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Co-creating a coastal climate service to prioritise investments in erosion prevention and sea-level rise adaptation in the Maldives

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ABSTRACT

While the prioritisation of scarce resources for climate adaptation is becoming a priority for low and middle income countries, the climate service literature addressing adaptation prioritisation decisions is scarce. This paper contributes to filling this gap by presenting a co-creation process carried out in the Maldives among representatives of government, civil society and researchers. Together, we identified the need to improve a ranking method currently used by the Maldivian government to prioritise islands for investments in erosion prevention. As a solution we developed a layered index. The first layer of this index captures the objective dimension of the problem through an erosion hazard subindex, using the three variables wave energy, reef health and reef flat minimum width. The second layer captures the normative dimension through a multi-criteria analysis using the erosion hazard subindex as one criterion next to other stakeholder selected criteria such as critical infrastructure, economic activity, per capita income and the potential to house additional people that resettle from riskier places as sea-level rise progresses. Results of this new ranking method show that socio-economic criteria were considered more important by the stakeholders than the biophysical criterion of erosion hazard. Among the top-ranked islands are many regional centres but also less populous islands that have a large potential to house additional people. Lessons learnt from the co-creation process highlight the importance of assembling interdisciplinarity teams, fostering mutual learning among project participants, and designing research projects that do not prescribe upfront the exact problems to be addressed and methods to be applied.

1. Introduction

Prioritisation of scarce resources for climate risk management and adaptation is a specific class of problems that climate services will increasingly need to address, in particular for low and middle income countries. With the impacts of climate change being felt virtually everywhere (IPCC, 2021), an important policy question for governments with limited resources is to prioritise which adaptation problem in which location to address first. This is specifically true for costly infrastructure-based adaptation measures as found in the coastal sector. Prioritisation problems have been widely studied in related fields such as biodiversity protection (Cullen and Cullen, 2012), health risk (Montibeller et al., 2020) and environmental risk of pharmaceuticals (Roos et al., 2012), but not much in climate adaptation.

Prioritisation in climate adaptation in a low and middle income context is challenging specifically for two reasons. First, data for

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modelling climate related risks and supporting prioritisation is often scarce, and so are resources for gathering this data. Hence, detailed surveys cannot be conducted in each location and pragmatic choices need to be made on how environmental risks are to be assessed. Second, objective aspects, i.e. aspects relating to the biophysical processes causing climate risk, and subjective aspects, i.e. aspects relating to the adaptation goals, other policy priorities and the preference of stakeholders, are often tightly intertwined.

Generally, it is widely accepted that both of these aspects call for a transdisciplinary co-creation approach for climate service development, in which stakeholders and researchers work together to co-design objectives and co-produce methods and results targeted at specific decisions and policy processes that the users of the climate service are confronted with (Hewitt et al., 2017; Jacobs and Street, 2020; Lourenço et al., 2016; Suhari et al., 2022; Vincent et al., 2018). Despite the importance of this co-creation process, most of the literature focus on only presenting the results of this process rather than also documenting the process itself and the design decisions that have been taken within.

This paper addresses these gaps and challenges and aims to contribute to the development of a literature on climate services addressing adaptation prioritisation problems. Specifically, we present the co-creation of an index for prioritising investments in coastal erosion measures on the Maldives, a low-lying atoll island nation in the Indian Ocean, consisting of around 1,200 islands of which 187 are currently inhabited. Due to scarce land and high population densities, coastal erosion of inhabited islands is a major concern for the Maldivian society and addressing erosion is a key responsibility of the Maldivian government. As many islands experience coastal erosion, and national budgets are limited, the Maldivian government must prioritise among islands.

2. Materials & methods

2.1. The biophysical context

The Maldives with its dispersed geography and the low-lying character of the islands is recognized to be among the countries that are most vulnerable to climate change and sea-level rise. The 187 inhabited islands are spread over a distance of about 870 km from North to South, with average land elevations ranging from 0.5 m to 2.3 m above mean sea-level (Wadey et al., 2017). The Maldives are facing a range of climate change impacts including coastal flooding and erosion enhanced through sea-level rise, and the salinization of groundwater lenses. Coastal erosion is already widespread today, as it is in other low-lying atoll islands, because sediment movement is specifically pronounced in such islands, also independent from anthropogenic sea-level rise, because atolls consist of unconsolidated biogenic material from coral reefs (Duvat, 2019; Holdaway et al., 2021; Mycoo et al., 2022).

Irrespective of anthropogenic climate change and sea-level rise, there are three main sets of factors that drive the coastal erosion in the Maldives (Fig. 1). First, the main direct drivers of coastal erosion in the Maldives are ***currents and waves*** (Kench, 2012). These produce seasonal patterns of shoreline change driven by a reversal of wind direction through the monsoon, which are often balanced annually. Beyond seasonal fluctuations, extreme wave events hitting the shore cause major shoreline change and erosion (Wadey et al., 2017). Irrespective of the offshore wave direction, waves thereby influence the entire perimeter of reef island shorelines, because waves refract and diffract around reef platforms (Kench, 2012).

The second set of factors relates to the ***morphology of the coral reefs*** surrounding the islands, which modulate waves and currents in several ways (Aslam and Kench, 2017) (Fig. 1). Coral reefs substantially reduce the wave energy that arrives at the shoreline by breaking the wave at the fore reef and dissipating the wave energy as the wave travels over the reef flat (Lowe et al., 2005). The wider the reef flat, the more wave energy is dissipated and the less wave energy arrives at the shoreline causing erosion.

The third set of factors relates to **reef health**, as coral reefs are often degraded through anthropogenic drivers such as acidification, pollution, fishing and tourism (Hughes et al., 2017a), as well as climate change (see next paragraph). Degraded reefs have a lower bottom friction than healthy ones, leading to more energetic waves hitting the shoreline and enhancing erosion (Quataert et al., 2015a). Furthermore, coral reef degradation also reduces the biodetritic production of sediment, resulting in less sediment supplied to the lagoon, and this sediment deficit can exacerbate erosion (Aslam and Kench, 2017).

