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Shifting to ecological engineering in flood management: Introducing new uncertainties in the development of a Building with Nature pilot project

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ABSTRACT

Building with Nature (BwN) is an innovative approach in flood policy, which aims to use natural system dynamics and materials for the design and realization of flood management projects. However, as natural dynamics are inherently unpredictable, the use of BwN design principles requires a fundamentally different approach to uncertainty in flood management. In this paper, we identify and classify the key uncertainties in the development process of a specific project using BwN design principles: the Sand Engine. Our results indicate that uncertainty about the social implications of applying BwN design principles is more relevant for project development than uncertainty in the factual knowledge base of the natural system. Although uncertainty did not hamper project development in this specific case, the changes in project design evoked by the use of BwN principles do not seem to be followed by proper changes in the development process preceding the project's implementation: in the Sand Engine project's development process, uncertainty is evaluated rather similar as in the current flood management practices. We claim that new approaches towards dealing with uncertainty are needed, to successfully address the uncertainties typical to projects using BwN design principles.

1. Introduction

The key role of uncertainty in policy development is increasingly acknowledged in numerous scientific disciplines, including environmental sciences (Van der Sluijs, 2007; Mysiak et al., 2008; Maxim and Van der Sluijs, 2011) and water policy science (Pahl-Wostl et al., 2007, 2011). Contemporary flood management generally concerns the construction of rigid and often large-scale infrastructure, such as dikes, dams and storm surge barriers. In such an approach, often referred to in the literature as the command-and-control approach, emphasis is on reducing uncertainties and designing systems that can be predicted and controlled (Holling and Meffe, 1996). Although structures such as dikes and storm surge barriers have been relatively successful in the (recent) past, the highly optimized systems they create are vulnerable to unpredictable events greater than foreseen in the structure's design (Carlson and Doyle, 1999; Davidson-Hunt and Berkes, 2003), for instance an extreme storm well beyond expectations. Furthermore, despite the fact that human activities significantly alter the functioning of ecosystems (Vitousek et al., 1997) and threaten the sustainability of natural systems such as marine environments (Levin and Lubchenco, 2008), the effects of the command-and-control flood management approach on natural processes are often not properly taken into account (Richter et al., 2003). Over recent years, changes in weather conditions and extreme events (Milly et al., 2008), accompanied by a changing perception of human responsibility towards incorporating ecological values in

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water policy (Gleick, 2000), have led to an increasing desire for ecologically sustainable water management (Richter et al., 2003), as well as sustainable development of coastal ecosystems (Adger et al., 2005) and flood management systems in general (Werritty, 2006). Command-and-control approaches do not seem fit to cope with these future challenges regarding the role of nature and ecology. Therefore, the paradigm of water management is slowly changing towards more nature-inclusive approaches (Pahl-Wostl et al., 2011).

Currently, in the Netherlands, an innovative nature-inclusive approach to flood management is emerging and being studied in a national research program, called Building with Nature (BwN). BwN is a form of ecological engineering (sensu Mitsch and Jørgensen, 2003) in flood management, as BwN design principles promote the use of natural materials and dynamics – such as sediment, vegetation, wind and currents – for the realization of effective flood management projects, while exploring opportunities for nature development (Van Dalfsen and Aarninkhof, 2009; Aarninkhof et al., 2010). The use of BwN design principles for flood management purposes can result in a variety of possible designs. For instance, researchers are studying the use of large-scale coastal sand nourishments or specific vegetation for flood protection and the application of oyster beds to prevent erosion of tidal flats (Borsje et al., 2011). However, the use of ecology and natural dynamics inherently adds high and often irreducible levels of uncertainty to a project's design process (Bergen et al., 2001). Hence, use of BwN design principles suggests that a fundamentally different attitude by stakeholders towards uncertainty in water policy and flood management is required. Instead of aiming at uncertainty reduction and control, the inclusion of nature and its unpredictable dynamics in the project design demands that policy development actors have the capacity to recognize and properly deal with the presence of higher levels of uncertainty.

Where scientists are familiar with the concept of scientific uncertainty, policy-makers and the public at large generally prefer certainty and deterministic solutions (Bradshaw and Borchers, 2000). Uncertainty can influence policy and project development in numerous ways. For instance, a situation of indecisiveness can occur when policy-makers are uncertain about which measure out of a set of policy alternatives is most appropriate (Mysiak et al., 2008). Uncertainty can create anxiety, cause retrenchment and paralyse action (Nowotny et al., 2001; Van Asselt, 2005). Hence, projects can be severely delayed, may suffer from insufficient funds or can even be cancelled if the level of uncertainty is perceived as unacceptable. For example, Hommes et al. (2009) describe the case of the harbour extension of Mainport Rotterdam, a water engineering project at the Dutch coast in which final decisions were enormously delayed, partly due to time-consuming consultations about uncertainties concerning the effects on silt, nutrients and biota in the Wadden Sea.

In short, while the presence of uncertainty is inherent to the design principles of BwN, it is still undesirable in the current policy and project development practices. This contradiction leads us to the hypothesis that the development process of projects using BwN design principles is susceptible to be hampered by uncertainty due to the inherent unpredictability and incomplete knowledge of the natural system. To assess this hypothesis, it is of paramount importance to have a clear understanding of which uncertainties are most relevant to policy-makers, managers and the public in projects using BwN design principles. When the key uncertainties of the BwN approach are identified, strategies can be developed to manage these uncertainties effectively to prevent unnecessary cost and time overruns, or even cancellation, of promising initiatives. To this end, we performed an in-depth case study of the Sand Engine project, the first large-scale project in the Netherlands based on BwN principles. In this paper, we identify and classify the relevant key uncertainties from the perspective of the development process of the Sand Engine project. Furthermore, we analyse whether the required change of attitude by stakeholders towards uncertainty when using BwN principles is accompanied by a change in the evaluation of uncertainty by project development actors.

This paper is structured as follows. In Section 2, we discuss how we define and classify uncertainty. Section 3 describes the methodology of our study. Section 4 introduces the Sand Engine case study and the characteristics of its development process, while the results are presented in Section 5. In Section 6, we discuss the implications of our study's results. In the final section, we draw conclusions and point out the direction of our future research.

