

PDF hosted at the Radboud Repository of the Radboud University Nijmegen

The following full text is a postprint version which may differ from the publisher's version.

For additional information about this publication click this link.

<http://repository.ubn.ru.nl/handle/2066/128081>

Please be advised that this information was generated on 2020-10-22 and may be subject to change.

How to structure and prioritize information needs in support of monitoring design for Integrated Coastal Management

Pim Vugteveen^{a}, Marieke M. van Katwijk^a, Etiënne Rouwette^b & Lucien Hanssen^c*

^aDepartment of Environmental Science, Institute for Water and Wetlands Research, Radboud University Nijmegen
Heyendaalseweg 135
6525 AJ Nijmegen, The Netherlands
p.vugteveen@science.ru.nl; m.vankatwijk@science.ru.nl

^bMethodology Department, Nijmegen School of Management, Radboud University Nijmegen
Thomas van Aquinostraat 1
6525 GD Nijmegen, The Netherlands
e.rouwette@fm.ru.nl

^cDeining Societal Communication & Governance
Peter Scheersstraat 26
6525 DE Nijmegen, The Netherlands
l.hanssen@fo.nl

*Corresponding Author:

Address Dr. Pim Vugteveen
 Department of Environmental Science
 Institute for Water and Wetlands Research, Faculty of Science
 Radboud University Nijmegen
 P.O. Box 9010
 6500 GL NIJMEGEN
 The Netherlands

Email p.vugteveen@science.ru.nl

Telephone +31 24 3652623

Abstract

Integrated Coastal Management cannot operate effectively without reliable information and knowledge on changes in the environment and on the causes of those changes. Monitoring is essential to provide data needed for a real understanding of socio-economic and ecological functioning in multi-user nature areas. We present a web-based and comprehensive assessment methodology to articulate, structure and prioritize information needs and ensuing monitoring needs. We applied this methodology in the Dutch Wadden Sea region, which includes a designated UNESCO World Heritage nature reserve. The methodology consisted of the following steps: i) exploring social-ecological issues of concern and defining the monitoring scope; ii) articulating information needs expressed as tractable questions; iii) elaborating monitoring needs; iv) grounding in scientific models and current monitoring; v) synthesizing assessment findings into target entities, i.e. analysis variables for monitoring. In this paper we focus on the first three steps. As part of our methodology we performed two online surveys amongst a broad range of stakeholders and amongst monitoring professionals. In case of the Dutch Wadden Sea region, main monitoring questions were related to biodiversity and food web relations; effects of fisheries and its pressures on the ecosystem; channel and port dredging; spatial planning and multifunctional use; sustainable energy production; and effects of changing storm regimes due to climate change. Subsequently we elaborated these general issues into analysis variables within five themes. The presented methodology enables large scale and unbiased involvement of stakeholders in articulating information needs in a multi-user nature reserve like the Wadden Sea. In addition the methodology facilitates the input and feedback of monitoring professionals by providing a detailed elaboration of monitoring needs.

Keywords: information needs, adaptive monitoring, stakeholder involvement, Wadden Sea, integrated coastal management, social-ecological system

1. Introduction

Integrated coastal management cannot operate effectively without reliable information and knowledge on changes in the environment and on the causes of those changes. Research and monitoring are key components of an informed process for policy and decision making (Hanssen et al., 2009; Pouwels et al., 2011; Wortelboer and Bischof, 2012). To support evidence-based policy making long-term monitoring is needed to provide better understanding of ecosystem functioning in relation to human use. Long-term monitoring is especially relevant to the Wadden Sea, which is considered as one of the most important tidal areas in the world. Large parts are designated nature reserves and constitute a World Heritage Site since 2009 (CWSS, 2008). Concerns over the state of the Wadden Sea region and the impacts of anthropogenic activities have created the need for high-quality, long-term datasets as a basis for an integrated understanding of environmental and socio-economic changes (De Jonge et al., 2012; Kabat et al., 2012). Deficiencies and insufficiencies in relevant data, information, and knowledge have been however reported as main impediments with regard to such an integrated understanding for management (Douve and Ehler, 2011; Vos et al., 2000).

In the Netherlands the *Wadden Sea Long-Term Ecosystem Research* project (WaLTER) has been recently initiated to develop a blue print for an integrated monitoring network for the Dutch Wadden Sea region (www.walter.nl). Initiated by a number of research institutes and organisations that carry out long-term measurements and research, WaLTER aims to improve and integrate existing monitoring programmes, identify and fill possible gaps in the current monitoring network, and make existing and new data more readily accessible (WaLTER project team, 2010). Ultimately WaLTER aims to be the main platform for regional adaptive monitoring and learning. Advancement of the WaLTER portal and monitoring network addresses a major challenge identified by Kates et al. (2001), i.e. how to integrate and extend today's operational systems for monitoring and reporting on environmental and social conditions, so that more useful guidance for efforts aimed at a transition toward sustainability is created.

It has been argued that many environmental monitoring systems lack a clear purpose. A mere 'knowing-what-is-going-on' argument often seems to motivate the effort (Vos et al., 2000). However, such a vague argument cannot be used to derive clear objectives and will easily result in 'dataleptomania', i.e. the uncontrolled desire to collect more data. Altogether this may lead to the so-called 'data-rich-but-information-poor syndrome' (Timmerman et al., 2010a). Efficient and effective monitoring therefore calls for an explicit articulation of stakeholder information needs as well as their translation into monitoring requirements (Lindenmayer and Likens, 2009; McNie, 2007).

A structured dialogue between information users on the one hand, and information producers on the other is essential in order to ensure that information supplied by the monitoring program is tailored to the needs of users and based on best available scientific understandings (Maddox et al., 1999; Sutherland et al., 2011; Timmerman et al., 2000; Vaughan et al., 2007).

A thorough assessment of information needs and their subsequent elaboration into requirements for monitoring network design are explicitly incorporated into the WaLTER project setup. In this paper we describe the respective steps of a web-based and comprehensive assessment methodology to articulate, structure and prioritize information needs and ensuing monitoring needs. We describe the results of its application in the context of adaptive monitoring in the Dutch Wadden Sea region. Section 2 introduces the rationale and conceptual framework that underlie our assessment of information and monitoring needs. Next Section 3 describes the methodological steps of our approach. Section 4 reports the results from the performed assessment in the context of Wadden Sea. Finally Section 5 discusses the implications of our findings for socio-ecological monitoring and Integrated Coastal Management in general.

2. Monitoring for Integrated Coastal Management

Integrated Coastal Management (ICM) involves a management process cycle that emphasizes the learning aspects of monitoring and evaluation, i.e. *adaptive* management. Adaptive management has been advocated as an approach to deal with the incomplete knowledge about the system being managed, allowing action in the face of uncertainty in the short run while information gaps are filled in over the longer term (Lee, 1999; Loucks et al., 2005; Stem et al., 2005). An adaptive management strategy is highly appropriate for the Wadden Sea region. The region is characterized by a high level of complexity and dynamics in which social and natural drivers are so inextricably intertwined that the notion of ‘social-ecological system’ is appropriate (Kabat et al., 2012).

Improved understanding of the complex interplay of natural processes and socio-economic activities in the Wadden Sea region does not only call for an adaptive, but also an *integrative* form of monitoring and management as well. In line with EU principles on ICM (European Commission, 2002) this means collecting data on ecological as well as socio-economic subsystems, and the use of integrative indicators in management (De Jonge et al., 2012).

Furthermore, it has been widely acknowledged that *long-term* monitoring efforts are essential for gaining understanding of complicated social-ecological systems such as the Wadden Sea region. Long-term data are important for many reasons, i.e. defining baseline conditions, detecting and evaluating changes in the ecosystem as may occur in response to management interventions, as well

as evaluating responses to disturbances and stresses that act on a long time scale like climate change (Day 2008; Lindenmayer and Likens, 2009; Parr et al., 2003).

Figure 1 shows the basic elements required for an adaptive management cycle in the project context of WaLTER. Monitoring is not an end in itself but derives its function and value from the context in which it is used (Lyons et al., 2008; Nichols and Williams, 2006). Generally monitoring networks perform three functions: signalling, controlling and investigating (Stem et al., 2005). The first two of these functions are mainly policy-driven while investigative monitoring is principally research-driven. These functions are also captured in the types of monitoring used by the European Water Directive, wherein a distinction is made between surveillance, operational and investigative monitoring (European Commission, 2003).