The fourth set of factors is related to ***human modifications of the shoreline***, in particular the hardening of the shoreline through coastal protection infrastructure such as groynes, seawalls and revetments. Hard structures along the coast interrupt longshore sediment transport, thus favouring erosion in nearby areas. They also interrupt cross-shore sediment transport and thus limit the possibility for islets adjusting to new waves and sea-level conditions (McLean and Kench, 2015a). Hence,

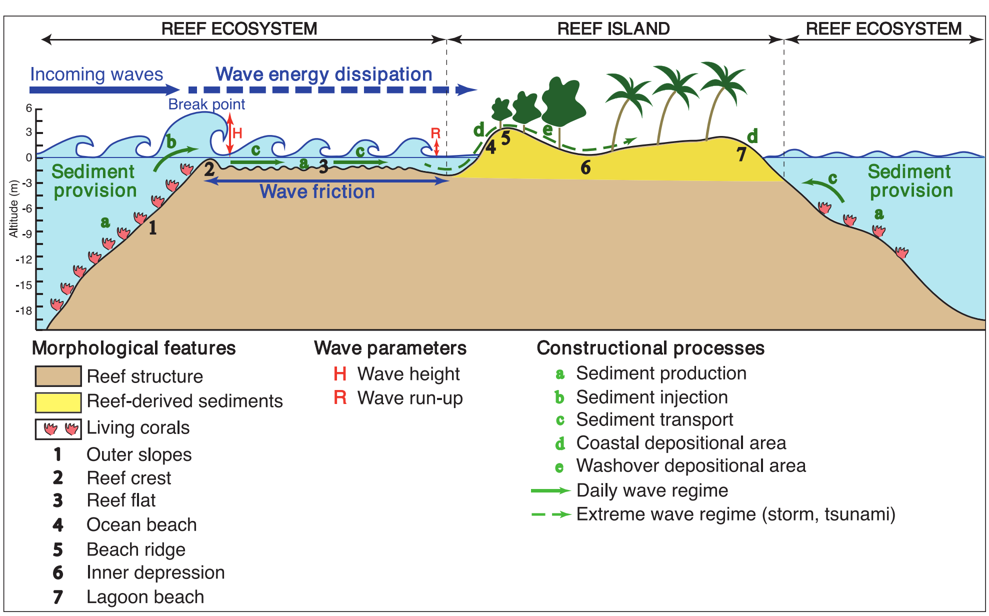

Fig. 1. The main biophysical processes controlling coastal atoll island dynamics. Adapted from Duvat and Magnan (2019).

coastal defences that have been constructed to prevent erosion, may actually exacerbate erosion on the longer run, leading to a higher risk of erosion on these islands as compared to islands with unmodified shorelines (Nunn et al., 2021; Pisapia et al., 2017; Rasheed et al., 2020).

Observational evidence shows that either of these factors can dominate and cause erosion or accretion of atoll islands (Duvat, 2019). For example, Aslam and Kench (2017) showed that in the Huvadhoo Atoll, 45% of atoll islands were eroding, 40% stable and 15% increasing in surface area, with small islands being more prone to erosion. Yet they also showed the major influence of human interventions. Recent research also shows that additional factors, such as aeolian transport, can play a role in favoring lagoonward sedimentation (Hilton et al., 2019), which also means that vegetation can play a role in favoring sediment accumulation. Like in other atoll islands (Duvat, 2019), it can be possible to identify areas where specific processes play a key role (e.g., currents in passes, sediments from corals along islands exposed to energetic waves, etc.), but making a generic picture from these fragmented evidence would not reflect well the diversity of situations that take place on the ground.

Climate change and sea-level rise influence these sets of factors in several ways. Higher sea-levels reduce the natural potential of the reef surrounding the islands to protect against erosion through reducing the energy of waves before they hit the shore (Bramante et al., 2020). The extent to which this happens is strongly dependent on the reef health, which in turn is negatively affected by climate change induced ocean warming (Hughes et al., 2017b) and ocean acidification (Kroeker et al., 2013). When a reef is healthy, both the reef and the associated island can grow with rising sea levels, within certain limits, depending on the rate and acceleration of SLR (Montaggioni, 2005; Perry et al., 2018), as the bio-detritic productivity of a healthy reef will maintain sediment supply to the islands (Tuck et al., 2019). Recent studies that have looked at a large number of coral islands in the Pacific and Indian Oceans found that about 90% of these islands were either stable or have increased in area over the last decades of sea-level rise (Duvat, 2019; Holdaway et al., 2021). This even included islands in regions where sea-level rose 3 to 4 times faster than the global average (McLean and Kench, 2015b). In contrast, when a reef is not healthy, or even dead, it will not rise with rising sea levels, which means that the reef's wave energy dissipation function decreases with rising sea-level, and wave energy at the coast will consequently increase (Quataert et al., 2015b).

2.2. The social context

Land scarcity is a general problem that rapidly developing and urbanising small island states are facing (Nurse et al., 2014) and hence combating a loss of land through erosion is a major societal interest. The government of Maldives has been making annual decisions on which islands to prioritise in combating coastal erosion for a number of years. The legal basis of this decision is the Environment Protection and Preservation Act of Maldives 1993, revised in 2016 (Ministry of Environment and Energy, 2016, p. 93). This act established a public investment scheme to implement coastal protections to reduce coastal risks with a focus on islands with severe erosion. Based on this, the Ministry of Environment, Climate Change and Technology developed the so-called ***red list*** (Fig. 2), an index weighting the five variables of observed erosion intensity, population, critical infrastructure, economic activity and population consolidation potential. The last variable refers to the capacity of an island to house additional people and is explained in more detail in the next paragraph. The red list is then used to prepare the annual fiscal budget for erosion protection and erosion protection projects are funded on the top-ranked islands (Gussmann and Hinkel, 2021a).

The potential of an island to house additional people (i.e., population consolidation potential) is an important criteria for erosion management in the Maldives, because concentrating population on fewer islands reduces the both the cost of bringing government services and coastal protection to islands. Due to the former aspect, population consolidation was an official policy formulated in the 7th National Development Plan 2006–2010. More recently this consolidation policy has been abandoned in favour of a more decentralized development strategy (Gussmann and Hinkel, 2020). Nevertheless, the potential of an island to house additional people remains an important criteria in public discourse.

All inhabited islands are considered in the prioritization through the red list except the capital islands of Malé and Hulhumalé, because these islands are not part of the allocation procedure for erosion management as these islands are currently well protected by sea-walls and revetments. According to the last census in 2014, 189 islands were inhabited (National Bureau of Statistics, 2014). The two islands L. Gaadhoo and L.Kalhaidhoo were subsequently de-settled, because these islands suffered severe tsunami impacts in 2004 and their former inhabitants were relocated to L. Gan (Azfa et al., 2022; Gussmann and Hinkel, 2021b). Hence, 185 islands are considered by the red-list and subsequently in this paper.

