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A participatory modelling approach to cognitive mapping of the socio-environmental system of sandy anthropogenic shores in the Netherlands

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ABSTRACT

Sandy Anthropogenic Shores (SAS) are coasts formed or heavily modified by moving large amounts of dredged sand from offshore towards the land. Subsequently, natural processes such as waves, wind, and currents are spreading the sand, where wind can transport sand into the foredune area and reinforce the foredune for long-term coastal safety. Besides improving safety, more expansive beaches and artificial lagoons, which may be part of a SAS design, provide new space for human activities and animal and plant habitats. The landscape of SAS is influenced by humans who manage and utilise the shore for various objectives, including flood safety, recreation, and ecological functions. Consequently, the sustainable management of multifunctional and multi-actor systems like SAS becomes challenging and requires an inter- and transdisciplinary approach to analyse the trade-offs between various socio-environmental functions. Although numerous studies of SAS have been conducted, they have had a sectoral, disciplinary approach and mainly focused on the natural aspects of SAS. In this study, we applied participatory modelling to explore the role of social systems (management activities and their interactions with natural systems) in SAS to broaden insight beyond natural systems and improve management and social acceptance of managerial decisions. We conducted several interviews and workshops with multiple stakeholders. We discussed different management aims and activities in SAS, the essential socio-environmental drivers of the managerial activities, their interactions, and the managerial indicators for analysing the various SAS functions. The elicited knowledge was structured in the form of a collective cognitive map (CCM) developed with stakeholders. We used the designed cognitive map for a qualitative assessment of the influence of some managerial decisions on trade-offs between the multiple functions of SAS. The developed CCM provides suitable ground to start the discussion with multiple stakeholders on the design of SAS as a new coastal management approach.

1. Introduction

Globally, sandy shores experience a range of threats that are enhanced by climate change and increasing population pressures, including flooding, coastal erosion, sediment deficiency, and landscape and habitat degradation (Herman et al., 2021; Escudero et al., 2020; Brière et al., 2018; Stronkhorst et al., 2018). Based on the sea-level rise (SLR) scenario of 0.2–0.8 m by the 21st century, approximately 6000 to 17,000 km^2 of coastal areas worldwide may disappear (Hinkel et al., 2013). These predictions make protecting the coastline a priority worldwide, especially in low-lying countries like the Netherlands.

In recent decades, the integrated coastal zone management (ICZM) approach has emerged in combination with the nature-based solutions (NBS) philosophy (Nesshöver et al., 2017) as an approach for reaching sustainable protection of coastal zones. ICZM proposes an integrated management and planning strategy, taking into account all individual sectors' interests to the greatest possible extent with appropriate consideration of the full range of temporal and spatial scales (Marzetti

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et al., 2016). Within this paradigm, NBS proposes solutions that combine natural processes and materials with engineering. Mangrove forest restoration in the case of muddy coasts (Gijsman et al., 2021; Kok et al., 2021; Ellison et al., 2020) and sand nourishment in the case of coasts with dunes and beaches (van Bergen et al., 2020; Davison et al., 1992) are examples of NBS for coastal flood risk management. Compared to the traditional hard engineering solutions (e.g. storm surge barriers and groynes), NBS have such advantages as lower costs (Van Rijn, 2011) and consideration of ecosystem services in coastal areas, accounting for both the dynamics of the natural system (e.g. sands, waves, winds, currents) and the social system (recreation, nature development, economic values) (Chen et al., 2022; Somarakis et al., 2019).

Recent developments in nature-based coastal management of sandy shores have witnessed an increase in the scale of the nature-based interventions (Huisman et al., 2021; Vikolainen et al., 2017) leading to the creation of what we refer to as Sandy Anthropogenic Shores (SAS). SAS are the sandy shores that have been newly created or extensively modified by moving large amounts of dredged sand from offshore to near the coast, (re)creating features like beaches, dunes, lagoons, etc, which keep evolving after initial construction. This innovative approach harnesses natural processes such as waves, winds, and currents to distribute sand to reinforce the dunes, thus providing long-lasting coastal protection lasting for decades. In contrast, small-scale nourishment typically offers only short-term protection lasting a few years (Vermaas et al., 2019). Alongside addressing flood safety, SAS improves the landscape quality by expanding beaches, thereby creating more recreational space and supporting environmental features like lagoons, which serve both recreational activities (e.g. boating and kitesurfing) and nature development (e.g. birds nesting). While the dredging and repositioning of sand from the deep North Sea can disrupt ecosystems and benthic life (Gerdes et al., 2021), reducing replenishment frequency helps preserve flora and fauna. However, mega-nourishments do not exhibit clear advantages over other methods, as they can bury habitats and organisms, and different nourishment strategies yield comparable effects that scale with sediment volume (Herman et al., 2021). A crucial concern still arises regarding the impact of short-term managerial actions on the natural evolution of the SAS ecosystem and the long-term objective of strengthening dunes for flood safety. Managers of SAS may make short-term decisions in response to various natural processes (e.g., storm waves and tides) and social objectives (e.g., political, economic, and psychological aims).

Complex systems like SAS are socio-environmental systems in which natural phenomena and social institutions are firmly intertwined (Dietz et al., 2003). This implies that human activities within coastal zones can influence the trajectory of SAS's landscape development, and conversely, the SAS landscape and natural conditions can impact human behaviour. This interdependence between social and natural systems becomes particularly critical in multifunctional solutions such as SAS, involving multiple stakeholders encompassing beach users, entrepreneurs, policymakers, and managers. These stakeholders hold different values, views, aims, likes, and dislikes about the coast. Considering these varieties, these stakeholders play different roles that can impact the use or management of SAS differently. Hence, it is essential to understand the socio-environmental conditions that trigger managerial decisions and, reciprocally, how management actions influence the multifunctional performance of SAS. This understanding forms the foundation for integrated and sustainable management of SAS.

During the last decade since the construction of the first SAS, several research groups have studied various physical (D.W. Poppema et al., 2022; Pourteimouri et al., 2021; Hoonhout and de Vries, 2017; De Bakker et al., 2016; Huisman et al., 2016; van der Weerd and Wijnberg, 2016), ecological (Herman et al., 2021; Van Egmond et al., 2018; Cohen et al., 2010), and socioeconomic (Wienhoven et al., 2021; Aukes et al., 2020; Goossen et al., 2019) aspects of SAS. While these studies have provided valuable insights into SAS behaviour concerning flood defence, ecological development, and socioeconomic function, there is a lack of holistic research that analyses the interactions among these functions as part of a coupled socio-environmental system. Furthermore, the conducted studies mainly focused on exploring the effects of natural processes on flood safety or nature development.

Integrating mutual knowledge exchange between coastal researchers and managers is essential to provide researchers with a clear understanding of the social demands and help managers reconsider possibilities offered by coastal studies (Brugnach and van den Hoek, 2023; Lazarus et al., 2016). In recent decades, Participatory Modelling (PM) has been widely employed for qualitative and quantitative analysis of socio-environmental systems like SAS (Coletta et al., 2021; Butler and Adamowski, 2015; Carmona et al., 2013; Brugnach and Ingram, 2011). PM involves scientists and public stakeholders who, working together, "create formalised and shared representations of reality" (Gray et al., 2016). PM offers several benefits, such as integrating knowledge across disciplines, accounting for the values and beliefs of various stakeholders (Glynn et al., 2017), promoting co-learning and co-decision making, and facilitating dialogue between scientists and policymakers (Paolisso and Trombley, 2017; Voinov et al., 2016).

In this study, our objective is to elicit knowledge about the social systems within SAS, specially focusing on the management activities and their interactions with the environmental system. We aim to understand how this insight into the socio-environmental system of SAS can contribute to improve management practices. To achieve this, we employ PM to address the following research questions:

- Which managerial activities have been carried out by different stakeholders in SAS, and why?
- Which social, economic, ecological, and physical factors within SAS act as triggers for these managerial activities, taking into account the values and aims of various stakeholders?
- How do the interactions among these factors influence the co-benefits experienced by the various stakeholders?

The knowledge elicited regarding the social system and its interactions with the natural system is presented in a socio-environmental conceptual model of SAS. Subsequently, we conduct a qualitative analysis using the developed conceptual model to explore the impact of particular SAS characteristics on each system function.

2. Material and methods

2.1. Study areas

2.1.1. Sand Motor (SM)

The Sand Motor[1] was created in 2011 along the west coast of the Netherlands, between the cities of Rotterdam and The Hague. It was constructed as a large hook-shaped peninsula for which approximately 21 million m^3 of offshore dredged sand was used (Taal et al., 2016). Notably, the design of the Sand Motor incorporates an artificial lagoon, occupying around 8 ha and situated near the centre of the peninsula (Fig. 1a). This innovative project highlights the implementation of the Dutch coastal management strategy, employing multifunctional mega-nourishments and emphasises a 'learning by doing' approach (Arens and Mulder, 2008). It has been designed to feed the adjacent coasts and dunes and will thus disappear over time as a recognisable feature, with an expected lifetime of about 20 years (Luijedijk and Van Oudenhoven, 2019). The project has involved several public and private organisations, such as the Ministry of Transport, Public Works, and Water Management (Rijkswaterstaat), the Province of South Holland, the local Water Board, local municipalities, research institutes, entrepreneurs, and NGOs (Baltissen, 2016).

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[1] https://dezandmotor.nl/en/.