Figure 1. Adaptive management cycle based on monitoring. The WaLTER project supports adaptive management by addressing (new) information questions and learning, therefore using policy-driven (surveillance and operational) and research-driven monitoring (investigative). Adapted from Parr et al. (2003).

In management, monitoring is needed to evaluate to what extent what we are doing is wise, efficient, effective and equitable. This requires the data and information derived from monitoring to be credible, legitimate, and salient. Credibility refers to how authoritative and reliable information is,

while legitimacy refers to how fair and respectful the production of information is in terms of considering opposing values, concerns, and perspectives of different stakeholders. Finally salience deals with how relevant and usable information is to decision making bodies or publics. Although these aspects are all critical in relation to monitoring design and effectiveness, they are often neglected (Cash et al., 2002; 2003; McNie, 2007; Timmerman et al., 2001). Credibility challenges monitoring design to be based on robust and state-of-the-art science-based models about the ecological and socio-economic functioning of the system. The WaLTER project aims to develop an online portal for data as well as information products, thereby contributing to information production as well as diffusion. Here legitimacy trade-offs apply to the translation of data into unbiased information, especially information that is produced to support policy-making. The legitimacy aspect is highly significant in complex multi-stakeholder nature reserves like the Wadden Sea where conflicts of interest frequently arise (Floor et al., 2013; Runhaar and van Nieuwaal, 2010). Finally the salience criterion demands that relevant information needs of potential users are taken fully into account in monitoring strategies and design of the data and information portal. These three requirements to information value are to be taken into equal consideration and need to be balanced in the overall design of the WaLTER monitoring network. As the salience of information production is a generally underappreciated aspect of monitoring design (Lindenmayer & Likens, 2009), this aspect will be the focus of this study.

Adopting an adaptive monitoring framework means that monitoring activities can be refined and adapted as new understandings emerge or new information needs arise. The iterative monitoring and evaluation steps visualized in Figure 1 ensure on-going learning for adaptive management processes. The monitoring network that WaLTER develops is envisioned as an active 'learning institution' for enhancing the capabilities of involved actors to influence and participate in management planning, implementing adaptive monitoring processes in response to new information questions by stakeholders or new scientific insights. Institutional learning is here defined as the sharing and reflection on facts and values that takes place amongst both individuals and groups to improve ICM and taking agreed actions (Armitage et al., 2008; Biggs et al., 2012; Cundill and Fabricius, 2009). Over time WaLTER is envisioned to grow into the formal monitoring authority for the region, responsible for assisting implementation, training and agenda-setting for adaptive monitoring. It is to function as a reference platform of quantitative data and information against which future management and scientific progress can be effectively compared.

3. Methodology for assessing information needs in WaLTER

We applied a web-based and comprehensive assessment methodology to articulate, structure and prioritize information needs and ensuing monitoring needs. The methodology involves the following steps: i) Exploring social-ecological issues of concern and defining the monitoring scope; ii) Articulating information needs expressed as tangible and tractable questions; iii) Elaborating monitoring needs; iv) Grounding in scientific models and current monitoring; v) Synthesizing assessment findings into target entities or monitoring. The coherence between these steps is visualized in Figure 2. Each of the steps is described in more detail below. The WaLTER project applies this structured approach in the Dutch Wadden Sea region. So far the first three steps have been completed and these present the focus of this paper.

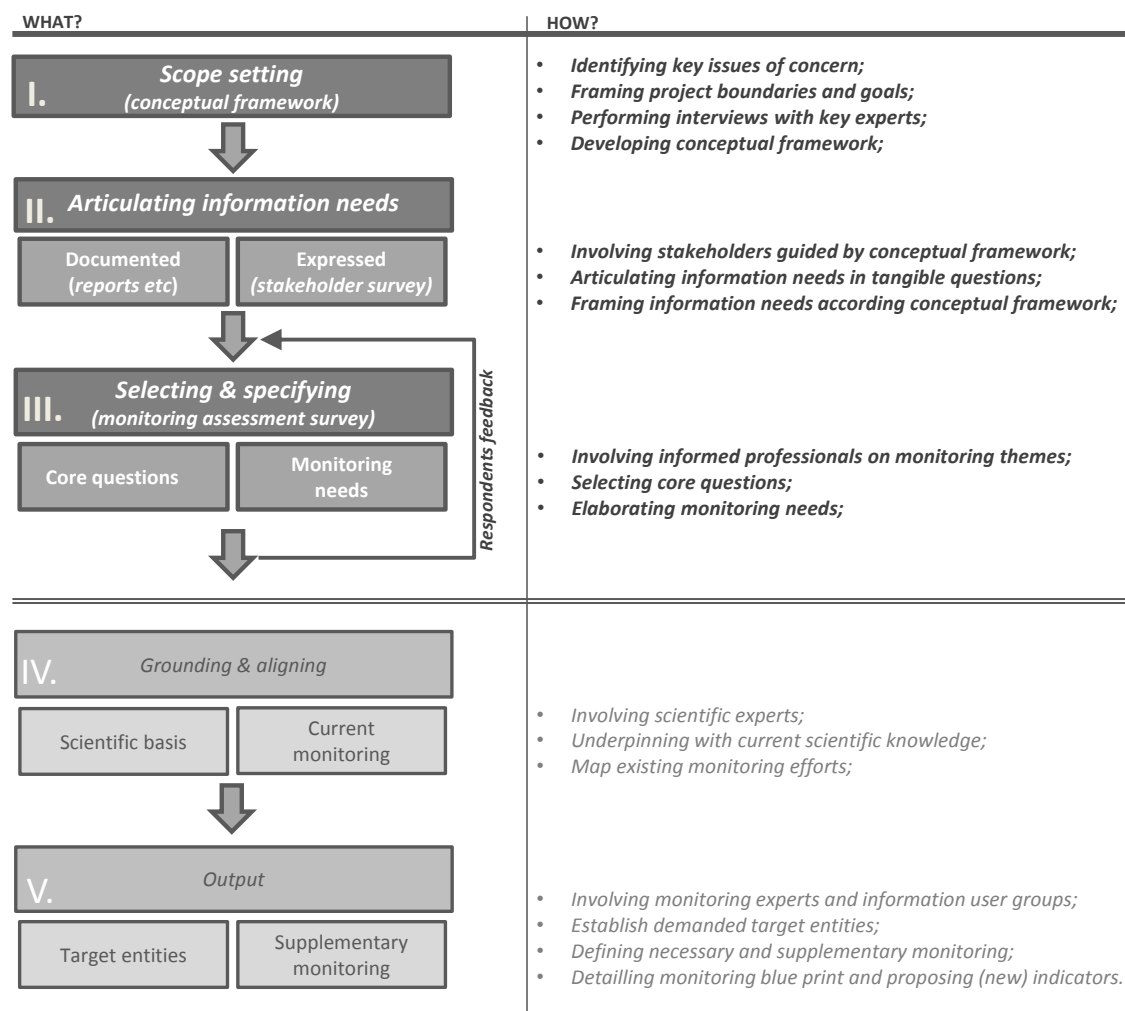


Figure 2. Assessment of information and ensuing monitoring needs. Steps I, II and III are addressed in this study.

3.1 Scope setting

The first step focused on exploring the scope of the monitoring network to be developed. Therefore, the key policy and social-ecological issues of concern in the Wadden Sea region were abstracted from policy documents and media items. Additionally, exploratory interviews were performed with leading experts and representatives of major programmes driving developments in the region. These programmes are introduced in Box 1. The desk study and interviews were also used to identify relevant stakeholder groups and potential participants for our surveys performed in the next assessment steps.

Box 1. Challenges for the management of the Wadden Sea region

Challenges for policy and management in the Dutch Wadden Sea region are evident in a number of major developments and prevailing policy programmes. These developments characterize the complex interplay between natural processes and socio-economic activities in the region.

In a major plan for restoring natural values in the Wadden Sea, called *Programme Towards A Rich Wadden Sea*, NGO's and government bodies aim to cooperate in improving management of physical infrastructures, coastal defences, fisheries, and other forms of exploitation. An important component of the programme includes a transition process of the mussel fishery sector towards *sustainable fisheries* (PRW, 2010).

