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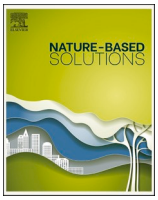

Sand nourishment for multifunctional coastal climate adaptation: three key implications for researchers

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ABSTRACT

Increased climate impacts threaten coastal functions globally, highlighting the need for multifunctional coastal climate adaptation. Sand nourishment can adapt sandy coasts to sea level rise, mitigate erosion, increase flood safety, enhance ecological habitats and expand recreational space. Therefore, sand nourishment is increasingly regarded as a promising nature-based strategy for coastal climate adaptation. However, despite this growing recognition, the assessment of how sand nourishment design impacts multifunctional adaptation remains limited. In this perspective article, we argue for three key lessons for researchers to optimise assessing multifunctional coastal climate adaptation by sand nourishment. We conducted stakeholder workshops to scope and inform our perspective, performed semi-structured literature reviews to concretise and validate this for international applications, built a qualitative model to visualise our interdisciplinary overview of how nourishments impact coastal multifunctionality, reflected on this in expert workshops, and identified implications for researchers. In this manner, we assessed the effects of nourishment design on coastal morphology, ecology, socio-economics and ecosystem services in realising the key policy goals of flood safety, nature and recreation. We found that sand nourishment design can result in conflicts between policy goals, generate ambiguous outcomes and lead to system-wide feedback effects. As such, we identified three key lessons: (1) conflicts between policy goals require informing political decision-making on prioritisation between coastal functions, (2) concreteness is needed on otherwise ambiguous functions, and (3) ongoing, multidisciplinary system-wide monitoring is essential. We thus call for a holistic approach to sand nourishment design and encourage researchers from diverse expertise and localities to expand on and adapt our findings to optimise informing sand nourishment design for delivering multifunctional coastal climate adaptation worldwide.

1. The need for understanding the multifunctionality of sand nourishments

Globally, there is an increasing need to develop strategies for multifunctional climate adaptation. Sandy coasts offer multiple societal functions but are under threat worldwide, with projections indicating that up to half of these coasts will face severe erosion by the end of the century [1]. Meanwhile, the natural capacity of these coasts to accommodate erosion is reduced, as their backshores are heavily occupied by human infrastructure, especially in densely populated areas [2]. Hence,

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adaptation strategies are called for that not only maintain coastal safety but also pursue the additional policy goals provided by sandy coasts, including, for instance, their benefits to biodiversity and cultural practices [3]. Traditionally, coastal flood safety was ensured by hard-engineered coastal infrastructure, such as dams and dikes, but this has shifted towards utilising sand nourishments. For sand nourishments, off-site sand is placed on the beach or shoreface to increase the volume in the coastal profile [4]. While compensating for erosion, this volume increase can also provide recreational space and enhance ecological habitats, thus benefitting the policy goals of flood safety, recreation and nature simultaneously [5]. Here, 'nature' should be understood broadly, including both ecological and cultural benefits [6]. By supplying ecosystem services for multiple policy goals, sand nourishments can thus promote coastal multifunctionality [7].

Recognising these potentially multifunctional effects of sand nourishments, research has developed from focusing on morphology in the 1970s and 1980s [8] towards combining multiple perspectives, including ecological and socio-economic ones, at the beginning of the 21st century [9]. Recently, sand nourishments have been increasingly regarded as 'natural solutions' that deliver 'win-wins' for multiple functions [10]. This optimistic multifunctional potential is also underlined in policy literature. For instance, sand nourishments are described as nature-based solutions (i.e., potentially providing multiple benefits) to combat increased climate impacts on coasts [3].

While the multifunctional potential of sand nourishments has been recognised in policy and research, the academic assessment of how sand nourishments deliver multifunctional outcomes can still be improved. Sand nourishments are increasingly designed with multiple functions in mind (e.g., [11]). However, research on sand nourishments and nature-based solutions has not yet fully captured how these interventions can lead to optimal multifunctional outcomes [12–14]. For instance, sand nourishments specifically designed to mitigate coastal erosion can have detrimental, unforeseen implications on the local landscape aesthetics and recreational quality [15], and biodiversity [16–18]. To promote multifunctional climate adaptation by sand nourishment, it is therefore essential to acknowledge the interconnections between their different functions [5]. Such knowledge provides insights into potential trade-offs, synergies and unintended consequences of an intervention [19], which allows coastal planners to better manage and optimise the outcomes of sand nourishments for multifunctional adaptation strategies [20].