2.3. The co-creation process

It is widely acknowledged that providing usable climate information is not about climate information producers handing over information to a users of this information, but rather about the producers and users of information collaboratively developing, in short ***co-creating***, climate information products and services tailored to the specific context (Hewitt et al., 2017; Lourenço et al., 2016; Vincent et al., 2018). The reason for this is that understanding user needs is not trivial. Systematic accounts of, and empirical investigations into, user needs are scarce, at least in the coastal domain (Hinkel et al., 2019; Le Cozannet et al., 2017; Tribbia and Moser, 2008). Simply asking users about their needs may be misleading, as needs may not be apparent, may be affected by cognitive bias (Tversky and Kahneman, 1974), and are embedded in diverse social contexts and diverging interests of stakeholders (Hinkel et al., 2018). Co-creation addresses these challenges by situating climate service development in a particular context, recognizing diverse opinions, articulating clearly defined and shared goals and carrying out an

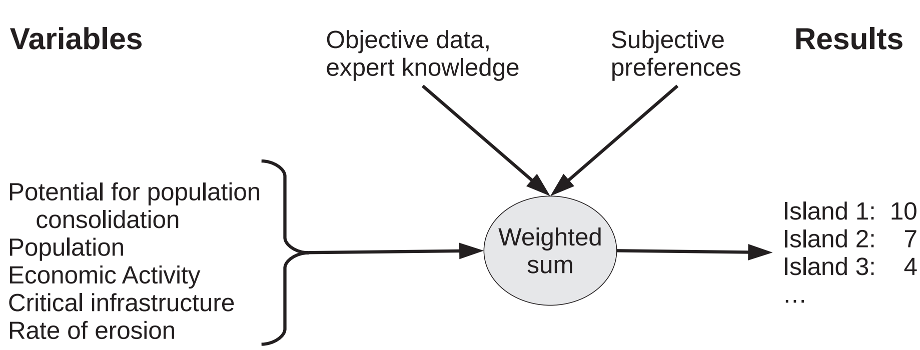

Fig. 2. Current approach of the “red list” towards island prioritisation for erosion management.

interactive and iterative co-development process that allows for mutual learning (Norström et al., 2020).

In the context of this paper, co-creation took place within a consortium of government and civil society representatives from the Maldives together with researchers involved in the European research project INSeaPTION (INtegrating SEA-level Projections in climate services for coastal adaptation), which was part of the European Research Area for Climate Services (ERA4CS). In this project, a range of coastal climate services were co-created by first identifying, together with stakeholders, ongoing decisions that require information on sea-level rise and coastal risk. In the context of the Maldives, the first decision identified was the one on how high newly created land should be elevated in face of sea-level rise, which is covered in van der Pol et al. (2022). The second decision identified was the need to better prioritise investments into coastal erosion management, which is the one covered in this paper.

Co-creation for addressing the erosion problem involved stakeholders from both the government and the civil society. The governmental representatives (n = 5) were officials from the Ministry of Environment, Climate Change and Technology, involved in providing advice to the government on which islands to be prioritised, and officials from the Ministry of National Planning, Housing and Infrastructure, responsible for the implementation of coastal protection measures. Representatives from civil society (n = 4) were environmental researchers from Maldives National University and members of environmental non-governmental organisations. Criteria for the selection of representatives were experience in coastal management and gender. Hence, gender was well balanced in this process (4 female, 5 male). Civil society representatives were predominantly female, while government representatives were predominately male.

Interactions with all of these stakeholders led to the establishment of the following four user needs:

- ***User need 1***: Improve the biophysical assessment of erosion hazard, in particular with regards to the limitation of the red list approach. The red list considers the biophysical side of erosion in terms of only a single indicator: the observed erosion (i.e., observed erosion intensity). Furthermore, this indicator is difficult to measure objectively, as official and continuous measurements of erosion rates are not available and costly to attain. Current accounts of ongoing erosion are based on subjectively observed erosion intensity across the islands. Furthermore, this single indicator does not consider the processes that drive erosion.
- ***User need 2***: Provide a more systematic and publicly defendable method for aggregating biophysical and socio-economic factors determining the prioritisation of islands for erosion management. The current red list approach uses an ad-hoc approach based on expert judgement of the people from the Ministry.
- ***User need 3***: The new approach should build upon the existing approach as this increases legitimacy and acceptability. While this naturally limits the potential for innovation, continuity is important to the stakeholders, otherwise there is the risk that the approach would not be applied by decision makers.
- ***User need 4***: A practical approach is needed that can be implemented taking into account data availability.

2.4. Co-designed approach

There was consensus among stakeholders and researchers that the prioritization approach to be developed should be an index for several reasons. Indices are widespread and specifically suited methods for situations in which decisions must be made with limited resources in data-scare contexts (Hinkel, 2011; OECD, 2008), as is often the case for prioritization decisions (need number 4), specifically in low and middle income countries. In our case, prioritization addresses 185 inhabited islands, for which it would be impossible to gather detailed data and implement proper hydro- and morphodynamic models assessing all processes relevant for the erosion for each island. Furthermore, the original red list is also an index, and hence staying with an index addresses need number 3.

In order to address need number 2, the new index is designed as two nested indices (Fig. 3). A first subindex aggregates the three measurable biophysical drivers of incident wave energy, reef width and reef health into an erosion hazard subindex (Need 1). See Section 2.5 for details. This subindex is then used together with other criteria considered relevant by the stakeholders (Need 3) in a participatory Multi-Criteria Analysis (MCA), yielding the overall index as its result. The approach cleanly separates between the objective factors that drive the erosion hazard and subjective preferences of those taking the decision and being affected by it (Need 2). The former are aggregated via expert judgement into an erosion hazard subindex, while the latter are aggregated via the MCA into an island erosion management priority score.

2.5. Erosion hazard subindex

Selection of indicators. Indicators for the erosion hazard subindex were chosen to i) cover the main drivers of current and future erosion hazard in the context of the Maldives as summarized in Section 2.1 (User need 1), and ii) to be based on available data or data that can easily be obtained for all inhabited islands (User need 4). This led us to consider the following three indicators of wave energy, reef flat minimum with and reef threat (Table 1), covering 3 of the 4 sets of factors driving erosion on atoll islands reviewed in Section 2.1. Each indicator is described in more detail below. The forth set of factors related to human modifications of the islands could not be considered, because data on this indicator was not available for all inhabited islands and also could not be gathered due to limitations in the availability of digital images (Duvat and Magnan, 2019a; Duvat and Magnan, 2019b).