2. Definition and classification of uncertainty

In the literature, there is still no commonly accepted definition of the concept of uncertainty. For instance, Funtowicz and Ravetz (1990) describe uncertainty as *a situation of inadequate information*. This definition suggests that uncertainty will decrease if the amount or quality of information available increases. However, Van Asselt and Rotmans (2002) recognize that uncertainty can also prevail even in situations where sufficient information is available. An increase of information can result in an increase of our awareness of knowledge gaps, and thus in an increase of uncertainty (Van Asselt, 2000). Therefore, to help grasp all dimensions of uncertainty, Walker et al. (2003) define uncertainty as *any departure from the unachievable ideal of complete determinism*. This definition still regards uncertainty as a rather mathematical concept with the underlying assumption that uncertainty can always be *deterministically* characterized.

Van der Sluijs (2006) argues that uncertainty is much more than just numbers and probabilities: it is increasingly understood as a concept with both quantitative and qualitative dimensions, involving more than just statistical errors or inexact numbers. Findings from the study of Van der Keur et al. (2008) support this statement, as they conclude that more qualitative uncertainties than statistical uncertainties are present in policy development for integrated water resources management. In the context of major public projects, factors such as commercial and competitive pressures, conflicting social, political and institutional norms and rules with project financial and technical goals, and the shifting requirements of project stakeholders can all be sources of uncertainty (Jaafari, 2001). Maxim and Van der Sluijs (2011) define uncertainty as a lack of knowledge quality, arguing that *lack of knowledge* is only a part of the broader issue of *knowledge quality*. Koppenjan and

Klijn (2004) grasp both the technical and social dimensions of uncertainty by adding *strategic uncertainty* (unexpected strategic actions of stakeholders) and *institutional uncertainty* (handling of policy development and the interaction between actors) to the knowledge-oriented *substantive uncertainty* (unavailability or different interpretations of knowledge).

Brugnach et al. (2008) address the topic of uncertainty from the perspective of multi-actor decision-making processes, in which the interaction between actors is just as essential for the interpretation of a problem as the available factual knowledge. Uncertainty is defined as *the situation in which there is not a unique and complete understanding of the system to be managed* (Brugnach et al., 2008). This definition regards uncertainty as much more than just a deficit of factual knowledge, including the many different interpretations regarding the problem and its solution that may coexist in a collective decision-making process. Policy development actors have different backgrounds, diverging preferences, and conflicting interests and values, which influence the framing of problems and the type of solutions chosen. Thus, actors may either interpret knowledge differently or use different knowledge during the framing process, the activity through which the meaning of a situation is negotiated among different actors (Putnam and Holmer, 1992; Gray, 2003; Dewulf et al., 2004). So, in decision-making processes where multiple actors are involved, the simultaneous presence of different but equally valid knowledge frames is unavoidable. This may lead to ambiguity, a type of uncertainty that indicates that there are multiple possible interpretations of a situation (Weick, 1995). The relevant dimension of ambiguity is something ranging from unanimous clarity to total confusion caused by too many people voicing different but still valid interpretations (Dewulf et al., 2005).

Following the definition of Brugnach et al. (2008), we distinguish between three different types of uncertainty:

- **Unpredictability** – uncertainty due to unpredictable or chaotic behaviour of, e.g. natural processes, human beings or social processes;
- **Incomplete knowledge** – uncertainty due to the imperfection of our knowledge, e.g. due to lack of specific knowledge, data imprecision or approximations;
- **Multiple knowledge frames** – uncertainty due to the presence of multiple knowledge frames or different but (equally) valid interpretations of the same phenomenon, problem or situation.

Furthermore, we classify – following Brugnach et al. (2008) – in which part of the system to be managed the uncertainty is present. It is useful to make such a distinction between the different parts as it supports policy-makers to structure their knowledge about the system, though the three different parts of the system are all closely interrelated. Furthermore, strategies to manage uncertainties can be more specifically tailored to the part of the system in which the uncertainty is present. The following parts of the system to be managed are distinguished:

- **Natural system** – uncertainty concerning aspects such as climate impacts, water quantity, water quality and ecosystems knowledge;
- **Technical system** – uncertainty concerning technical elements and artefacts that are deployed to intervene in the natural system knowledge;
- **Social system** – uncertainty concerning economic, cultural, legal, political, administrative and organizational aspects knowledge.

Combining the types of uncertainty and the system in which the uncertainty is present yields a two-dimensional uncertainty classification matrix (Table 1). Similar to other scholars, such as Raadgever et al. (2011), this matrix was used to classify the uncertainties identified in our research.

3. Method

For our research, we used three main data sources to identify the relevant uncertainties in our case study, the Sand Engine project. A detailed description of this innovative sand nourishment project will follow in Section 4. First, data were collected by document analysis. Publication of key documents is a method of communicating project progress, results and

Table 1 – Uncertainty classification matrix.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems	*unpredictability of the natural system*	*incomplete knowledge of the natural system*	*multiple knowledge frames regarding the natural system*
Technical system Infrastructure, technologies, innovations	*unpredictability of the technical system*	*incomplete knowledge of the technical system*	*multiple knowledge frames regarding the technical system*
Social system Economic, cultural, legal, political, administrative and organizational aspects	*unpredictability of the social system*	*incomplete knowledge of the social system*	*multiple knowledge frames regarding the social system*

Adopted from Brugnach et al. (2008).

Table 2 – Key policy documents reviewed (names translated from Dutch).