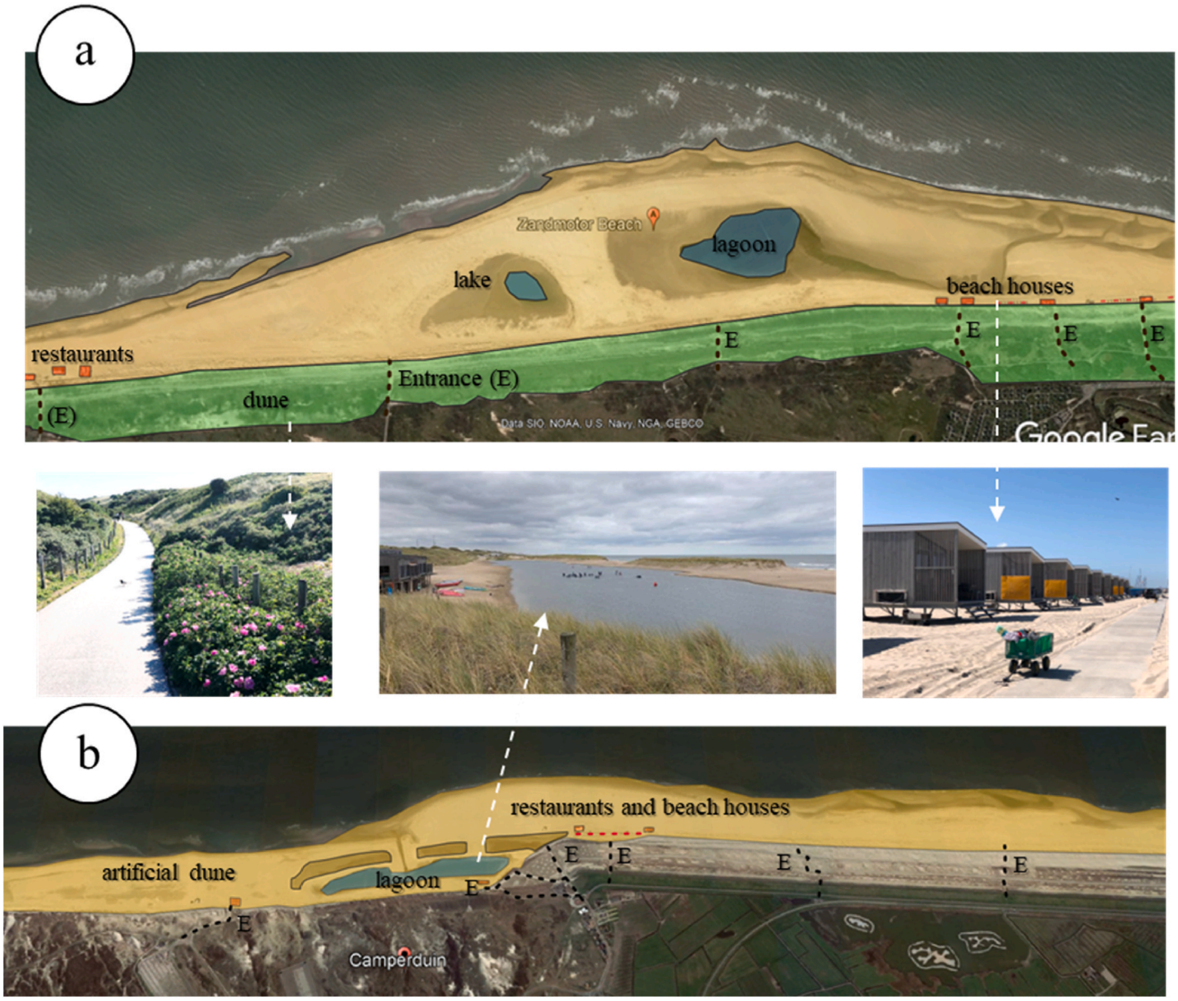

Fig. 1. Maps and photos of sample SASs: a) Sand Motor, b) Southern part of the Hondsbossche Dunes (HBD).

2.1.2. *Hondsbossche Dunes (HBD)*

The Hondsbossche Dunes is a non-experimental SAS in the Netherlands, located in front of the Hondsbossche and Pettemer Zeewering (HPZ). In 2003, the HPZ, a traditional sea dyke of almost 8 km in length built in the 19th century, was identified as one of the weak points in the coastal defence of the Dutch coastline (Van Slobbe et al., 2013). The coastal managers sought a more flexible and multifunctional solution to improve safety and enhance landscape quality. After approximately eight years of investigation, multiple stakeholders with diverse interests widely endorsed the proposal to convert the concrete dike into sandy dunes (Aukes et al., 2020). In 2015, the HBD was constructed by depositing around 30 million m^3 of offshore sand onto the seaside section of the dike (Kant, 2021). The landscape design of the HBD incorporates a shallow foreshore (new beach), an artificial dune with varied shapes and a central lagoon, integrating flood safety, recreation, and nature development (Fig. 1-b). Unlike the SM, the HBD's purpose is not to feed the neighbouring coastline but to expand pre-existing dunes behind it. Like SM, multiple public and private companies participate in this project, such as Rijkswaterstaat, the Water Board of North Holland, provincial governments, municipalities, and dredging companies (Aukes et al., 2020).

2.2. *Methodology*

This section outlines the methodology employed to construct the socio-environmental conceptual model of SAS using a participatory modelling approach.

2.2.1. *Cognitive map*

Various methods exist for representing stakeholders' perceptions and understanding of a given reality, such as a problem, a system, a process, etc. (Bruno et al., 2021; ElSawah et al., 2013; Fairweather, 2010). Cognitive mapping (CM) has been widely used in numerous studies to visually and logically depict the relationships among elements of a system or a problem (Beaudoin et al., 2022; Ahmad and Xu, 2021; Vanermen et al., 2020). A CM consists of concepts represented as nodes and casual relationships represented as arrows connecting the concepts (Hester, 2015). In our study, we define concepts as essential components of the sandy beach system, encompassing functions, aims, variables, physical elements (e.g., sand, water, vegetation), processes (e.g., erosion, deposition), management actions, and other relevant aspects that contribute to the system's functioning. These concepts are interdependent and interact with each other, forming a complex web of relationships that we aim to capture in our cognitive map. Each arrow in the map has a '+' or '-' sign. The '+' sign indicates that an increase or decrease in a particular concept has the same influence on another concept (e.g. increase in one concept causes an increase in another, or a reduction in one concept causes a decrease in another). The '-' sign represents a balancing interaction (e.g., an increase in one concept results in a decrease in a connected concept or vice versa).

2.2.2. *The stakeholders*

According to the research objective, we employed PM to investigate the management activities in SAS and the interactions between managerial actions and the natural system. In our study, the potential stakeholders are people who have been involved in administrative or economic activities related to SAS and whose actions have influenced the natural system of SAS or have been influenced by it. Based on the previous studies by Van Alphen (1995) and Aukes et al. (2020), Dutch coastal management involves numerous public and private sectors at different national and local levels. At the national level, the Public sector is represented by the director for Public Works and Water Management (called Rijkswaterstaat in Dutch). At the regional level, there are provinces, Water Boards, and local municipalities. The administrative and private sectors encompass research institutes, water companies, environmental protection agencies, dredging and construction companies, NGOs, and owners of beach houses and restaurants, among others. Based on this definition, we provided a list of stakeholders from the above-mentioned organisations involved in SAS. During the PM processes, some participants introduced additional stakeholders associated with the Sand Motor or HBD. So, we used the snowball sampling approach and updated the list of stakeholders (Goodman, 1961). Appendix A provides a comprehensive list of stakeholders engaged in various stages of the PM processes.

2.2.3. *The applied PM processes*

Fig. 2 shows the participatory process plan implemented in this research to develop SAS's socio-environmental cognitive map. The PM plan was evaluated and approved by the Natural Sciences and Engineering Sciences Ethics Committee of the University of Twente with reference number 2021.58. The PM process comprised four main steps. Initially, we conducted individual semi-structured interviews with each of the identified stakeholders. Following the analysis of the interview content, we prepared the preliminary list of contents of a CM and developed individual cognitive maps (ICM) of each participant. We ran two workshops in the final two stages to update the concept list and build the SAS collective cognitive map (CCM). The following paragraphs provide a detailed description of each step of the participatory approach, including interviews and workshops.

2.2.3.1. Individual semi-structured interviews. As a first step, we conducted semi-structured interviews with stakeholders from management organisations and entrepreneurs connected to the SAS (Table 1). The objective was to gain insight into how various stakeholders perceive SAS, their past and present experiences (or actions), and the link between their interpretation of conditions and decision-making. As shown in Table 1, we interviewed 28 people from different organisations between April to July 2021, with each interview lasting approximately 1 h. Due to the Covid-19 pandemic, the interviews were conducted online through Microsoft Teams. The main interview questions are provided in Appendix B. Follow-up questions were also discussed to clarify certain aspects of the interviewees' responses. Prior to initiating the interview, we asked for permission to record the session; and all participants agreed. We used the Otter. oi for the transcription of the recordings. Then, the transcribed content was verified by listening to the recording.

2.2.3.2. Interview transcript analysis. Given the limited number of interviews, we manually analysed the transcripts to assess them based on the following five questions:

1 What are the **main activities** conducted on SAS by various management and business sectors?
2 What are **the goals** behind these activities?
3 How have these activities been performed (**action mechanism**)?
4 Which **natural or social factors** are affected by these actions or affect them?
5 How do stakeholders **evaluate the performance of SAS** based on their goals? (indicators and criteria)

After analysing the interviews, we derived a preliminary list of concepts related to each SAS function. These concepts were then clustered into different categories: organisational aims, regulations, biophysical elements, constant variables, processes, indicators and criteria, management actions, and effects. Next, we proceed to build the SAS socio-environmental individual cognitive map (ICM) by tracking the relationships between the concepts. We shared the developed ICM with the relevant participants to receive their feedback. In some cases, we conducted follow-up interviews to delve deeper into specific areas. Appendix C shows an example of the interview transcript analysis.

2.2.3.3. Workshops. Subsequently, we organised workshops separately with selected stakeholders from different management sectors in Sand Motor and HBD on October 28, 2021 and November 3, 2021, respectively. The workshops aimed to update the list of identified concepts from interviews and develop the socio-environmental collective cognitive map of SAS. Each workshop lasted 3 h, with ten stakeholders for Sand Motor and three for HBD. After a brief introduction describing the study and workshop objectives, including the cognitive model structure, we asked participants to use sticky notes to identify critical concepts related to the SAS socio-biophysical system. These concepts, which refer to the components contributing to the system's functions, including recreation, nature development, and flood safety, were based on the participant's experience and knowledge. The identified concepts were then placed on a board, and stakeholders were asked to cluster them. Participants then discussed the importance of each identified concept. A total of 125 concepts were identified, making it infeasible to discuss all of them within the given time frame. Therefore, the facilitator proposed a general structure of the relationships between the identified concepts, considering the participants' discussions on the importance of each

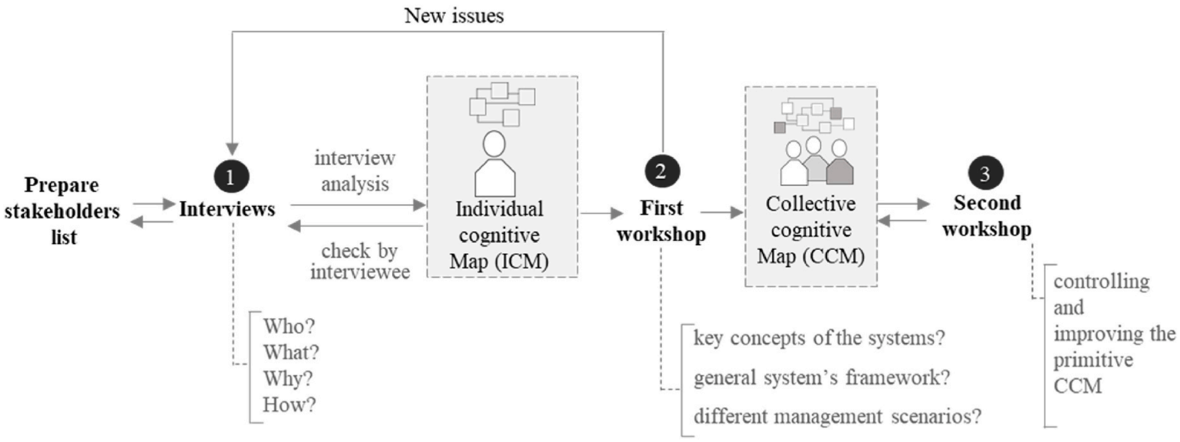

Fig. 2. Schematic plan of the participatory modelling approach.

concept. The workshops were recorded with the consent of all participants for future review and extraction of useful information.