The first indicator we consider is incident ***wave energy***, because waves are the dominant driver of erosion hazard in the Maldives (Kench, 2012). Wave energy does not only indicate current erosion hazard, but also future hazard, because waves heights will be raised with rising sea-levels (Wadey et al., 2017). To develop this indicator, we make two assumptions that allow us to collect data for this indicator for a large number of islands as necessary in our case. First, we assume that it is sufficient to evaluate wave energy only from the strongest wave family affecting the shoreline of each island. Maldivian islands are affected by the three different families of waves, which are tradewind waves, distance source Southern swells waves and Northwestern waves (Amores et al., 2021). For each island, we identify which of the three wave families is the strongest. Second, to measure wave energy, we compute a simplified wave energy proxy (W_k) using the parameters, wave length ($L = 1 / T_p$) and significant wave height (H_s). The wave energy proxy is measured using H_s from the dominant wave family, according to the following equation: $W_k = L^* H_s^2$ (Lecacheux et al., 2012). Wave characteristics (H_s, T_p, W_k) are obtained from Amores et al. (2021), who provide these at 33,160 locations around the Maldives, with a spatial resolution around 500 m at the coasts. We identify, for each island, the closest wave data point. Note that for islands inside the atolls, wave energy was not calculated because the General Bathymetric Chart of the Oceans (GEBCO) data used for this calculation is not reliable within lagoons. As wave energy is generally low for islands inside lagoons, these islands received the lowest wave energy score of 1 (see normalisation section below).

The second indicator we consider is the ***minimum width of the reef flat***, as this determines how much of the incident wave energy is dissipated over the reef flat and hence how much energy is left at the coast to drive erosion. For a given incident wave energy, a narrower reef flat leads to greater wave energy at the coast, compared to a wider reef flat. This indicator only captures today's erosion hazard, but also includes human modifications of the reef flat, which is widespread in the Maldives. For example, reef widths have been reduced by reclaiming

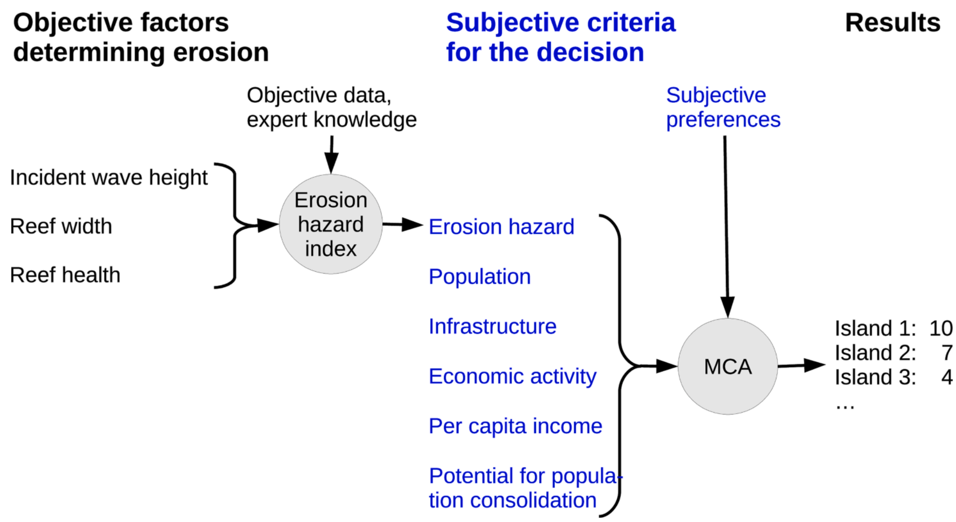

Fig. 3. Improved approach towards island prioritisation for erosion management based on separating objective factors and subjective criteria.

Table 1
Definition and measurement of factors making up an erosion hazard subindex.

Erosion hazard indicator	Definition	Measurement
Wave energy	Incident wave energy before wave transformation on the reef flat. Higher wave energy values increase the erosion hazard.	Wave energy of the dominant wave family based on data from Amores et al. (2021)
Reef flat minimum width	Smallest distance from reef edge to shoreline of an island. Narrow reef flat width increases erosion hazard.	Minimum distance between shoreline and reef flat from shape-file polygons that were available at the Ministry for all inhabited islands.
Reef threat	Threats to reef health that are likely to lead to degradation of reefs, which in turn increases the erosion hazard.	Taken from Burke et al. (2011), who aggregate information on both local (e.g., coastal development, pollution, overfishing) and global (e.g., sea surface temperature, ocean acidification) reef threats.

new land within the reef flat. We measure minimum reef flat width using a Geographic Information System as the smallest distance between reefs and islands polygons.

The third indicator we consider is ***reef threat***, which measures the likelihood of a reef to be degraded in the future due to local and global threats. As explained above, degraded reefs enhance erosion, because degradation reduces the reefs' abilities to dissipate wave energy, grow with SLR and supply sediment to the island. Reef flat is used as a proxy for reef health, because no detailed data on reef health was available. Reef threat indicates mostly future reef health and hence integrates the effect of future climate change and sea-level rise. Indicator values are taken from Burke et al. (2011), who measure reef threat through aggregating a set of indicators of both local (e.g., coastal development, watershed-based pollution, marine-based pollution, overfishing) and global (e.g., thermal stress, ocean acidification) threats. The authors assumed that the local reef threats increase with proximity to a given threatening activity, measured through Geographic Information Systems. Thresholds for local threats were calibrated based on available observations of impacts on coral reefs. Global threats were modelled and calibrated against the observation of sea surface temperature and bleaching events. Finally, Burke et al. (2011) assign classes for reef threat "low threat", "medium threat", "high threat", "very high threat" to the reefs worldwide, which we assign to the respective islands.

Normalisation. As the reef threat indicator was already in a categorical scale, for reasons of consistency, we also normalise wave energy and reef width to the same categorical scale using 5 classes of 1 to 5, with 5 standing for the highest erosion hazard. We use the 20th, 40th, 60th and 80th percentiles to form the boundaries of the classes.

Aggregation of indicators. We follow the general principle to use simple aggregation techniques if no argument can be provided in favour of more complex approaches (argument of insufficient reason), which also increases transparency and salience of indices (Hinkel, 2011; OECD, 2008). Following the work of Gornitz (1991), Gornitz et al. (1997) on the Coastal Vulnerability Index (CVI), we test the sensitivity of various simple geometric and arithmetic aggregation techniques. We do this by varying one and two indicator values for different values of the third indicator and then choosing the aggregation technique that is least sensitive to this variation. This turns out to be the arithmetic mean $(x_1 + x_2 + x_3)/3$ and we apply this as the standard aggregation technique. We also use the second aggregation technique of the geometric mean $(x_1\, x_2\, x_3)^{1/3}$ as an alternative aggregation method, because arithmetic aggregation implies that a high value of one indicator can be fully compensated by low values in other indicators. This may, however, not be the case, in particular with regards to reef threat, because a high reef threat (i.e., an unhealthy reef that does not deliver sediments anymore) cannot necessarily be fully compensated by, e.g., a wide reef crest.

2.6. Multi-criteria analysis and prioritisation index

Selection of criteria. The selection process started with the original criteria used by the red-list approach (User need 3), but also considered further criteria suggested by the users. The final set of criteria thus attained is shown in Table 2. The set differs only in two aspects from the set of the original red list. First, the erosion severity index was substituted by the newly developed erosion hazard subindex. Second, there was consensus among both government and civil society participants that islands with low per capita income should be prioritized. Hence we added this criterion.