In this perspective paper, we aim to contribute to the ongoing dialogue about how sand nourishments can promote multifunctional coastal climate adaptation, by identifying key implications for researchers. To this end, we integrated our perspectives as researchers from several Dutch universities and research institutes on the impacts of sand nourishments on coastal geomorphology, socioeconomics, ecology and ecosystem services. Our perspective was informed and shaped by workshops with stakeholders and experts. We iteratively concretised and validated this perspective for international applications through semi-structured literature reviews. We visualised the impacts of sand nourishments on multiple functions in a qualitative model. In internal workshops, we reflected on the integrated effects of sand nourishments from an interdisciplinary system's perspective. As such, we identified three lessons and implications for researchers assessing the multifunctionality of sand nourishments for coastal climate adaptation worldwide.

Below, we firstly describe how we formed our perspective. Secondly, to clarify and communicate our understanding of the system's effects of sand nourishment, we show an overview of their integrated effects visually, after which we describe three key lessons for researchers. These lessons entail our perspective on how researchers can optimise assessing the multifunctional effects of sand nourishments for coastal climate adaptation.

2. Integrating and forming perspectives

Our perspective on optimising research on multifunctional sand nourishments was informed by workshops and ongoing dialogues with stakeholders. From 2020 to 2023, we conducted 4 workshops with 12 Dutch stakeholders involved in planning and managing sand nourishments, including policymakers, NGOs and executive organisations from local to national levels. In these workshops, we discussed how sand nourishments can deliver multifunctional climate adaptation and the potential implications for decision-making on sand nourishment design, planning, maintenance and evaluation. These workshops were performed in the context of the C-SCAPE research project, for which we investigate how sand nourishments can contribute to climate adaptation strategies that increase coastal multifunctionality. These discussions informed, enriched and scoped our perspective.

To validate our perspective for wider international application, we performed complementary semi-structured literature reviews (see the Appendix for their detailed outcomes). We refer to these reviews as 'semi-structured' as we searched for literature with a preset approach and subsequently applied expert reflection and interpretation to advance the reviews. This approach allowed us to follow emerging patterns, create shared definitions of variables, and integrate qualitative insights and perspectives from distinct areas of expertise (see [21]). The preset approach to our literature reviews followed the scoping obtained at the stakeholder workshops. It was structured by our expertise on four features of the coastal system: socioeconomics, geomorphology, ecology and ecosystem services, which together reflect the impacts of nourishment design on coastal multifunctionality. For these four features, we gathered information in the current academic literature on how sand nourishment design can impact the overarching goals of nature, recreation and flood safety by mitigating erosion and adapting coasts to increased climate impacts. These are the most commonly recurring policy goals for which sand nourishments are utilised [5,22]. We ensured that the literature represented sand nourishment effects for a wide range of localities. As nourishment design variables, we considered cross-shore placement location, nourishment volume and nourishment frequency, since these variables are most frequently adjusted to generate multifunctionality. We thus did not include all potential design variables, e.g., leaving out sediment size, longitudinal nourishment location, sand colour and locally dependent elements such as the presence of coral reefs or seagrass. As these areas of expertise do not reflect all potentially relevant information on the impacts of nourishment design on coastal multifunctionality, these reviews present a subset of how the entire coastal system is impacted, and can be adjusted and expanded by researchers rooted in other localities and academic disciplines – which we strongly encourage.