List of key policy documents
Ambition Agreement Sand Engine
Project Start Note EIA Sand Engine
Guidelines EIA Sand Engine
Morphological Calculations Report
Environmental Impact Assessment (EIA) Sand Engine
Note of Answer to EIA Sand Engine
Swimming Safety Report
Monitoring and Evaluation Plan
Questions & Answers from Dutch parliament
Historical report on ammunition in North Sea
Sand Engine permits

ideas to both project stakeholders and the public at large. The documents we reviewed primarily describe and discuss the technical content of the Sand Engine project. These key documents were carefully studied to identify uncertainty in the context of the written text. Table 2 shows a short overview of the key documents reviewed in this research (see Appendix A for a more detailed list). Second, three public information meetings were attended. During these meetings, the public at large was offered the opportunity to pose questions, express their appreciation or concerns about the Sand Engine project and to file complaints. Minutes were made for these meetings and these were studied. Table 3 shows a list of several keywords and topics that were specifically of interest for our study, both for the document analysis and the analysis of the meetings.

Table 3 – Key issues signalling the presence of uncertainty.

Key issues
Issues where *uncertainty* or *risk* is explicitly mentioned (e.g.: currently, it is highly uncertain what the exact sea level rise will be until 2100);
Issues where an *assumption* or an *estimation* is made (e.g.: it is assumed that sea level rise will be 1 m until 2100);
Issues where (a) *scenario(s) with a probability of occurrence* is given (e.g.: there is a 75% chance that sea level rise will be more than 1 m);
Issues where (a) *scenario(s) with an idea of likelihood* of occurrence is given (e.g.: sea level is more likely to be 2 m than 1.5 m in 2100);
Issues where a (range of) *possible scenarios without having an idea of likelihood* of occurrence (e.g.: sea level rise will be between 1 m and 3 m until 2100);
Issues where it is expressed that there is *ignorance* about the (future) situation (e.g.: nobody has an idea what sea level rise will be in 2100);
Issues where *lack of knowledge* is expressed and *cannot be decreased* (e.g.: weather conditions cannot be predicted over a 20-year time period);
Issues where *lack of knowledge* is expressed but *additional knowledge can be acquired* (e.g.: the effect of a measure is currently unknown but it can be studied by a small-scale practical experiment);
Framing or priority differences of stakeholders (e.g.: while expert A states that climate change is the cause of sea level rise, actor B claims that there is no evidence for climate change and thus disagrees that climate change is the cause of sea level rise);
Other interesting issues that are suspected to be an uncertainty but not stated.

Third, in April and May 2011, we interviewed six main project actors – three (former) members of the Sand Engine project team, one member of the project steering group and two experts involved in the Environmental Impact Assessment (EIA) and modelling – to identify the uncertainties that were essential in the Sand Engine's development process. The interviews provided an opportunity to identify uncertainties not reported in the key documents. We chose this specific group of interviewees, as they are or were directly involved – either as chairman, manager or expert – in several phases of the Sand Engine project's development process. Henceforth, for the interviewees, identifying and managing the Sand Engine project's uncertainties was a part of their (daily) activities. The interviews were conducted in the Dutch language, took between one and two hours, and were recorded and transcribed.

We performed semi-structured interviews, using a standardized interview protocol with seven open-ended main questions and several follow-up questions. At the start of the interview, the interviewees were invited to elaborate on their definition or understanding of the topic of uncertainty. Thereafter, the interview continued with an iterative process of identifying uncertainties and elaborating on the uncertainty's relevance for the Sand Engine's development process. For instance, the interviewees were invited to address whether the uncertainties (potentially) had an effect on the continuation of the project. Furthermore, we posed questions about how the identified uncertainties were managed or coped with.

After identifying the uncertainties explicitly and implicitly addressed in the key documents, during public information meetings and during the interviews, the results from these three analyses were combined into one comprehensive list. Thereafter, the identified uncertainties were classified using the adopted uncertainty matrix, as presented in Section 2. We constructed an uncertainty matrix for each phase of the Sand Engine's development process, to create an overview of the development of uncertainty over the course of the project.

4. Case study: the Sand Engine project

4.1. *Case description*

The Sand Engine (in Dutch: Zandmotor) is an innovative, 21.5 million m^3 sand nourishment project, carried out near Ter Heijde in the Dutch province of South Holland. After a development process of approximately three years, construction finally started in March 2011. The innovative aspects of the Sand Engine project are its size – currently, the annual sand nourishment volume for the entire Dutch coast has a target value of 12 million m^3 – and especially its post-construction operating principles. After construction, the large amount of sand nourished will spread along the coast by the natural dynamics (waves, currents and wind). This means that the coast, both beach area and dunes, will expand in a fairly natural way. Hence, the Sand Engine project is a clear-cut example of the nature-inclusive BwN approach.

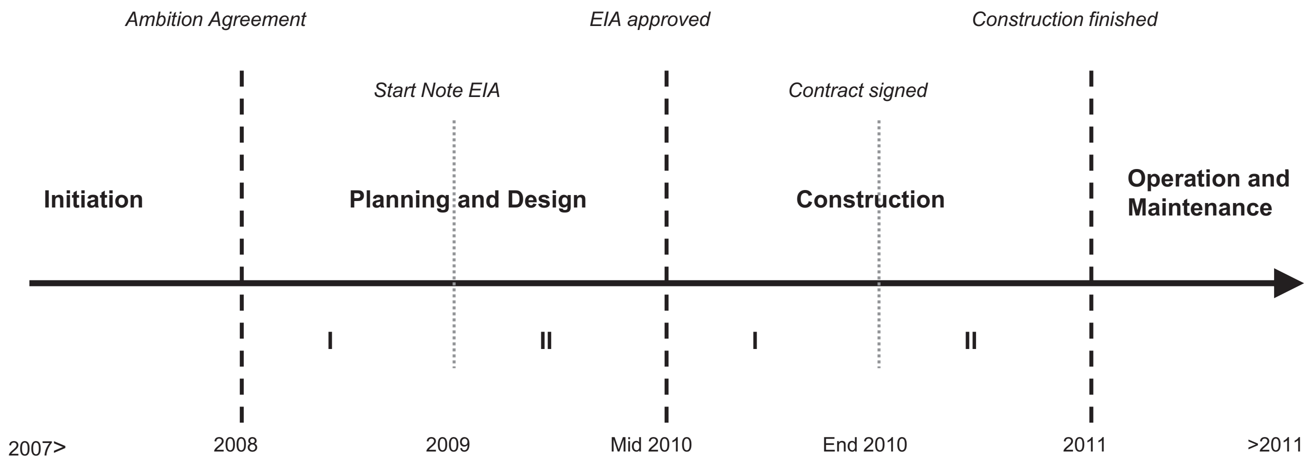

Fig. 1 – Timeline of Sand Engine development process.