Normalisation of criteria. Following the current praxis of the red list, all criteria data were normalised to a scale ranging from 0 to 100 using the min–max normalisation method, which is one of the most popular normalisation techniques in environmental applications of indices (Talukder et al., 2017). The advantage of the min–max method is that the normalised data has defined lower (here 0) and upper (here 100) bounds. The disadvantage is that the scores are sensitive to outliers. To mitigate this problem, the data of those indicators that span several orders of magnitude (population, critical infrastructure and income)

Table 2
Definitions and measurement details of the criteria used in the multi-criteria analysis.

Criterion	Definition	Measurement
Erosion hazard subindex	Susceptibility of an island to past and future erosion	See Section 2.3.
Population	Number of inhabitants on an island.	Census data of 2014
Critical infrastructure	The number of critical infrastructures such as harbours, airports, hospitals, sewage facilities, desalination plants, mosques, power generation and communication infrastructure.	Accumulated Public Sector Investment from 2014 to 2019 per island.
Economic activity	Economic activities carried out on the island such as agriculture, fisheries, production, tourism.	Employment rate per island from the 2014 Census data.
Per capita income	The average annual income per person.	Household income survey 2016 (on the level of atolls)
Potential for population consolidation	Availability of land for housing additional people.	Inverse of population density

were logarithmized prior to normalisation.

Aggregation of criteria. We used the Analytical Hierarchy Process (AHP) for the multi-criteria analysis. AHP is an established decision-support method (Greco et al., 2016; Le Cozannet et al., 2013), which uses pairwise comparisons of criteria to translate subjective preferences of users into weights for aggregating decision criteria into one score (Saaty, 1980). Subjective preferences of Maldivian stakeholders were elicited in a focus-group session, which is an effective method for collective discussion and elicitation of preferences (O.Nyumba et al., 2018). After an introduction and general discussion, all criteria were compared pairwise by each participant. Results for each comparison were recorded on a 1–9 Likert-scale ranging from "both criteria are equally important" to "criteria A is extremely more important than criteria B" or "criteria B is extremely more important than criteria A" (Franek and Kresta, 2014). Finally, we calculated the resulting weights of the criteria for each participant, as well as the resulting average weights across the participants.

Key for the validity of the AHP are consistent pairwise comparisons. For this, transitivity ($a_{i,k} = a_{i,j} * a_{j,k}$) and reciprocity ($a_{i,j} = 1/a_{j,i}$) are necessary conditions, where $a_{i,j}$ stands for the value of a pairwise comparison between criteria i and j (Saaty, 1980). Calculating the consistency ratio (CR) as put forward by Saaty (1980), our initial weights did not meet the established consistency threshold of CR less than 0.1. The literature puts forward two solutions to reduce this inconsistency. First, Saaty (1980) suggests finding the most inconsistent judgements and then asking the user to reconsider these. Second, linearization techniques provide the closest consistent matrix to a given non-consistent matrix by using an orthogonal projection in a given linear space (Benítez et al., 2011). We opted for the second solution.

3. Results

3.1. Erosion hazard subindex

Concerning the individual components of the erosion hazard subindex (Fig. 4), we find that 20% of the islands have a wave energy below 9 sm^2, 50% below 233 sm^2 and 80% below 1,990 sm^2. The islands ranked highest in terms of wave energy are those exposed to Southern swell waves (e.g., S.Maradhoo, S.Maradhoo-Feydhoo and S.Hithadhoo), followed by three islands affected by the Northwest wave family (AA. Maalhos, AA.Feridhoo, and AA.Himandhoo). The first island affected mainly by the trade wind wave family (L.Maandhoo) is ranked 48 out of the 185 islands. 20% of the islands have a minium reef width below 15 m, 50% below 46 m and 80% below 152 m. No evident correlation was found between minimum width and wave energy. For reef threat, we find that 45% of the islands are in the "low threat" class, 48% in the "medium threat" class, 6.3% in the "high threat" class and 1.2% in the "very high threat" class.

The erosion hazard subindex values are shown in Table 3 for the top 20 ranked islands using both arithmetic and geometric means for aggregation. The top 7 islands are the same for both ranking methods and the variation in terms of ranks remains relatively small beyond the top 7. The most relevant factor in the top ranked islands is the reef width, which is larger or equal to 4 for the top-20 islands except for HA. Thurakunu and M.Muli. The island ranked first is S.Hithadhoo, the capital of Seenu atoll (Addu city), as it is directly exposed to Southern swell waves and has only a narrow reef (reef width = 10 m) to protect itself from the incoming wave energy. The neighbouring island of S. Meedhoo, also part of Addu city, is in a similar situation and is ranked fourth in our index. The island ranked second is K. Vilingili, which is a fully urbanised island neighbouring the capital island of Malé, similarly has no reef width and this is paired with a high reef threat but a more modest wave energy score. Currently, moderate erosion prevention measures are in place. However, this is going to change soon because the Maldivian government plans to construct a bridge between Malé and K.

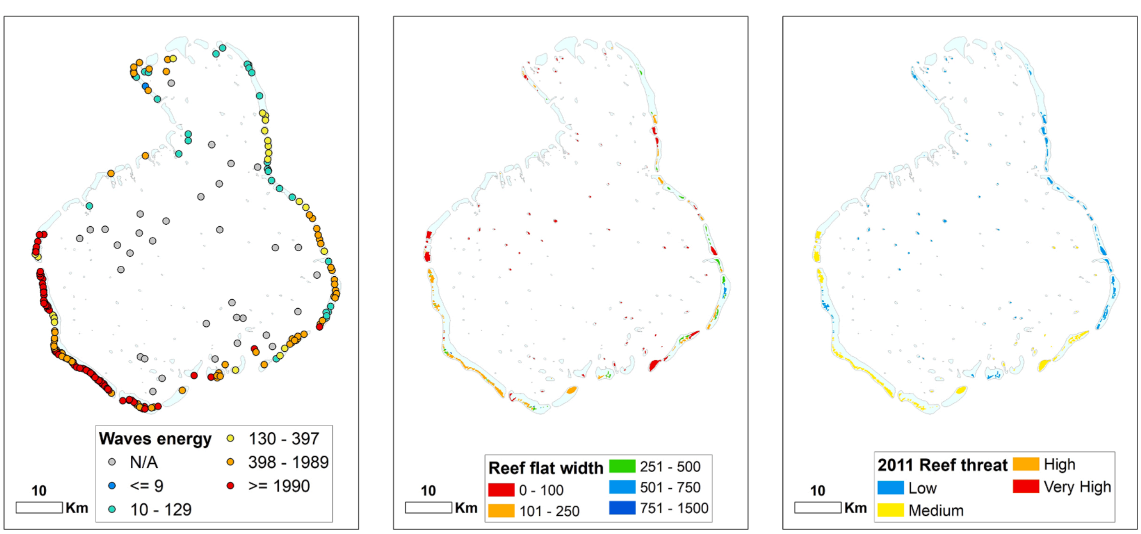

Fig. 4. Wave energy (left), reef flat minimum width (centre) and reef threat (right) for islands in the Huvaduh atoll.

