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Analysing the cascades of uncertainty in flood defence projects: How "not knowing enough" is related to "knowing differently"

Ronald E. van den Hoek [a,*], Marcela Brugnach [a], Jan P.M. Mulder [a,b], Arjen Y. Hoekstra [a]

[a] University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE Enschede, The Netherlands
[b] Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands

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ABSTRACT

It is increasingly recognized that uncertainty concerns more than statistical errors and incomplete information. Uncertainty becomes particularly important in decision-making when it influences the ability of the decision-makers to understand or solve a problem. While the literature on uncertainty and the way in which uncertainty in decision-making is conceptualized continue to evolve, the many uncertainties encountered in policy development and projects are still mostly represented as individual and separated issues. In this paper, we explore the relationship between fundamentally different uncertainties – which could be classified as unpredictability, incomplete knowledge or ambiguity – and show that uncertainties are not isolated. Based on two case studies of ecological engineering flood defence projects, we demonstrate that important ambiguities are directly related to unpredictability and incomplete knowledge in *cascades of interrelated uncertainties*. We argue that conceptualizing uncertainties as cascades provides new opportunities for coping with uncertainty. As the uncertainties throughout the cascade are interrelated, this suggests that coping with a particular uncertainty in the cascade will influence others related to it. Each uncertainty in a cascade is a potential node of intervention or facilitation. Thus, if a particular coping strategy fails or system conditions change, the cascades point at new directions for coping with the uncertainties encountered. Furthermore, the cascades can function as an instrument to bridge the gap between actors from science and policy, as it explicitly shows that uncertainties held relevant in different arenas are actually directly related.

1. Introduction

Sea level rise due to climate change is a major concern for many countries around the world and calls for adaptive management of coastal zone areas (Nicholls and Cazenave, 2010) and coastal ecosystems (Thom, 2000), in order to create social–ecological resilience to coastal disasters (Adger et al., 2005). Regarding coastal protection, ecological engineering – the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both (Mitsch and Jørgensen, 2003) – seems to be a promising approach towards a sustainable future, as the feasibility of multiple alternative strategies is being researched (see Borsje et al., 2011 for a review). A prominent example of ecological engineering for coastal protection purposes is Building with Nature (BwN), a Dutch water management approach that aims to utilize natural dynamics (e.g., wind and currents) and natural materials (e.g., sediment and vegetation) for the realization of effective flood defences, while providing opportunities for nature development (De Vriend and Van Koningsveld, 2012). The basic philosophy of this approach is not exclusive for the Netherlands. The paradigm of water management is slowly changing from command-and-control approaches – hard engineering approaches emphasizing on reducing uncertainties and designing systems that can be predicted and controlled (Holling and Meffe, 1996) – towards more nature-inclusive approaches (Pahl-Wostl et al., 2011) and the use of natural dynamics in water management projects receives increasing international follow-up. Initiatives such as the Working with Nature approach of PIANC and the Engineering with Nature approach of the US Army Corps of Engineers are based on philosophies similar to the Building with Nature approach (Van Slobbe et al., 2013).

Although projects based on BwN design principles appear to foster the natural environment of the coastal zone in which they are implemented, a potential drawback of this ecological engineering concept is that the use of natural dynamics adds inherent uncertainty and ecological complexity to the designs created (Bergen et al., 2001). As weather conditions are

* Corresponding author. Tel.: +31 53 489 1013
E-mail address: r.e.vandenhoek@utwente.nl (R.E. van den Hoek).

unpredictable and our knowledge about natural system behaviour is incomplete, the outcomes of a BwN project are far from certain on beforehand. However, the uncertainties encountered during the development of a promising BwN project do not exclusively originate from shortcomings or inadequacies in the knowledge base. While the active involvement of local stakeholders is regarded as beneficial in order to come to better BwN solutions (De Vriend and Van Koningsveld, 2012), these stakeholders might have rather different or even conflicting views regarding the project. This can easily lead to ambiguity, a fundamentally different kind of uncertainty originating from the presence of too many possible interpretations of a situation (Weick, 1995). In previous research, Van den Hoek et al. (2012) found that ambiguity about the social implications of BwN projects is far more important for decision-making than uncertainty about the behaviour of the natural dynamics or the natural system, since these ambiguities could potentially hamper the project development process. Moreover, as time and spatial scales are not fixed in BwN projects, unanticipated developments can be expected at any moment. This suggests that, instead of a standard rigid uncertainty management plan, these dynamic projects require an uncertainty management approach that can be adapted to changing conditions.

While it is important to make a distinction between incomplete knowledge, unpredictability and ambiguity – because their nature is fundamentally different – they are not independent in the context of BwN projects (Van den Hoek et al., 2012). However, it is not fully clear what kind of relationship between different uncertainties exists. Even though the existence of such a relationship could be perceived as yet another complexity in an already complex field, it might also provide major benefits in the form of unexplored approaches to cope with interrelated uncertainties in water management projects. This is important because, in multi-actor decision-making processes, uncertainties that have a different nature normally require fundamentally different coping strategies (Walker et al., 2003; Van der Keur et al., 2008; Kwakkel et al., 2010; Brugnach et al., 2011). Common responses to cope with incomplete knowledge and unpredictability in decision-making are to acquire more information, e.g., by performing additional research and consulting experts, or to increase the top-down control over the process, e.g., by limiting the number of participants and centralizing the decision authority (Koppenjan and Klijn, 2004), but such strategies are unfit to solve a situation of ambiguity (Brugnach et al., 2011). However, if different uncertainties are interrelated, this situation might change since it suggests that coping with a particular uncertainty will influence those with which it is related. For instance, successfully coping with a particular situation of incomplete knowledge might influence an ambiguity with which it is related in a positive way.

In this paper, our objective is to explore the relationship between different uncertainties. To this end, we combine the relational approach to uncertainty of Brugnach et al. (2008) with theory on cascades of uncertainty from climate change literature in order to elucidate new ways for coping with uncertainty. We aim to illustrate that those managing a project can benefit from the relationship between different uncertainties in order to adaptively manage uncertainty in initiatives such as BwN projects. Therefore, we study two BwN pilot projects (namely, the Safety Buffer Oyster Dam and the Sand Engine case), identify several *cascades of interrelated uncertainties* and address how these cascades were managed.

This paper is structured as follows. First, we discuss the relational approach to uncertainty that we adopt and address our method for describing relations between different uncertainties (Sections 2 and 3). Second, we discuss our two case study projects, identify the most important uncertainties for each project and the uncertainties related to them, and describe how the project team managed these uncertainties during project development (Sections 4 and 5). Third, we discuss the characteristics of the cascades of interrelated uncertainties and the implications of our findings for uncertainty management (Section 6). In the last section, we present our main conclusions.

2. Theoretical concepts

2.1. Adopting a relational approach to uncertainty

We adopt the approach to uncertainty of Brugnach et al. (2008) that addresses the topic from a relational point of view, paying particular attention to how an actor (e.g., a decision-maker) relates to a problem situation he or she is to decide upon. Much can be uncertain regarding the characteristics of this problem, its possible solutions and the knowledge available about the system under consideration. However, this uncertainty has no particular significance or meaning for an actor involved in the decision-making process, until it leads to a situation in which it influences his or her ability to determine what the problem is or which action path to pursue. For example, in river basin management, uncertainty about the runoff of the river basin in itself may not be of importance for a decision-maker. However, when this decision-maker has to decide about raising the dikes along the river, he or she may become concerned about the characteristics of the river basin. As data about runoff is essential knowledge to come to an informed decision concerning the dikes, the uncertainty about this characteristic of the river basin now becomes significant and acquires meaning for the decision-maker. In short, an uncertainty has no meaning in itself, but acquires meaning when the decision-maker establishes a knowledge relationship with the system he or she aims to manage. Thus, uncertainty refers to *the situation in which there is not a unique and complete understanding of the system to be managed.*

According to the adopted conceptualization, uncertainty can originate from incomplete knowledge, unpredictability or ambiguity (Fig. 1). Incomplete knowledge and unpredictability are recognized by many authors in the literature (see Van Asselt, 2000

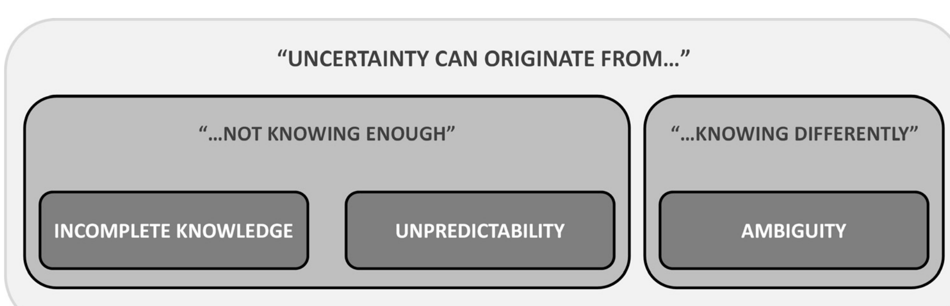

Fig. 1. Schematization of the adopted uncertainty conceptualization.

or Walker et al., 2003 for a review). Incomplete knowledge originates from the imperfection of our knowledge, which may be reduced by additional research. It concerns what *we do not know* at this moment, but might know in the future if sufficient time and resources are available to perform additional research or collect more data. For instance, data might be imprecise but could be improved by more accurate measurements or model predictions could be improved by developing better models. Unpredictability is caused by the inherent chaotic or variable behaviour of, e.g., natural processes, human beings or social processes. Thus, it is different from incomplete knowledge: unpredictability concerns what *we cannot know* and therefore cannot be fully reduced by doing more research.