2.2.3.4. Developing the final collective cognitive map of the SAS socio-environmental system. We developed the preliminary socio-environmental CCM of SAS by considering the general structure of the interactions between concepts discussed by stakeholders during the interviews and workshops as presented by the ICMs. Stakeholders have specific goals and utilise various indicators to evaluate their progress towards achieving those goals. These indicators are influenced by the socio-environmental characteristics of the SAS. The management sectors closely monitor the system and assess the indicators. If their expectations are not met, they will take action to pursue their goals. Consequently, their actions impact certain characteristics of SAS, creating a continuous feedback loop.

To translate this story into CCM, we categorised the identified concepts into three main groups: nature development, recreation, and flood defence, considering the primary functions of SAS and reflecting stakeholders' goals in general. Connection nodes were established using concepts that were mentioned by multiple stakeholders, even if they were discussed from different perspectives regarding their impact on the system. These connection nodes allowed us to merge the ICMs and construct the CCM. For visualisation purposes, we utilised Miro (https://miro.com), an open-access platform, to create the preliminary CCM. We shared the link with stakeholders and conducted an online workshop with 10 participants (see Table 1). Incorporating the participants' feedback, we refined and finalised the socio-environmental CCM of SAS.

3. Results

3.1. The socio-environmental cognitive model of SAS

Fig. 3 shows the developed socio-environmental CCM of SAS. This model includes the main concepts that were identified and the interactions between them. The spatial boundary includes the modified or built section of the beach through mega sand nourishment, as well as the entire landward area of the dune. Our study excluded the urban or rural areas located inland of the dunes, as well as the offshore area of the nourishment, from the SAS system. The temporal boundary of the research is decades (about 30 years), considering the lifetimes of both SAS study areas. The system includes concepts related to natural, social, and economic issues within the spatial boundary. Stakeholders have identified 125 concepts. Some relevant concepts have been aggregated to reduce complexity. For example, aeolian processes are natural phenomena involving the movement of sand and dust by wind, driven primarily by wind forces and including emission, transport, and deposition processes. In our CCM, we identified several related concepts, such as wind-driven sedimentation, erosion, sand transport direction, armouring, and layers of sand, and aggregated them under the concept of aeolian processes. Within these boundaries, the internal and external concepts of the system are shown in black and red colours, respectively. In total, the CCM includes 33 internal and five external concepts. The number of identified concepts and lines between them was pretty large, which makes the CCM very complex. To simplify the CCM, we employed a duplicate variable called 'ghosts' in blue, which was nested inside angle brackets ('<>') and used as input for another variable (Bureš, 2017). The concepts captured in the CCM are categorised into variables, processes, and indicators. In Fig. 3, we show processes inside circular arrows and indicators in rectangles. This makes it easier to distinguish between different types of concepts. The CCM includes three sub-systems: recreation, flood defence, and nature. In addition to the '+' and '–' signs described in the methodology section, we used the '?' sign, where it is hard to say whether the interaction between two given concepts is positive or negative. In addition, Figs. 3–5 highlight certain connections between concepts in green (for increase) and red (for decrease) when a change in one concept results in an improvement or worsening of another concept. For instance, when beach vegetation cover increases, aeolian processes decrease, and this connection is indicated in red. The model tracked the interactions between identified variables and processes and the influence of these interactions on indicators assigned by managers to evaluate various system functions. In the next section (3.2), we will provide a detailed explanation of each sub-system of the developed CCM. Following that, in section 3.3, we will use the CCM to investigate the impact of changes in sediment size, recreational facilities, and beach vegetation on various functions of the SAS, as well as the interactions between system elements.

3.2. Each sub-system overview

This section provides detailed information on the main identified concepts of each sub-system, including the internal interactions between concepts within a sub-system, as well as the interactions between sub-systems. We also discuss management actions related to each sub-system.

3.2.1. The flood defence subsystem

Rijkswaterstaat applies two indicators called "basic coastline" and "coastal foundation" for flood safety assessment. The term basic coastline is an indicator for short-term (0–20 years) flood safety assessment, aiming to dynamically maintain the coastline at a specific position (Lodder and Slinger, 2022). On the other hand, Rijkswaterstaat applies the term "coastal foundation" to assess long-term (>20 years) flood safety goals, referring to the sediment volume between the landward edge of the dunes and the 20 m depth contour of the North Sea (Rijkswaterstaat, 2021). The participants from the Waterboard also consider dune height as another indicator for assessing the safety of the dune and the hinterland behind it against flood.

The sediment volume in the SAS system is an important variable affecting the basic coastline, coastal foundation, and dune height. Natural processes, including aeolian and marine processes, primarily influence the sediment volume. Aeolian processes transport sediment toward the dunes based on wind direction, speed, and duration, resulting in dune growth. Changes in the sediment volume of dunes caused by aeolian processes affect the width and height of the dunes. According to the participants, vegetation cover, sediment size, sediment materials, sediment moisture, and groundwater level affect aeolian processes. For example, the nourished sediment on the Sand Motor contains a large proportion of shells. Over time, these shells cause surface armouring on the top layer of the beach, decreasing sediment transport from the nourished beach to the dunes. On beaches with sparse vegetation, the wind will locally slow down and divert around the vegetation, leading to sedimentation in the wake of the vegetation (Mayaud and Webb, 2017). When the vegetation extends onto this newly deposited sediment and is dense enough with roots in the sediment, it will limit the erosion of deposited sand and increase the likelihood of baby dune (embryo dunes or incipient dunes) growth on the vegetated beach. Therefore, beach vegetation and embryo dune may hinder the development of the main dune on the beach's landward side by affecting sediment exchange dynamics. Marine processes also affect sediment volume on beaches and dunes. Depending on the storm surge level, part of the sediment will be washed offshore. Long-term sea-level rise, driven by climate change (external factor), is a crucial factor affecting both marine processes (storm tide and storm wave) and aeolian processes.

Mega sand nourishment serves as a management action for long-term coastal safety. Additionally, managers of the beach and dunes mentioned other potential short-term activities, including:

- Using sand fencing to trap wind-blown sand.
- Planting vegetation on the foredune or dune foot to catch the wind-blown sand.

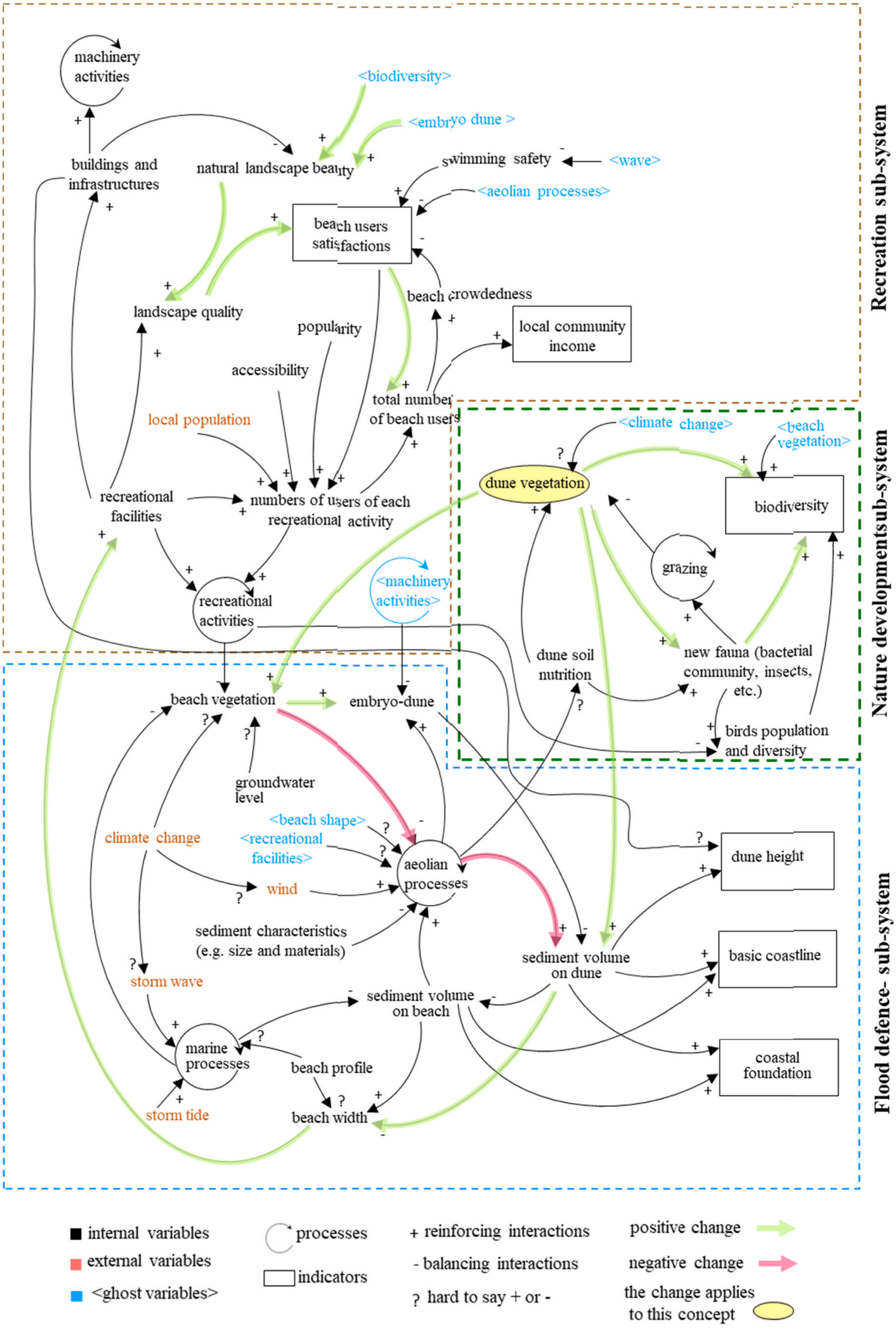

Fig. 3. Influence of improved dune vegetation cover on various functions of SAS in the socio-environmental collective cognitive map (CCM) developed with stakeholder participation.