To give an overview of the system effects of sand nourishments on coastal multifunctionality, we visualised and conceptualised these literature reviews iteratively into a qualitative model. A qualitative model is ideally suited to visualize and gain insight into a socio-ecological system's structure, dynamics and drivers. It allowed us to link diverse scientific disciplines, and bring together and evaluate variables that may otherwise be difficult to relate [19]. We iteratively integrated and translated the knowledge of the literature reviews into the model (Fig. 1), following the methodology described by Haila & Levins [19]. The model consists of sand nourishment design options as input variables, the system effects as mediating variables and connections, impacts on the policy goals as output variables, and the general causal and directional relations as arrows between those. We included information as a mediating variable if it had a unique effect and was affected by another variable in the model. If two variables had the same relations to others or did not alter the model dynamics uniquely, we considered them as one overarching variable. We connected variables if there was a distinct increasing or decreasing causal relationship between them. If the effects could be both increasing and decreasing, we separated one of the two variables to distinctly show each effect. The arrows thus indicate

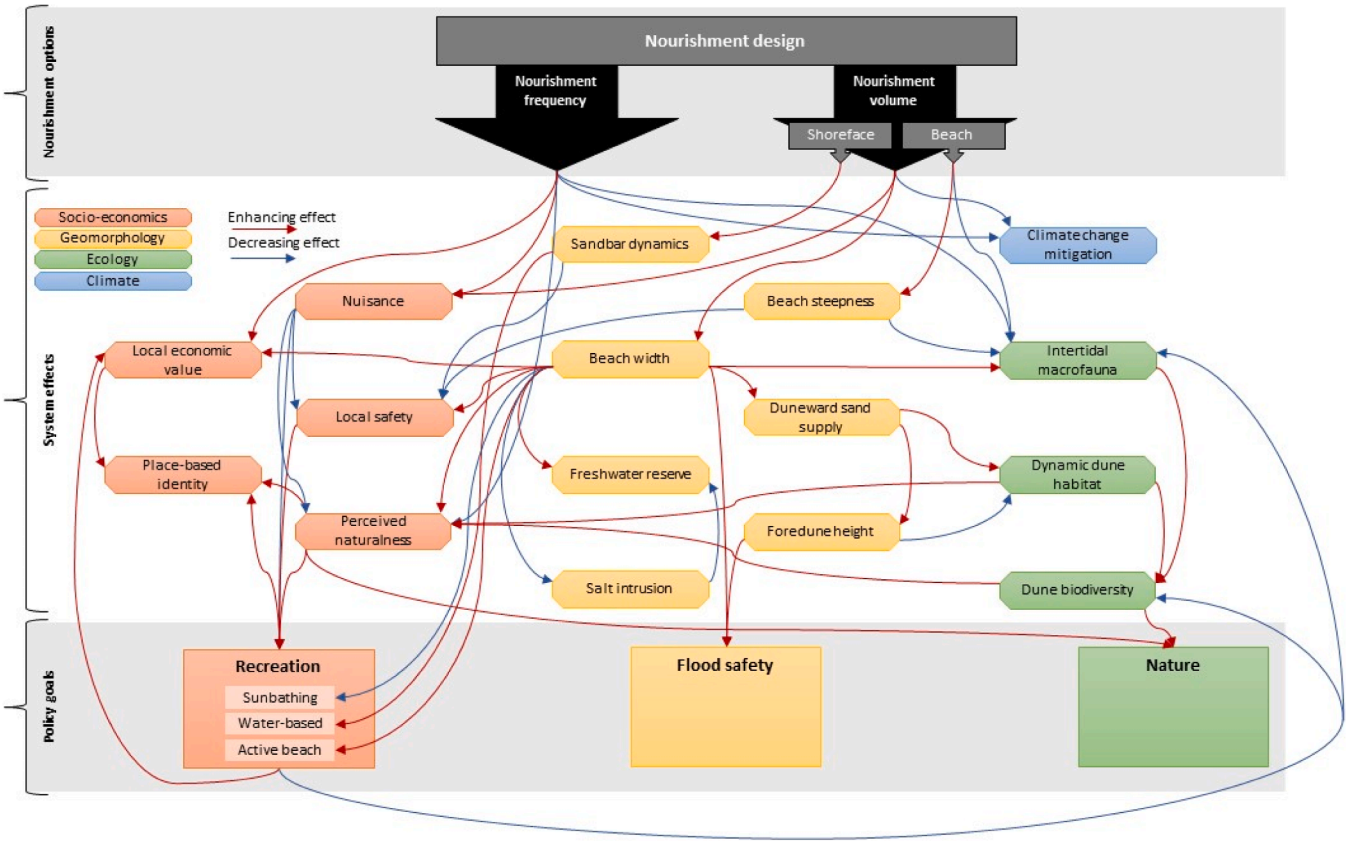

Fig. 1. Qualitative model illustrating the potential processes and interactions following sand nourishment design. The nourishment design options are depicted at the top of the figure. The effects on the coastal system are displayed in the middle horizontal section. The policy goals most strived for in multifunctional coastal climate adaptation are depicted at the bottom of the figure. Arrows demonstrate increasing or decreasing general causal relations between the variables, which can be enhanced by previous effects. For definitions, detailed descriptions and references to literature for the variables and interactions shown, see the Appendix.

the direction and general impact of this relationship – not our view on the desirability of this impact. The effects can accumulate; if a variable with a decreasing effect on the next is increased, the net effect on the latter variable is a stronger decrease. The directions of the relationships reflect a generic pattern (based on literature) that may deviate locally, depending on, e.g., the environmental, policy and management context. This model construction followed the literature reviews and expert assessment iteratively, in which the authors had to be in agreement on the variables and their causal connections.