Ambiguity is an uncertainty of a different kind, as it is not about what we do not or cannot know: it is about actors *knowing differently*. Ambiguity refers to the situation in which there are different and sometimes conflicting views on how to understand the system to be managed (Dewulf et al., 2005; Brugnach et al., 2008; Renn et al., 2011). Actors can differ about how to understand the system, e.g., about where to put the boundaries of the system or what and whom to put as the focus of attention, or they can differ in the way in which the information about the system is interpreted, e.g., about what the most urgent problems are (Brugnach et al., 2008). Even though all three kinds of uncertainty refer to what a decision-maker knows about the system, their nature is very different. While the relevant dimension of incomplete knowledge and unpredictability ranges from complete deterministic knowledge to total ignorance (Walker et al., 2003, 2010), the relevant dimension of ambiguity is something ranging from unanimous clarity to total confusion caused by too many people voicing different sensible interpretations (Dewulf et al., 2005).

Furthermore, the adopted relational approach to uncertainty distinguishes between three different parts of the system to be managed in which uncertainty can be present. Uncertainty in the natural system concerns aspects such as climate impacts, water quantity, water quality and ecosystems. Uncertainty in the technical system concerns technical elements and artefacts that are deployed to intervene in the natural system. Uncertainty in the social system concerns economic, cultural, legal, political, administrative and organizational aspects. Although it is useful to make this distinction as it supports decision-makers to structure their knowledge, it is important to acknowledge that the natural, technical and social system are all closely interrelated and interdependent. The integration of human and natural systems – which the BwN philosophy actively pursues by using natural dynamics as a ‘technological instrument’ – implies that the reciprocal relationship of human–nature interactions is explicitly acknowledged, recognizing that each human action will be followed by responses from the natural system and vice versa (Liu et al., 2007).

As the natural, technical and social parts of the system are related (Fig. 2), we argue that an uncertainty can concern more than just one of these subsystems. Uncertainties in the areas 1, 2 and 3 mainly concern only a single subsystem, either the natural, technical or social one. However, an uncertainty can also concern both the natural and technical system (area 4), the technical and social system (area 5) or the natural and social system (area 6). For instance, knowledge about the effects of a particular technology on an ecosystem might be incomplete (hence: in area 4), the uncertain impact of a technology can be interpreted from a societal perspective (hence: in area 5) or an unpredictable natural phenomenon might influence a human activity (hence: in area 6). In all these examples, the uncertainty at hand cannot be clearly classified in one of the subsystems as there is no clear and transparent distinction possible. Finally, some uncertainties can concern all subsystems (area 7). For example, uncertainty about which technology to apply in a flood defence project (e.g., a command-and-control or a BwN approach) also has implications for both the natural system and social activities (hence: classify in area 7).

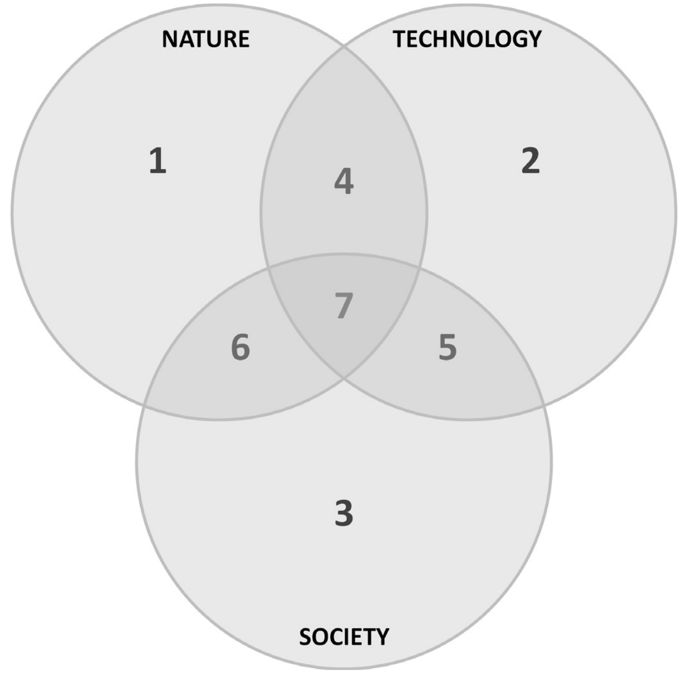

Fig. 2. Schematization of the system to be managed and its different parts.

2.2. The cascade of uncertainty

Several scholars have acknowledged that there can be a causal relationship between different uncertainties. For example, in the context of international business, Miller (1992) states that it is a shortcoming that the risk and uncertainty literature mostly focus on individual uncertainties and calls for taking a multi-dimensional perspective of interrelated uncertainties. In health care literature, Hines (2001) argues that in cases when facing serious illness, efforts to find an effective intervention strategy should account for the interrelatedness of multiple uncertainties. Van Asselt (2000) explicitly mentions the relationship between incomplete knowledge and unpredictability, stating that the former can originate from the latter. Furthermore, in the context of modelling (e.g., Draper, 1995) and sensitivity analysis (e.g., Saltelli, 2000), uncertainty propagation is often described: the phenomenon that uncertainty in the input variables and parameters of a model propagates to an even larger uncertainty in the output of the model.

Although several authors mention that there can be a relationship between different uncertainties, there is only limited attention for how ambiguity is related to other uncertainties. Warmink et al. (2010) discuss uncertainty in environmental models and show that a particular uncertainty can often be broken down in several more specific uncertainties (either incomplete knowledge, unpredictability and/or ambiguity). Regarding model-based environmental decision-making, Van der Sluijs et al. (2005) remark that uncertainty in the knowledge base and differences in framing of the problem are interrelated aspects. More specifically, Van der Sluijs (2012) mentions that ambiguous knowledge assumptions and ignorance can lead to uncertainty in the knowledge base. However, it remains rather unclear what the implications of such a relationship would be.

In climate change studies, the process of uncertainty propagation – in translating global climate change predictions into regional scenarios and eventually impact assessments – has been described as the cascade of uncertainty or the uncertainty explosion (Schneider, 1983; Henderson-Sellers, 1993; Mitchell and Hulme, 1999; Jones, 2000; Schneider and Kuntz-Duriseti, 2002; Wilby and Dessai, 2010; Refsgaard et al., 2012). For example, climate predictions – which are highly uncertain due to our limited understanding of the climate system – describe an expected range of temperature increase and sea level rise over a specific period. Although these predictions can be used as input in, for instance, a coastal development model, the use of the model will accumulate the uncertainty as it is a simplified representation of reality. As a result, the uncertainty in the model outcomes is probably larger than the uncertainty in the input data. Decision-makers using the model outcomes to develop robust adaptation measures will probably propose solutions with major safety margins that are larger than the original climate input data would have required. Hence, this example illustrates that the incomplete knowledge or unpredictability in the input of the model is gradually amplified throughout the described cascade.

3. Methods

In this paper, we combine the relational approach to uncertainty of Brugnach et al. (2008) with the theory on the cascade of uncertainty from climate change literature, in order to describe *cascades of interrelated uncertainties*, expressing the relationship between different uncertainties in projects based on BwN design principles. We use the structure of Fig. 2 to visualize these uncertainty cascades, in order to illustrate that uncertainties can concern several parts of the human–technology–nature system.

For this research, we used several data collection methods. For the Safety Buffer Oyster Dam project (Section 4), first, we attended meetings of the project's knowledge development team in March 2012 and the sounding board – consisting of stakeholders – in April 2012. Whereas the meeting of the knowledge team was recorded and transcribed, the sounding board meeting could not be recorded but minutes were made. For both meetings, we studied the data to identify important uncertainties, discussion themes and stakeholder issues in the Safety Buffer project. Second, we conducted four interviews with main project actors (performed by two interviewers) and nine interviews with stakeholders (performed by one interviewer) in July, August and September 2012. During three of these interviews, two respondents were interviewed instead of one. Thus, in total, we spoke to six main project actors (three at the executive and three at the project level) and ten stakeholders. The semi-structured interviews were conducted in the Dutch language, took about 1 h, and were recorded and transcribed. Two interview protocols (one for the project actors and one for the stakeholders) with up to fourteen open-ended main questions were used as a guide and checklist during the interviews. During the interviews, the interviewees were invited to elaborate on those project topics that were most important for them, but that also caused the hardest discussions within the project. During the course of the interviews, several uncertainties regarding the discussed project topics were explicitly or implicitly mentioned.

For the Sand Engine project (Section 5), we used two main data collection methods. First, three public information meetings were attended, during which stakeholders and the general public had the opportunity to pose critical questions, express their appreciation or concerns about the project and to file complaints. We made minutes of these meetings, and used these to identify important uncertainties and to understand the diverging viewpoints regarding the project. Second, in April and May 2011, we interviewed three (former) members of the project team, one member of the project steering group and two experts – involved in the Environmental Impact Assessment (EIA) and modelling – about the most important uncertainties encountered during project development, how these could have hampered the project and how the uncertainties were coped with. In the period from May until November 2012, we performed three additional interviews to acquire specific information about the Sand Engine's recreational safety situation. The interviewees were invited to elaborate on the safety measures regarding recreation, the reasons why measures were changed and which specific uncertainties were coped with. The semi-structured interviews were conducted in the Dutch language, took between one and two hours, and were recorded and transcribed. Two interview protocols (one for the 2011 interviews and one for the 2012 interviews) with up to ten open-ended main questions and several follow-up questions were used as a guide and checklist during the interviews.