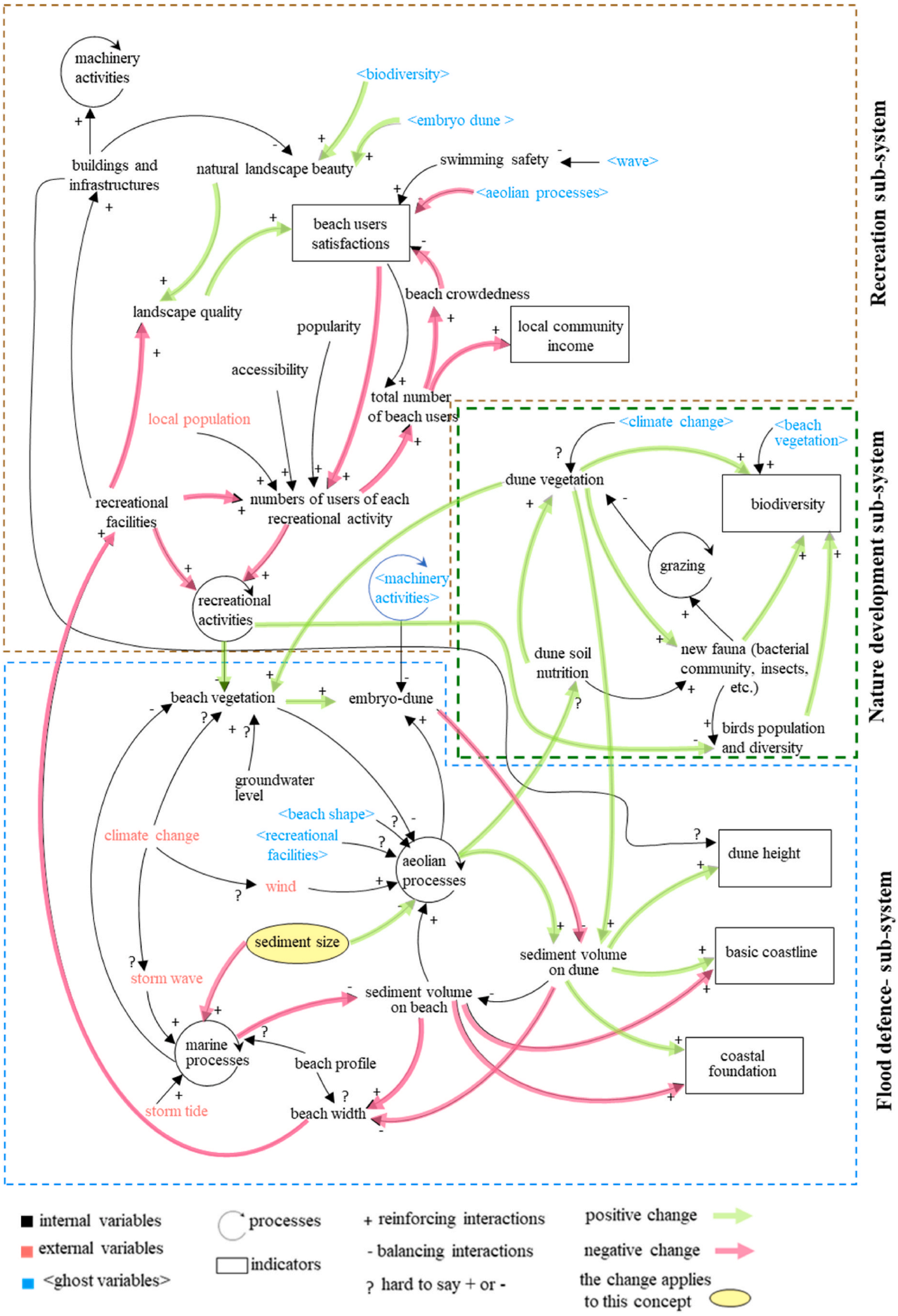

Fig. 4. Influence of decreasing the average sediment size on various elements of the SAS system. The application of CCM in SAS design and management.

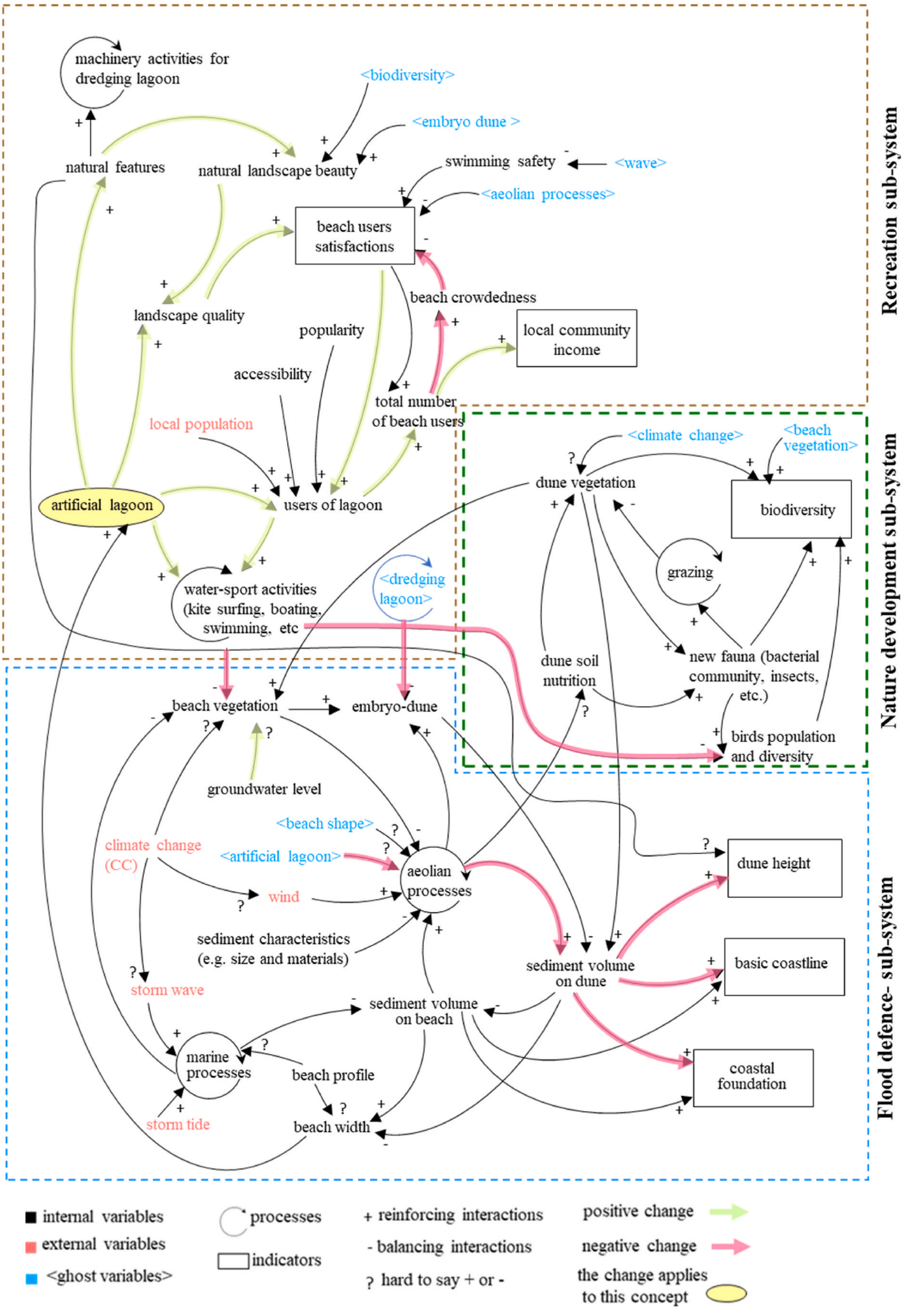

Fig. 5. Influence of building an artificial lagoon for recreation on various elements of the SAS System: The application of CCM in SAS design and management.

- Removing beach vegetation to restore or enhance the blowing of sand towards dunes.
- Conducting small-scale renourishment (shoreface, beach, or dune) to maintain the coastline.

3.2.2. The recreation subsystem

According to the participants, the main goals of recreational development in SAS are to increase the local community's welfare and well-being. These indicators are used to assess the recreation function of SAS. During the workshop, we discussed with participants how the management sectors consider the community's welfare and well-being. Finally, the local people and beach users' satisfaction and the benefit of the local economy were assigned as factors representing the local community's well-being and welfare, respectively. The impactful variables on user satisfaction were identified based on the discussion with stakeholders and the findings of a study by Goossen et al. (2019) about recreation on the Sand Motor. These variables include beach crowdedness, facilities quality and quantity, natural landscape beauty, swimming safety, and sand nuisance.

The mega nourishment in both study areas has resulted in wide beaches, providing enough space for various recreational facilities and activities. The beaches in the Netherlands are classified into different categories, such as family beaches, water sports beaches, protected natural beaches, wind farms, and so on, based on the landscape quality plan developed by the provincial government in collaboration with other organisations such as Rijkswaterstaat, Waterboard, municipalities and nature organisations. The landscape quality plan determines the types of facilities and, consequently, the types of recreational activities on the beach. For example, if a specific location is designated as a family beach in the spatial plan, more recreational facilities like restaurants, beach houses, and children's playgrounds will be developed there. The provision of various recreational facilities, such as a lagoon, beach houses, water sports schools, restaurants, etc., will affect the number of beach visitors and the level of crowdedness. Depending on the types of recreational facilities on the beach, beach users may spend money, which provides economic benefits for the local community. The recreational facilities on the beach can be temporary or permanent. These facilities and their maintenance may negatively affect the sediment exchange between the beach and dunes as well as the beach vegetation. Ultimately, this can hinder dune growth.

The management activities related to recreation functions that were discussed during the workshop include:

- Monitoring the beach for swimming safety through the presence of lifeguard stations and patrols on the beach.
- Developing new facilities such as restaurants, beach houses, and car parking.
- Cleaning the beach.
- Implementing tourist marketing strategies to enhance the popularity of SAS.
- Maintaining recreational facilities.
- Modifying the spatial plan, such as transitioning from sports activities or family zones to nature-conservation zones.
- Nourishing the beach to provide adequate space for recreation.

3.2.3. The natural development subsystem

Biodiversity, encompassing flora and fauna varieties, serves as an indicator for assessing the ecological development of SAS. The Natura 2000[2] Directives are employed to evaluate the ecological development of SAS. Natura 2000 is a network spanning all 27 European Union countries, aiming to ensure the long-term survival of Europe's most valuable and endangered species and habitats.

Nature organisations consider vegetation diversity and coverage, especially on the dunes, as essential variables for analysing vegetation conditions in SAS. The stakeholders identified the aeolian process as an impactful factor that shapes the natural dynamics of dunes and alters the characteristics of dune soil (grain size and nutrients). Soil nutrients, groundwater level and quality, grazing, and climate change play significant roles in determining the quality and quantity of the dune vegetation. The bird diversity and numbers are other critical ecological factors in the dune area. Human recreational activities, especially during the bird breeding season, have adversely affected the bird population on SAS. Also, fine-grained sediments allow macrofauna to grow, making environments more fertile for birds. The relationship between macrofauna diversity and the physical characteristics of the SAS is more complex and depends on the variables not shown in the developed CCM. These variables include wave height and energy, beach face slope, sediment penetrability and moisture content, and so on. (Janssen and Mulder, 2005; McLachlan et al., 1993).

During the workshop, some dune management policies to increase biodiversity were discussed with the stakeholders, including:

- Restricting public access to natural dune areas.
- Managing human activities on beach and dune areas.
- Limiting groundwater extraction in dune areas.
- Providing recommendations to Rijkswaterstaat regarding appropriate sediment characteristics (e.g., geochemistry and grain size distribution) in line with nature development goals before implementing new renourishment projects.
- Creating notches on dunes to increase natural dynamics on dunes (Riksen et al., 2016).
- Raising public awareness about the natural values of the system.

3.3. SAS multifunctional behaviour analysis

As mentioned in the introduction, the advantage of SAS compared to traditional flood risk management solutions is its multifunctionality and potential to enhance coastline flood protection for a longer period. However, the integrated and adaptive management of multifunctional systems like SAS is challenging. In this section, we used the developed CCM to highlight potential conflicts of interest that may arise from various management decisions about nourishment. To achieve this, we assume that during the new SAS nourishment, one of these factors (sediment size, recreational facilities, or beach vegetation) has been altered, while maintaining the other elements of the SAS system the same as the condition prior to the new nourishment.