Following global trends, international trade and transport flows have significantly increased in the region, triggering the expansion of agribusinesses, port infrastructures and chemical industries along the coast, the latter especially in the Eemshaven and Delfzijl areas. Energy production and associated offshore industries constitute a major and growing sector in the region. Developments include the planning and building of new power stations, the extraction of natural gas below the Wadden Sea and developing offshore wind parks. It has been recognized that these large-scale investments have benefits especially outside the region but possibly have negative environmental impacts within the Wadden Sea area.

Climate change and anticipated sea-level rise will put pressure on the safety of the inhabitants of the Wadden Sea region. They pose a threat to regional economic activities and infrastructures. The national *Delta Programme* focuses on safety protection against high water and maintaining freshwater supply into the future. Part of the programme is specifically directed at the Wadden Sea region (Delta Programme, 2012).

Demographic developments pose major challenges for the future as well. In particular the coastal areas are dealing with out-migration resulting in population decline and a decline of local social facilities.

The Dutch Wadden Sea region is part of an international context: ecologically, economically and politically. Since 1978, The Netherlands, Denmark and Germany have been working together on the protection and conservation of the Wadden Sea covering management, monitoring and research, as well as political matters. From 1987 onwards the *trilateral cooperation* has been coordinated by the Common Wadden Sea Secretariat (CWSS). Important information activities include coordination of the Trilateral Monitoring and Assessment Program (TMAP) and the production of Quality Status Reports.

The orientation and scope setting phase informed the development of a conceptual framework to give direction to the strategic goals of the WaLTER monitoring network. As shown in Figure 3, two main services are anticipated for the network and its online portal: supplying monitoring data as well as offering derived information products on high profiling issues for the Wadden Sea region such as climate change, fisheries, port developments, nature etc.

The framework presented here combines two basic systemic concepts to capture and anticipate key data and information needs, and to give direction to the design of the WaLTER monitoring network. The conceptual framework is used to structure the design process and assure that the full scope of information needs and their underlying monitoring elements are covered (Timmerman, 2011).

The framework incorporates a social-ecological system perspective for delineating the full scope of desired monitoring data. The WaLTER project aims for monitoring in support of sustainable regional development as well as the integrated management of all activities occurring in or affecting the Dutch Wadden Sea region. Management efforts towards achieving sustainable developments under conditions of social–ecological change need to be based on the understanding that all humanly used resources are embedded in complex social-ecological systems (SESs), i.e. that the management system consists of interconnected ecological, economic, social and political domains of organization (Holling, 2001; Kates et al., 2001; Ostrom, 2009).

Effective monitoring design demands the definition of tractable ecological and socio-economic questions, and choosing the most relevant target entities among a host of possibilities in complex systems (Lindenmayer and Likens, 2009, 2010). Based on conceptual models of the social-ecological system, relevant target entities can be derived and incorporated into the monitoring network. Hereby some target entities are important because they represent critical processes (e.g. nutrient budgets) whereas others are important because they represent societal values at stake (e.g. liveability).

Directing monitoring efforts at key system variables improves the likelihood that acquired data will be useful for studying and dealing with future social-ecological issues (Lovett et al., 2007). In order to capture important SES phenomena for management, target entities for monitoring should ideally reflect all the key elements of causal-effect chains and social responses in the system, allowing the identification of factors driving system changes and their consequential impacts. The conceptual framework as shown in Figure 3 incorporates a simplified version of the DPSIR (Drivers-Pressures-State-Impacts-Responses) approach to ensure comprehensive information (Atkins et al., 2011; Bowen and Riley, 2003; Maxim et al., 2009). The system analytic logic of this approach can be used to structure required target entities, i.e. indicators in a framework of pressures, state, benefits and responses (i.e. PSBR approach). It includes indicators targeting four focal areas: threats to the

system, the state of the system, ecosystem services and resulting benefits, and institutional responses (Jones et al., 2013; Sparks et al., 2011).

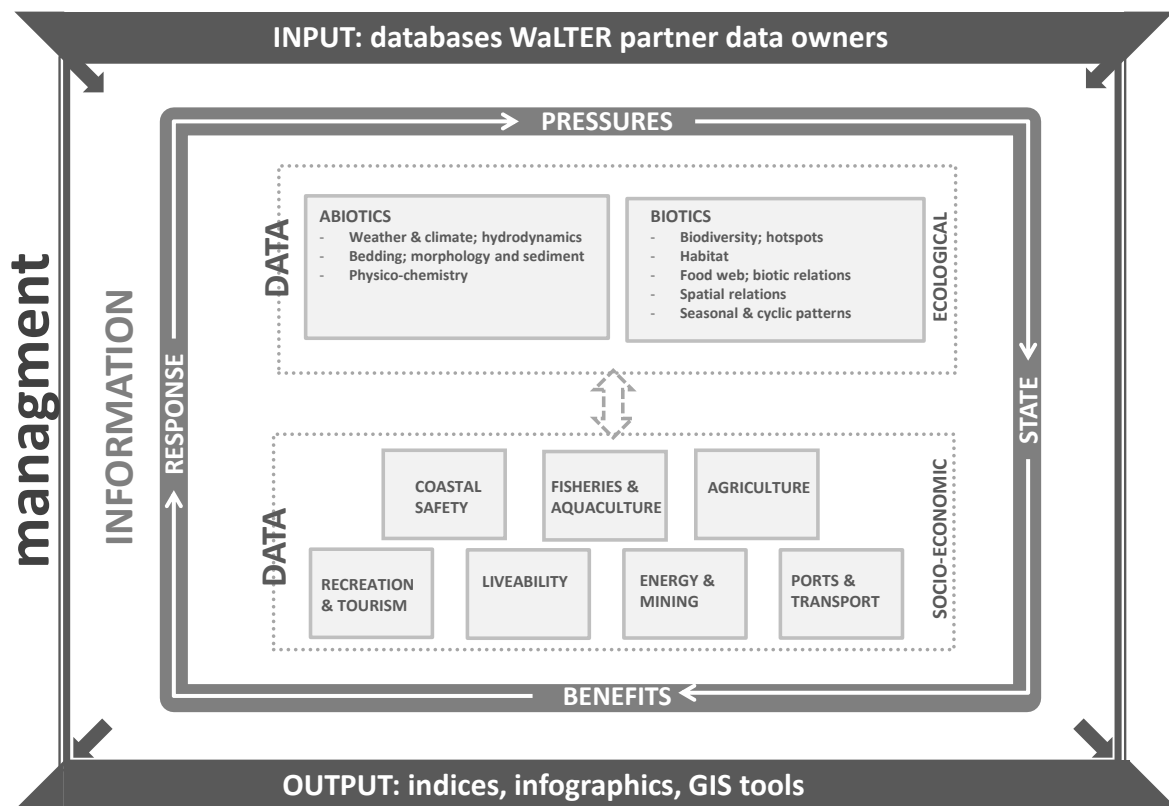


Figure 3. The WalTER conceptual framework. It involves three levels: data, information, and management. The framework combines two systemic concepts: the SES concept guides data input whereas the PSBR approach guides indicator development at information level.

3.2 Articulating information needs

An inventory of information needs was performed based on two sources. First we assessed the policy and research questions in recent documentation on the Wadden Sea region, yielding information questions articulated in policy memoranda, policy advisory reports, as well as research questions as expressed in academic research reports and programmes.

Next an inventorying survey was developed aimed to identify stakeholder information needs.

First stakeholders were invited to detail the issues of concern in terms of threats and opportunities as perceived by them. Then the focal section of the survey invited respondents to articulate their information needs and formulate them as tangible questions. The Survey Monkey software package was used for design and distribution of the survey (www.surveymonkey.com). The online survey was pre-tested within a small pilot group and then sent to over 300 persons covering all major

stakeholder groups in the Wadden Sea region. Among them were representatives of government bodies, industries, nongovernmental organizations, research institutes and universities. A total of 133 respondents (43 % response rate) completed the survey. Combining both documented and expressed information needs a database was built containing over 1100 questions. All questions were checked for relevance to programmatic long-term monitoring and tractable questions were selected. Next the database was cleaned and checked semantically. Redundancies were removed and questions were rephrased, merged or expanded. This ultimately left 538 questions in the database. The nature of the questions was both fundamental as well as applied and represented a broad scope of issues. The questions were classified in five key social-ecological themes: Climate & Water Safety, Nature, Fisheries, Ports & Energy, and Sustainable Use of the Wadden Sea Region. Having filtered and redefined our database into tractable information needs, the next step focused on assessing the high priority questions and the monitoring needs for addressing them.