For both cases, we identified multiple uncertainties from the interview transcriptions and minutes, and used available project documentation and communication as additional material. Furthermore, we consulted interviewees or other project actors to acquire additional specific information if needed. The uncertainties identified were first classified according to the uncertainty typology discussed in Section 2.1. Thereafter, we assessed which uncertainties were perceived as most important by the interviewees by considering two aspects: the uncertainty's potential impact and its project-wide relevance for the actors. During the interviews, we invited the interviewees to elaborate on the impact an uncertainty could have on the project's development process (e.g., can it lead to substantial cost overrun, a substantial delay or even project cancellation?). Thus, we were able to assess whether an uncertainty was important (e.g., potentially leading to a significant budget increase of €500,000) or not (e.g., only leading to a delay of 1 day). Moreover, after finalizing the series of interviews and meetings, we assessed during which interviews and meetings a particular uncertainty was brought up. If an uncertainty was brought up during several interviews and meetings, this clearly implies that it has a project-wide relevance according to multiple actors and is not just the 'favourite subject' of one actor.

The uncertainties that were perceived as most important by the interviewees all appeared to be ambiguities, because these were most frequently mentioned and potentially could have had a major impact on the project's development process. Therefore, we used these ambiguities as the basis of our analysis. Inspired by causal loop diagrams, for each ambiguity, we traced other uncertainties (either incomplete knowledge, unpredictability or ambiguity) with which it is related, both directly and more indirectly. Thus, we identified several cascades of interrelated uncertainties that were of major importance in our case study projects. In the figures we use to present the cascades (see Fig. 3 for an example), black arrows express that an uncertainty is related to another uncertainty. Furthermore, for each uncertainty, colours indicate if the uncertainty dominantly concerns unpredictability (green), incomplete knowledge (blue) or ambiguity (red). Finally, we compared the cascades to address their similarities and differences and to elaborate what our findings suggest regarding uncertainty management.

4. Case study I: Safety Buffer Oyster Dam

4.1. Case study description

The Oyster Dam is a compartment work located in the Eastern Scheldt estuary. With a total length of approximately 10.5 km, it is

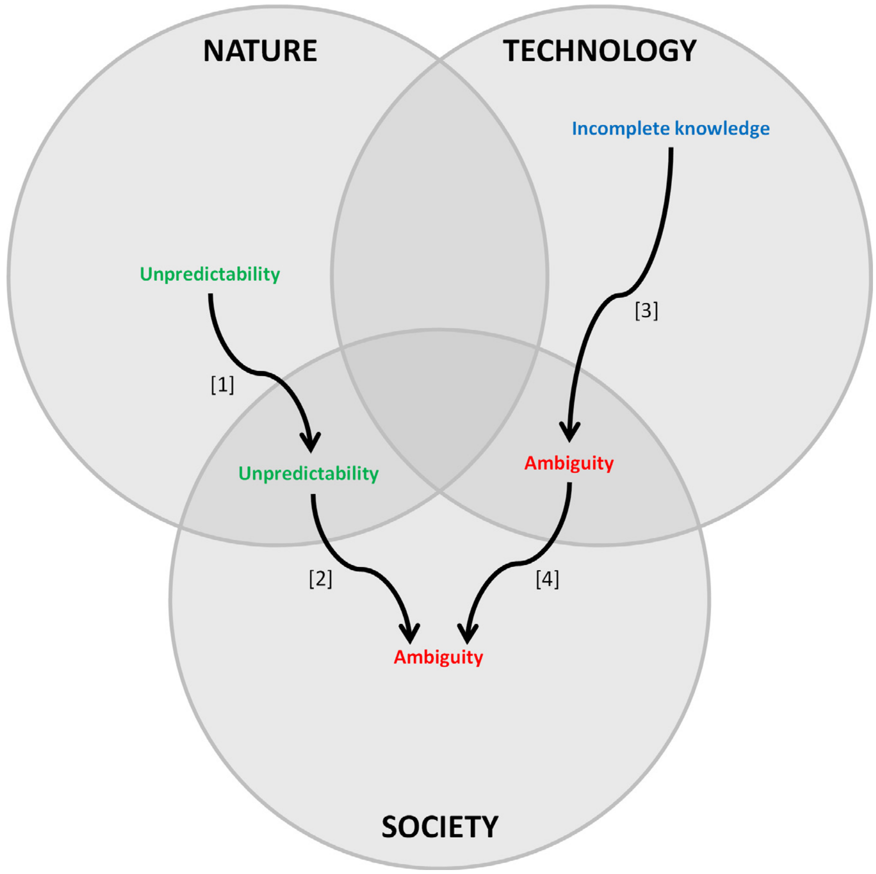

Fig. 3. Example of a cascade of interrelated uncertainties. Text colours represent the kind of uncertainty: incomplete knowledge (blue), unpredictability (green) and ambiguity (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the longest dam of the so-called Delta Works which were implemented as a response to the dramatic flooding of the South-Western delta of the Netherlands in 1953. Along with flood protection for the hinterland, one of the Oyster Dam's main functions is to decrease the total area of the estuary in order to increase the tidal difference of ebb and flood tide that had dropped after construction of the Eastern Scheldt Storm Surge Barrier. While this storm surge barrier is a key flood protection work as it closed off the Eastern Scheldt estuary, it also reduced the tidal movement in the estuary by approximately 25% (Mulder and Louters, 1994; Vranken et al., 1990). Due to the construction of the Oyster Dam and the Philips Dam – another compartment work in the estuary – the tidal difference decrease was limited to approximately 10% compared to the tidal difference before the construction of the Eastern Scheldt Storm Surge Barrier (Eelkema et al., 2012; Mulder and Louters, 1994). Furthermore, the inflow of additional sediment from the North Sea into the water system of the Eastern Scheldt is negligible due to the storm surge barrier, while the distribution of sediment towards the estuary's channels remains constant. This imbalance between the Eastern Scheldt morphology and hydrodynamics leads to an internal redistribution of sediments, causing the erosion of the existing salt marshes and mudflats, and thus the loss of valuable ecological habitat and natural foreshore protection. Hitherto, this so-called Sand Hunger problem remains unsolved.

The Safety Buffer Oyster Dam pilot project (in Dutch: Veiligheidsbuffer Oesterdam) is a sand nourishment of 425.000 m^3 in front of the Oyster Dam – spread over a length of approximately 2 km – to reduce future maintenance efforts, while simultaneously restoring one of the eroded tidal flats to its historical state (see Fig. 4 for a map). Additionally, an erosion-preventing artificial oyster reef is planned to be constructed north of the nourishment area. The sand required for the nourishment operations will be mined by dredging ships at the locations Wemeldinge (14 km from the nourishment location) and Lodijksche Gat (8 km from the nourishment location). The Safety Buffer project is a distinct example of the application of BwN design principles: both the nourishment and the reef aim to cope with the effects of the Sand Hunger problem by using natural materials and dynamics, while concurrently strengthening the foundation of the existing compartment work.

At the moment, the actual nourishment works are expected to start after the summer of 2013. Nevertheless, a successful outcome of the pilot project has been far from certain. The initiative is developed by an unusual coalition, formed by two Dutch governmental agencies and a non-governmental professional environmental interest organization. Each organization draws from its own basic interests, cultures and working procedures during the course of this specific project development process. Furthermore, the project development team invited stakeholders potentially affected by the initiative to participate in the development process. However, not every stakeholder in the project area was spontaneously willing to commit or contribute to the proposed plans.

4.2. Results

4.2.1. Sand mining

We identified important cascades of interrelated uncertainties regarding the impact of the Safety Buffer project's sand mining activities and the preferred location for these activities. First, cascade [5]–[6]–[7] in Fig. 5 concerns the small-scale professional

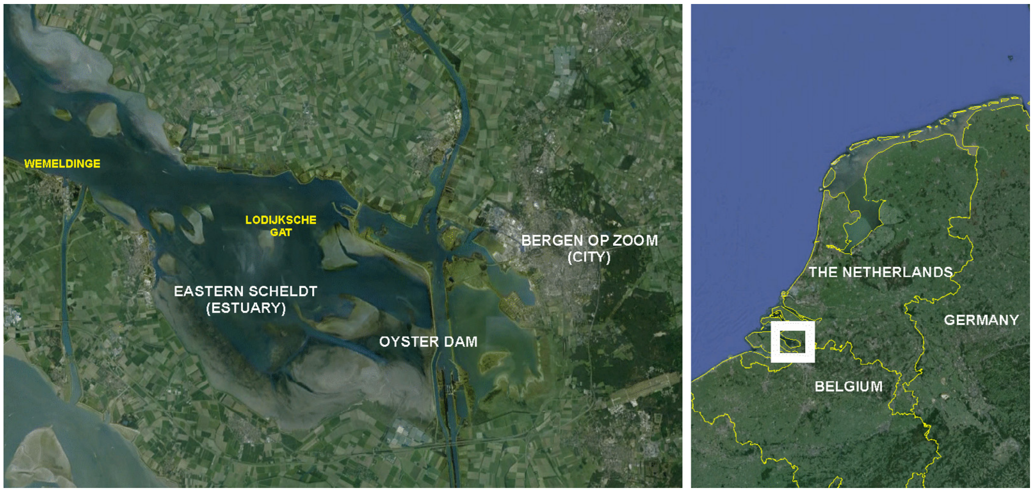

Fig. 4. Location of the Oyster Dam and Eastern Scheldt estuary in the Netherlands.
Source: Google Earth.

fishermen, for whom the sand mining area loses a major part of its economic attractiveness as the fish habitat is disturbed. Although the uncertainty is rather low – it is clear enough that a large part of the nutrients in the upper layer of the estuary bed will disappear due to the mining activities – it remains unclear to what extent the fish population will be influenced. Second, for the shellfish industry (cascade [1]–[2]–[3]–[4] in Fig. 5), the sand mining activities could have an indirect, unpredictable financial impact. Dredging usually causes the formation of a plume of suspended sediment, which can have negative impacts on fish and shellfish (Wilber and Clarke, 2001). Under specific weather and tidal conditions, this plume could drift off towards cultivated shellfish beds and cover these beds under a suffocating layer of sediment. Furthermore, the plume could cover the nutrient-rich upper layer of a highly populated fish habitat near the mining area.