We performed several workshops among the co-authors during and after the development of literature reviews and the model. In these, we interpreted the system effects of sand nourishments to assess how sand nourishment design impacts nature, flood safety and recreation, and to identify implications for researchers. Classification of the elements in the model and relationships between the different elements were verified during these expert workshops, resulting in the visualization of the multifunctionality of sand nourishments as depicted in Fig. 1. We also reflected on how nourishment design could affect the drivers of the individual policy goals, how these drivers interrelate, and what conflicts and synergies result from those. We related this information to the current literature on multifunctional sand nourishments, and we analysed its implications for decision-making to optimise multifunctional sand nourishment design. This culminated in three key lessons for researchers on the multifunctional potential of sand nourishments for coastal climate adaptation worldwide.

3. Visualising the multifunctionality of sand nourishments

Our qualitative model illustrates how sand nourishment design can affect the policy goals of recreation, flood safety and nature from the integrated perspectives of geomorphology, ecology, socioeconomics and ecosystem services (Fig. 1). The large number of relationships within and between the features of the coastal system is striking; many variables causally influence other variables in this system, connecting all features of the coastal system and policy goals considered in this study. This highlights how interdisciplinary and multifaceted the impacts of sand nourishments are. For definitions, detailed descriptions and references to literature for the variables and interactions shown, see the Appendix. Below, we highlight some key points of this model.

Geomorphological variables affect the system's outcomes in different ways, affecting both the system's socioeconomic and ecological components diversely (Fig. 1). Notably, the system's socioeconomic aspects predominantly influence the ecological components and do so mostly with a decreasing effect. Conversely, fewer effects lead from the system's ecology to its socioeconomics.

Zooming in on the role of distinct variables, at least two variables steer the multifunctional effects of sand nourishments: beach width and how coastal users perceive the area's naturalness. Beach width has the most diverse impact on the other variables and influences all policy goals. The perceived naturalness links the effects of sand nourishments on ecology to the socioeconomics of the coast.

Regarding nourishments' effects on the three policy goals, distinct aspects of the overarching policy goals are affected differently. More precisely, the sunbathing recreationist generally favours a narrower beach to be closer to the seashore, whereas the active recreationist utilises a wider beach for on-land activities [23–25]. The presence and dynamics of sandbanks can decrease the swimmer safety in the water [26,27], but can also be considered necessary for water-based recreation such as surfing [28–30]. While sand nourishments generally increase the flood safety of the coastline, they can decrease the local safety of the

users, e.g., due to increased construction work and currents [27]. Also, both the occurring biodiversity and how the naturalness of the area is perceived shape the benefits of nourishments to achieving the policy goal of nature, as an interplay between ecology and culture-specific socio-economic elements [6,31–33].