3.3.1. Planting vegetation

One of the management decisions discussed during interviews and workshops is whether to plant vegetation, such as Ammophila Arenaria (marram grass), on the foredune (the side nearest to the sea) or dune foot after nourishment. Fig. 3 shows the influence of increased dune vegetation cover on various functions of SAS. It shows that a higher dune vegetation cover reduces the intensity of aeolian processes by minimising erosion and raising sedimentation. The reduction in sand transport over the dunes enhances the satisfaction of beach visitors and local residents by reducing wind-blown sand and salt spray. Over time, the dune vegetation may spread onto the beach, leading to embryo dune growth. The embryo dune growth improves the natural beauty of the landscape, attracting visitors interested in nature. However, developing the embryo dune will decrease the sediment transport between the beach and the main dune. Thus, embryo dune growth can impede sediment transport between the beach and the main dune, potentially hindering the increase in main dune height, which is crucial for flood safety in locations where higher dunes are necessary. This consideration is essential when deciding where to plant vegetation. Reducing sand transport slows down sediment loss on the beach and minimises the rate of beach width decrease caused by the expansion of the dune towards the sea. Consequently, recreational facilities and businesses will be less

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[2] https://www.natura2000.nl/.

threatened by beach area shrinkage.

3.3.2. *Decreasing the average sediment size*

Fig. 4 illustrates the influence of reducing the average sediment size compared to the natural sediment size of the coast in our study areas before nourishment. This reduction can be achieved, for example, by introducing silt and mud into the sediment. Decreasing the sediment size intensifies aeolian processes, which can accelerate dune growth but also lead to the shrinkage of beach area due to dune expansion. This has positive implications for flood defence and negative implications for the recreational functions of the SAS. In terms of the ecological values, sediments with a higher portion of silt and mud content provide more suitable conditions for the growth of macrofauna, serving as a richer food source for birds. Additionally, the geochemical characteristics of the sediment, such as organic content, salt, and metals or sediment PH, can influence the soil characteristics of dunes when sand is transported from the beach to the dunes through aeolian processes. In the long-term, these changes will affect the ecological system of the dune areas (Cohen et al., 2010). In the developed CCM, we highlighted the influence of decreasing the sediment size on soil nutrients in green by assuming the sediment being used for mega sand nourishment includes materials improving the ecological values of the dune environment.

The choice of sediment material and size is restricted by the characteristics of the available sediment resources. Dredging companies often transport sediment from nearby resources to reduce transportation costs. Therefore, selecting an appropriate source to enhance other system functions, such as nature development, may incur additional costs when sediment needs to be sourced from farther away. This necessitates negotiation between relevant stakeholders to decide who should bear these extra costs.

3.3.3. *Building an artificial lagoon for recreation*

Making decisions about the types of recreational facilities (e.g. restaurants, beach houses, artificial lagoons, cycling paths, car parking, beach entrances) and their numbers (e.g. how many restaurants?) is a challenging aspect of SAS management. The artificial lagoon in SAS is an environmental feature added to enhance the beauty and natural aspects of the landscape while providing opportunities for recreational activities such as boating, paddle surfing, and kitesurfing. We used the CCM to examine how the presence of an artificial lagoon on a SAS beach affects various socio-environmental elements of the system and its multifunctional behaviours.

Fig. 5 shows the influence of adding an artificial lagoon on SAS's multiple functions. Based on the stakeholder opinions, the lagoon on the Sand Motor was intended to improve the natural value of the landscape. After construction, the lagoon became a popular spot for kitesurfing. In Hondsbossche Dunes as well, the lagoon is mainly utilised for recreational purposes. Lagoons on SAS beaches attract individuals interested in water sports activities, particularly beginners who prefer the calm waters compared to the open sea. This attracted local entrepreneurs to establish water sports schools on SAS, stimulating the local economy. However, water sports activities have negative influences on nature. For example, kitesurfing has a negative influence on nature, specifically impacting bird diversity and populations, especially during bird nesting seasons. However, the fertile sediment surrounding the lagoon serves as a food source for birds. Mechanical tools used in water sports, such as board and boat motors or landing kites on dune areas, also adversely influence the vegetation cover. From a flood safety perspective, the lagoon becomes an obstacle in delivering sediment to the dunes located behind it, as it captures significant amounts of drifting sand, hindering their expected development. Simultaneously, the sand deposited into the lagoon decreases its area and depth, leading to dissatisfaction among users and entrepreneurs.

In conclusion, it is crucial to assess the short-term and long-term influences of recreational facilities before designing and developing them. It is important to ask questions such as: Who are the users? What activities will they engage in? What are their needs? Which infrastructure needs to be developed? How will these activities and infrastructures influence other system functions in the short and long term? On average, how many users will each facility attract to the beach? What are the economic benefits of these facilities for the local community? For instance, we only utilised the developed CCM for a qualitative analysis of the lagoon. Other recreational facilities such as beach houses, restaurants, and children's playgrounds can be assessed in a similar manner.

4. Discussion

4.1. *From flood safety to holistic coastal management*

Considering the high priority of flood safety in the Netherlands, clearly the majority of decisions are made with a strong focus on that. However, in some cases, such as when selecting the spatial shape of the Sand Engine (Gaussian bell shape) or constructing an artificial lagoon and lake, decisions were made to gain public endorsement. Our results reveal that these decisions may have controversial impacts on the flood safety objective. To address these challenges, the development and utilisation of CCM during the initial planning phase of multifunctional projects like SAS, as well as its continuous updating during design, construction, and implementation phases, can help evaluate the influence of specific decisions on other elements within the system. This approach allows for a comprehensive assessment of the multifunctional behaviour of the coastal system and ultimately contributes to a more holistic and sustainable approach to coastal management.

The higher priority given to flood safety compared to socio-environmental concerns has also influenced previous studies conducted on the coastal system. When focusing on the flood safety sub-system in our developed CCM, we come across several national and international studies investigating the impacts of aeolian and marine processes on dune growth (Luijedijk et al., 2019; Smit et al., 2019), the interaction between vegetation cover and aeolian processes (García-Romero et al., 2019; Dupont et al., 2014, Nield and Baas, 2008), the impacts of climate change on marine processes (Lobeto et al., 2021; Cooper et al., 2020; Grabemann et al., 2015), and the interaction between recreational facilities and aeolian processes (Pourteimouri et al., 2023; D. W. Poppema et al., 2022). However, studies examining the interactions between landscape quality (such as types of facilities, natural value of the landscape, and accessibility) and beach visitors' satisfaction and behaviours, as well as human activities and vegetation cover propagation, are rare. Similarly, there is a lack of research on the interaction between dune soil nutrition and vegetation diversity, as well as aeolian processes and dune natural dynamics. A better understanding of these interactions can provide a more realistic assessment of the potential influence of management decisions, not only on flood safety but also on other functions of the system.

In addition, we find that the indicators related to flood safety are well defined and there are several reports and publications (e.g., Wang et al., 2023; Lodder and Slinger, 2022; Lodder et al., 2020) that are in agreement regarding them. However, we rarely find a study or report that would define indicators for the related recreational, ecological or environmental issues, including biodiversity and beach visitors' satisfaction (well-being). Therefore, it is essential to encourage further studies and facilitate meaningful discussions among relevant stakeholders to establish more precise and explicit socio-environmental indicators and develop appropriate criteria for effectively evaluating the holistic system performance.

4.2. *Bridging the gap*

Despite cognitive mapping being used to study various complex socio-environmental systems, such as water resource management (Inam et al., 2015; Bakhshianlamouki et al., 2020; Zhang et al., 2021;

Nyam et al., 2021), water pollution (Diwakar and Thakur, 2012; Belayutham et al., 2016), and flood disasters (Rehman et al., 2019; Dzulkarnain et al., 2019), there is a limited number of research studies that have used this approach to assess specific issues in coastal systems. For example, Vasslides and Jensen (2016) conducted a study that mapped the estuarine system with the main focus on ecological function, while Furman et al. (2021) mapped the coastal system and assessed various stakeholder groups' perceptions of the main components of the system. Although there are similarities between the components of the system in the CCM being developed by Furman et al. (2021), their approach has not been formatted to assess the interaction between the multifunctional behaviour of the system by presenting concepts as indicators.

As mentioned, the previously conducted studies have had a sectoral approach regarding the SAS. We started to develop the first CCM of the SAS socio-biophysical system with the aim of using it as a tool for integrated management of the SAS systems, considering their multifunctionality. However, there is still much room for further development of the current CCM. For example, Bayesian Networks (BN) (Stelzenmüller et al., 2010, 2011, 2015; Neil et al., 2000; Torres-Toledano and Sucar, 1998) or Fuzzy Cognitive Mapping (FCM) (Özesmi and Özesmi, 2003; Kosko, 1986) approaches can be applied to improve our model and enable a semi-quantitative analysis of the SAS system's multifunctional behaviour under different scenarios. Both approaches require expert knowledge or quantified data to assign conditional dependencies among the identified concepts or determine the strength of connections between concepts in BN and FCM, respectively. Additionally, considering time scales of years or decades, several interactions mentioned here occur sequentially, one after the other. Therefore, to account for the consequential influences of these various interactions, we can also utilise the developed CCM as a roadmap for developing quantitative socio-environmental complex models, such as Agent-Based Models (ABM).

4.3. Limitations and recommendations

The outcomes of the PM process heavily rely on the involvement of participants. However, our PM effort was conducted during the COVID-19 pandemic, which involved lockdowns and restrictions. As a result, several key stakeholders who play a significant role in making final decisions could not attend, such as the policy department of the Rijkswaterstaat. Additionally, the perspectives of local communities and beach visitors, who are essential stakeholders, were not adequately reflected in our analysis. For future studies, we recommend incorporating the opinions of local residents and beach users by employing additional PM methods, such as surveys, separate workshops dedicated to these stakeholder groups, or utilising online platforms for discussion (Anjum et al., 2021). Gathering information about the primary motivations of stakeholders for visiting the SAS, their typical activities on the SAS, their likes and dislikes about the SAS, and what sets the SAS apart from other beaches would be valuable. Furthermore, it is crucial to consider the influence of sand dredging on benthic life in the initial stage of nourishment. Although our system focused on the beach and dune areas, the broader effects of NBS are also important and should be integrated into future studies to comprehensively assess the environmental impacts of SAS.

5. Conclusions

The developed CCM is based on stakeholder perceptions of the SAS and is a useful tool for understanding the potential impacts of changes made to improve a specific function, such as recreation, on other elements and functions within the system. It also helps to identify conflicts of interest that may arise from management actions driven by short-term socioeconomic aims or natural conditions. For instance, while a lagoon may provide a suitable environment for recreational activities in the short term, it can hinder the dynamics of sand transport between the beach and the dunes in the longer term. Identifying such conflicts allows stakeholders to engage in a dialogue and collaborate in finding solutions, thereby improving the integrated management of the system.

The Sand Motor project has the primary aim of "learning by doing." Therefore, we believe that the developed CCM should be updated at various stages of SAS development to incorporate practical and scientific knowledge obtained throughout the project lifespan. While our study focuses on the SAS in the Netherlands, the developed CCM can also be used for preliminary feasibility analysis of new SAS projects in other locations. Also, as in most PM projects, the participatory process fostered by the modelling exercise becomes even more important than its output (Voinov and Bousquet, 2010). We think that the process that we have designed can be well reproduced for other systems in other locations.