As the Sand Engine is a pilot project, it will be monitored extensively after construction to study whether this innovative sand nourishment method is capable of combining benefits for society (for instance, coastal maintenance and increased area for beach recreation) and development of the natural system (for instance, increased dune habitat for flora and fauna). Model calculations have given predictions for the development of the Sand Engine. Currently, it is expected that the distribution of the Sand Engine's sand along the coastline will take 20–50 years. Since weather conditions are unpredictable, especially over such a long period, this prediction of sand distribution by natural dynamics involves high levels of uncertainty. Hence, the Sand Engine project is an interesting case study for our research concerning the role of uncertainty in the development process of projects using BwN design principles.

4.2. *Development process of the Sand Engine project*

The development process of the Sand Engine project consists of six phases (Fig. 1). We reconstructed the timeline of this process using the project planning, the document analysis and the interviews. Each phase has its own characteristics, main activities and goals. Furthermore, the set of actors involved – who all have their own goals and interests – changes during the project and can differ from phase to phase. Van der Keur et al. (2008) address that different uncertainties are present in the various phases of project development. Therefore, we anticipate that different uncertainties will emerge and be relevant in the diverse phases of the Sand Engine development process.

In the Sand Engine *Initiation* phase, the potential of the several ideas was studied and the possibilities to create stakeholder commitment were explored. The phase ended with signing an ''Ambition Agreement'', in which for instance preliminary project goals are set, by several committed parties. The *Planning and Design I* phase was used to explore alternatives, identify knowledge gaps and establish guidelines for the EIA procedure. In the *Planning and Design II* phase, a preferred alternative was chosen from the set of four proposed designs and mitigating measures were defined to cope with potential undesired effects of the Sand Engine. In the *Construction I* phase, a tender was done to find a contractor for the project's construction and required permits were acquired. During the *Construction II* phase, the Sand Engine was constructed under the responsibility of Rijkswaterstaat. After construction, management of the Sand Engine peninsula was transferred to the Province of South Holland. In the current phase of the project, *Operation and Maintenance*, the project's outcomes are monitored, and the recreational safety and effects on the surroundings are controlled.

5. Results

Table 4 summarizes the uncertainties from all phases of the development process of the Sand Engine project, classified according to their type and the part of the system in which they are present. All uncertainties were either explicitly or implicitly mentioned in one or more key documents, during public information meetings or interviews. We constructed an uncertainty matrix for every project phase, summarizing the uncertainties relevant for project development in that specific phase (see Appendix B). These matrices contain the same uncertainties as Table 4, but provide insight in which particular phase(s) an uncertainty was present.

During our analysis, we recognized that three particular uncertainties were specifically addressed by at least four of the six interviewees. Moreover, the interviewees' description of the uncertainties expressed a high sense of urgency to actively cope with these issues as they potentially had severe consequences, namely cancellation of the Sand Engine project. Therefore, we argue that these uncertainties are typical examples of relevant key uncertainties for the Sand Engine project. We will now elaborate on these three uncertainties in more detail.

First, from an early stage in the project, there has been uncertainty about the influence of the Sand Engine on recreational conditions. These physical conditions in the coastal zone – for instance, the velocity of currents and the

Table 4 – Uncertainties in the Sand Engine (SE) project in the various phases of development.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems	How will the SE develop morphologically? (e.g., in terms of its shape and speed of development) What will be the effect of the SE on the currents? (e.g., eddy formation, velocity increase) What will be the yield of the SE (e.g., total beach area increase, erosion)?	What will be the effect of the SE on the groundwater level? What will be the effect of the SE on the fresh water supply (e.g., salt intrusion)?	Is it clear which aspects are most important regarding the project's nature development goals?
Technical system Infrastructure, technologies, innovations	What will be the effect of the SE on Scheveningen Harbour?	What is the relationship between sand mining and occasional findings of World War II ammunition on the beach?	Is World War II ammunition a potential recreational safety threat in the context of the SE? Are there clear standard requirements for the (measurement of) sand quality?
Social system Economic, cultural, legal, political, administrative and organizational aspects	How much money will stakeholders contribute to the project budget? What will be the effect of the SE on swimming conditions? What will be the effect of the SE on recreational conditions in general? What will be the effect of the SE on beach commerce? How will legal officials behave during construction?	Which permits are needed for the SE construction? Which effect will the SE have on houses near the coast (e.g., flooding of cellars)?	Is the construction tender economically attractive for potential contractors? Will the SE have an effect on the quality of drinking water? Is it clear who should be the competent authority for the SE nature permits? Are all key stakeholders willing to (financially) commit to the SE project? Is the chosen location optimal for the project or not? Is it clear which project goal has the highest priority? Should management of the SE be transferred as planned (31 October 2011) or after construction is finished? Can recreational safety in the vicinity of the SE be guaranteed?

presence of quicksand on the beach – are largely determined by natural dynamics such as the weather, which are inherently unpredictable. However, during project development, discussions have not focussed on physical *recreational conditions* – all parties involved agree that these conditions are highly uncertain – but on the social implication of *recreational safety*. Opponents of the project formed an anti-Sand Engine action committee and claim that it is unsafe to recreate in the Sand Engine's vicinity due the uncertainties around recreational conditions. However, according to the project team, uncertainties about the recreational conditions do not necessarily lead to an unsafe situation, if proper measures to control the recreational safety are taken. For instance, in the Sand Engine case, swimming is (temporarily) prohibited and active participation of the beach lifeguards was established, who received additional training. Although the interviewees were convinced that recreational safety is not at risk, there is still continuous attention for this issue. An interviewee stated:

> ''If it concerns uncertainties about safety... or uncertainties about health... [Those] are definitely uncertainties that can influence the entire societal debate. And then [can mean] 'end of project' as well.''