The shellfish and fishing sector had a specific view regarding the sand mining activities and preferred a sand mining location with only a minor probability of undesired suspended sediment transport towards their (shell)fish areas. Furthermore, they demanded that mining activities only take place during low tide. The project team acknowledged the stakeholder concerns and invited both sectors to participate in the search for an appropriate

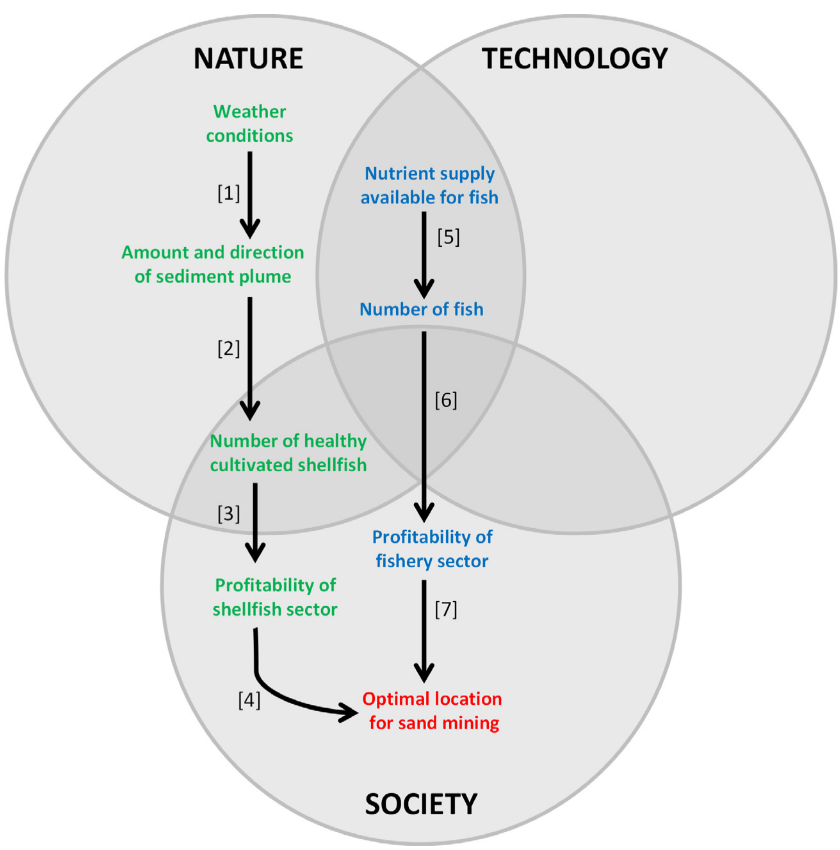

Fig. 5. Cascade of uncertainty regarding the impact of Safety Buffer sand mining on the (shell)fish sector. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sand mining location. During this process, several alternative locations were proposed and rejected. In the end, all participants agreed on the locations Wemeldinge and Lodijksche Gat. Furthermore, it was agreed that the sand mining activities will only take place during favourable tidal and weather conditions and impacts will be monitored extensively.

4.2.2. Sand nourishment

Regarding the sand nourishment activities, we identified three important cascades of interrelated uncertainties. First, similar to the sand mining activities, the nourishment could have negative – but yet unpredictable – financial consequences for the shellfish industry (Fig. 6). After the nourishment is completed, it is expected that the nourished tidal flat will slowly erode over time. However, on the short term, it is unpredictable how the eroded sediment will behave as this depends on the weather conditions. Potentially, the suspended sediment could flow towards cultivated shellfish beds in the vicinity of the nourishment area, on which it can have an adverse impact. While the oyster sector interpreted the project as a potentially harmful development, the mussel sector was rather certain that no adverse impacts will be experienced. The project team aims to assure the interests of the shellfish sector by formulating the boundary conditions that (1) the Safety Buffer is not allowed to have any negative effects on stakeholders and (2) all unforeseen damage has to be fully compensated.

To establish a successful development process, the project team invited all relevant stakeholders during the first steps of the project to participate. However, for indistinct reasons, the oyster sector did not participate – although they were invited for all relevant meetings and received all project documentation – and started opposing the project through the regional media and the regional political arena. In the end, representatives of the project team and the oyster sector had a meeting, negotiated that the initial Safety Buffer design would be discarded and jointly developed a new design. Furthermore, the actors agreed that the impacts of the initiative will be monitored extensively.

The second uncertainty cascade (Fig. 7) concerns the supposed financial consequences of the sand nourishment activities for some local fishermen, who have fishing grounds located north of the nourishment area. As the nourishment partially takes place on these fishing grounds, there is no doubt that a part of this area will – at least temporarily – disappear and become unfit for commercial activities. However, as these specific fishing grounds have not been used for over 10 years, it can be argued that the fishermen will not be financially damaged due the project. Therefore, it might not be needed to compensate for this area loss. However, due to unpredictable societal events – such as economic surprise or changes in the spatial use of the estuary – it might become necessary for the fishermen to recommence the use of these specific fishing grounds. To prevent problems in the project development process, the project team involved the fishermen in the creation of the plans and offered them a compensating area.

The third cascade concerns the effects of the sand nourishment activities on the benthic organisms or benthos (i.e., organisms – such as worms – living on and in the estuarine bed). This issue is interpreted differently by two stakeholders, namely a local environmental interest group and an organization for amateur fishermen. Although nourishments are generally considered an environmental-friendly method for coastal protection and restoration, there are significant negative impacts on the ecosystem in the short- and medium-term (Speybroeck et al., 2006). While the expectation is that most of the benthic organisms currently living in

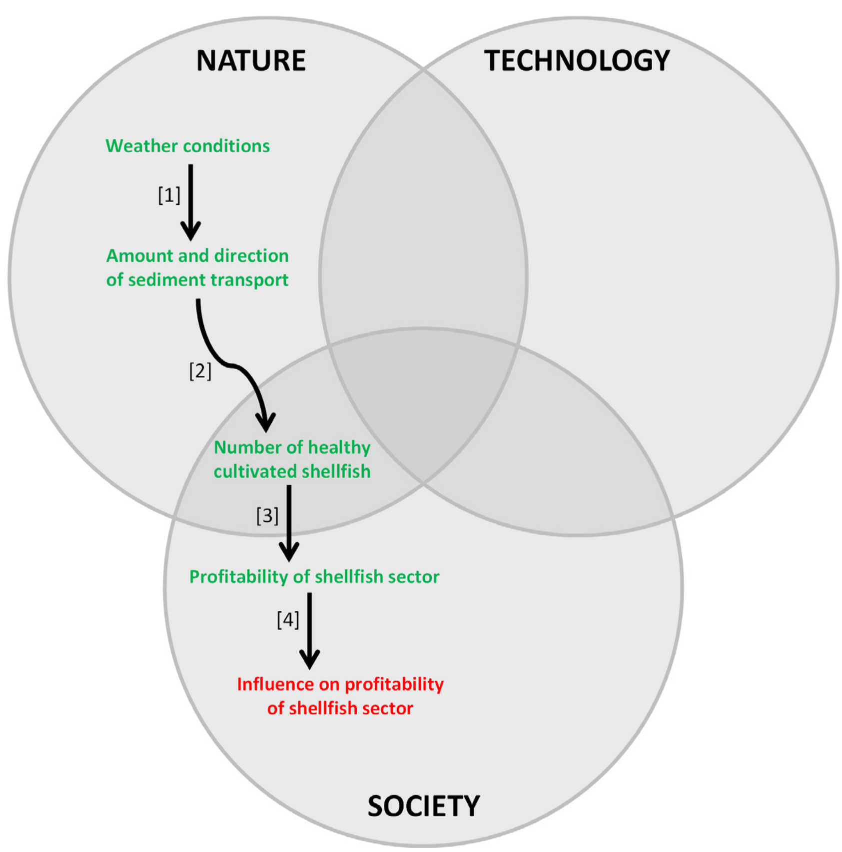

Fig. 6. Cascade of uncertainty regarding the impact of the Safety Buffer nourishment on the shellfish sector. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