It is important to consider the following questions:

What are the main objectives of implementing SAS as a coastal management approach? (Which functions? Which priorities? Which assessment criteria?)

Which socio-environmental variables, elements, and indicators from other SAS systems should be added or omitted compared to the CCM developed for the Netherlands case studies?

By addressing these questions, the CCM can be adapted and customised to suit the specific context and goals of SAS projects in different locations. Subsequently, it can be utilised for an initial qualitative assessment of various decisions regarding nourishment practices for the multifunctional SAS. These decisions may involve considerations such as the type of nourishment (e.g., shoreface, beach, or dune), profile shape (e.g., coastline form, slope, elevation), required sediment volume, sediment source, sediment characteristics (e.g., size, shape, geochemical characteristics), vegetation planting (including location and types), and facilities (e.g., lagoon, beach houses, restaurants, car parking, toilets), among others.

The example scenarios discussed in this paper exhibit higher complexity in terms of processes, variables, and interactions than what is represented in our aggregated model. To gain a better understanding of the SAS system behaviour under various management scenarios, it is necessary to quantify the developed CCM, which can be implemented in a computer simulation. Existing quantitative models utilised for SAS design primarily focus on flood safety and consider the interactions between natural elements and processes within the SAS. However, they fail to account for the social system and the influence of various socio-environmental characteristics of the SAS on the overall system behaviour. The developed CCM serves as an essential first step in conceptualising the diverse agents, processes, and interactions, which is essential for the development of a quantitative model of the SAS socio-environmental system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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their time and unique knowledge and experience about SAS during interviews and workshops.

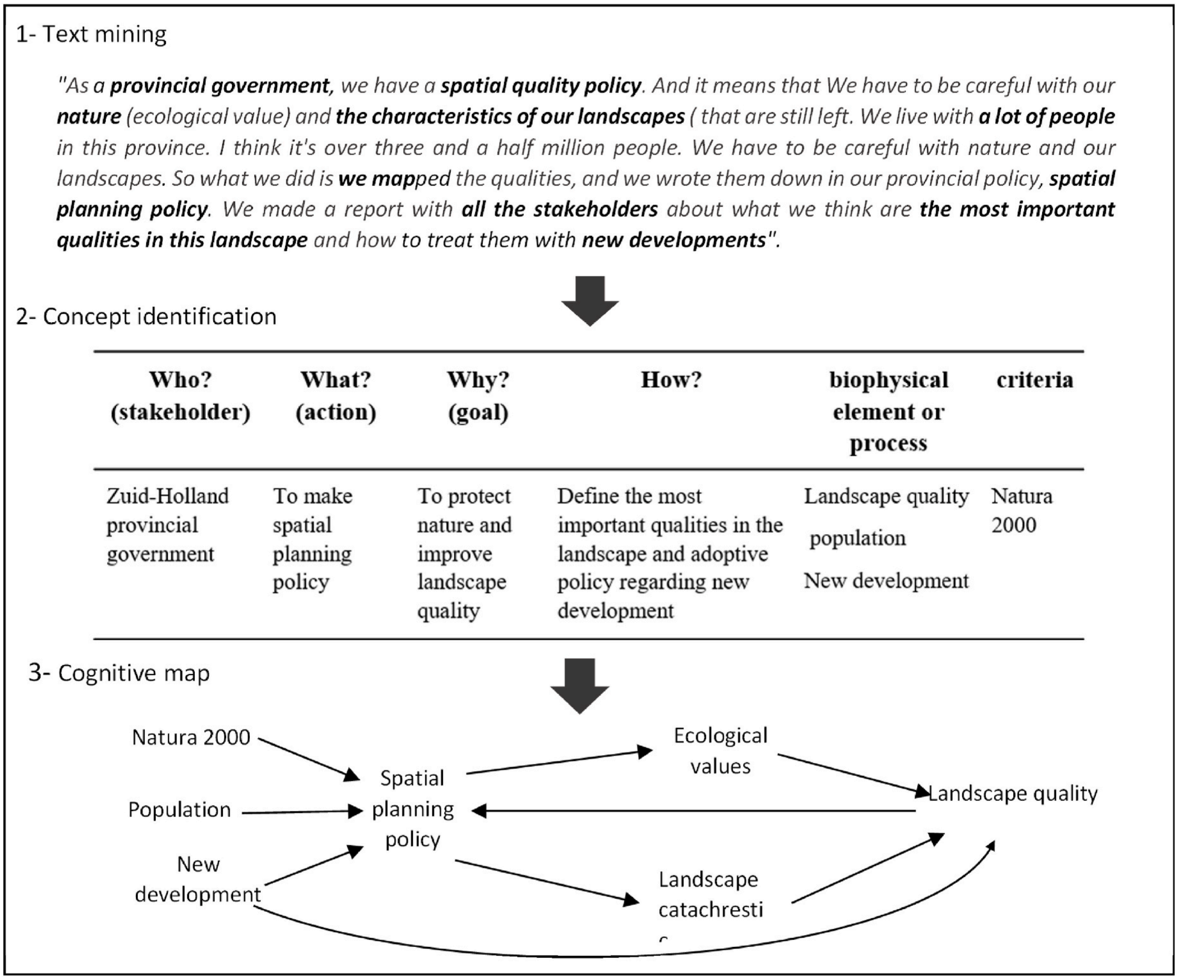
Appendix A. Information about participants in different stages of this study

Organisation	Activities' domain	Study area	Number of participants from each organisation		
			Interviews	First workshop	Second workshop
Rijkswaterstaat	Flood safety	SM	3	2	2
		HBD	1	–	
Waterboard	Flood Safety	SM	4	1	1
		HBD	1	1	
Provincial government	Nature and recreation	SM	2	1	–
		HBD	–	–	
Municipalities	Recreation	SM	2	–	1
		HBD	1	2	
Research institutes	Knowledge development	SM	7	3	4
		HBD		–	
Water companies	Water supply	SM	1	1	–
		HBD	–	–	
Entrepreneurs	Recreation	SM	2	–	–
		HBD	1	–	
Environmental organisations	Nature	SM	–	–	2
		HBD	2	–	
Contractors	Nourishment and maintenance	SM	–	–	–
		HBD	1	–	

Appendix B. The main discussion questions of the interviews

Phase	Questions	Time
Warm-up	Could you introduce yourself and explain your responsibility in Sand Motor/Hondsbossche Dune (sandy anthropogenic shores in the Netherlands)?	10 min
Core-discussion	Which values do Sand Motor/Hondsbossche Dune may have for your organisation?	40 min
	What do you do to achieve or keep these values on Sand Motor/Hondsbossche Dunes?	
	How often do you do each of these activities?	
	To do these actions, which organisation, public or private, directly or indirectly collaborates with you?	
	What are your main challenges or concerns related to these activities?	
	What would be your plan to deal with them?	
Wrap-up	Is there any other important subject that we have not discussed?	10 min
	Who else do you recommend us to interview?	

Appendix C. Procedures to translate the interviews' context to a cognitive map



1- Text mining

"As a ***provincial government****, we have a* ***spatial quality policy****. And it means that We have to be careful with our* ***nature*** *(ecological value) and* ***the characteristics of our landscapes*** *(that are still left. We live with* ***a lot of people*** *in this province. I think it's over three and a half million people. We have to be careful with nature and our landscapes. So what we did is* ***we mapp****ed the qualities, and we wrote them down in our provincial policy,* ***spatial planning policy****. We made a report with* ***all the stakeholders*** *about what we think are* ***the most important qualities in this landscape*** *and how to treat them with* ***new developments****".*

2- Concept identification

Who? (stakeholder)	What? (action)	Why? (goal)	How?	biophysical element or process	criteria
Zuid-Holland provincial government	To make spatial planning policy	To protect nature and improve landscape quality	Define the most important qualities in the landscape and adoptive policy regarding new development	Landscape quality population New development	Natura 2000

3- Cognitive map

References

Ahmad, S., Xu, B., 2021. A cognitive mapping approach to analyse stakeholders' perspectives on sustainable aviation fuels. Transport. Res. Transport Environ. 100, 103076 https://doi.org/10.1016/j.trd.2021.103076.

Anjum, M., Voinov, A., Taghikhah, F., Pileggi, S.F., 2021. Discussoo: towards an intelligent tool for multi-scale participatory modeling. Environ. Model. Software 140, 105044. https://doi.org/10.1016/j.envsoft.2021.105044.

Arens, S.M., Mulder, J.P.M., 2008. Dynamisch kustbeheer goed voor veiligheid en natuur. Land+ water 9, 33–35.

Aukes, E., Lulofs, K., Bressers, H., 2020. (Mis-) matching framing foci: understanding policy consensus among coastal governance frames. Ocean Coast Manag. 197, 105286 https://doi.org/10.1016/j.ocecoaman.2020.105286.

Bakhshianlamouki, E., Masia, S., Karimi, P., Van Der Zaag, P., Sušnik, J., 2020. A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin, Iran. Sci. Total Environ. 708, 134874 https://doi.org/10.1016/j.scitotenv.2019.134874.

Baltissen, J., 2016. The Story of the Sand Engine. Rijkswaterstaat. file:///C:/Users/ebakh/Downloads/Delfland%20Coast_Document%202.pdf.

Beaudoin, C., Mistry, I., Young, N., 2022. Collaborative knowledge mapping to inform environmental policy-making: the case of Canada's Rideau Canal National Historic Site. Environ. Sci. Pol. 128, 299–309. https://doi.org/10.1016/j.envsci.2021.12.001.

Belayutham, S., Gonzalez, V.A., Yiu, T.W., 2016. The dynamics of proximal and distal factors in construction site water pollution. J. Clean. Prod. 113, 54–65. https://doi.org/10.1016/j.jclepro.2015.11.075.

Brière, C., Janssen, S.K., Oost, A.P., Taal, M., Tonnon, P.K., 2018. Usability of the climate-resilient nature-based sand motor pilot, The Netherlands. J. Coast Conserv. 22 (3), 491–502. https://doi.org/10.1007/s11852-017-0527-3.

Brugnach, M., van den Hoek, R., 2023. Embracing ambiguity in climate change adaptation for more effective responses to new uncertain shorescapes conditions. Mar. Pol. 152, 105626 https://doi.org/10.1016/j.marpol.2023.105626.

Brugnach, M., Ingram, H., 2011. Rethinking the role of humans in water management: toward anew model of decision-making. Water, Cultural Diversity, and Global Environmental Change: Emerging Trends, Sustainable Futures? Springer 13, 49–64. https://doi.org/10.1007/978-94-007-1774-9_4.

Bruno, M.F., Motta Zanin, G., Barbanente, A., Damiani, L., 2021. Understanding the cognitive components of coastal risk assessment. J. Mar. Sci. Eng. 9 (7), 780. https://doi.org/10.3390/jmse9070780.

Bureš, V., 2017. A method for simplification of complex group causal loop diagrams based on endogenisation, encapsulation and order-oriented reduction. Systems 5 (3), 46. https://doi.org/10.3390/systems5030046.