3.3 Specifying monitoring needs

Separate assessments of monitoring needs were conducted for each of the five themes using customized and sophisticated online survey techniques. Experts in monitoring and professionals familiar with Wadden Sea monitoring data were invited to prioritize the assessed information questions and translate them into monitoring needs. The latter included the specification of relevant measurement units and spatial and temporal resolutions of interest, as well as suggestions for useful and promising innovations in monitoring techniques. We explicitly invited informed professionals in monitoring since stakeholders may have overlapping interests and may not be aware or directly interested in key environmental variables that should be monitored. This specifically concerns underlying environmental variables that influence more general aspects of how systems function, i.e. baseline variables that the WaLTER project is particularly interested in identifying.

Box 2 outlines the general design of the survey as applied to all five thematic assessments. In preparing the individual assessments, the design and contents were cross-checked with project leaders from major policy programmes in the Wadden Sea region (see Box 1). A selected pilot group pre-tested and checked the contents, presentation, formulation and flow of the survey. Respondents received a fee for participating. The Qualtrics software package was used for design and distribution of the survey (www.qualtrics.com). A web-based application provides major advantages over traditional paper versions as surveys can be easily distributed and carried out online. All data can be automatically saved, imported and processed. After processing and analysis the general findings of the survey were reported back to the respondents and they were invited to provide feedback.

Box 2. Monitoring needs survey outline and definitions

Section I (Q1-2)	<i>Respondent personal information</i> <ul style="list-style-type: none">• Name, organization, field and level of expertise
Section II (Q3-6)	<i>Selecting key questions</i> <ul style="list-style-type: none">• Two-step selection process to definitive key information questions
	<u>Per selected key question:</u>
Section III (Q7-14)	<i>Indicating required monitoring type and scale</i> <ul style="list-style-type: none">• Surveillance, operational, or investigative monitoring• Continuous, periodical or event-dependent monitoring• Long-term or temporarily monitoring• Indication relevant scale resolution
Section IV (Q15)	<i>Specifying what needs to be analyzed</i> <ul style="list-style-type: none">• Defining essential analysis variables
Section V (Q16)	<i>Specifying what needs to be measured</i> <ul style="list-style-type: none">• Defining monitoring needs• Indicating relevant frequencies & spatial resolutions
Section VI (Q17-19)	<i>Additional information</i> <ul style="list-style-type: none">• Indicating essential current monitoring activities• Indicating (technical) innovations in monitoring

3.4 The next steps

The assessment of information and monitoring needs is to be followed by a check against current scientific understanding and against existing monitoring programmes. This specific analysis of the scientific basis and current monitoring efforts is part of the WaLTER design process but as mentioned earlier, is beyond the scope of this paper. We will therefore only briefly describe the next steps to complete the overall picture of our approach in the WaLTER project.

Rigorous and relevant scientific substantiation is fundamental for identifying and specifying key relations and variables to be monitored (Lindenmayer and Likens, 2010). Proposed measurements should be derived from the best available understandings of the monitored system to increase the likelihood that the monitoring network will offer relevant and credible information and achieve its objectives (MacDonald and Smart, 1993; Pullin et al., 2009).

Importantly, grounding of the design also involves a mapping of the information supply, i.e. what is currently being monitored. This requires a complete overview of existing monitoring networks and databases that are relevant to the predefined monitoring scope. This overview is necessary to analyse the information gap, i.e. the gap between the information needs (demand) and available

information from existing monitoring programmes and data sources (supply). Confronting information supply and demand helps to decide which information needs are not yet addressed or sufficiently met, which synergetic possibilities may be present in current and planned monitoring efforts, and which monitoring efforts are redundant (Daams and Sijtsma, 2013; Timmerman et al., 2001). In the end all acquired design information builds up to a detailed blueprint for monitoring, including choices for target entities and specific measurement requirements concerning spatial and temporal resolutions of interest.

4. Results: information and monitoring needs for the Wadden Sea region

For the monitoring needs survey an average response rate of 52 % was achieved. To identify information needs priorities each respondent selected a short list of 10-15 questions out of a long list of information questions (Table 1). Across all respondents and thematic assessments 58-96 % of the information questions were selected as being the most important and relevant.

Table 1 summarizes the results from the information needs survey (A) and monitoring needs survey (B). It presents the total number of information questions inventoried and included in the next five thematic assessments, the survey response rates, number of respondents, the share (%) of key questions selected by the respondents per theme, and finally the share (%) of most selected key questions, i.e. being selected at least four times in the selection process.

Table 1. Summary of information needs survey and monitoring needs survey

<i>Summary</i>		# included questions	% response rate	# respondents	% key selected	% top selected
A.	Information needs survey (respondent group: stakeholders)					
	Documented	639				
	Expressed through survey	463	43	133		
	After redundancy and semantic checks	538				
B.	Monitoring needs survey (respondent group: monitoring professionals)					
1.	Climate & Water Safety	103	63	17	70	40
2.	Nature	191	55	16	58	15
3.	Fisheries	72	53	16	96	36
4.	Ports & Energy	62	53	18	80	34
5.	Sustainable Use WSR	110	36	16	64	21

4.1 Information priorities

In the monitoring needs survey (Table 1, B1-B5), information needs were categorized into different themes and topics. Figure 4 depicts the thematic and topical distribution of the most frequently selected key questions (i.e. selected by at least four respondents). As shown, major topics include: large system processes and biodiversity (22% and 20% respectively; theme Nature), the effects of fishing (37%; theme Fisheries), morphological development (35%; theme Climate & Water Safety), energy production (35%; theme Ports & Energy), and sustainable economic development (50%; theme Sustainable Use of the Wadden Sea Region).