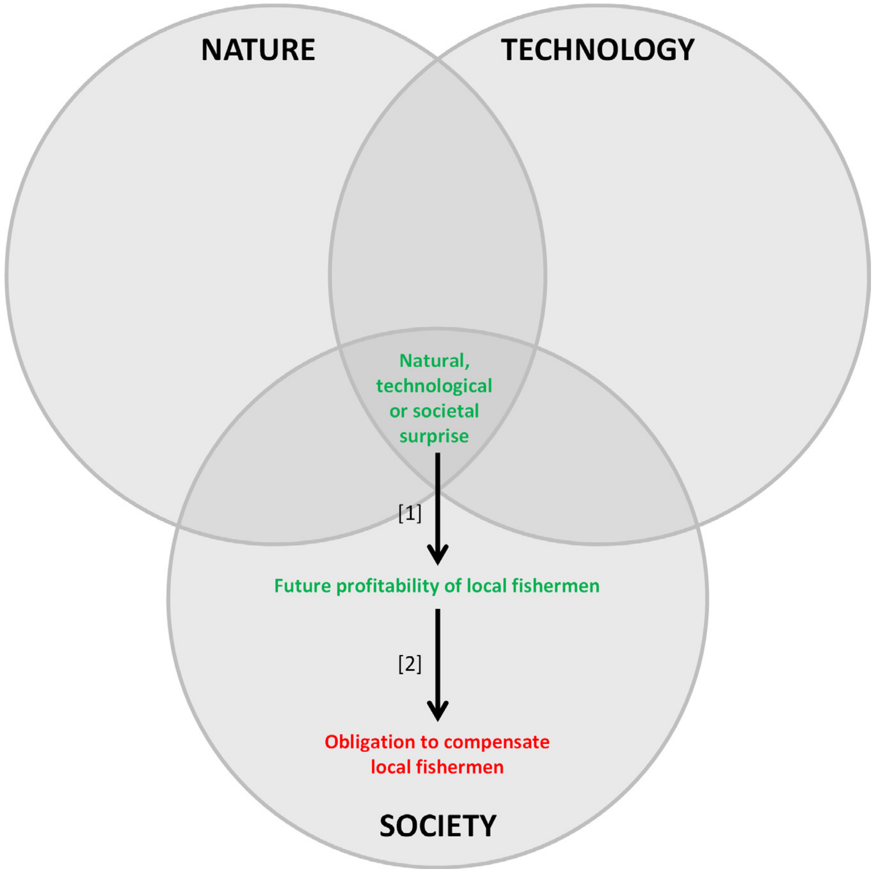

Fig. 7. Cascade of uncertainty regarding the impact of the Safety Buffer nourishment on local fishermen. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the tidal flat will not survive the Safety Buffer nourishment, it is uncertain how quickly the community will recover. For a local environmental interest group, the project was not acceptable given its uncertain impact on the benthos community (cascade [1]–[2] in Fig. 8). Whereas the project team chose an innovative design that only required nourishing half of the existing tidal flat, the environmental interest group believed that the project encompassed a nourishment of the entire flat. As a result, the project team needed to initiate extensive discussions with the environmental interest group to persuade them of the positive intentions of the project. Moreover, the recovery of the benthos community will be monitored.

Differently, an organization that protects the interests of amateur fishermen interpreted the aforementioned issue from a hobby fishing perspective (cascade [3]–[4] in Fig. 8). Specific benthic organisms are used as offshore fishing bait, which is expensive to buy in shops but for free at designated bait extraction areas. Whereas a large-scale nourishment will probably lead to significantly lower bait levels during the first five years after the nourishment, exact estimations are unavailable because bait levels depend on how quickly the benthos community recovers. As the Oyster Dam area is one of the most visited areas for bait extraction, the amateur fisherman organization demanded an alternative area based on their official permit for using the Oyster Dam tidal flat. Although the project team and the amateur fishermen organization jointly examined alternative extraction areas, they disagreed about whether it was legally required to offer an alternative area: the Dutch government is allowed to withdraw the permit for 'water management and safety reasons'.

5. Case study II: Sand Engine Delfland

5.1. Case study description

The sandy Holland coastline continues to erode due to a decreasing amount of sediment from river sources, on-going land subsidence and sea level rise due to climate change. Hence, if the condition of the Holland coast is not attended to, serious flooding problems can be anticipated. In order to cope with the coastal erosion problem, the Dutch government implemented the Dynamic Preservation policy: the sandy coastline has to be maintained at its 1990 position by performing periodic, relatively small-scale, sand nourishments (Hillen and Roelse, 1995). Currently, the annual sand nourishment volume for the Dutch coast has a target value of 12 million m^3/year, while an increase to at least 20 million m^3/year is needed to preserve the sediment balance of the Dutch coast (Mulder et al., 2011).

Sand Engine Delfland (in Dutch: Zandmotor) is an innovative, 21.5 million m^3 sand nourishment pilot project near Ter Heijde in the Dutch province of South Holland (see Fig. 9 for a map). After a project development process of approximately three years, the Sand Engine peninsula was constructed between March and July 2011. It is a large-scale experiment to test the feasibility of mega-sand nourishments, which are anticipated to be more cost-effective and less disturbing for the natural environment due to their long expected lifespan of 20–50 years. The project is based on BwN design principles, as the large amount of sand nourished will spread along the coast by the natural dynamics (waves, currents and wind), thus gradually creating a larger beach area with higher dunes. It is expected that the Sand Engine contributes to coastline

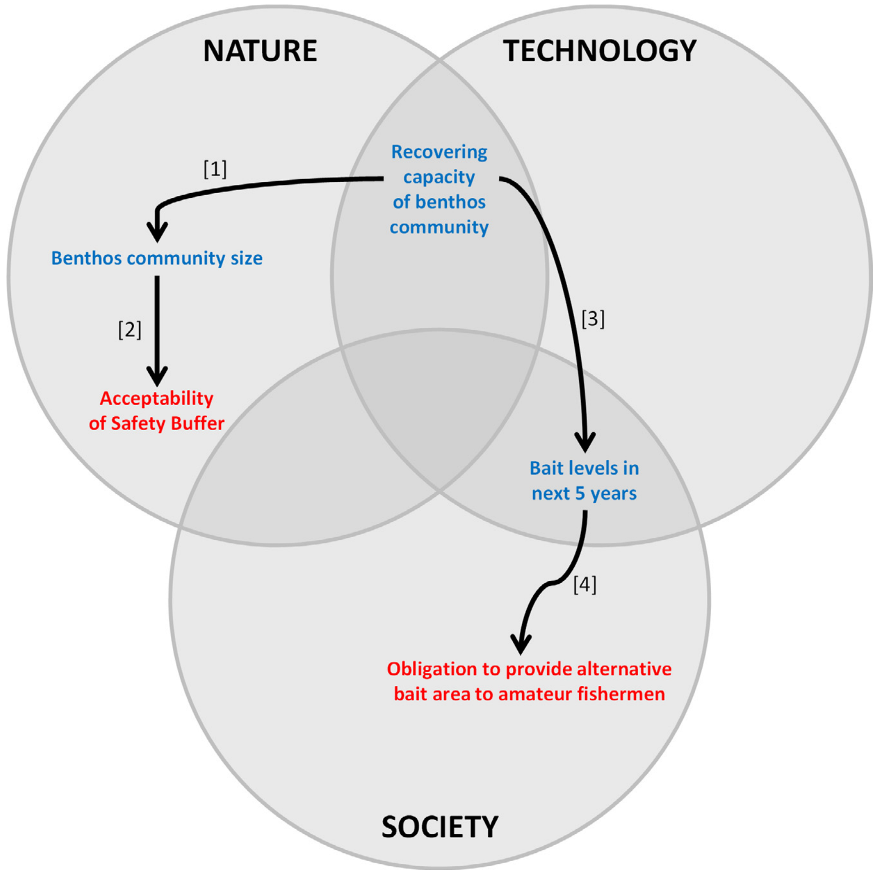

Fig. 8. Cascade of uncertainty regarding the impact of the Safety Buffer nourishment on benthos. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Location of the Sand Engine in the Netherlands.
Source: Google Earth.

maintenance and flood safety, provides additional room for nature by increasing the dune habitat for flora and fauna, and creates opportunities for new forms of recreation such as kite-surfing.

As the Sand Engine was constructed in 2011, it is currently subject to a monitoring and evaluation programme which will last until, at least, 2016. It is extensively studied whether a mega-sand nourishment is capable of combining the aforementioned benefits for the human–technology–nature system in which it is implemented. However, since the weather conditions that drive the sediment transport are highly unpredictable – especially over a 20–50 year period – the project involves high levels of uncertainty which threatened the successful development of the Sand Engine.

5.2. Results

5.2.1. Sand mining

Contrary to the Safety Buffer case, we did not identify any Sand Engine-specific issues regarding the sand mining activities. While sand mining in the Safety Buffer case will take place in the Eastern Scheldt estuary with many stakeholders affected, the sand for the

Sand Engine was mined 10 km offshore in the North Sea where stakeholders are only marginally affected. More importantly, for the Safety Buffer project, a project-specific sand mining permit is required. For stakeholders affected, it is relatively easy to appeal against such a permit. For the Sand Engine project, no project-specific permit was required as it was part of the national permit for regular coastal nourishments under the Dynamic Preservation policy.

5.2.2. Sand nourishment

With regard to the Sand Engine nourishment, we identified several important cascades of interrelated uncertainties. The first issue concerned the effects of the project on the local drinking water supply (Fig. 10). There is incomplete knowledge regarding the precise effects of creating a major peninsula – such as the Sand Engine – in front of the existing beach area on the groundwater level and consequently, on the groundwater transport patterns. An extension of the coast due to the Sand Engine will lead to a widening of the freshwater table in the dune area. As a result, internal transport patterns of fresh water will change. This may lead to a decrease of efficiency of the existing drinking water pumping infrastructure. More importantly, it induces the danger of mixing contaminated groundwater from a polluted dune section with the drinking water table. While the local drinking water stakeholder was concerned about these potential effects of the Sand Engine and requested additional research, the project team at first was convinced that the limited knowledge available was sufficient to expect no adverse consequences for the drinking water supply. Because the drinking water stakeholder was planning an escalation regarding this issue as it was clearly unacceptable for them, the project team had to change their viewpoint. After a study of the hydrological processes, it was concluded that the Sand Engine might have significant effects on the ground and drinking water situation if no proper mitigating measures were taken. Therefore, negotiations between the two actors resulted in the installation of a pumping station, aimed to preserve the original groundwater table. Moreover, adaptations to the design of the beach area in the vicinity of the Sand Engine were made and the groundwater situation will be monitored extensively.

The second cascade identified concerns financial aspects regarding the Sand Engine (Fig. 11). As the Sand Engine is an innovative experiment, it is yet unpredictable if the concept will be successful. As the sediment transport along the coast on the short term is driven by unpredictable natural dynamics, this major uncertainty is the foremost determinant of the efficacy of the mega-nourishment concept. Additionally, while the Sand Engine's construction budget was restricted to 50 million euros, its sand volume had to be at least 18.5 million m^3. As these restrictions meant that constructors would only get half of the price regularly paid for a Dutch nourishment, the project team was concerned that the major dredging companies might refuse to construct the Sand Engine under the given preconditions. On the other hand, the Sand Engine could also be interpreted as a long-term investment, an innovative concept which draws extensive international attention and could result in an increase of dredging assignments worldwide. In order to prevent difficulties during the development process, the project team chose a participatory approach and started lobbying to assess its feasibility as early as possible. This approach resulted in a smooth and successful tender procedure for the Sand Engine's construction.

