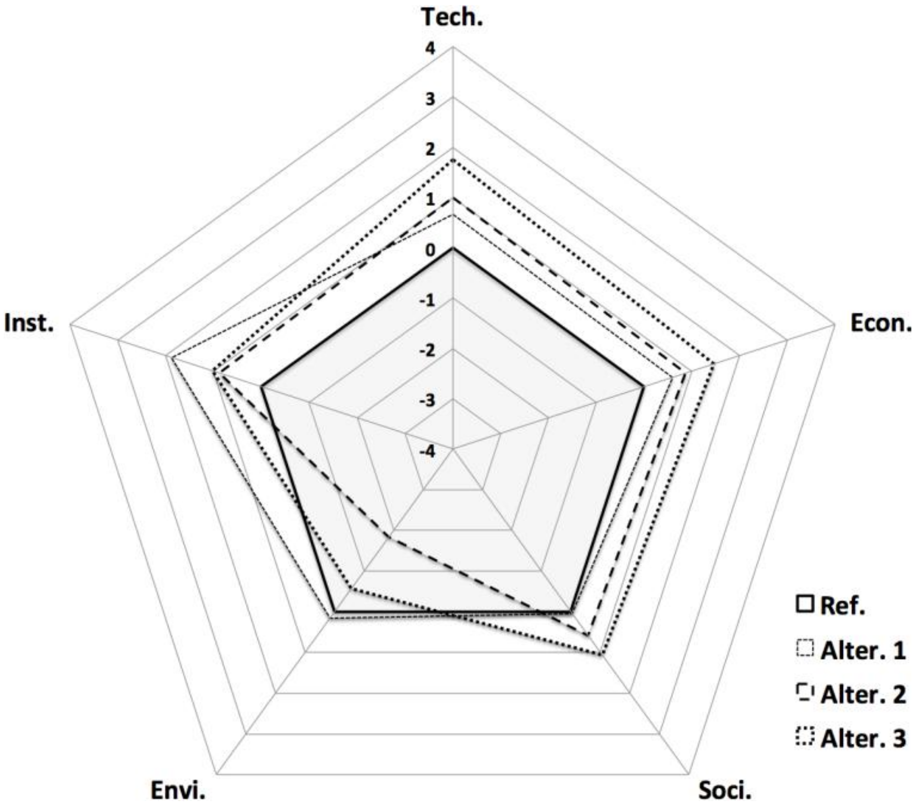


Fig. 4. Graphical comparison of the sustainability profiles (source: authors).

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.

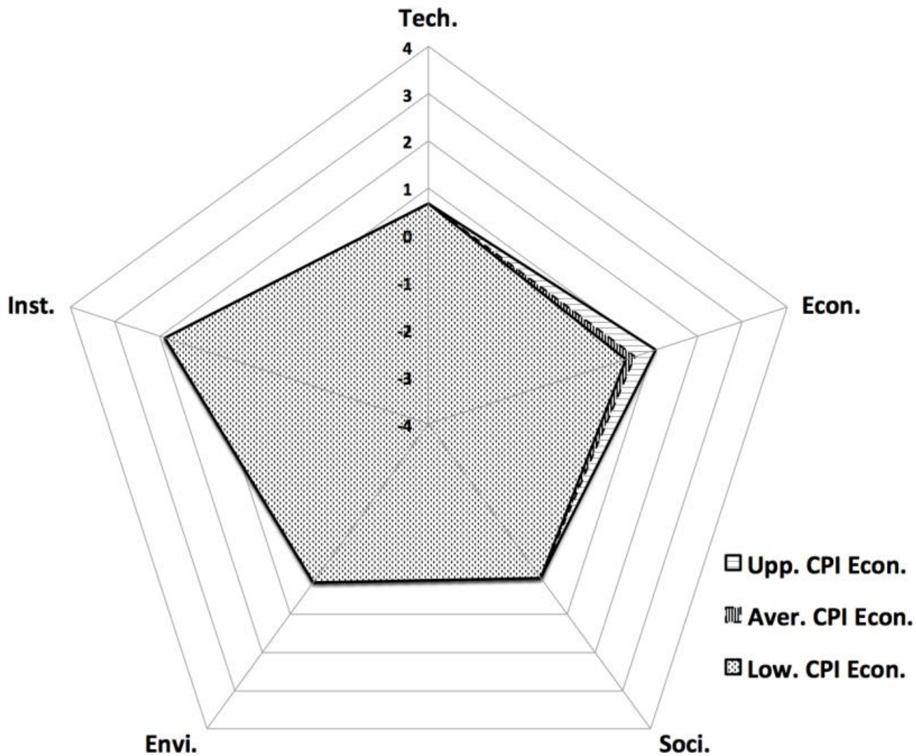


Fig. 5. Sustainability profile under uncertainty (source: authors).

NHESSD
2, 207–259, 2014

A decision-supporting methodology

A. M. Edjossan-Sossou et al.