Butler, C., Adamowski, J., 2015. Empowering marginalized communities in water resources management: addressing inequitable practices in Participatory Model Building. J. Environ. Manag. 153, 153–162. https://doi.org/10.1016/j.jenvman.2015.02.010.

Carmona, G., Varela-Ortega, C., Bromley, J., 2013. Participatory modelling to support decision making in water management under uncertainty: two comparative case studies in the Guadiana river basin, Spain. J. Environ. Manag. 128, 400–412. https://doi.org/10.1016/j.jenvman.2013.05.019.

Chen, W.L., Muller, P., Grabowski, R.C., Dodd, N., 2022. Green nourishment: an innovative nature-based solution for coastal erosion. Front. Mar. Sci. 8, 814589 https://doi.org/10.3389/fmars.2021.814589.

Cohen, D.A., Marsh, T., Williamson, S., Derose, K.P., Martinez, H., Setodji, C., McKenzie, T.L., 2010. Parks and physical activity: why are some parks used more than others? Prev. Med. 50, S9–S12. https://doi.org/10.1016/j.ypmed.2009.08.020.

Coletta, V.R., Pagano, A., Pluchinotta, I., Fratino, U., Scrieciu, A., Nanu, F., Giordano, R., 2021. Causal loop diagrams for supporting nature based solutions participatory design and performance assessment. J. Environ. Manag. 280, 111668 https://doi.org/10.1016/j.jenvman.2020.111668.

Cooper, J., Masselink, G., Coco, G., Short, A., Castelle, B., Rogers, K., Anthony, E., Green, A., Kelley, J., Pilkey, O., 2020. Sandy beaches can survive sea-level rise. Nat. Clim. Change 10, 993–995. https://doi.org/10.1038/s41558-020-0697-0.

Davison, A.T., Nicholls, R.J., Leatherman, S.P., 1992. Beach nourishment as a coastal management tool: an annotated bibliography on developments associated with the artificial nourishment of beaches. J. Coast Res. 984–1022. https://www.jstor.org/stable/4298052.

De Bakker, A.T.M., Brinkkemper, J.A., Van der Steen, F., Tissier, M.F.S., Ruessink, B.G., 2016. Cross-shore sand transport by infragravity waves as a function of beach steepness. J. Geophys. Res.: Earth Surf. 121 (10), 1786–1799. https://doi.org/10.1002/2016JF003878.

Dietz, T., Ostrom, E., Stern, P.C., 2003. The struggle to govern the commons. Science 302 (5652), 1907–1912. https://doi.org/10.1126/science.1091015.

Diwakar, J., Thakur, J.K., 2012. Environmental system analysis for river pollution control. Water, Air, Soil Pollut. 223, 3207–3218. https://doi.org/10.1007/s11270-012-1102-z.

Dupont, S., Bergametti, G., Simoëns, S., 2014. Modeling aeolian erosion in presence of vegetation. J. Geophys. Res.: Earth Surf. 119, 168–187. https://doi.org/10.1002/2013JF002875.

Dzulkarnain, A., Suryani, E., Aprillya, M.R., 2019. Analysis of flood identification and mitigation for disaster preparedness: a system thinking approach. Procedia Comput. Sci. 161, 927–934. https://doi.org/10.1016/j.procs.2019.11.201.

Ellison, A.M., Felson, A.J., Friess, D.A., 2020. Mangrove rehabilitation and restoration as experimental adaptive management. Front. Mar. Sci. 7, 327. https://doi.org/10.3389/fmars.2020.00327.

ElSawah, S., Mclucas, A., Mazanov, J., 2013. Using a cognitive mapping approach to frame the perceptions of water users about managing water resources: a case study in the Australian capital territory. Water Resour. Manag. 27 (9), 3441–3456. https://doi.org/10.1007/s11269-013-0357-5.

Escudero, M., Mendoza, E., Silva, R., 2020. Micro sand engine beach stabilization strategy at Puerto Morelos, México. J. Mar. Sci. Eng. 8 (4), 247. https://www.mdpi.com/2077-1312/8/4/247/pdf?version=1587377982.

Fairweather, J., 2010. Farmer models of socio-ecologic systems: application of causal mapping across multiple locations. Ecol. Model. 221 (3), 555–562. https://doi.org/10.1016/j.ecolmodel.2009.10.026.

Furman, K.L., Aminpour, P., Gray, S.A., Scyphers, S.B., 2021. Mental models for assessing coastal social-ecological systems following disasters. Mar. Pol. 125, 104334 https://doi.org/10.1016/j.marpol.2020.104334.

García-Romero, L., Delgado- Fernández, I., Hesp, P.A., Hernández -Calvento, L., Viera-Pérez, M., Hernandéz-Cordero, A.I., Cabrera- Gámez, J., Domínguez -Brito, A.C., 2019. Airflow dynamics, vegetation and aeolian erosive processes in a shadow zone leeward of a resort in an arid transgressive dune system. Aeolian Research 38, 48–59. https://doi.org/10.1016/j.aeolia.2019.03.006.

Gerdes, E., Koning, R., Kort, M., Waardenburg, H.S.B., 2021. Policy Evaluation Sand Engine 2021, vol. 9. Rijkswaterstaat, Rotterdam. https://dezandmotor.nl/en/downloads-archive/policy-evaluation-sand-engine-2021/.

Gijsman, R., Horstman, E.M., van der Wal, D., Friess, D.A., Swales, A., Wijnberg, K.M., 2021. Nature-based engineering: a review on reducing coastal flood risk with mangroves. Front. Mar. Sci. 8 https://doi.org/10.3389/fmars.2021.702412.

Glynn, P.D., Voinov, A.A., Shapiro, C.D., White, P.A., 2017. From data to decisions: processing information, biases, and beliefs for improved management of natural resources and environments. Earth's Future 5 (4), 356–378. https://doi.org/10.1002/2016EF000487.

Goodman, L.A., 1961. Snowball Sampling. The Annals of Mathematical Statistics, pp. 148–170. https://www.jstor.org/stable/2237615.

Goossen, C.M., Langers, F., Donders, J., 2019. Beleving en gebruik van de Zandmotor. Wageningen University & Research (in Dutch). https://library.wur.nl/WebQuery/wurpubs/569638.

Grabemann, I., Groll, N., Möller, J., Weisse, R., 2015. Climate change impact on North Sea wave conditions: a consistent analysis of ten projections. Ocean Dynam. 65, 255–267. https://doi.org/10.1007/s10236-014-0800-z.

Gray, S., Paolisso, M., Jordan, R., Gray, S. (Eds.), 2016. Environmental Modeling with Stakeholders: Theory, Methods, and Applications. Springer. https://doi.org/10.1007/978-3-319-25053-3.

Herman, P.M., Moons, J.S., Wijsman, J.W., Luijendijk, A.P., Ysebaert, T., 2021. A mega-nourishment (sand motor) affects landscape diversity of subtidal benthic fauna. Front. Mar. Sci. 8, 643674 https://doi.org/10.3389/fmars.2021.643674.

Hinkel, J., Nicholls, R.J., Tol, R.S., Wang, Z.B., Hamilton, J.M., Boot, G., Vafeidis, A.T., McFadden, L., Ganopolski, A., Klein, R.J., 2013. A global analysis of erosion of sandy beaches and sea-level rise: an application of DIVA. Global Planet. Change 111, 150–158. https://doi.org/10.1016/j.gloplacha.2013.09.002.

Hester, P., 2015. Analyzing stakeholders using fuzzy cognitive mapping. Procedia Comput. Sci. 61, 92–97. https://doi.org/10.1016/j.procs.2015.09.159.

Hoonhout, B., de Vries, S., 2017. Aeolian sediment supply at mega nourishment. Coastal Engineering 123, 11–20. https://doi.org/10.1016/j.coastaleng.2017.03.001.

Huisman, B.J.A., De Schipper, M.A., Ruessink, B.G., 2016. Sediment sorting at the Sand Motor at storm and annual time scales. Mar. Geol. 381, 209–226. https://doi.org/10.1016/j.margeo.2016.09.005.

Huisman, B.J.A., Wijsman, J.W.M., Arens, S.M., Vertegaal, C.T.M., Van der Valk, L., Van Donk, S.C., Vreugdenhil, H.S.I., Taal, M.D., 2021. Results of the Monitoring- and Evaluation Program (MEP) for the Period 2011 to 2021. Deltares, Delft, The Netherlands. https://dezandmotor.nl/app/uploads/2022/01/Sand-Motor-in-perspective-Monitoring-and-Evaluation-report.pdf.

Inam, A., Adamowski, J., Halbe, J., Prasher, S., 2015. Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: a case study in the Rechna Doab watershed, Pakistan. J. Environ. Manag. 152, 251–267. https://doi.org/10.1016/j.jenvman.2015.01.052.

Janssen, G., Mulder, S., 2005. Zonation of macrofauna across sandy beaches and surf zones along the Dutch coast. Oceanologia 47 (2). https://bibliotekanauki.pl/articles/47535.pdf.

Kant, M., 2021. Van Hondsbossche dijk naar Hondsbossche duinen: een modelstudie naar de effecten van een zandsuppletie op het grondwater regime. http://resolver.tudelft.nl/uuid:da491bd4-405a-43e3-b1c6-f73ed01a3e9b.

Kosko, B., 1986. Fuzzy cognitive maps. Int. J. Man Mach. Stud. 24, 65–75. https://doi.org/10.1016/S0020-7373(86)80040-2.

Kok, S., Bisaro, A., de Bel, M., Hinkel, J., Bouwer, L.M., 2021. The potential of nature-based flood defences to leverage public investment in coastal adaptation: cases from The Netherlands, Indonesia and Georgia. Ecol. Econ. 179, 106828 https://doi.org/10.1016/j.ecolecon.2020.106828.

Lazarus, E.D., Ellis, M.A., Murray, A.B., Hall, D.M., 2016. An evolving research agenda for human–coastal systems. Geomorphology 256, 81–90. https://doi.org/10.1016/j.geomorph.2015.07.043.

Lobeto, H., Menendez, M., Losada, I.J., 2021. Future behavior of wind wave extremes due to climate change. Sci. Rep. 11, 1–12. https://doi.org/10.1038/s41598-021-86524-4.

Lodder, Q., Slinger, J., 2022. The 'Research for Policy'cycle in Dutch coastal flood risk management: the Coastal Genesis 2 research programme. Ocean Coast Manag. 219, 106066 https://doi.org/10.1016/j.ocecoaman.2022.106066.

Lodder, Q.J., Slinger, J.H., Wang, Z.B., Van Gelder, C., 2020. Decision making in Dutch coastal research based on coastal management policy assumptions. In: Coastal Management 2019: Joining Forces to Shape Our Future Coasts. ICE Publishing. https://doi.org/10.1680/cm.65147.291.

Luijedijk, A., De Vries, S., Van Het Hooft, T., De Schipper, M., 2019. Predicting dune growth at the sand engine coupling the Delft3D flexible mesh and aeolis models. In: Coastal Sediments 2019: Proceedings of the 9th International Conference, pp. 1319–1326. https://doi.org/10.1142/9789811204487_0115.