Table 3
The top 20 ranked islands according to the erosion hazard subindex using arithmetic and geometric mean aggregation methods.

Rank arithmetic mean	Rank geometric mean	Island	Arithmetic mean	Geometric mean	Reef width	Reef threat	Wave energy
1	1	S.Hithadhoo	4.6	4.5	5.0	3.8	5.0
2	2	K.Vilingili	4.3	4.2	5.0	5.0	3.0
3	3	Adh.Mandhoo	4.2	4.0	5.0	2.5	5.0
4	4	S.Meedhoo	3.9	3.9	4.0	3.8	4.0
4	5	HA.Uligamu	3.9	3.8	5.0	3.8	3.0
4	5	HDh.Nolhivaramu	3.9	3.8	5.0	3.8	3.0
7	7	Th.Thimarafushi	3.8	3.7	4.0	2.5	5.0
7	7	HA.Filladhoo	3.8	3.7	5.0	2.5	4.0
7	7	HA.Baarah	3.8	3.7	5.0	2.5	4.0
7	7	Sh.Milandhoo	3.8	3.7	5.0	2.5	4.0
11	28	Dh.Kudahuvadhoo	3.8	3.1	5.0	1.3	5.0
11	28	Sh.Komandoo	3.8	3.1	5.0	1.3	5.0
13	11	HDh.Hanimaadhoo	3.6	3.6	4.0	3.8	3.0
13	11	M.Muli	3.6	3.6	3.0	3.8	4.0
13	20	HA.Mulhadhoo	3.6	3.3	5.0	3.8	2.0
13	20	HA.Thurakunu	3.6	3.3	2.0	3.8	5.0
13	20	M.Mulah	3.6	3.3	5.0	3.8	2.0
18	13	Dh.Hulhudheli	3.5	3.4	4.0	2.5	4.0
18	13	HA.Thakandhoo	3.5	3.4	4.0	2.5	4.0
18	13	L.Maamendhoo	3.5	3.4	4.0	2.5	4.0

Thilafushi, which will pass through K.Vilingili, which in turn will be accompanied with significant coastal protection measures and a fortification of the Eastern and Southern part of the island.

The top-10 islands also feature some densely populated atoll capitals or regional centres like HDh.Nolhivaramu, Th.Thimarafushi and Sh. Milandhoo. However, the top-10 also includes some less populated islands like Adh.Mandhoo, HA.Uligamu, HA.Filladhoo and HA.Baarah, all scoring high due to their very limited protection through reefs (i.e. low reef width).

3.2. Multi-criteria analysis and prioritisation index

Table 4 shows the weights for the criteria of the prioritisation index, which have been established through the AHP, and compares these to the weights that have previously been used in the red-list. The weights established by the civil society representatives are roughly similar to those established by the government representatives. The biggest difference is that the island population receives twice the weight by civil society representatives as compared to the government representatives. Erosion hazard scores highest in both cases, which relates to the need to better include the biophysical driver of erosion as expressed in the co-creation process (User need 1). The second highest weights are given to the potential for population consolidation, which shows that the policy of concentrating population on well-protected islands is still popular among the stakeholders, despite the fact that recent planning regulation has officially abandoned this policy (Gussmann and Hinkel, 2020). In the red-list, the potential for population consolidations had received the highest weight, because at the time the red-list was designed, the population consolidation policy was still officially in place.

The top 20 islands ranked according to the prioritisation index are shown in Table 5, together with their overall scores and individual scores for each component criteria, using the arithmetic mean aggregation method for the erosion hazard subindex and the weights established by the government representatives. Similarly to the erosion hazard subindex, the top ranked island is S.Hithadhoo with a score of 84. S.Hithadhoo is the capital of Addu city and second largest settlement in the Maldives following the greater Malé area. Hence S.Hithadhoo scores highest in terms of the population, and also very high in terms of critical infrastructure. For the same reason, S.Hithadhoo scores lowest on per capita income, because being the second largest city in the Maldives, the total island income is high. The bottom-ranked island is ADh.Kuburudhoo with an overall score of 37.

Among the top 10 ranked islands, are islands that have received additional population via the population consolidation policy before or in the aftermath of the tsunami 2004. Namely these islands are Sh. Milandhoo (which is the most populous island in Shaviyani atoll), HDh. Hanimadhoo, HDh.Nohivaranfaru and Dh.Kudahuvadhoo. Protecting these islands against erosion is meaningful, given that population consolidation has already occurred there. Additionally, HDh.Hanimaadhoo is one of the regional centres in the North of the Maldives, featuring a regional airport, which makes the prioritisation of the island more relevant.

Seeing some of these regional centres high up in the ranking is not a surprise, but the top 20 list also includes some of the smaller islands and these should be of interest to policymakers, because they are at risk to be overlooked as a result of their small population size. Furthermore, in terms of a long term strategy for allocating coastal protection some of the smaller islands in the top 20 offer a great strategic potential. For example, HA.Filladhoo has a small population of less than 600 people but offers a large potential for population consolidation while simultaneously having a high economic activity. Protecting such an island is important as it has a high potential for relocating population to this island in the future when sea-levels will be higher. Similar arguments hold for HA.Uligamu and ADh.Mandhoo.

Table 4
Weights for the components of the prioritisation index established through the Analytical Hierarchy Process compared to the weights used in the original prioritisation method called red-list.

Source of weights	Erosion serverity	Erosion hazard	Potential for population consolidation	Critical infrastructure	Economic activity	Island population	Per capita income
Red-list	0.25	N/a	0.35	0.10	0.10	0.20	N/a
Government	N/a	0.32	0.22	0.20	0.12	0.07	0.06
Civil society	N/a	0.30	0.26	0.15	0.09	0.14	0.05

Table 5
Scores of the prioritisation index and its component criteria for the top 20 islands, using the arithmetic mean aggregation method for the erosion hazard subindex and the weights established by the government representatives.