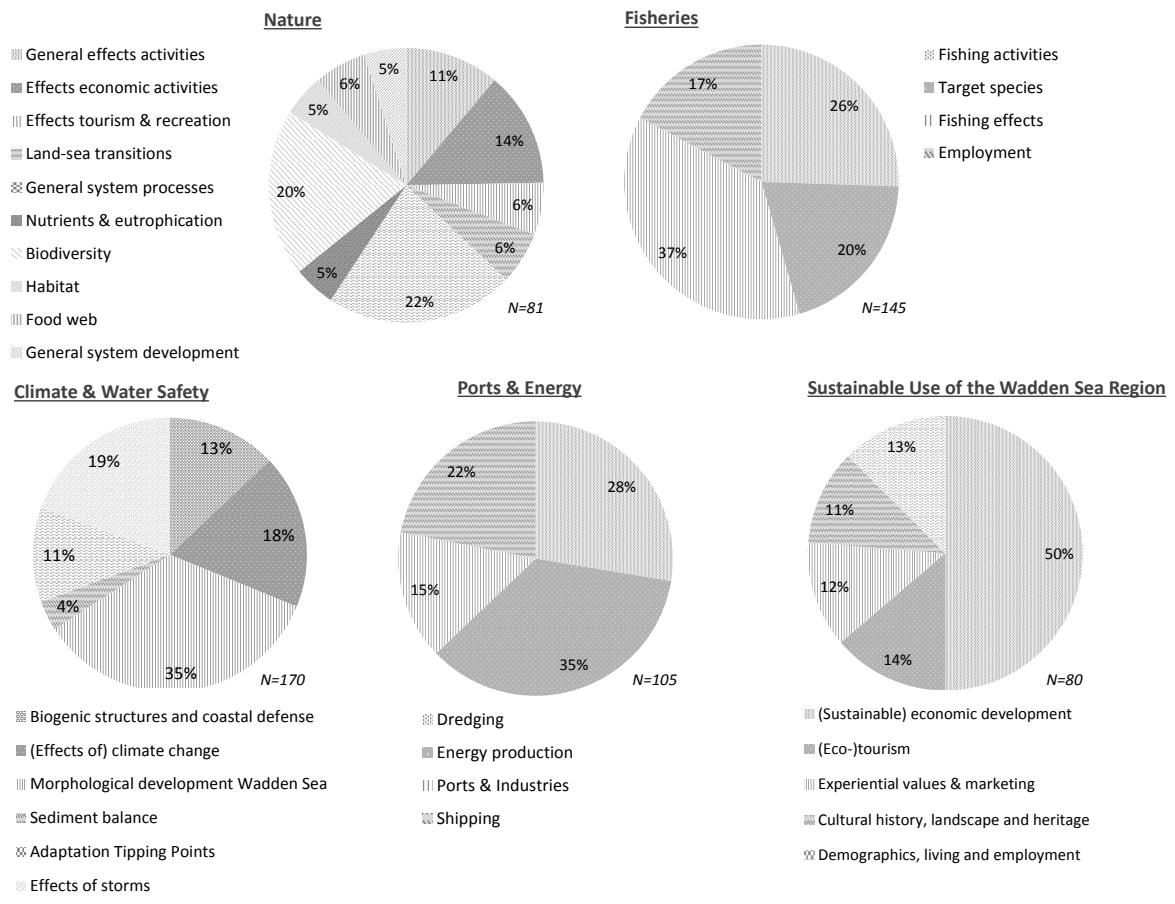


Figure 4. Thematic and topical distribution of the most frequently selected key questions. N presents the aggregate number of times key questions were selected by respondents (i.e. at least 4 times per question).

On average about 75 per cent of the information questions were selected at least once, i.e. being labelled the key questions. Out of these key questions almost a third was selected four times or more.

Table 2 presents the top-5 ranking of selected key questions (>4 times selected), thus representing the information priorities that are most shared amongst respondents. Looking at these questions most are formulated in a straightforward way and express well-defined information needs. Questions in the Ports & Energy and Sustainable Use of the Wadden Sea Region surveys are generally broader in nature.

Table 2. Top 5 ranking of key questions for each thematic assessment in the monitoring needs survey.

<p>Climate & Water Safety</p> <ol style="list-style-type: none"> 1. What are the changes in storm climate? 2. What are the changes in water levels? 3. What is the sediment demand due to climate change? 4. What is the impact of storms on sediment transport in and to the Wadden Sea? 5. How do natural dynamics and robustness of the islands change as a consequence of climate change and sea level rise (i.e. washover, storm erosion)?
<p>Nature</p> <ol style="list-style-type: none"> 1. What are the morphological, sedimentological and biological effects of bottom trawling fisheries? 2. What impacts introduced exotic species in the Wadden Sea ecosystem? 3. What is the effect of totally closed areas on the development of biodiversity? 4. What are the effects of climate change on development of the food web? 5. What are the effects of water pollution on different parts of the food web?
<p>Fisheries</p> <ol style="list-style-type: none"> 1. How high is the fishing pressure in the Wadden Sea in terms of quantities of fish and fished area? 2. What are the possibilities for exploitation of new species such as Ensis and the Japanese oyster? 3. What is the impact of North Sea fishing on populations in the Wadden Sea of fish species whose habitat lies in both the North Sea and the Wadden Sea? 4. What are the effects of shrimp fishing on the ecosystem? 5. What are the effects, particularly on the food web, of large-scale application and fishing using Mussel Seed Capture Installations (MZI's)?
<p>Ports & Energy</p> <ol style="list-style-type: none"> 1. What form of renewable energy is the least damaging to the ecosystem and economically the most profitable? 2. What effects has the broadening and deepening of channels, in relation to shipping, port and wind farm developments, on nature and channel patterns in the Wadden Sea? 3. Can ecological dredging techniques reduce effects on the system and what is the best method? 4. What is the impact of noise pollution on marine mammals? 5. What are possible effects (e.g. subsidence and earth quakes) of energy developments such as thermal storage as well as possibly carbon capture and storage in the future?
<p>Sustainable Use of the Wadden Sea Region</p> <ol style="list-style-type: none"> 1. What spatial functions and ecological / economic qualities can strengthen each other within multifunctional area developments and which work against each other? 2. How is tourism developing in the Wadden area? 3. What are the expected developments for various economic sectors in terms of expansion or reduction? 4. What spatial qualities deserve preservation and which require reinforcement from the perspective of different interests? 5. Which agricultural activities are sustainable at which location, fitting into the landscape and being economically profitable?

Table 3 presents the most frequently mentioned analysis variables per theme. Analysis variables represent the measurable target entities of interest within expressed information needs (see Figure Box 2). Per thematic assessment the overall results presented in Tables 2 and 3 will be shortly discussed in the next paragraphs.

Table 3. Most cited analysis variables per thematic assessment

	Climate & Water Safety	Nature	Fisheries	Ports & Energy	Sustainable Use of the Wadden Sea Region
1)	Bathymetry/bed level	Benthos	Catches	Dredging sludge	Tourism
2)	Waves	Fish	Fishing effort	Vessels (movements)	Societal values
3)	Sediment transport	Nutrients	Population size & composition	Water	Social facilities
4)	Morphology	Birds	Stock	Biota	Businesses
5)	Erosion & sedimentation	Species (general)	Effects	Silt	Population
6)	Sediment composition	Primary production	Growth and density	Sediment	Visitors

Note: Cites of analysis variables range from 9 to 32 times.

4.2 Climate & Water Safety

The high ranking information needs regarding the theme Climate & Safety mainly concern the effects of climate change in terms of sea level rise, future morphological development, and the impact of storms. More specifically, questions focus on changes in storm climate, water levels, and sediment balance and transport. Considering the time scale of climate change issues it is not surprising that a need for long-term monitoring is indicated. Bathymetry/bed level, waves and sediment transport are mentioned as principal analysis variables. Current monitoring is considered sufficient regarding water level monitoring. However, respondents indicate that accommodating identified information needs requires monitoring to be directed at sand nourishments, storms, sediment transport, sediment (turbidity, particle size distribution) and wave dissipation.

4.3 Nature

Major information needs relate to the impact of seabed disturbing activities on biodiversity such as bottom trawling and dredging. Other information priorities concern the impact of recreation on

breeding birds and marine mammals as well as the impact of water pollution in parts of the food web, especially of micro plastics. Additional information needs involve the effects of the introduction of non-native species and the effects of climate change, specifically in relation to food web development. Current monitoring efforts are found particularly inadequate in regard to questions about elementary system processes such as nutrient cycling and primary production. Respondents further express the (continued) need for surveying of bird, benthos and fish populations.

4.4 Fisheries

Information priorities mainly focus on the extent and distribution of fishing efforts and on the ecological impacts of fishing pressure (specifically shrimp), especially on the seabed and benthos populations. Furthermore respondents selected questions about sustainable fishing operations (e.g. flexible target species, the effects of bottom trawling versus other techniques). In addition, information needs concern fish population dynamics, specifically fish migration in fresh-salt water transition zones. Important analysis variables concern fishing efforts, as well as tracking catches in terms of duration, location, and the various forms of fisheries. Ecological target entities are the population sizes and composition of target species and the sizes and development of fish stocks.

4.5 Ports & Energy

The topic of energy production figures prominently in the list of selected questions. Information priorities concern the impacts of energy production on the natural system, especially the cumulative effects of power stations (e.g. cooling water, coal shipping) and the effects of new ways of energy production (e.g. wind parks). Information questions on dredging activities and techniques are also prominent, particularly the effects of moving sludge in the system. These topics are also related to the widening and deepening of shipping channels. The intensity of shipping and tracking risks of oil- and chemical calamities are mentioned, as well as the disturbance of marine mammals as a result of wind parks and shipping. Prominent analysis variables concern volumes, distribution and locations of sludge and physical-chemical parameters of water, including water turbidity and temperature, water levels and flow velocities.