4. Lessons learned to optimise the multifunctionality of sand nourishments

4.1. Lesson 1: Conflicts between policy goals require informing political decision-making on priorities

Through our workshops, reviews and discussions, we found that multifunctional sand nourishments are not only a clear win-win for nature, flood safety and other policy goals. This adds nuance to suggestions in academic literature (e.g., [34,35]) that illustrate sand nourishments as such. Synergies between policy goals can indeed occur, but conflicts between them must also be acknowledged. Recently, awareness of such potential conflicts has been growing [5,14]. Below, we illustrate these with one example of a potential synergy and two examples of potential conflicts.

A potential win-win design option involves enhancing beach width. This can increase recreational space and contribute to wave attenuation. It can also enhance dune-ward wind-driven sand supply, which, in turn, can lead to more dynamic foredunes, thus supporting more dune biodiversity [36], and increases foredune volume and height, which also benefits flood safety [37,38]. In contrast, increasing the nourishment volume over its frequency can lead to conflicting outcomes on the policy goals. Increased volume reduces the negative impact on intertidal macrofauna by allowing more recolonization time [39], thereby reducing the impact on local biodiversity and benefitting the policy goal of nature. However, larger volumes can also lead to restricted beach access and strong currents [26,27], hence reducing recreation potential. Another conflict between policy goals follows from placing a nourishment on the beach, instead of on the shoreface. Beach nourishment can create fewer sand banks and hazardous currents, benefiting the safety and recreational potential for swimmers. However, this placement location severely affects the intertidal macrofauna, reducing the coastal biodiversity and benefits to the policy goal of nature.

Researchers can improve purposeful multifunctionality by informing decision-makers of potential conflicts between policy goals (Fig. 2). Since conflicts between policy goals are likely to arise when applying sand nourishments, their multifunctionality can be improved by carefully and explicitly prioritising these goals, which opens up new research directions. Acknowledging the multifunctional effects of sand nourishment is the first step for this. However, conflicts between values are inherent in design choices, sand budgets will shrink, and emissions and costs will rise with increasing climate impacts [40,41]. Hence, nourishment design becomes increasingly challenged and will entail more sensitive deliberations on which coastal functions to maintain. Such choices constitute political decision-making. Addressing the conflicts and synergies between climate adaptation goals is thus not merely a technical but also an inherently political choice, which should be taken together with decision-makers and society [42]. Even in cases where multifunctional outcomes are considered, not all stakeholders might agree on the optimal or right prioritisation of the limited resources. Incorporating these perspectives fairly leads to more legitimate, better-informed and supported interventions [43,44]. Researching such political decisions on sand nourishment design entails, for instance, investigating which stakeholders are affected by implementing sand nourishments as climate adaptation, investigating how they would prioritise the potential outcomes and finding ways to incorporate these fairly [45]. The political nature of choosing the right manner of adaptation is increasingly acknowledged in research on multifunctional assessments [7] and nature-based solutions [46,47]. Yet, in assessing sand nourishment strategies for coastal climate adaptation specifically, this brings new directions for future research.

4.2. Lesson 2: Concreteness is required on otherwise ambiguous functions

The outcomes of multifunctional sand nourishments may be ambiguous if the individual policy goals are not defined precisely. Distinct aspects of the policy goals can conflict, and if these broad goals are not legitimately specified, this can lead to undesired and unfair outcomes [48,49]. For instance, if nourishments' effects on 'nature' or 'recreation' are measured by specific indicators without acknowledging that these reflect a particular understanding of these goals, the assessment may lead to ambiguity and conflicts with stakeholders [50]. While this gap between broad evaluation categories and specific indicators has been recognised in research on indicator development [51], we find that the policy goals are still often regarded as unitary terms when assessing sand nourishments.