Rank	Island	Total score	Score erosion hazard subindex	Score population	Score critical Infrastructure	Score economic activity	Score per capita income	Score potential for population consolidation
1	S.Hithadhoo	84	100	100	97	31	38	82
2	Sh.Milandhoo	81	79	62	81	94	54	89
3	HDh. Nolhivaramu	80	81	62	81	75	55	93
4	HDh. Hanimaadhoo	79	71	63	79	87	55	96
5	S.Meedhoo	78	81	62	80	71	38	92
6	HDh. Nolhivaranfaru	77	69	50	81	82	55	96
7	HA.Filladhoo	77	79	37	68	90	29	100
8	HA.Baarah	76	79	52	73	68	29	97
9	Dh. Kudahuvadhoo	75	76	67	81	82	63	70
10	M.Muli	74	71	45	82	94	37	80
11	M.Mulah	74	71	53	78	85	37	84
12	HA.Uligamu	74	81	28	58	85	29	98
13	Sh.Kaditheemu	73	60	50	78	95	54	90
14	R.Fainu	73	60	24	70	90	100	97
15	Gn.Fuvahmulah	73	50	94	98	63	63	86
16	HA.Kelaa	73	60	50	77	93	29	97
17	N.Maalhendhoo	73	69	39	72	80	62	89
18	GDh.Thinadhoo	73	69	84	100	63	50	61
19	Th.Guraidhoo	73	69	54	83	95	65	65
20	ADh.Mandhoo	72	88	27	40	93	29	93

4. Discussion

4.1. The co-creation process and the prioritization method developed

The co-creation process was evaluated positively by the users for several reasons. First, this process was a truly joint effort between stakeholders and researchers, from the very beginning to the very end. The process started with a user-driven identification of the decision problem to be addressed (i.e. the prioritization of erosion management) and ended with the writing of this paper, which some of the stakeholders joined as co-authors. Another aspect evaluated positively by the users was that not only the European researchers participated in the work conducted in the Maldives, but that Maldivian users also participated in the technical project meetings held in Europe. This interchange enabled us to gain an in-depth mutual understanding of the respective challenges both researchers and practitioners are confronted with in the context of coastal erosion and sea-level rise. Two other aspects that were evaluated positively by the users, and that contributed to the in-depth mutual understanding, were joint field campaigns to collect data, and training sessions on wave modelling with the novel model UHAINA developed by consortium partners (Filippini et al., 2018). All insights gained, and feedback received, were directly incorporated into the co-creation processes to make sure that user-needs could be met. Arguably, a major further success factor was that we could build upon long-standing good working relationships between researchers and Maldivian stakeholders, a point frequently highlighted as a success factor in co-creation (Brandt et al., 2013; Cash et al., 2003; Norström et al., 2020; Reed, 2008).

The new method is an improvement as compared to the original method, because all user needs (described in Section 2.3) could be met. The new method has improved the biophysical assessment of erosion hazard (User need 1) through incorporating indicators representing 3 of the 4 sets of factors influencing coastal erosion (see Section 2.2). Only the degree of human modification could not be considered due to a lack of data on this indicator for all inhabited islands. Furthermore, the new method provides a cleaner and more publicly defendable method for aggregating objective (here the components of the erosion hazard subindex) and subjective (here socio-economic indicators) factors playing a role in the determining the prioritisation of islands for erosion management (User need 2), by the separation of theses two aspects into two nested indices. The new approach also builds upon the existing approach (User need 3), by having the same form (i.e., it is also an index) and using a similar set of indicators as the original one. Finally, the new approach can be applied to all 185 islands through using existing data (User need 4).

One further indication of success of the development of the prioritization index is that the weights given to the individual criteria are remarkably similar between government and civil society representatives. Both groups considered normative criteria to be more important than the objective criterion of erosion hazard: While the erosion hazard contributes about one third to the final score, the other criteria contribute with two thirds. Government representatives put a slight emphasis on economic indicators (critical infrastructure and economic activity) in comparison to civil society representatives, who put more weight on social indicators (potential for population consolidation and population on the islands).

One apparent limitation regarding the erosion hazed subindex is that it cannot fully capture the complexity of atoll island erosion. As detailed models and data are not available and impossible to gather and implement for each of the 185 islands, there is currently no alternative to index development. The option not to decide does not exist, as the island prioritization decision needs to be made every year. The challenge that index development thus needed to address is to use available data, and state-of-the-art understanding of atoll island erosion, in the existing decision making process. While we are confident that we have achieved this, the accuracy of the index can only be validated in the longer run through observing the progression of erosion in all islands. Building up observation systems that continuously measure erosion should thus be a priority.

In any case, the index-based approach presented here should only be a first step in a decision making procedure that targets the prioritisation of Maldivian islands. The approach is useful for screening the large number of islands and selecting a subset to be considered in a more detailed analysis before deciding on which specific projects to invest in. Such detailed analysis may also consider aspects that have not been considered in the prioritisation index developed here. For example, information on the investment volume needed for individual projects could be considered in order to choose islands based on cost-effectiveness. Such cost-effectiveness analysis would be a substantial effort that can only be carried out for a small set of projects and/or islands.

4.2. Implications of the application of the new prioritization method

One aspect of the annual application of the erosion prioritization index that warrants discussion is that, in the long run, it may favour the continuation of a hard protection pathway for those islands that are already heavily protected. Following Haasnoot et al. (2013), we use the term pathway as sequence of adaptation options applied over time. The hard protection lock-in is caused by two reinforcing feedback loops. First, hardening the coast exacerbates erosion, which in turn requires more hardening of the coast or replenishment of sediment. Second, hardening the coast also creates incentives for developing more houses and infrastructures, which in turn leads to higher scores of the criteria island population and critical infrastructure.

It is thereby important to note that locking into a hard protection strategy is not generally wrong, as a superficial read of the climate adaptation decision making literature emphasising the avoidance of lock-ins (Haasnoot et al., 2013; Mycoo et al., 2022; Walker et al., 2013) may suggest. While the avoidance of lock-ins is an important criterion for decision making under deep uncertainty, coastal adaptation decisions are generally multi-criteria decisions, with other criteria such as cost or social acceptance also being relevant (Oppenheimer et al., 2019; Townend et al., 2021). Furthermore, how the multiple criteria shall be weighted against each other is a normative decision. Only in rare cases will stakeholders have lexicographic preference, e.g., prefer to avoid lock-ins at all costs. An example of such a rare case is arguably the Thames Estuary 2100 project, in which a 21st century sea-level rise of several meter was considered in order to be safe in any possible future world no matter how much this would cost (Ranger et al., 2013). In other cases, stakeholders may prefer to lock into a hard protection strategy because its social or economic benefits outweigh its costs, e.g., as exemplified by the development of the Maldivian island of Hulhumalé (Bisaro et al., 2019).