4.6 Sustainable Use of the Wadden Sea Region

Spatial planning and multifunctional use received the highest ranking in the Sustainable Use thematic assessment. Information priorities concern trends in different market developments in the region

linked to opportunities for sustainable innovations in economic sectors. Specifically the development of tourism is of interest, especially in relation to pressures on nature. Furthermore the consequences of demographic developments such as migration and population decline. Suggested analysis variables especially consider business and production figures, e.g. employee numbers, regional competitiveness, productivity rates and information on business sales and turnover rates. Monitoring needs concern economic market developments, and the costs and benefits of sustainable production especially for the aquaculture and fisheries sector. In addition, better insight in the values and the touristic marketing potential of the Wadden Sea region requires data on qualities such as tranquillity, space and nature experiences. The economic value of local products and their marketing linked to World Heritage status are mentioned, as well as the touristic and economic potential of the cultural-historical tradition of the region. Analysis variables on demographics include population dynamics, population composition, migration and commuting behaviour. The lack of fundamental system knowledge concerns insight into the cumulative effects of economic activities on the ecological system and the limits of pressures and disturbances that the system can handle.

4.7 Monitoring needs and innovations

Monitoring needs

According to the monitoring professionals who participated in our surveys, current monitoring efforts are insufficient or inadequate to address all current information needs. Important reasons for this concern are the availability and accessibility of data. Lack of data is related to procedural and technical aspects. Monitoring data sets are sometimes fragmented and dispersed across different data portals and databases, are not standardized, may be using different meta-data descriptions or are not made accessible at all. In addition there are parameters that are not yet included in the current monitoring programmes. Finally the resolution of some data series is deemed insufficient in terms of frequency and spatial coverage. This specifically applies to basic data such as temperature, acidity and primary production. According to the survey the limitations of current monitoring programmes are related to a lack of system understanding as well. Respondents particularly mention a lack of understanding of the driving forces of fish and benthos population dynamics (including reproduction and dispersion), as well as food web relationships that consider human use in an integrated way. Furthermore, a lack of understanding about the geo- and hydromorphological effects of dredging was mentioned, especially at the scale of the entire Wadden Sea estuary. Finally, monitoring efforts are found insufficient regarding the explanatory factors in socio-economic development. Respondents observe that generic data are available on demographic trends, but indicate that data are lacking on underlying processes and causalities.

Respondents who participated in our survey were asked to indicate the type of monitoring required to address their information needs. In the survey we distinguished between surveillance, investigative and operational monitoring roles. Surveillance monitoring was predominantly suggested for tracking developmental trends in the system. This relates to tracking population trends of different species and trends in basic physic-chemical system parameters. For socio-economic monitoring it concerns demographics and economic trends, specifically in tourism. A considerable part of the articulated information needs call for investigative monitoring to gain deeper understanding of system functioning. For these research questions respondents more often indicated the need for temporary and more intense monitoring, after which less intensive long-term monitoring should subsequently be installed. Such an approach has been mentioned as relevant for better understanding the effects of dredging for example.

In addition to the type of monitoring required to address key questions, respondents were asked to indicate relevant temporal and spatial resolutions for selected questions. Defined spatial resolutions of monitoring ranged from micro to local, regional, national and global scales, and differed across themes. In the Nature assessment respondents noted the need for monitoring at regional scales, such as the Western versus the Eastern Wadden Sea. Directing monitoring efforts and analysis at the scale of tidal basin units is considered highly relevant for collecting hydromorphological and ecological data. Respondents indicate that current measurements are not mutually comparable as they are performed in a limited number of geographic areas. This makes it difficult to present total estimations for the Wadden Sea as a whole.

The respondents expressed the need for realizing a robust infrastructure for long-term baseline monitoring that spatially covers the entire Wadden Sea Region and enables analysis at the whole system scale. A large spatial coverage is considered important for understanding comprehensive system processes such as sediment fluxes and biodiversity trends. Thereby relevant system boundaries for analysis should not be restricted to the Wadden Sea but should extend to the adjacent North Sea, for example in relation to fisheries questions on fish population dynamics. Alternatively smaller spatial resolutions are associated with several socio-economic information needs as articulated in the Ports & Energy and Sustainable Use of the Wadden Sea Region assessments. In the latter assessment respondents indicated the need of monitoring at local and micro levels such as at individual businesses. The necessity for acknowledging different temporal resolutions in monitoring was noted across all thematic assessments. Several respondents indicated that currently used temporal monitoring resolutions are too low to follow particular system changes and trends, and should for example be per year, per season or even per tide. Obviously better understanding of climatic issues requires long-term monitoring while economic questions on production for example are associated with shorter time scales resolutions.

Innovations

Respondents were asked to suggest useful and promising innovations in monitoring techniques. For several analysis variables respondents indicated that dynamics in space and time are too large to describe them based on conventional measurement techniques. This concerns hydromorphological dynamics for example. There is a need for novel methodologies that are able to follow system processes at temporal and spatial scales allowing better system understanding. Across all themes the potential of remote sensing techniques was mentioned as a major innovation in monitoring, enabling monitoring in a non-invasive way at a large scale. In general recent technical and informational developments have significantly increased the measurement potential, enabling 24-hour-7 days-a-week monitoring using automated measuring systems. A wider application of automated systems in Wadden Sea monitoring has been suggested, either by increasing the number of permanent measurement stations or by more widely applying so called 'ferry-boxes'. Such boxes may be applied to vessels regularly cruising the Wadden Sea. It has also been suggested to make better use of the data from the Automatic Identification System (AIS) used in shipping, which is an automatic tracking system for identifying and locating vessels. AIS is already widely used in commercial shipping but extending the application of transponders to recreational boating is important to allow monitoring the spatial distribution of recreational use as well. This is deemed valuable given the high number of recreational vessels in the Dutch Wadden Sea. In addition e-logbook fishing registration is considered a key innovation to improve the monitoring of fisheries activities and production. Other suggestions relate to the use of drones for mapping sea grass, mussels etc., as well as the extended application of audio, photo and video techniques to visually and acoustically monitor marine mammals for example. Finally specific innovations in biological monitoring include automated DNA screening to quickly detect the presence of different species in the water. Notably few suggestions on innovations followed from the assessment on Sustainable Use of the Wadden Sea Region. This might suggest that currently applied techniques in socio-economic monitoring are able to fulfil information needs, or that relatively limited innovation is happening in this domain of monitoring. An interesting innovation at least presents the use of data of mobile phones to monitor visitor movements and areal use.

5. Conclusions and discussion

This paper described and elaborated the design and application of a methodology for assessing information and monitoring needs in the context of adaptive monitoring in the Dutch Wadden Sea

region. The methodology presented here aims at improving the salience of information production for Integrated Coastal Management (ICM) and involves distinct steps as outlined in Figure 2. Central in the methodology is the online application of surveys for articulating and prioritizing information needs and for subsequent monitoring needs. Notably electronic communication and application provides major advantages over traditional techniques as they facilitate effective survey distribution, as well as customization and automation of the process (Sutherland et al., 2011). Making use of these advantages, our surveys proved useful as a tool for effective participation. A large and broad representation of stakeholder groups and monitoring professionals in the Dutch Wadden Sea region participated in the assessment process. High response rates were established (43% in the information needs survey and 52% in the monitoring needs survey respectively). Monitoring professionals received a fee for participating and were prompted to provide feedback on overall results. These conditions for participation received positive response by the respondents. The outcome of any assessment exercise such as performed in this study is the product of the people who participated. By definition survey results may be influenced by the interests and agendas of respondents (Sutherland et al., 2011). However, broad participation and representation of institutions and stakeholders achieved in this study as well as an assessment of information priorities based on expert judgement help to prevent bias towards individual interests, and help to ensure the legitimacy of the survey's results and subsequent monitoring design choices that will be made. The monitoring needs survey made clear that respondents feel that current monitoring efforts in the Wadden Sea region are insufficient or inadequate for addressing all existing information needs. Mentioned most often were reasons linked to the availability and accessibility of data, as well as data that are not standardized and fragmented. Some data sets are available but not fully accessible. In addition there are parameters that are not yet included in the current monitoring programmes, especially involving baseline parameters of general system processes. The WaLTER project has been specifically set up to address the important information gap of baseline information. The lack of baseline information can pose a serious problem for adaptive management because learning about complex systems takes time. Years of data are required to understand the extent of natural variability in some populations and habitat conditions, for example, and that understanding in turn may be crucial to interpreting population fluctuations (Doremus, 2011; Lindenmayer and Likens, 2009).