Second, the effects of the Sand Engine on groundwater levels and, consequently, on drinking water quality due to possible saltwater intrusion were an important issue in the Construction I phase. The project team claimed that changes in groundwater levels would not have significant effects on drinking water quality, as long as some minor mitigating measures were taken. However, a project stakeholder framed a situation of incomplete knowledge, arguing that there was not enough factual knowledge to support the claim that effects on groundwater levels would not be substantial. Hence, while the project team viewed the lack of factual knowledge as a minor concern, the project stakeholder framed the lack of knowledge as a major problem. Therefore, the stakeholder demanded additional research and even considered filing an official complaint, potentially causing significant and unacceptable delays. In the end, the project team adapted their own knowledge frame and commissioned an additional study regarding the groundwater problem. This study showed that the Sand Engine potentially had significant effects on drinking water quality. The problem was eventually solved by negotiating proper mitigating measures, such as installing a pumping station to transport salt sea water out of the vicinity of the drinking water area. For project development, the groundwater and drinking water uncertainties were a grave issue, as an interviewee clearly illustrated:

> "That was the largest uncertainty of last year, groundwater problems... That could have really stopped the project... If we did not have a contract with a constructor by the end of 2010, necessary funding [would be retrenched]. Then we wouldn't have had funding for the project and that would have meant ['end of project']."

Third, uncertainty about the financial commitment of stakeholders has been a continuing issue of attention. In the Initiation phase, the Province of South Holland was enthusiastic about the Sand Engine idea and took it as a promising initiative. However, several governmental agencies at the national level claimed that such an expensive experiment was undesirable, especially given the economic crisis at that time. In the end, an agreement was reached on a total available budget of limited size. However, in the Planning and Design II phase, the project team became anxious that potential constructors (i.e., dredging companies) would not adopt the team's knowledge frame that the Sand Engine would be an economically feasible project within the available budget. A potential constructor might also adopt a rather negative frame – constructing the Sand Engine is economically unattractive – and might decide not to commit to the project. One of the interviewees declared the following regarding this uncertainty:

> "We had a budget ceiling of €50 million... We needed 18.5 million m^3 [of sand] to construct it... [The price of a cubic meter of sand] was half of what was paid for nourishment works at that moment. So in terms of pricing, [it was] not very attractive for a constructor. So [that] was an uncertainty. Yes. Are we going to get a constructor for this job?... We could not afford a failed tender. Then, we would [leave 2010 and cross into 2011]."

6. Discussion

6.1. *What are the most important types of uncertainty related to BwN?*

There were many uncertainties identified in the Sand Engine case, but the uncertainties varied in the importance they had in project development. Our results suggest that uncertainty due to the existence of multiple knowledge frames, which causes ambiguity, is most important for BwN project development. First, the number of uncertainties due to the existence of multiple knowledge frames was larger than both the number of uncertainties due to unpredictability and incomplete knowledge (see Table 4). Second, as expressed in Section 5, we found out that the uncertainties about recreational safety, drinking water quality and financial commitment – which are all due to the existence of multiple knowledge frames – were more important for project development actors than other uncertainties. According to several interviewees, these uncertainties led to ambiguity about sensible social implications – for example, to what extent recreational safety in the vicinity of the Sand Engine can be controlled – which could have severely hampered or even terminated the development process. However, according to the same interviewees, the uncertainties did not hamper project development in the end as they were properly coped with.

We observe that ambiguity can emerge when the *significance* or *consequences* of either unpredictability or incomplete knowledge are framed differently by project actors. For instance, the ambiguity about how the Sand Engine affects drinking water quality was due to two conflicting interpretations of the *significance* of incomplete knowledge of the effects on groundwater levels. While one project stakeholder framed that the incomplete knowledge was a major problem and needed to be reduced by additional research, the project team initially framed that it was only a minor concern and there was no significant need for further study. In the end, the ambiguity was solved by negotiating appropriate mitigating measures, such as installing a pumping station. Similarly, the ambiguity about how the Sand Engine affects recreational safety was due to conflicting interpretations of the *consequences* of unpredictable coastal zone conditions. While the project team argues that the presence of the Sand Engine does not necessarily lead to an unsafe situation, project opponents claim that lethal accidents will certainly happen and demand to stop the project. In the end, the ambiguity was solved using specific safety control measures, namely prohibiting swimming in the vicinity of the Sand Engine and participating with and training beach lifeguards. These two examples show that the uncertainties – which are both ambiguities – were not solved by acquiring more information to reduce the underlying lack of factual knowledge, but by negotiation and participation of project actors. As ambiguity originates from the presence of conflicting knowledge frames, acquiring more information does not solve this specific type of uncertainty (Brugnach et al., 2011). Facilitating dialogues, participation and negotiation are essential to cope with the presence of conflicting knowledge frames and create mutual understanding among the actors involved (Brugnach and Ingram, 2012).

Contrary to what we hypothesized, uncertainty about the natural dynamics was not directly hampering Sand Engine project development. Instead, our observations imply that it is more important to manage the implications of the project on the activities of society than to cope with the incomplete knowledge or unpredictability of nature and its dynamics. Uncertainty about social implications can be a powerful tool to hamper project development and influence the actors involved. For instance, the aforementioned anti-Sand Engine action committee recognized the power of the uncertainties about recreational safety and drinking water quality. They attempted to actively use these health and safety issues to negatively influence the perception of the public and project actors, during public meetings and via the media. Moreover, the action committee was able to mobilize politicians in the Dutch parliament for their cause. Parliament members posed official questions about recreational safety (reviewed document 1; see Appendix A) and drinking water quality (reviewed document 2; see Appendix A), and even explicitly demanded to stop the project. The anti-Sand Engine action committee did not focus their efforts on the unpredictable effects of the natural dynamics on recreational conditions or the incomplete knowledge about effects on groundwater levels (uncertainties in the natural system). They specifically focussed on recreational safety and drinking water quality (uncertainties about the social implications of the Sand Engine), as it is more easy to influence the public opinion and impose a negative knowledge frame to project development actors when safety issues seem to be at stake.