Regarding the third uncertainty cascade, in the local political arena, it was observed that the Sand Engine might have adverse impacts on stakeholder activities in the surrounding municipalities (Fig. 12). Specifically, there were concerns about the impact of

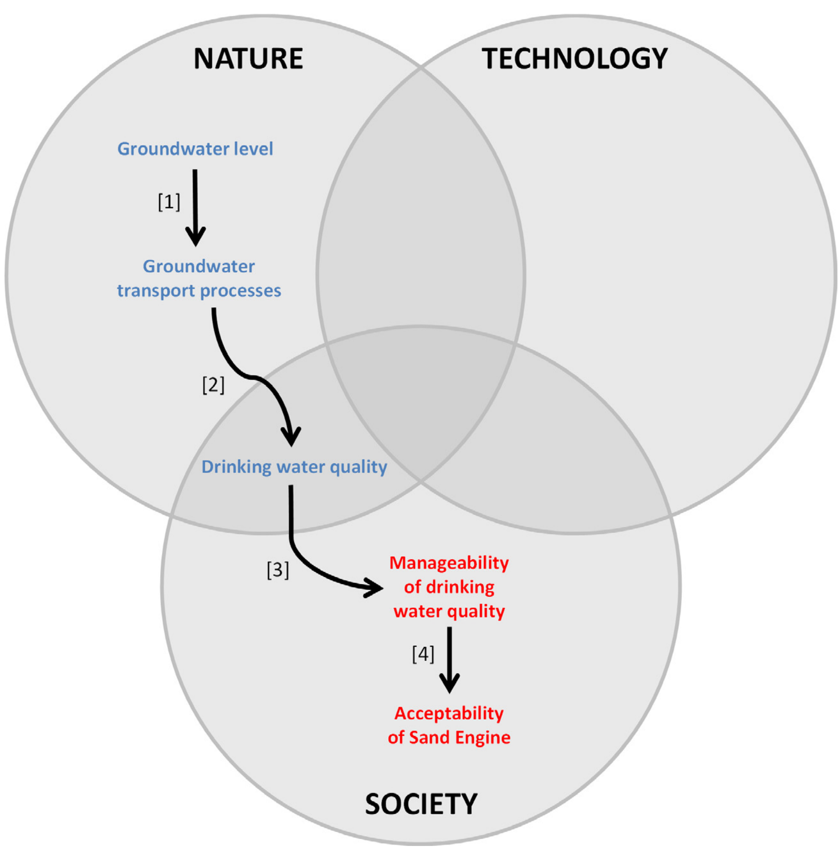

Fig. 10. Cascade of uncertainty regarding the impact of the Sand Engine on drinking water quality. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

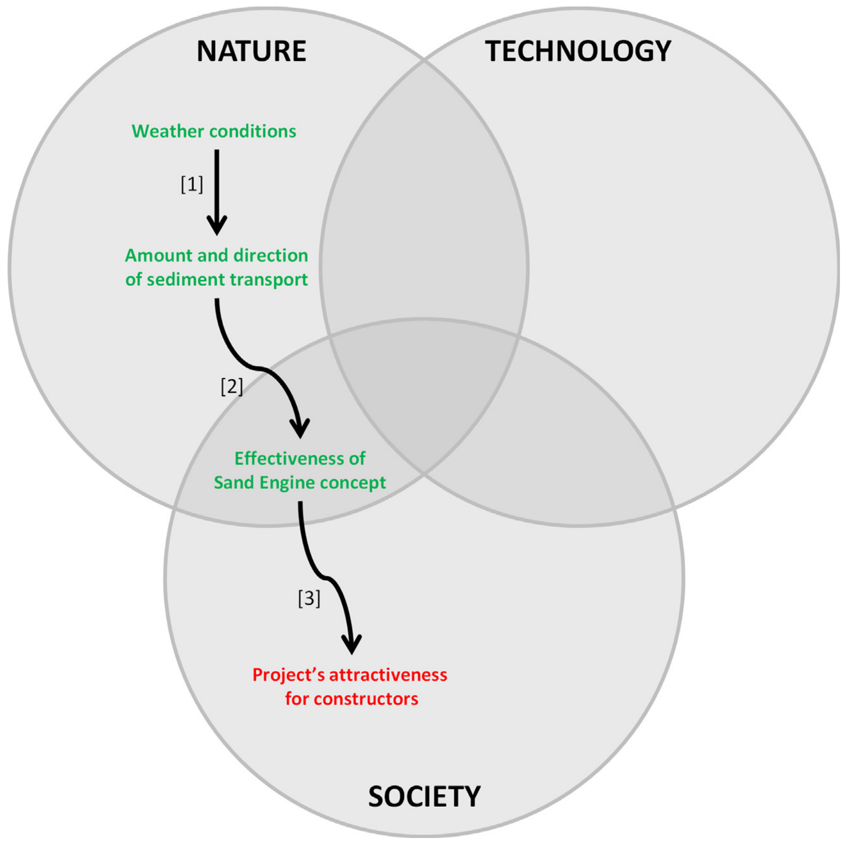

Fig. 11. Cascade of uncertainty regarding the attractiveness of the Sand Engine for constructors. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the project on Scheveningen Harbour. Local politicians figured that the nourished sediment could potentially lead to an increasingly shallow harbour entrance, hindering its activities and eventually having an unpredictable negative financial impact. As a result, there were different views regarding the preferred location and shape of the Sand Engine in the early stages of the project. The project team chose an approach of persuasive communication to convince the opposing politicians that no harm would be done to the harbour activities.

5.2.3. Recreational safety: an uncertain issue of paramount importance

Finally and most importantly, the Sand Engine has major implications regarding recreational safety. The specific aspect of swimmer safety continues to be an issue of paramount importance, even after the project's implementation. During the development process, a group of local residents formed the 'Stop the Sand Engine' committee to express their concerns about the impacts on the recreational safety situation. During project development, they were fiercely supported in the Dutch parliament by one of the large political parties. The cascade of interrelated uncertainties concerning this particular issue has two branches, namely concerning swimmer safety (cascade [1]–[2]–[3]–[6] in Fig. 13) and beach recreation safety (cascade [4]–[5]–[6] in Fig. 13).

As the weather conditions that drive the Sand Engine development are inherently unpredictable, the near-shore water conditions and thus swimming conditions are unpredictable as well. While the project team views swimmer safety as an important but manageable issue, the opponents of the project believe that accidents are a certainty. Similarly, the opponents fear that the project activities will transport dumped ammunition to the beach area. After World War II, residual German ammunition was dumped in the North Sea at specific sites 18 km offshore. However, some fishermen, who were paid to carry out this task, already started dumping some bombs shortly after leaving the harbour. Whereas the locations of the dedicated dumping sites are well-charted, the whereabouts of preliminary dumped ammunition are unknown and could theoretically be located at the Sand Engine's mining area. If the ammunition would not be detected by the preventive sea-bed scans and manage to get past the anti-ammunition grid of the dredging ships, it could end up on the beach and be a potential hazard. However, during past sand nourishments, hardly any negative experiences with ammunition took place. To address the recreational safety situation, the project team intended to have extensive dialogues with the opposing committee. However, according to the project team, the opponents declined invitations to discuss the project. Furthermore, multiple parliamentary questions regarding this subject had to be answered. Nevertheless, the opponents were not successfully convinced. In the end, the responsible Ministry decided to implement the project, overruling the opponents.

During the development process of the Sand Engine, the management plans regarding the swimmer safety situation mainly concentrated on communicative measures – such as 'do not swim' signs – and developing well-trained life guard brigades. However, after project implementation, the life guard brigades reported in April 2012 that they observed fast and potentially dangerous currents in the tideway at the Sand Engine. These circumstances were perceived as problematic as the official start of the bathing season was approaching (i.e., on the 15th of May) and the life guard brigades were unable to be fully operational by that time. Therefore, they requested the regional government to take

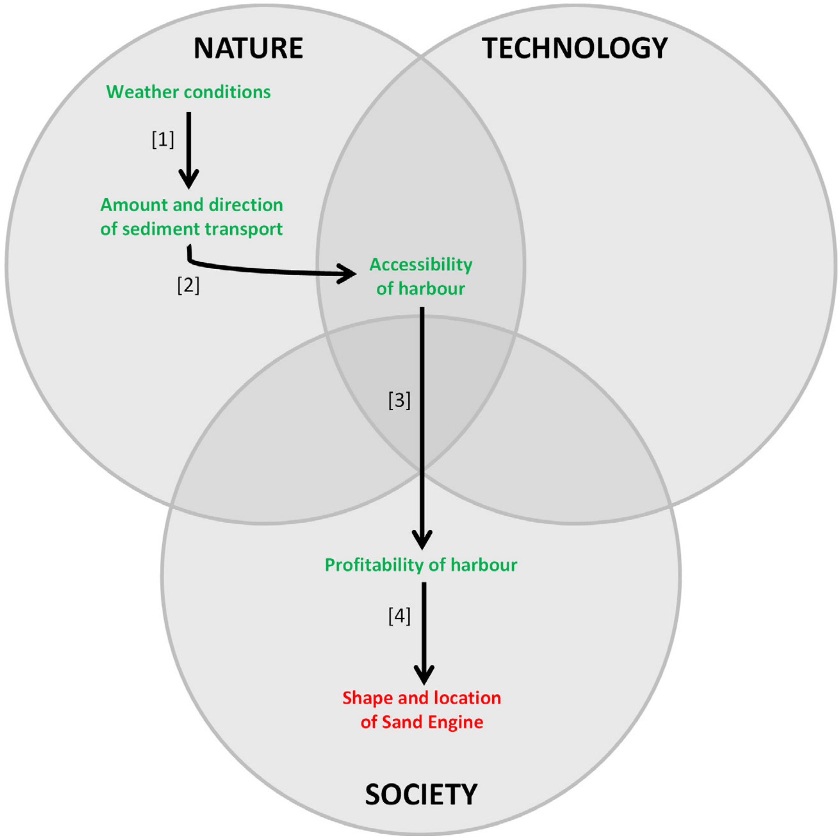

Fig. 12. Cascade of uncertainty regarding the impact of the Sand Engine on Scheveningen Harbour. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

additional safety measures to prevent accidents. An interviewee stated that the following advice was given regarding these additional measures:

> "We advise them: either do nothing but warn people with [additional] 'do not swim' signs, or if really needed close [the tideway] with sand, or fence it off. Well, in any case: [do] not [use] stones... But preferably: do nothing. Because, well, you actually only disturb [the Sand Engine] if you manually move sand or nourish additional sand there. And in fact that is something we do not want."