Another aspect indicated by respondents concerns the spatial resolution of monitoring efforts, which is deemed insufficient in terms of adequate frequency and spatial coverage. Kabat et al. (2012) point out that consideration of appropriate scales presents a major challenge for monitoring and management of the Wadden Sea region. For ecological monitoring it is necessary to be able to compare regional scales, such as the Western versus the Eastern Wadden Sea. Monitoring at the

level of tidal basin units is considered relevant for collecting hydromorphological and ecological data (see also Wolff, 2013). Taken together, the results of our survey indicate a need for realizing improved monitoring that spatially covers the whole Wadden Sea region and enables whole system analysis.

Monitoring at relevant temporal and spatial scales demands important methodological choices in monitoring design (Cash et al., 2006). Technical innovations are necessary to allow a multi-scale monitoring design that is required for complex social-ecological issues (Mirtl, 2010). In our study, respondents stressed the importance of continuous improvement and development of novel techniques like remote sensing methodologies in order to monitor long-term system processes like sea level rise and demographics. Remote sensing is a major upcoming technique to increase long-term monitoring capacity and extend spatial coverage while reducing invasive and costly sampling at the ground. The application of automated techniques in general is acclaimed for its potential to address specific information needs that require continuous monitoring. However, the potential of automated techniques to collect 'infinite' data does emphasize the need for good data management and advanced tools for data mining and analysis.

Extensive literature is available on monitoring design and assessment in natural resource management. Several studies acknowledge the importance of information needs assessment (Douve and Ehler, 2011; Onkelinx et al., 2008; Sutherland et al., 2011), though structured specification of information needs is still a step in the information production process that few studies address (Timmerman, 2011; Van Koningsveld et al., 2005). Timmerman et al. (2001) developed a methodology for specifying information needs and acknowledged the need for appropriate "breakdown structures" of policy objectives into information needs, in order to provide confidence that the relevant issues are discussed. In our study we used both the SES perspective and the PSBR indicator approach for structuring information and monitoring needs, as captured in the conceptual framework presented in Figure 2. By combining these concepts we aimed at a balanced and inclusive framework that facilitated a comprehensive assessment of information needs addressing human use and sustainable development. By applying the updated PSBR approach (Sparks et al., 2011), which includes benefits instead of mere ecological impacts, we extended the guiding breakdown structure by linking ecological effects to socio-economic effects. This allowed a better structuring and translation of identified information needs. Timmerman et al. (2001) reported difficulties in defining the information needs in such a way that a monitoring network could be defined from it. In contrast, we explicitly developed an assessment methodology that allows the translation of information needs into design requirements by involving the expertise of monitoring

professionals. We find that following this methodological approach enables tangible input to be acquired for monitoring design, in our case a blue print of the WaLTER monitoring network.

When developing the WaLTER network for adaptive management (Figure 1), it should be realized that adaptive management and monitoring comes with costs (Doremus, 2011). Access to funding is an obvious factor influencing the success of the WaLTER project. It will be essential for the project to build trust and prove its right for existence to funding agencies and regional industries (fisheries, agriculture, shipping, tourism, energy production). Importantly the WaLTER project has to show that long-term adaptive monitoring is not a luxury but should be a public service and a core part of responsible ICM for the Wadden Sea region. Fundamental for ensuring the salience of coastal management processes is that the WaLTER project develops into an active 'learning institution' for capacitating stakeholders, implementing adaptive monitoring processes in response to new information needs by stakeholders or new scientific insights. Involvement of information users to specify these needs and bring them into the monitoring process is thereby imperative. Active ownership of information users in the monitoring network could therefore best be realized but this will necessarily impose demands on participating information users (time investment, commitment etc.) and on the organization of the ICM process itself (Cundill and Fabricius, 2009; Timmerman, 2011).

Overall our assessment made clear that current monitoring efforts and currently available data are not sufficient to answer the comprehensive information questions as articulated by stakeholders in the Wadden Sea region. An integrative understanding about nature, cultural heritage and regional socio-economy of the Dutch Wadden Sea region is considered essential for a sustainable future of the region (Kabat et al., 2012). The web-based assessment of information and monitoring needs presented here demonstrates a useful approach that is applicable to other coastal regions for accomplishing appropriate social-ecological monitoring supported by stakeholders and experts.

Acknowledgments

The authors wish to express their gratitude to the respondents who participated in the surveys. This publication is part of the activities performed within the framework of the 'Wadden Sea Long-Term Ecosystem Research (WaLTER)' project, which is funded by the Dutch Waddenfonds and by the Provinces of Noord-Holland and Fryslân (www.walterproject.nl).

References

- Armitage, D.R., Plummer, R., Berkes, F., Arthur, R.I., Charles, A.T., Davidson-Hunt, I.J., Diduck, A.P., Doubleday, N.C., Johnson, D.S., Marschke, M., McConney, P., Pinkerton, E.W., Wollenberg, E.K., 2008. Adaptive co-management for social–ecological complexity. *Frontiers in Ecology and the Environment* 7 (2), 95-102.
- Atkins, J.P., Burdon, D., Elliott, M., Gregory, A.J., 2011. Management of the marine environment: Integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Marine Pollution Bulletin* 62 (2), 215-226.
- Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., Leitch, A.M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M.D., Schoon, M.L., Schultz, L., West, P.C., 2012. Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources* 37 (1), 421-448.
- Bowen, R.E., Riley, C., 2003. Socio-economic indicators and integrated coastal management. *Ocean & Coastal Management* 46 (3–4), 299-312.
- Cash, D.W., Clark, W.N., Alcock, F., Dickson, N., Eckley, N., Jäger, J., 2002. Saliency, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making, KSG Faculty Research Working Paper Series. Harvard University.
- Cash, D.W., Adger, W.N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., Young, O., 2006. Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World. *Ecology and Society* 11 (2), article 8.
- Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences* 100 (14), 8086-8091.
- Cundill, G., Fabricius, C., 2009. Monitoring in adaptive co-management: Toward a learning based approach. *Journal of Environmental Management* 90 (11), 3205-3211.
- Doremus, H., 2011. Adaptive Management as an Information Problem. *North Carolina Law Review* 89, 1455-1495.
- CWSS, 2008. Nomination of the Dutch-German Wadden Sea as a World Heritage Site. World Heritage Nomination Project Group, Wilhelmshaven Germany, pp. 200.
- Daams, M.N., Sijtsma, F.J., 2013. Planting the SEED: Towards a Spatial Economic Ecological Database for a shared understanding of the Dutch Wadden area. *Journal of Sea Research* 82, 153-164.

- Day, J., 2008. The need and practice of monitoring, evaluating and adapting marine planning and management – Lessons from the Great Barrier Reef. *Marine Policy* 32 (5), 823-831.
- De Jonge, V.N., Pinto, R., Turner, R.K., 2012. Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' 'ecosystem approach'. *Ocean & Coastal Management* 68, 169-188.
- Delta Programme, 2012. Delta Programme 2013. Working on the delta, the road towards the Delta Decisions. Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs Agriculture and Innovation,, The Hague, pp. 112.
- Douve, F., Ehler, C., 2011. The importance of monitoring and evaluation in adaptive maritime spatial planning. *Journal of Coastal Conservation* 15 (2), 305-311.
- European Commission, 2002. Recommendation of the European Parliament and of the Council of 30 May 2002 concerning the implementation of Integrated Coastal Zone Management in Europe. European Commission, Brussels.
- European Commission, 2003. Monitoring under the Water Framework Directive, Guidance document nr. 7. Working Group 2.7 - Monitoring. European Commission, Brussels.
- Floor, J.R., van Koppen, C.S.A., Lindeboom, H.J., 2013. A review of science–policy interactions in the Dutch Wadden Sea — The cockle fishery and gas exploitation controversies. *Journal of Sea Research* 82, 165-175.
- Hanssen, L.S.A.M., Rouwette, E., Van Katwijk, M.M., 2009. The role of ecological science in environmental policy making: from a pacification toward a facilitation strategy. *Ecology and Society* 14 (1), article 43.
- Heemskerk, M., Wilson, K., Pavao-Zuckerman, M., 2003. Conceptual models as tools for communication across disciplines. *Conservation Ecology* 7 (3), article 8.
- Holling, C.S., 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4 (5), 390-405.
- Jones, J.P.G., Asner, G.P., Butchart, S.H.M., Karanth, K.U., 2013. The 'why', 'what' and 'how' of monitoring for conservation, *Key Topics in Conservation Biology* 2. John Wiley & Sons, pp. 327-343.
- Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., McCarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grubler, A., Huntley, B., Jager, J., Jodha, N.S., Kaspersen, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore Iii, B., O'Riordan, T., Svedlin, U., 2001. ENVIRONMENT AND DEVELOPMENT: Sustainability Science. *Science* 292 (5517), 641-642.