Furthermore, our results show that uncertainty regarding technical issues is of even less relevance than the uncertainty regarding nature and its dynamics. First, in the Sand Engine project, the number of uncertainties in the technical system is much lower than in the natural and social systems (see Table 4). Second, several interviewees declared that the project does not present any technological challenges as it is not innovative regarding its nourishment technology. As one of our interviewees stated:

> "Technically, [the Sand Engine] is not very exciting. Sand nourishment, the Dutch can do that, right? But other parties as well. There is a lot of [technical expertise]. That is not what all the fuss is about... The specificity of this project is in speed, in cooperation and in [managing] the environment. [Those] are the real dynamics and uncertainties."

6.2. *How does the use of BwN principles change the policy arena?*

Policy and project development fundamentally changes when using a BwN approach instead of a command-and-control approach. Current flood management approaches typically focus on the relatively short term of 5–10 years (Van der Brugge et al., 2005) and are often based on building rigid structures – such as dikes – with a well-defined spatial scale. An interviewed expert addressed why people generally prefer such solutions:

> "The need to get a hold on the dynamic world is translated into a static image of the world. A picture. Well, the world looks like this [and] that is reassuring. Hence, that leads to [choosing] a dike [as flood protection measure]."

BwN changes this landscape of static pictures in a dynamic world, as ecological engineering designs involve larger scales than contemporary engineering (Odum, 1989). First, as BwN projects are driven by unpredictable natural dynamics, it is hard to define the exact length of the temporal scale of the project. Projects based on BwN principles will typically be long-term projects, such as the Sand Engine with an expected life span of 20–50 years. Second, the exact spatial scale of a BwN project is hard to define. BwN solutions generally use flexible materials, such as sand, which will adapt and distribute under the influence of natural dynamics without respecting human-defined administrative divisions, such as municipalities, provinces and even countries. An interviewee illustrated the increased complexity due to temporal and spatial scales with a metaphorical example:

> "For Rijkswaterstaat, it is quite easy. They say: I only have to [assure] that there is sufficient sand in [the] coastal system... But the province and the municipalities – then you are already zooming in – say: 'it is in my interest that [the sand] does not come on my doorstep but on [another] doorstep'. And why do they say that? [They have] interests on a smaller scale and the short term. And the visitor of the beach: he looks at an even smaller scale... 'At my entrance of the beach, I want to [actually] see the beach'. Additionally, you have to link the interests on the different scales with each other. Well, that is just very complicated. That is thus the largest difficulty of the project."

Moreover, the use of a BwN approach makes it more difficult to determine to what extent stakeholders should be involved during project development. First, while command-and-control solutions generally address a single water policy issue such as flood protection, BwN approaches integrate multiple disciplines and therefore have multiple goals. Due to the increasing number of goals, the number of interested stakeholders – each with their own knowledge frames – is likely to increase as well. Second, as the spatial scales of a project using BwN design principles are variable, the number of (non-)governmental parties that perceive to be in the sphere of influence of the project can be larger than in a command-and-control project. Furthermore, as a BwN solution has a variable temporal scale, government officials have to make decisions about projects of which the effects are unpredictable and might not be visible before the next election period. It seems logical that this consideration will affect the preferences of such government officials when comparing a project that uses BwN design principles and a well-defined command-and-control project, although it is not exactly clear in what way.

In short, evaluating a BwN solution based on its short-term effects on a fixed spatial scale – as project development actors are used to with the command-and-control flood management approach – is less suitable given the large-scale characteristics of BwN projects. However, we observe that project development actors still tend to evaluate the Sand Engine project, which is based on BwN design principles, as if it was a command-and-control project. Fundamental changes are not yet fully taken into account. For instance, in the public debate about recreational safety, focus is on the short term – the effect on the *current* swimming safety at the Sand Engine site – and limited attention is given to the equally relevant effects in later years. Another example is that it was unacceptable for some local politicians that the Sand Engine might have effects on Scheveningen Harbour. However, regarding such effects, no guarantees can be given as the Sand Engine's behaviour is not constrained by human-defined administrative divisions. Furthermore, the uncertainty about drinking water quality was partially caused by the difficulty to determine which stakeholders to involve or not. The complaining stakeholder was not a participant in the Sand Engine project team or a project group during the Planning and Design phases. As a result, the stakeholder's input and concerns emerged at a late and thus rather inconvenient moment, causing a situation of ambiguity.

6.3. *Why did uncertainty not hamper project development in this case?*

Contrary to what we hypothesized, we observe that none of the identified uncertainties – despite that project actors were anxious about several subjects – hampered project development in the Sand Engine case. Some additional studies were required to clarify particular issues – for instance, effects on drinking water quality – but in the end, no serious delays were caused by uncertainty. We argue that there are two main reasons that project development in this specific case was not hampered by uncertainty.

First, the governmental parties committed to the Sand Engine project formed a social coalition, which can be a powerful means to assure that one frame prevails over other – less desirable – frames (Kaplan, 2008). According to four interviewees, both actors inside and outside the project team perceived the Sand Engine as ''an innovation that must become reality''. One interviewee illustrated the consequences of this positivistic attitude:

> ''The lights were always on green. They did not want to be bothered by the things that we do not know... [On the other hand], if you could have addressed [those things] more accurately, that [would not automatically mean] that you would have decided not to construct [the Sand Engine].''

Interviewees characterized Sand Engine project development as a relatively fast process, but also stated that it was not allowed to take any risks regarding individual or societal safety. However, the abovementioned statement of the interviewee suggests that some uncertainties might have received less-than-regular attention in project development.

Second, the Sand Engine case is a pilot project and has an experimental character that deviates from regular projects. A pilot status can be used as an insurance to failure, as it enables risk minimization and facilitates dealing with uncertainty (Vreugdenhil et al., 2010). For instance, creating opportunities for new recreational activities is a goal of the Sand Engine project. However, it was not specified which types of recreation or how many recreants should be attracted, which means we cannot accurately measure success or failure of the project regarding recreational development. Similarly, other project goals were also formulated rather nonspecific and difficult to measure. This implies that a high level of certainty is not required – virtually any possible outcome can be interpreted as successful – and thus, the effect of uncertainty is minimized.