We note that distinctive aspects of recreation, safety and nature are affected differently by sand nourishment design. For instance, active recreationists (e.g., runners and hikers) may profit from a wider beach, while sunbathing and water-based recreation may be negatively affected by the increased distance to the waterline. Sand nourishment design may also affect distinct aspects of safety differently. A large nourishment volume enhances flood safety, but can also increase beach steepness and currents, decreasing swimmer safety. Also, sand nourishments can harm

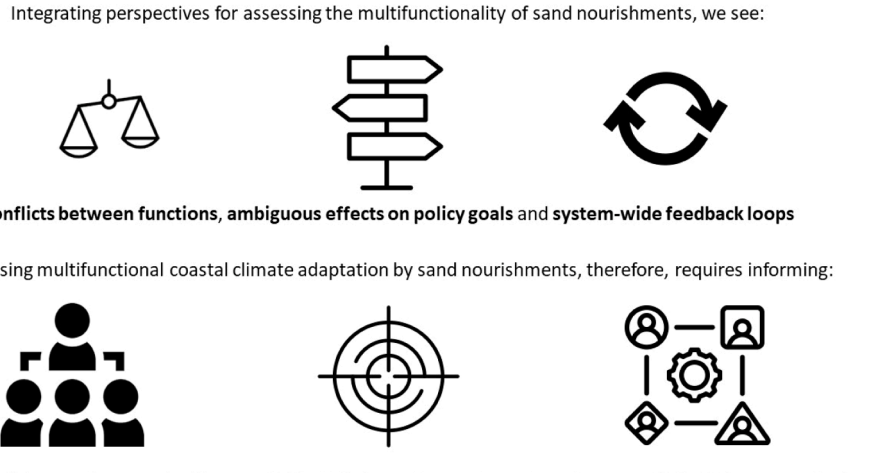

Fig. 2. Lessons learned for optimising multifunctional coastal climate adaptation by sand nourishment

intertidal macro-fauna and thereby the biodiversity of the beach in the short term. However, in the long term, they may increase the perceived naturalness, as they benefit the dune-ward sand supply, dune dynamics and dune biodiversity.

We stress the need for ongoing dialogue between researchers and decision-makers to formulate explicitly what outcomes could and should be delivered by multifunctional sand nourishments. While open terminology can be useful for gathering stakeholder support and collaboration, it contrasts with the need for concreteness in, for instance, goalsetting, assessing potential impacts, and evaluating and assessing performance [50]. This dichotomy between open terminology and concreteness for assessment has been described as a challenge in defining indicators for nature-based interventions [52]. Specific indicators have been developed for applying and assessing sand nourishments, but, the 'right' indicator depends on the context it is used and the information available [53]. Stakeholders might hold diverse perspectives on what achieving a policy goal might entail, and they might thereby disagree on whether an indicator reflects that performance [54]. Therefore, as nourishments are increasingly utilised to benefit multiple functions and impact more stakeholders, research can improve informed decision-making by developing indicators that explicitly inform on the status of achieving policy goals and the diverse perspectives thereon. Having an explicit view of what constitutes desired outcomes depends on effective and reciprocal communication with legitimate decision-makers [55]. In this communication, decision-makers with a democratic mandate may precisely define policy goals, while researchers provide insight into how nourishments may affect those goals. Furthermore, this communication should be iterative, to allow for adapting and adjusting the multifunctional design towards the outcomes that are both desired and feasible. Research that aims to inform optimising the multifunctional outcomes of sand nourishments could for instance investigate the interpretations and variability of these policy goals, as has been proposed for climate adaptation planning [56].

4.3. *Lesson 3: Monitor system-wide – and keep on doing so*

Designing sand nourishments for a policy goal may lead to unforeseen feedback effects. For instance, a nourishment may be designed with a larger beach width to attract additional visitors. These extra visitors may, however, put pressure on biodiversity, by, for instance, harming dune vegetation [57]. This may reduce the area's perceived naturalness, decrease the capacity of the foredunes to bind sediment or alter the identity visitors attach to the place. Such effects may decrease the area's attractiveness, resulting in fewer visitors – a negative feedback loop for the recreational function of the beach. Nourishments with wider beaches may also increase the recreational potential of the coast, leading to increased identity building with the area and therefore increased societal pressure to sustain this recreational potential. The relationships in the coastal systems can be context-dependent and differ, for instance, in their temporal development, which leads to increased complexity of overseeing and monitoring multifunctional outcomes.