- Kabat, P., Bazelmans, J., Van Dijk, J., Herman, P.M.J., Speelman, H., Deen, N.R.J., Hutjes, R., 2009. Kennis voor een duurzame toekomst van de Wadden: Integrale Kennisagenda van de Waddenacademie. Waddenacademie-KNAW, Leeuwarden, pp. 124.
- Kabat, P., Bazelmans, J., van Dijk, J., Herman, P.M.J., van Oijen, T., Pejrup, M., Reise, K., Speelman, H., Wolff, W.J., 2012. The Wadden Sea Region: Towards a science for sustainable development. *Ocean & Coastal Management* 68, 4-17.
- Lee, K.S., 1999. Appraising Adaptive Management. *Conservation Ecology* 3 (2), article 3.
- Lindenmayer, D.B., Likens, G.E., 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. *Trends in Ecology & Evolution* 24 (9), 482-486.
- Lindenmayer, D.B., Likens, G.E., 2010. The science and application of ecological monitoring. *Biological Conservation* 143 (6), 1317-1328.
- Loucks, D.P., van Beek, E., Stedinger, J.R., Dijkman, J.P.M., Villars, M.T., 2005. Appendix B: Monitoring and Adaptive Management, *Water Resources Systems Planning and Management*. UNESCO Paris.
- Lovett, G.M., Burns, D.A., Driscoll, C.T., Jenkins, J.C., Mitchell, M.J., Rustad, L., Shanley, J.B., Likens, G.E., Haeuber, R., 2007. Who needs environmental monitoring? *Frontiers in Ecology and the Environment* 5 (5), 253-260.
- Lyons, J.E., Runge, M.C., Laskowski, H.P., Kendall, W.L., 2008. Monitoring in the Context of Structured Decision-Making and Adaptive Management. *Journal of Wildlife Management* 72 (8), 1683-1692.
- MacDonald, L.H., Smart, A., 1993. Beyond the guidelines: practical lessons for monitoring. *Environmental Monitoring and Assessment* 26, 203-218.
- Maddox, D., Poiani, K., Unnasch, R., 1999. Evaluating Management Success: Using Ecological Models to Ask the Right Monitoring Questions, in: Sexton, W.T. (Ed.), *Ecological Stewardship: A Common Reference for Ecosystem Management*. Pergamon Press Inc.
- Margoluis, R., Stem, C., Salafsky, N., Brown, M., 2009. Using conceptual models as a planning and evaluation tool in conservation. *Evaluation and Program Planning* 32 (2), 138-147.
- Maxim, L., Spangenberg, J.H., O'Connor, M., 2009. An analysis of risks for biodiversity under the DPSIR framework. *Ecological Economics* 69 (1), 12-23.
- McNie, E.C., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental Science & Policy* 10 (1), 17-38.
- Mirtl, M., 2010. Introducing the Next Generation of Ecosystem Research in Europe: LTER-Europe's Multi-Functional and Multi-Scale Approach, in: Müller, F., Baessler, C., Schubert, H., Klotz, S. (Eds.), *Long-Term Ecological Research*. Springer Netherlands, pp. 75-93.

- Nichols, J.D., Williams, B.K., 2006. Monitoring for conservation. *Trends in Ecology & Evolution* 21 (12), 668-673.
- Onkelinx, T., Verschelde, P., Wouters, J., Bauwens, D., P., Q., 2008. Ontwerp en evaluatie van meetnetten voor het milieu- en natuurbeleid. Leidraad voor de meetnetontwerper. Instituut voor Natuur- en Bosonderzoek, Brussel, pp. 112.
- Ostrom, E., 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* 325 (5939), 419-422.
- Parr, T.W., Sier, A.R.J., Battarbee, R.W., Mackay, A., Burgess, J., 2003. Detecting environmental change: science and society--perspectives on long-term research and monitoring in the 21st century. *Science of the Total Environment* 310 (1-3), 1-8.
- Pouwels, R., Opdam, P., Jochem, R., 2011. Reconsidering the effectiveness of scientific tools for negotiating local solutions to conflicts between recreation and conservation with stakeholders. *Ecology and Society* 16 (4), article 17.
- PRW, 2010. Naar een Rijke Waddenzee. Programmaplan voor natuurherstel in de Waddenzee, p. 86.
- Pullin, A.S., Knight, T.M., Watkinson, A.R., 2009. Linking reductionist science and holistic policy using systematic reviews: unpacking environmental policy questions to construct an evidence-based framework. *Journal of Applied Ecology* 46 (5), 970-975.
- Runhaar, H., van Nieuwaal, K., 2010. Understanding the use of science in decision-making on cockle fisheries and gas mining in the Dutch Wadden Sea: Putting the science-policy interface in a wider perspective. *Environmental Science & Policy* 13 (3), 239-248.
- Sparks, T.H., Butchart, S.H.M., Balmford, A., Bennun, L., Stanwell-Smith, D., Walpole, M., Bates, N.R., Bomhard, B., Buchanan, G.M., Chenery, A.M., Collen, B., Csirke, J., Diaz, R.J., Dulvy, N.K., Fitzgerald, C., Kapos, V., Mayaux, P., Tierney, M., Waycott, M., Wood, L., Green, R.E., 2011. Linked indicator sets for addressing biodiversity loss. *Oryx* 45 (03), 411-419.
- Stem, C., Margoluis, R., Salafsky, N., Brown, M., 2005. Monitoring and Evaluation in Conservation: a Review of Trends and Approaches. *Conservation Biology* 19 (2), 295-309.
- Sutherland, W.J., Fleishman, E., Mascia, M.B., Pretty, J., Rudd, M.A., 2011. Methods for collaboratively identifying research priorities and emerging issues in science and policy. *Methods in Ecology and Evolution* 2 (3), 238-247.
- Timmerman, J.G., Beinat, E., Termeer, K., Cofino, W., 2010a. Analyzing the Data-Rich-But-Information-Poor Syndrome in Dutch Water Management in Historical Perspective. *Environmental Management* 45 (5), 1231-1242.
- Timmerman, J.G., Beinat, E., Termeer, C.J.A.M., Cofino, W.P., 2010b. Specifying information needs for Dutch national policy evaluation. *Journal of Environmental Monitoring* 12 (10), 1907-1917.

- Timmerman, J.G., Boer, J., Hisschemöller, M., Mulder, W., 2001. Specifying information needs: improving the working methodology. *Regional Environmental Change* 2 (2), 77-84.
- Timmerman, J.G., Ottens, J.J., Ward, R.C., 2000. The Information Cycle as a Framework for Defining Information Goals for Water-Quality Monitoring. *Environmental Management* 25 (3), 229-239.
- Van Koningsveld, M., Davidson, M.A., Huntley, D.A., 2005. Matching Science with Coastal Management Needs: The Search for Appropriate Coastal State Indicators. *Journal of Coastal Research*, 399-411.
- Vaughan, H.H., Waide, R.B., Maass, J.M., Ezcurra, E., 2007. Developing and delivering scientific information in response to emerging needs. *Frontiers in Ecology and the Environment* 5 (4), W8–W11.
- Vos, P., Meelis, E., Ter Keurs, W.J., 2000. A Framework for the Design of Ecological Monitoring Programs as a Tool for Environmental and Nature Management. *Environmental Monitoring and Assessment* 61 (3), 317-344.
- WaLTER project team, 2010. WaLTER - Wadden Sea Long-Term Ecosystem Research. Projectplan Waddenfondsaanvraag Tender 2010/1, pp. 82.
- Wolff, W.J., 2013. Ecology of the Wadden Sea: Research in the past and challenges for the future. *Journal of Sea Research* 82, 3-9.
- Wortelboer, F.G., Bischof, B.G., 2012. Scenarios as a tool for supporting policy-making for the Wadden Sea. *Ocean & Coastal Management* 68, 189-200.