Although uncertainty did not hamper project development in the Sand Engine case, our results are valuable for anticipated future developments regarding sand nourishments and projects based on BwN principles in the Netherlands. According to the Delta Commission (2008), the annual sand nourishment volume in the Netherlands needs to increase to a level of 85 million m^3 per year in the period until 2050. Moreover, BwN solutions are explicitly mentioned as the preferred approach to strengthen the Dutch coasts (Ministry of Infrastructure and the Environment, 2009). Hence, more large-scale sand nourishments with similar volumes and design principles as the Sand Engine – and thus, with similar public attention, opposition, actor behaviour and project development processes – can be foreseen in the near future. If such initiatives based on BwN principles no longer have the pilot status, it is well possible that their project development process will be hampered by uncertainties similar to those identified in this paper.

7. Conclusions

Uncertainty is much more than a deficit of factual knowledge. This classic scientific interpretation of uncertainty – still commonly used in, for instance, engineering communities – does not capture the fundamental consideration that uncertainty gets meaning and value in the project development via its social implications. In the policy arena, multiple actors with different knowledge frames and interests interact and aim to influence the process and each other's frames (Brock and Durlauf, 2001). While managing uncertainty, bridging the gaps between these actors from different communities – such as engineers, politicians, scientists and the public at large – and creating mutual understanding about the subject at hand is far more important than reducing incomplete knowledge or increasing our control over the unpredictable systems to be managed. These findings are in accordance with recent other studies. For instance, Lach et al. (2005) conclude that managing ambiguous relationships becomes far more important than managing the uncertainties of the structures and routines in water management. However, the results from our study suggest that actors still tend to evaluate the Sand Engine, a project based on BwN design principles, as if it was a command-and-control flood management approach.

New approaches towards dealing with uncertainty are needed that can deal with all kinds of unforeseen developments (Walker et al., 2010), which can always be anticipated regarding the unpredictable nature of projects using BwN design principles. However, more importantly, new approaches are needed to cope with uncertainty due to framing differences and ambiguity (Brugnach et al., 2011), as the standard responses to cope with uncertainty – information gathering and top-down management – are no longer sufficient (Koppenjan and Klijn, 2004). Strategies are needed to cope with the diverging knowledge frames and interests of stakeholders, because they have different roles and backgrounds. Increasing participation, cooperation and dialogues between stakeholders can be powerful tools in this respect (Brugnach et al., 2011; Brugnach and Ingram, 2012). Nevertheless, it is important to realize that uncertainty due to multiple knowledge frames can have different backgrounds and characteristics and often has a relationship with other, knowledge-related uncertainties.

Simultaneously, we need to address the increased complexity of the systems to be managed when using a BwN approach. Existing knowledge frames need to adapt to the increasing uncertainty due to both changing temporal and spatial scales. Currently, this increasing complexity is still easily associated with an increase of potential health and safety risks. People tend to overestimate the probability of occurrence of events of which the potential consequences are easily imagined and severe (Thacher, 2009). Early communication with stakeholders is needed to create awareness about and acceptance of the fundamental differences between projects based on BwN design principles and the command-and-control flood management approach. We anticipate that effectively coping with these differences and other uncertainties associated with the BwN approach will be a critical success factor for this promising new initiative in the field of water management.

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Appendix A. Documents reviewed

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Appendix B. Uncertainties in each project development phase

Tables B.1–B.6 summarize the uncertainties that were identified as playing an explicit or implicit role in the individual phases of the Sand Engine's development process.

In the *Initiation* phase (Table B.1), we identified unpredictability about how the Sand Engine and the natural system will behave after it is constructed. Furthermore, it was unpredictable how much money stakeholders were willing to contribute to the project. Several government parties were discussing about the necessity of the Sand Engine and had different knowledge frames about whether it was acceptable to perform such a large-cost project in a period of economic problems. Hence, the commitment of important governmental stakeholders was still ambiguous.

In *Planning and Design I* (Table B.2), the unpredictable behaviour and effects of the Sand Engine had social implications: there was uncertainty about effects on swimming and recreational conditions. Furthermore, there was ambiguity concerning the project's goals and optimal location. Rijkswaterstaat wanted the Sand Engine to contribute to coastal safety, while the province of South Holland was mostly interested in enhancing the recreational quality of the coastal zone. The municipalities all had their own local goals and interests. As a result, all parties preferred a different project location. A specific theme in the location discussion was Scheveningen Harbour, as effects of the Sand Engine on this harbour were unacceptable for local politicians.

In *Planning and Design II* (Table B.3), a more specific uncertainty concerning the project goals emerged. As no specific and measurable nature development goals were defined in either the EIA or another project document, the ecologists involved in the Sand Engine project were unable to construct a shared knowledge frame during ecology-oriented project workshops. Some ecologists preferred alternatives that promote existing nature, where others favoured alternatives that potentially attract new species. Regarding the recreational conditions, discussions focussed on the more socially oriented issue of recreational safety. Furthermore, there was uncertainty

Table B.1 – Uncertainties in the Initiation phase of Sand Engine (SE) project development.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems	How will the SE develop morphologically? (e.g., in terms of its shape and speed of development) What will be the effect of the SE on the currents? (e.g., eddy formation, velocity increase) What will be the yield of the SE (e.g., total beach area increase, erosion)? What will be the yield of the SE (e.g., total beach area increase, erosion)?		
Technical system Infrastructure, technologies, innovations			
Social system Economic, cultural, legal, political, administrative and organizational aspects	How much money will stakeholders contribute to the project budget?		Are all key stakeholders willing to (financially) commit to the SE project?