Luijedijk, A., Van Oudenhoven, A., 2019. The Sand Motor: A Nature-Based Response to Climate Change: Findings and Reflections of the Interdisciplinary Research Program NatureCoast. Delft University Publishers-TU Delft Library. https://scholarlypublications.universiteitleiden.nl/access/item%3A2984153/view.

Marzetti, S., Disegna, M., Koutrakis, E., Sapounidis, A., Marin, V., Martino, S., Roussel, S., Rey-Valette, H., Paoli, C., 2016. Visitors' awareness of ICZM and WTP for beach preservation in four European Mediterranean regions. Mar. Pol. 63, 100–108. https://doi.org/10.1016/j.marpol.2015.10.005.

Mayaud, J.R., Webb, N.P., 2017. Vegetation in drylands: effects on wind flow and aeolian sediment transport. Land 6 (3), 64. https://doi.org/10.3390/land6030064.

McLachlan, A., Jaramillo, E., Donn, T.E., Wessels, F., 1993. Sandy beach macrofauna communities and their control by the physical environment: a geographical comparison. J. Coast Res. 27–38. https://www.jstor.org/stable/25735721.

Neil, M., Fenton, N., Nielson, L., 2000. Building large-scale Bayesian networks. Knowl. Eng. Rev. 15, 257–284. https://doi:10.1017/S0269888900003039.

Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., 2017. The science, policy and practice of nature-based solutions: an interdisciplinary perspective. Sci. Total Environ. 579, 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106.

Nield, J.M., Baas, A.C., 2008. The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. Global and Planetary Change 64 (1–2), 76–92. https://doi.org/10.1016/j.gloplacha.2008.10.002.

Nyam, Y.S., Kotir, J.H., Jordaan, A.J., Ogundeji, A.A., 2021. Developing a conceptual model for sustainable water resource management and agricultural development: the case of the Breede River catchment area, South Africa. Environ. Manag. 67, 632–647. https://doi.org/10.1007/s00267-020-01399-x.

Özesmi, U., Özesmi, S., 2003. A participatory approach to ecosystem conservation: fuzzy cognitive maps and stakeholder group analysis in Uluabat Lake, Turkey. Environ. Manag. 31, 518–531. https://doi.org/10.1007/s00267-002-2841-1.

Paolisso, M., Trombley, J., 2017. Cognitive, material and technological considerations in participatory environmental modeling. In: Environmental Modeling with Stakeholders. Springer, Cham, pp. 3–23. https://doi.org/10.1007/978-3-319-25053-3_1.

Poppema, D.W., Wijnberg, K.M., Mulder, J.P., Hulscher, S.J., 2022. Deposition patterns around buildings at the beach: effects of building spacing and orientation. Geomorphology 401, 108114. https://doi.org/10.1016/j.geomorph.2022.108114.

Poppema, D.W., Baas, A.C., Hulscher, S.J., Wijnberg, K.M., 2022. Cellular automaton modelling of the effects of buildings on aeolian bedform dynamics. Aeolian Research 59, 100840. https://doi.org/10.1016/j.aeolia.2022.100840.

Pourteimouri, P., Campmans, G.H., Wijnberg, K.M., Hulscher, S.J.Y., 2023. How wind direction and building spacing influences airflow patterns and sediment transport patterns around a row of beach buildings: a numerical study. Aeolian Research 61, 100867. https://doi.org/10.1016/j.aeolia.2023.100867.

Pourteimouri, P., Campmans, G.H., Wijnberg, K.M., Hulscher, S.J., 2021. A numerical study on the impact of building dimensions on airflow patterns and bed morphology around buildings at the beach. J. Mar. Sci. Eng. 10 (1), 13. https://doi.org/10.3390/jmse10010013.

Rehman, J., Sohaib, O., Asif, M., Pradhan, B., 2019. Applying systems thinking to flood disaster management for a sustainable development. Int. J. Disaster Risk Reduc. 36, 101101 https://doi.org/10.1016/j.ijdrr.2019.101101.

Rijkswaterstaat, 2021. Suppletieprogramma Kustlijnzorg; Uitgangspunten totstandkoming programma. Ministerie van Infrastructuur en waterstaat. https://aanmelden.khn.nl/cms/streambin.aspx?documentid=327518.

Riksen, M.J., Goossens, D., Huiskes, H.P., Krol, J., Slim, P.A., 2016. Constructing notches in foredunes: effect on sediment dynamics in the dune hinterland. Geomorphology 253, 340–352. https://doi.org/10.1016/j.geomorph.2015.10.021.

Smit, M.W., Bodde, W.P., Verheijen, A.H., Leenders, J., Wegman, C., 2019. Effect of aeolian processes on a constructed dune. In: Coastal Sediments 2019: Proceedings of the 9th International Conferencem, pp. 1340–1353. https://doi.org/10.1142/9789811204487_0117.

Somarakis, G., Stagakis, S., Chrysoulakis, N., Mesimäki, M., Lehvävirta, S., 2019. ThinkNature nature-based solutions handbook. https://doi.org/10.26225/jerv-w202.

Stronkhorst, J., Huisman, B., Giardino, A., Santinelli, G., Santos, F.D., 2018. Sand nourishment strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The Netherlands) and Aveiro (Portugal) in the 21st century. Ocean Coast Manag. 156, 266–276. https://doi.org/10.1016/j.ocecoaman.2017.11.017.

Stelzenmüller, V., Schulze, T., Fock, H.O., Berkenhagen, J., 2011. Integrated modelling tools to support risk-based decision-making in marine spatial management. Mar. Ecol. Prog. Ser. 441, 197–212. https://doi.org/10.3354/meps09354.

Stelzenmüller, V., Fock, H., Gimpel, A., Rambo, H., Diekmann, R., Probst, W., Callies, U., Bockelmann, F., Neumann, H., Kröncke, I., 2015. Quantitative environmental risk assessments in the context of marine spatial management: current approaches and some perspectives. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 72, 1022–1042. https://doi.org/10.1093/icesjms/fsu206.

Stelzenmüller, V., Lee, J., Garnacho, E., Rogers, S.I., 2010. Assessment of a Bayesian Belief Network-GIS framework as a practical tool to support marine planning. Mar. Pollut. Bull. 60, 1743–1754. https://doi.org/10.1016/j.marpolbul.2010.06.024.

Taal, M.D., Löffler, M.A.M., Vertegaal, C.T.M., Wijsman, J.W.M., Vander Valk, L., Tonnon, P.K., 2016. Development of the sand motor concise report describing the first four years of the monitoring and evaluation programme (MEP), Deltares. https://climate-adapt.eea.europa.eu/en/metadata/case-studies/sand-motor-2013-building-with-nature-solution-to-improve-coastal-protection-along-delfland-coast-the-netherlands/delfland-coast_document-1.pdf.

Torres-Toledano, J.G., Sucar, L.E., 1998. Bayesian networks for reliability analysis of complex systems. In: Progress in Artificial Intelligence—IBERAMIA 98: 6th Ibero-American Conference on AI Lisbon, Portugal, vol. 6. Springer, pp. 195–206. October 5–9, 1998., Proceedings.

Van Alphen, J., 1995. The Voordelta integrated policy plan: administrative aspects of coastal zone management in The Netherlands. Ocean Coast Manag. 26 (2), 133–150. https://doi.org/10.1016/0964-5691(95)00018-W.

Van Bergen, J., Nijhuis, S., Mulder, J., Wijnberg, K., 2020. Urban dunes: promoting BwN dune formation at nourished beaches through spatial design. Coastal Engineering Proceedings (36v). https://doi.org/10.9753/icce.v36v.management.23, 23-23.

Van der Weerd, A.J., Wijnberg, K.M., 2016. Aeolian sediment flux derived from a natural sand trap. J. Coast Res. 75 (10075), 338–342. https://doi.org/10.2112/SI75-068.1.

Van Egmond, E.M., Van Bodegom, P.M., Berg, M.P., Wijsman, J.W.M., Leewis, L., Janssen, G.M., Aerts, R., 2018. A mega-nourishment creates novel habitat for intertidal macroinvertebrates by enhancing habitat relief of the sandy beach. Estuarine. Coastal and Shelf Science 207, 232–241. https://doi.org/10.1016/j.ecss.2018.03.003.

Van Rijn, L.C., 2011. Coastal erosion and control. Ocean Coast Manag. 54 (12), 867–887. https://doi.org/10.1016/j.ocecoaman.2011.05.004.

Van Slobbe, E., de Vriend, H.J., Aarninkhof, S., Lulofs, K., de Vries, M., Dircke, P., 2013. Building with Nature: in search of resilient storm surge protection strategies. Nat. Hazards 66 (3), 1461–1480. https://doi.org/10.1007/s11069-013-0612-3.

Vanermen, I., Muys, B., Verheyen, K., Vanwindekens, F., Bouriaud, L., Kardol, P., Vranken, L., 2020. What do scientists and managers know about soil biodiversity? Comparative knowledge mapping for sustainable forest management. For. Pol. Econ. 119, 102264 https://doi.org/10.1016/j.forpol.2020.102264.

Vasslides, J.M., Jensen, O.P., 2016. Fuzzy cognitive mapping in support of integrated ecosystemassessments: developing a shared conceptual model among stakeholders. J. Environ. Manag. 166, 348–356. https://doi.org/10.1016/j.jenvman.2015.10.038.

Vermaas, T., Boersen, S., Wilmink, R., Lodder, Q., 2019. National analysis of nourishments; Coastal state indicators and driving forces for BergenEgmond the Netherlands. https://northsearegion.eu/media/18020/national-analysis_bergen_rws-deltares_20210713-final.pdf.

Vikolainen, V., Flikweert, J., Bressers, H., Lulofs, K., 2017. Governance context for coastal innovations in england: the case of sandscaping in North norfolk. Ocean Coast Manag. 145, 82–93. https://doi.org/10.1016/j.ocecoaman.2017.05.012.

Voinov, A., Kolagani, N., McCall, M.K., Glynn, P.D., Kragt, M.E., Ostermann, F.O., Pierce, S.A., Ramu, P., 2016. Modelling with stakeholders–next generation. Environ. Model. Software 77, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Software 25 (11), 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007.

Wienhoven, M., Schutte, H., Van Langevelde, A., Van Ossenbruggen, E., Schep, S., Grutters, M., 2021. Onderzoek naar de economische en sociale meerwaarde van de Zandmotor. Ecorys sites/default/files/2021-02/Onderzoek%20naar%20de%20economische%20en%20sociale%20meerwaarde%20van%20de%20Zandmotor.pdf.

Wang, Z.B., Lodder, Q.J., Van Der Spek, A.J., Slinger, J.H., Hoekstra, P., 2023. Developing a long-term management strategy to prepare the Dutch coast for the future, editorial of the VSI future Dutch coast. Ocean Coast Manag. 237, 106541 https://doi.org/10.1016/j.ocecoaman.2023.106541.

Zhang, T., Tan, Q., Zhang, S., Zhang, T., Zhang, W., 2021. A participatory methodology for characterizing and prescribing water-energy-food nexus based on improved casual loop diagrams. Resour. Conserv. Recycl. 164, 105124 https://doi.org/10.1016/j.resconrec.2020.105124.