As (swimmer) safety has the highest priority for the government in any case, it was decided – despite the aforementioned advice – to close off the tideway with a small stone dam. Other governmental agencies and research institutes were disappointed about the new command-and-control type of safety measure, as it is not in line with the use of BwN design principles. Nevertheless, in July 2012, the swimming conditions seemed to be rather favourable and it was decided that a swimming prohibition was no longer needed. During one of the weekends in August 2012, one person died at the Sand Engine (due to a heart attack) and life guards had to perform about 80 rescues. This caused rumours, leading to a renewed swimming prohibition immediately after that troublesome weekend.

At the end of the bathing season in September 2012, the stone dam was removed in order to restore the initial situation of the Sand Engine. Currently, it is not clear if similar safety measures will be required in future bathing seasons. For the 2013 bathing season, a pilot is planned with a newly developed swimming water prediction model. This model is intended to predict swimming conditions two days in advance and could be used by the life guards to judge potential risks in the Sand Engine area.

6. Discussion

In Sections 4 and 5, we discussed two flood defence projects based on BwN design principles and identified several cascades of interrelated uncertainties that were important during the development of these two initiatives. In this section, we reflect on the relationship between different uncertainties and discuss what the use of the uncertainty cascade concept implies for coping with uncertainty.

6.1. How are different uncertainties related in the two BwN projects?

By constructing a cascade of interrelated uncertainties for several apparent stakeholder issues (Figs. 5–8 and 10–13), we demonstrate that fundamentally different uncertainties are not independent but interrelated. Although the topics of the uncertainty cascades deviate widely – from recreational safety to the financial consequences of an initiative – our results demonstrate that in each cascade the relationship ultimately results in *ambiguity in the social system*. This comes as no surprise, as the core activities of both project actors and stakeholders are located in the social system, where they use diverging organizational or personal interests, values and beliefs as a set of criteria to assess the quality or acceptability of a project regarding the particular stakeholder issue evaluated. The only partial exception is the issue about the wellbeing of the benthos (cascade [1]–[2] in Fig. 8), where the amateur environmental interest group primarily evaluated the Safety Buffer project from a natural system

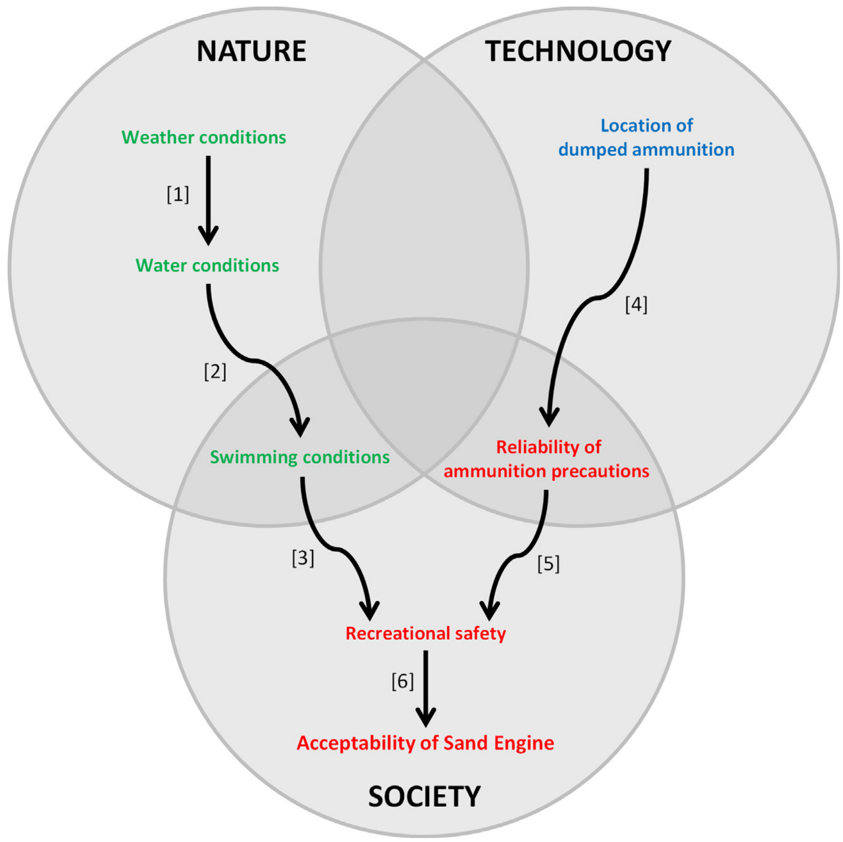

Fig. 13. Cascade of uncertainty regarding the impact of the Sand Engine on recreational safety. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

perspective. The cascades of interrelated uncertainties mainly originate from either the unpredictable natural dynamics driving the project or incomplete knowledge about the impacts of the applied technology on the natural system. This seems rather straightforward, as natural dynamics are a central aspect of BwN designs. As these designs have an innovative character, it is difficult to predict the effects such a technological intervention will have on the natural environment.

The uncertainty cascade approach we propose differs from existing concepts that address the relation between different uncertainties – such as the uncertainty propagation approach – because it not only acknowledges incomplete knowledge and unpredictability, but also explicitly takes ambiguity into account. In our case study projects, we observe that incomplete knowledge about and unpredictability of natural processes or impacts on the natural system are gradually re-interpreted from different societal perspectives, resulting in ambiguity. Hence, the uncertainty transfers from the natural system to the social system and its *societal importance* seems to amplify throughout the cascade. Moreover, the same physical phenomenon can yield two uncertainties that are fundamentally different, due to the fact that they are interpreted from a different perspective. An example is the uncertainty about the impact of the Safety Buffer on the benthos community. While the amateur environmental interest group views the organisms as 'animals' (in the natural system) affected by the applied technology (cascade [1]–[2] in Fig. 8), the amateur fishermen organization frames these organisms as 'fishing bait' and interpret the uncertainty as a negative impact of the technology on a societal function (cascade [3]–[4] in Fig. 8).

The recreational safety issues in the Sand Engine case provide an excellent illustration of how multiple uncertainties form cascade and are transferred between the different parts of the system to be managed. Cascade [1]–[2]–[3]–[6] in Fig. 13 originates from the unpredictable weather conditions, the main dynamic design mechanism of the project. While the weather conditions redistribute the nourished sediment along the coast, these dynamics also create unpredictable water conditions in the near-shore coastal zone (represented by [1]). Local stakeholders re-interpreted these water conditions from a societal perspective, namely as unpredictable swimming conditions near the Sand Engine (represented by [2]). Hence, the uncertainty – although physically the same process – is transferred from a natural perspective to a societal one and becomes more important in terms of project development. While the project team viewed that the recreational safety situation is under control due to preventive measures, the stakeholders were very concerned and even questioned the acceptability of the Sand Engine (represented by [3] and [6]). Cascade [4]–[5]–[6] in Fig. 13 originates from incomplete knowledge about the whereabouts of dumped ammunition. To prevent explosives from entering the dredging ships into the nourishment sand, the sea bed is sonar-scanned prior to the mining activities and the ships are equipped with anti-ammunition grids. During project development, the uncertainty about the whereabouts of the ammunition was transferred to a societal perspective (represented by [4]), as implicitly, the stakeholders that oppose the Sand Engine hold a different view regarding the precautionary measures than the project team. Consequently, while the project team views recreational safety as under control due to the precautionary measures, the opposing stakeholders still view ammunition on the beach as a certainty (represented by [5]). The example above illustrates how the incomplete knowledge and unpredictability in the natural and technical system is gradually translated into different uncertainties, is transferred to a social perspective in the cascade and becomes increasingly important in terms of project development.

6.2. How do we cope with the cascade of interrelated uncertainties?

We argue that using cascades for representing the interrelated uncertainties in a project opens new possibilities for coping with uncertainty, as each uncertainty in the cascade represents a potential node of intervention or facilitation. Consequently, it might not be necessary to cope with each uncertainty identified in a project. As the uncertainties in the cascade are interrelated, this suggests that successfully coping with uncertainties that are caused by incomplete knowledge or unpredictability contributes to successfully coping with an ambiguity that is related to these uncertainties. Similarly, incomplete knowledge or unpredictability could be influenced by successfully coping with another situation of incomplete knowledge or unpredictability with which it is related.