Table B.2 – Uncertainties in the Planning and Design I phase of Sand Engine (SE) project development.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems	How will the SE develop morphologically? (e.g., in terms of its shape and speed of development) What will be the effect of the SE on the currents? (e.g., eddy formation, velocity increase) What will be the yield of the SE (e.g., total beach area increase, erosion)?		
Technical system Infrastructure, technologies, innovations	What will be the effect of the SE on Scheveningen Harbour?		
Social system Economic, cultural, legal, political, administrative and organizational aspects	How much money will stakeholders contribute to the project budget? What will be the effect of the SE on swimming conditions? What will be the effect of the SE on recreational conditions in general?		Are all key stakeholders willing to (financially) commit to the SE project? Is the chosen location optimal for the project or not? Is it clear which project goal has the highest priority?

about the (economic) attractiveness of the Sand Engine for constructors (i.e., dredging companies).

In *Construction I* (Table B.4), there was uncertainty related to acquiring the required permits and about the attractiveness of the construction tender. In this phase, opponents of the Sand Engine project actively attempted to stop the project by pointing out potential recreational safety problems. Furthermore, the lack of knowledge about the effects on the fresh water supply created a severe commitment problem.

In *Construction II* (Table B.5), the attention in project development shifted to issues that could potentially endanger the successful construction and management of the project. Legal officials can behave unpredictable, take strategic decisions and some have legal power to stop the project. For instance, there was uncertainty concerning measurements of sand quality. The project team claimed that measurements were proper and quality was sufficient, where legal officials framed that measurements were not done properly and results proved that the sand was contaminated. Furthermore, there was uncertainty about the date that the management of the Sand Engine peninsula should be transferred from Rijkswaterstaat to the Province of South

Table B.3 – Uncertainties in the Planning and Design II phase of Sand Engine (SE) project development.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems	How will the SE develop morphologically? (e.g., in terms of its shape and speed of development) What will be the effect of the SE on the currents? (e.g., eddy formation, velocity increase) What will be the yield of the SE (e.g., total beach area increase, erosion)?	What will be the effect of the SE on the groundwater level?	Is it clear which aspects are most important regarding the project's nature development goals?
Technical system Infrastructure, technologies, innovations	What will be the effect of the SE on Scheveningen Harbour?		
Social system Economic, cultural, legal, political, administrative and organizational aspects	How much money will stakeholders contribute to the project budget? What will be the effect of the SE on swimming conditions? What will be the effect of the SE on recreational conditions in general? What will be the effect of the SE on beach commerce?		Is the construction tender economically attractive for potential contractors? Are all key stakeholders willing to (financially) commit to the SE project? Is the chosen location optimal for the project or not? Can recreational safety in the vicinity of the SE be guaranteed?

Table B.4 – Uncertainties in the Construction I phase of Sand Engine (SE) project development.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems		What will be the effect of the SE on the groundwater level? What will be the effect of the SE on the fresh water supply (e.g., salt intrusion)?	
Technical system Infrastructure, technologies, innovations		What is the relationship between sand mining and occasional findings of World War II ammunition on the beach?	Is World War II ammunition a potential recreational safety threat in the context of the SE?
Social system Economic, cultural, legal, political, administrative and organizational aspects	What will be the effect of the SE on swimming conditions? What will be the effect of the SE on recreational conditions in general?	Which permits are needed for the SE construction? Which effect will the SE have on houses near the coast (e.g., flooding of cellars)?	Is the construction tender economically attractive for potential contractors? Will the SE have an effect on the quality of drinking water? Is it clear who should be the competent authority for the SE nature permits? Are all key stakeholders willing to (financially) commit to the SE project? Can recreational safety in the vicinity of the SE be guaranteed?

Holland. The construction was highly successful and finished months earlier than planned. Where Rijkswaterstaat framed that management should be transferred as soon as construction was finished, the Province of South Holland was unwilling to assume responsibility earlier than the initially planned completion date.

In the *Operation and Maintenance* phase (Table B.6), only three uncertainties can currently be identified. Swimming and recreational conditions will be issues for monitoring by researchers. Moreover, opponents of the Sand Engine will probably continue to address recreational safety issues.

Table B.5 – Uncertainties in the Construction II phase of Sand Engine (SE) project development.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems			
Technical system Infrastructure, technologies, innovations		What is the relationship between sand mining and occasional findings of World War II ammunition on the beach?	Is World War II ammunition a potential recreational safety threat in the context of the SE? Are there clear standard requirements for the (measurement of) sand quality?
Social system Economic, cultural, legal, political, administrative and organizational aspects	What will be the effect of the SE on swimming conditions? What will be the effect of the SE on recreational conditions in general? How will legal officials behave during construction?		Are all key stakeholders willing to (financially) commit to the SE project? Should management of the SE be transferred as planned (31 October 2011) or after construction is finished? Can recreational safety in the vicinity of the SE be guaranteed?

Table B.6 – Uncertainties in the Operation and Maintenance phase of Sand Engine (SE) project development.

	Unpredictability Unpredictable behaviour of nature, humans or the system	*Incomplete knowledge* Imperfection of knowledge, inexactness, approximations and ignorance	*Multiple knowledge frames* Equally valid interpretations of a phenomenon
Natural system Climate impacts, water quantity, water quality, ecosystems			
Technical system Infrastructure, technologies, innovations			
Social system Economic, cultural, legal, political, administrative and organizational aspects	What will be the effect of the SE on swimming conditions? What will be the effect of the SE on recreational conditions in general?		Can recreational safety in the vicinity of the SE be guaranteed?

In short, we observe that the importance of the social implications of the Sand Engine gradually increased during project development, probably due to the gradually increasing involvement of stakeholders and societal interests. When initiatives become more concrete, it is more easy and important to imagine the consequences of such plans for society. For instance, in the Initiation phase, the uncertainty about the effect of the project on coastal conditions (uncertainty in the natural system) was identified. In the Planning and Design I phase, uncertainty about swimming conditions was identified as a specific theme (uncertainty in the social system). In the Planning and Design II phase, the important social discussion about the implications of the Sand Engine for recreational safety was fully exposed (uncertainty in the social system regarding societal implications). After the approval of the EIA at the end of the Planning and Design II phase, the focus in project development radically shifted from the physical aspects of the Sand Engine to the preparation of the construction and monitoring. During the Construction II phase (see Table B.5), uncertainty in the natural system was even completely absent in project development, as the main interest of this phase was the physical construction of the Sand Engine.

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