The presence of feedback loops and complex interactions demonstrates that the consequences of nourishment design may be dynamic and non-linear. This puts perspective to studies on multifunctional evaluation of sand nourishments that assume linear and static relations between the drivers of policy goals and their realisation, against which, for instance, the framework of ecosystem services has been cautioned (see, e.g., [58]). A common example involves assuming that the recreational value of the beach increases in line with its physical carrying capacity (e.g., [59,60]). Additionally, our observations align with the growing recognition of nature-based solutions in general as interventions with potentially complex outcomes [61], and coasts as complex socio-ecological systems [62], in which sand nourishments can lead to complex effects [5]. We, therefore, encourage further research on the variables that determine this complexity and its outcomes, their development over time, and the quantification of the non-linear outcomes of sand nourishment design. For instance, as has been suggested for decision-making under deep uncertainty, research assessing sand nourishments as adaptive and multifunctional nature-based adaptation strategies could focus on understanding what determines path dependencies [63].

Our findings strengthen the call for long-term, system-wide monitoring of multifunctional sand nourishments [64]. This monitoring can consider temporal variations in the delivery of multifunctionality and reactions to perturbations, relating to potentially complex dynamics [65]. Additionally, monitoring can focus on key variables that govern the system's multifunctionality – which include beach width and the perceived naturalness, given the policy goals of nature, flood safety and recreation. This monitoring can inform management with means to oversee and control the system's multifunctional outcomes. Moreover, as unforeseen feedback loops may occur, monitoring can consider that unexpected effects may arise, and appropriate resources should be reserved for adapting to these.

5. Towards an integrated design to optimise multifunctional sand nourishments

We identified three key implications for researchers to inform the design and evaluation of sand nourishments for multifunctional coastal climate adaptation. Contrary to literature suggesting clear win-win outcomes, we see that conflicts between policy goals also occur, specifically between flood safety and the other policy goals, and between nature and recreation. Moreover, relationships between these goals can be ambiguous, contain feedback loops and lead to conflicts within and between functions. We, therefore, argue that decision-makers can carefully prioritise between functions and define these explicitly, as the optimal nourishment design depends on what outcomes are desired, being a political decision for society. Our findings also imply that the policy goals are not as clear as they initially may seem. Explicitness, achieved in communication between researchers and decision-makers, is thus required in designing for and evaluating otherwise ambiguous functions. To accommodate for the complex socio-ecological dynamics, system-wide monitoring is required, as a continuous effort. We thus found system behaviour that calls for researchers and decision-makers to carefully define and prioritise the desired nourishment outcomes and to be prepared for complex system behaviour when designing for multifunctional climate adaptation.

In this perspective, we thus call for a holistic approach to assessing multifunctional sand nourishment, urging researchers to consider the need for explicit political prioritisation among policy goals, clear and reciprocal communication to address ambiguous outcomes, ongoing, multidisciplinary monitoring, and research into potential feedback effects and path dependencies. As an invitation to researchers from diverse expertise and localities, we encourage the expansion and adjustment of the proposed model, to optimise sand nourishment design for delivering multifunctional coastal climate adaptation globally.

CRediT authorship contribution statement

Haye H. Geukes: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Tosca T. Kettler:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Eva M. Lansu:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Vincent Bax:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Solveig Höfer:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Matthieu A. de Schipper:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Renske de Winter:** Writing – review & editing, Investigation, Funding acquisition. **Arjen P. Luijendijk:** Writing – review & editing, Supervision, Funding

acquisition. **Valerie C. Reijers:** Writing – review & editing, Supervision. **Peter M. van Bodegom:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Wietse I. van de Lageweg:** Writing – review & editing, Supervision, Funding acquisition. **Tjisse van der Heide:** Writing – review & editing, Supervision, Funding acquisition. **Alexander P.E. van Oudenhoven:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2024.100191.

Data availability

The outcomes of the literature reviews referred to in this article can be found in the Appendix.

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