Because incomplete knowledge, unpredictability and ambiguity can all be present in different parts of the human–technology–nature system, the strategies that can be used to manage the cascade of interrelated uncertainties are very diverse, as illustrated by the following example. In the Sand Engine case, there are multiple interpretations regarding the recreational safety situation. A direct method to cope with this ambiguity is to unite the efforts of the project team and opponents by jointly developing measures to safeguard the recreational situation, e.g., setting up a rescue brigade to watch over swimmers. Furthermore, communicative measures, such as ‘do-not-swim’ signs, can warn recreants about potential risks in the vicinity of the Sand Engine. However, the ambiguity can also be managed by coping with incomplete knowledge and unpredictability in the cascade. As discussed in Section 5.2.3, this occurred in practice after the Sand Engine’s implementation. For instance, in cascade [1]–[2]–[3]–[6] in Fig. 14, the discussed swimming water prediction model could be an useful supportive tool to signal stakeholders when swimming conditions might be dangerous. However, in practice, the Sand Engine’s managers decided to manage an uncertainty even higher up the cascade. By creating the stone dam, the Sand Engine was physically adapted to create more favourable water conditions with respect to recreational safety. However, as a stone dam is not in line with the BwN approach, a sandy adaptation would have been a better alternative. Such an adaptation could already have been anticipated during the design phase of the project. Furthermore, current weather prediction models could be improved in order to give more accurate predictions of the Sand Engine’s development. Similarly, in cascade [4]–[5]–[6] in Fig. 14, the project team could extensively communicate with the opponents to discuss the reliability of the techniques that prevent ammunition from entering the nourishment ships. One step up in the cascade, the project team might decide to commission a high-detail sonar assessment of the sea bed at the sand mining location in order to locate each single ammunition item present, to cope with the incomplete knowledge regarding the whereabouts of ammunition.

6.3. Towards adaptive uncertainty management

Flexible and adaptive approaches have been proposed to successfully implement policies and new infrastructures in the face of uncertain future system conditions and climate change (e.g., Hallegate, 2009; Wilby and Dessai, 2010; Haasnoot et al., 2013; Walker et al., 2013). We argue that the concept of the cascade of interrelated uncertainties is important for adaptive uncertainty management, as it provides insight to project teams and stakeholders about the uncertainties present and the diverse range of coping strategies available (as illustrated by the example in Section 6.2). As the uncertainties in the cascade are related, this suggests that coping with a particular uncertainty will influence those with which it is related. Thus, if a particular coping strategy falls short or system conditions change, the other points of facilitation and intervention in the cascade provide alternative

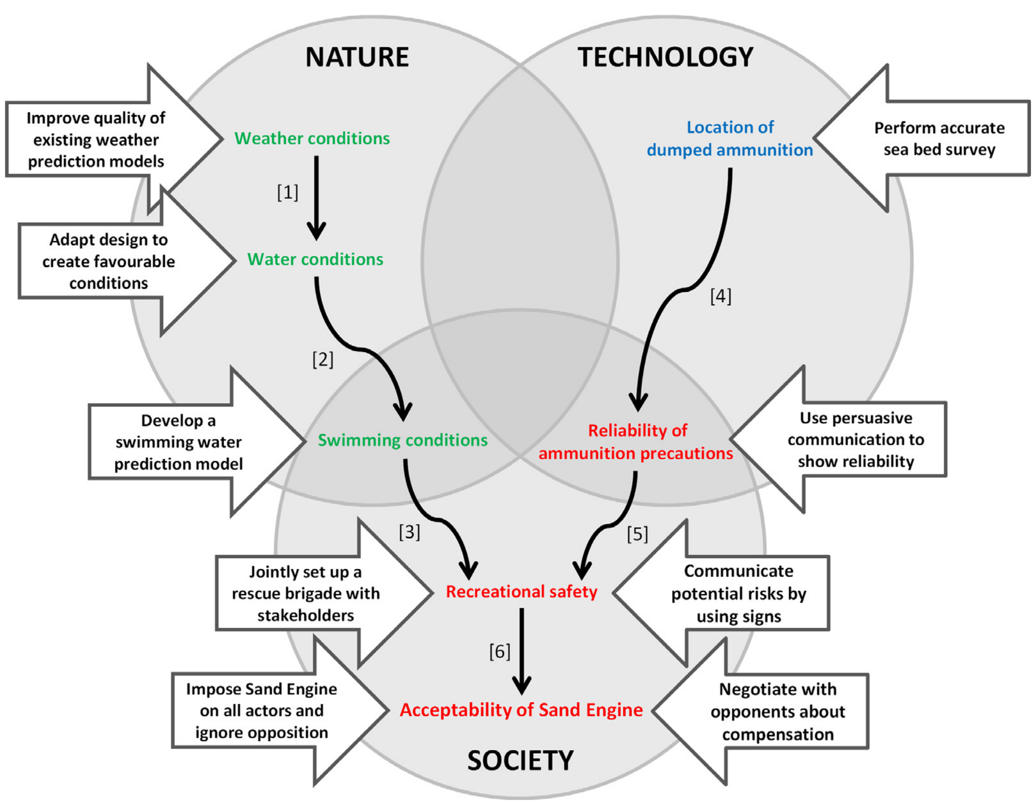

Fig. 14. Coping strategies for handling the Sand Engine’s recreational safety situation. Text colour coding is equal to Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coping strategies for the actors involved, offering the opportunity to adapt the uncertainty management approach that was previously pursued.

Although the cascades of interrelated uncertainties can be a powerful supportive tool to distinguish between the different nodes of intervention or facilitation available and to determine appropriate coping strategies, it is important to realize that those cascades are not necessarily static during and after the execution of a project. *Time* is a distinct aspect in projects based on BwN principles and the uncertainties associated with it (Van den Hoek et al., 2012). Ambiguity is particularly apparent *during project development* and stakeholders regularly want an issue to be resolved before giving their blessings to an initiative under development, as is illustrated by the following statements by two interviewees in the Safety Buffer case:

> "If there is no [compensating] alternative, then we will not just give our permission to nourish on that area" {1} "Before they commence, [compensation] has to be arranged... And if it is not arranged? Well, nowadays, it is like this: it is unpleasant, but we almost permanently have lawyers." {2}

Even after project implementation, new ambiguities may arise due to changes in legislations, political changes and changing actor preferences. Facilitating dialogues, participation and negotiation are essential to cope with ambiguity, in order to create a basis of mutual understanding among the actors involved (see e.g., Dewulf et al., 2005; Van der Keur et al., 2008; Brugnach and Ingram, 2012). While incomplete knowledge and unpredictability are important during project development, it is even more important to acknowledge that it will remain uncertain until *after project implementation* whether an uncertain phenomenon will actually occur in reality. For instance, although the unpredictability of weather conditions can be an issue of discussion during project development, the phenomenon under consideration is a natural dynamic process which will not manifest itself until after project implementation. As this unpredictability remains a Sword of Damocles during project development, this consideration affects the way in which we should cope with this specific kind of uncertainty. In the current practice of our two BwN projects, we observe that monitoring of natural phenomena and project effects is the most commonly used strategy to address the incomplete knowledge and unpredictability. This provides valuable knowledge to those managing the project in order to adaptively fine-tune previously made design choices, project characteristics and uncertainty coping strategies if needed.

7. Conclusions

In common uncertainty classification approaches, uncertainties are represented as more or less disconnected specific issues about which decision-makers, modellers, stakeholders or other actors do not have a complete or unique understanding. However, the results from our two BwN flood defence projects show that we can extend this view on uncertainty. Different uncertainties, which can be of a fundamentally different nature, are directly related in *cascades of interrelated uncertainties*.

Uncertainty and scientific knowledge are often perceived differently by scientists, decision-makers and the public at large, creating a science-policy gap (Bradshaw and Borchers, 2000). Actors from different disciplines and with diverging backgrounds can interpret uncertainty differently or can hold different forms of knowledge as important (Dewulf et al., 2005). Uncertainty is often characterized from the scientific perspective, such as a modeller's perspective (e.g., Walker et al., 2003). However, the understanding of knowledge and the interpretation of uncertainty are relational processes, as these processes depend on how the actors involved relate to each other and the context under consideration (Brugnach et al., 2008). The cascades of interrelated uncertainties can function as an instrument to explicitly connect the different uncertainties held relevant by different actors. Our cascade approach shows that the uncertainties experienced by a modeller can be important for a decision-maker and vice versa, as uncertainties that are interrelated in the cascade are relevant for each actor involved and not just for those from a specific perspective. Thereby, the cascades can be applied to establish links between all relevant actors – from science, policy and other disciplines – in order to come to better understood and jointly developed decisions under uncertain conditions.

While our results do not add new coping strategies to the already diverse range of methods to assess and handle incomplete knowledge, unpredictability or ambiguity (see e.g., Van der Sluijs et al., 2005; Refsgaard et al., 2007; Van der Keur et al., 2008; Brugnach et al., 2008, 2011; Raadgever et al., 2011; Brugnach and Ingram, 2012), the extended view on the nature of uncertainty we propose opens windows of opportunity for uncertainty management. As the uncertainties are interrelated, this implies that successfully coping with a particular uncertainty in the cascade could influence other uncertainties related to it. As a result, it may not be needed to manage each uncertainty present in a promising project. Furthermore, the cascades can support the adaptive management of uncertainties. If a particular coping strategy fails or system conditions change, the cascades can point at new directions for coping with the uncertainties encountered. This is of particular interest for specific initiatives – such as those based on BwN design principles – that are not static but may change over time.

Developing more detailed guidelines for coping with the cascades of interrelated uncertainties in operational project management will be a challenging task, but also an interesting opportunity for future research. Nature-inclusive flood defence projects receive increasing international attention (Van Slobbe et al., 2013) and are seen as a promising adaptation measure against sea level rise, one of the most apparent global environmental change issues our society faces. The use of cascades of interrelated uncertainties during the development of these projects – to support the adaptive management of uncertainty – may provide a key contribution to the successful implementation of these promising initiatives.

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