A second reason why lock-in is not generally wrong can be found in the large uncertainty about future sea-level rise and the fact that many of the Maldivian inhabited islands are already locked into a hard protection pathway (Duvat, 2020; Naylor, 2015). For those islands already locked-in, the question is not whether to avoid lock-in, but if and when to give up the lock-in. But also for the other densely populated islands it may make sense to embark onto a hard protection pathway in order to buy time until more is known about sea-level rise. According to the latest IPCC report, there is a 66% chance that sea-levels will rise by 0.3 to 1.1 m until 2100 under all emissions scenarios considered, with rises of up to 2 m or more also being possible (Fox-Kemper et al., 2021). In such situations, the adaptive decision making literature points towards delaying major decisions such as giving up an islands until more is known about sea-level rise (Haasnoot et al., 2013; Hallegatte et al., 2012; Hinkel et al., 2019). If sea-level rise turns out to follow low-end trajectories, the hard island development pathway can be continued for a long time or even forever. If sea-levels rise turns out to follow high-end trajectories, hard island development may only be a temporary solution and eventually islands may need to be given up. When this will be the case is not possible to determine now as it depends on many factors also beyond sea-level rise such as the willingness and fiscal ability of societies to pay for hard engineering (Hinkel et al., 2018; Oppenheimer et al., 2019). For example, in the case of the island of Hulhumalé it has been assessed that the island will be safe until the 2090s even under a high emission scenario and much longer under a low emission scenario (Brown et al., 2019).

It shall be noted that decisions involving questions of lock-in and giving up islands must consider the particular circumstances of each island. This involves carefully weighing all costs and benefits against each other, which should also consider the cost of changing strategies (e.g., locking-out of a hard protection pathway), as well as residual damage costs in the case of hard defences breaching or being overtopped by extreme events. Furthermore, such considerations must also take into account local factors influencing sea-levels such as vertical land movement and decadal ocean variability contributing to relative mean sea-level change, as well as changes in tides, surges and waves. From particular importance for atoll islands such as the Maldives is thereby the potential increase of wave height and energy in the case of a loss of corals as discussed above. Finally, the appraisal of alterative adaptation pathways must take into account the full range of sea-level and socio-economic uncertainty. A wide range of adaptative decision making tools such as adaptation pathway analysis (Haasnoot et al., 2013) and real-option analysis (Völz and Hinkel, 2023) are available for supporting these considerations.

It is also important to note that following the hard engineering pathway requires sound engineering practice and substantial resources. Regarding the former, many examples of poor implementation of hard protection measures have been documented for small islands generally (Mycoo et al., 2022) and the Maldives specifically (Kench, 2012). This does, however, not mean that hard protection generally fails in small islands. Conversely, many sound applications of hard engineering can be found in small islands, but generally these do not receive much attention in the adaptation literature. Next to the capital island of Male and Hulhumale, which are well protected by sea-walls and revetments, this also includes many of the islands that were destroyed and reconstructed after the 2004 tsunami such as, for example, Th.Vilufushi and GA.Vilingili (Bosschieter, 2007).

Regarding the resources required for the hard engineering pathway, it is important to note that this does not only include the capital and maintenance cost of coastal engineering, but also the cost of maintaining an “artificial” lifestyle such as the cost of importing or generating drinking water through de-salinisation. In terms of potentially giving up islands, the crucial aspect here is not absolute cost but affordability. Rural, less densely populated and economically weaker islands will only be able to afford such an “artificial” lifestyle through transfers. Conversely, many urban, densely populated and economically strong islands already live this “artificial” lifestyle and will likely be able to continue this for decades to come (Oppenheimer et al., 2019). For example, urban islands like Malé and Hulhumalé rely on desalination and import of drinking water, and about 80 peripheral islands require desalinated water shipments from the capital during the dry season, because their freshwater lenses have been degraded by overuse or flooding caused by the tsunami of 2004 (Ahmed, 2018). The same holds true for many other small island states (Falkland and White, 2020). Currently, the Maldives are well equipped to handle the costs of maintaining hard engineered islands due to a booming tourism sector, strong economic growth and a high demand for land (Bisaro et al., 2019).

The above discussion of the hard engineering island development pathway shows that this is not an option suitable nor desirable for all islands. For those islands that exhibit little disturbed coastal processes, including a healthy reef, a more meaningful strategy would be to conserve and restore natural sediment dynamics and the natural capacity of the reef-island system to adjust to climate pressures (Duvat and Magnan, 2019a; Duvat and Magnan, 2019b; Kench, 2012). This includes nature-based solutions such as the protection and restoration of reefs in order to maintain their sediment supply and wave dissipation functions, as well as the restoration of mangroves to provide additional shoreline protection.

The nature-based island development pathway may also include restoring the natural ability of inhabited islands to grow upwards with sea-level rise through controlled flooding, in which waves over-washing the islands deposited sediments onto the islands and build elevation. This can range from establishing a coastal buffer zone allowing sediment deposition at the coast, to allowing complete over-wash. To our knowledge, little practical experiences have been gained with building elevation through controlled flooding on inhabited atoll islands, but this is being practised in other context such as the small islands (Halligen) in the German Wadden Sea (Schindler et al., 2014) and the low-lying polders in Bangladesh (Amir et al., 2013). The challenge thereby is finding a safe and socially acceptable way of naturally building elevation on atoll islands.

If such efforts deliver fruitful results, it would also make sense to revisit the erosion hazard subindex developed here, which prioritizes inhabited islands with high wave energy and narrow reef flats for coastal protection, because these variables positively correlate with erosion hazard. At the same time, high wave energy increases wave run-up, over-wash and the delivery of sediment onto the islands and may thus ultimately contribute to building island elevation. This can, for example, be seen in the Huvadhoo atoll, where Aslam and Kench (2017) found an advancing shoreline on the southern rim of the atoll where islands are exposed to ocean swell. In any case, restoring natural processes should be a priority for uninhabited islands as this maximises their ability to grow upwards with sea-level rise, and, in turn, their ability to provide elevated land for future settlements, once the inhabited islands with limited or no upwards growth become too risky places to live.

5. Conclusion

This paper presented the co-creation of a climate service to improve a ranking method currently used by the government of the Maldives to prioritise islands for annual investments in erosion prevention. Co-creation involved government and civil society representatives and researchers of a European research project. The following four needs were articulated: i) better representing the biophysical drivers of erosion hazard, ii) separating biophysical and normative aspects of prioritisation, iii) building upon an existing approach as this increases legitimacy and acceptability, and iv) being able to cover all of the 187 inhabited islands of the Maldives, except the capital islands of Malé and Hulhumalé, using data that either exists or can be collected at low cost.

To address these needs, a two-layered index for ranking islands was developed. Its first layer captures the objective dimension of prioritisation in the form of an erosion hazard subindex, using the three variables incident wave energy, reef health and reef flat minimum width. The ranking method's second layer captures the normative dimension of prioritisation through a multi-criteria analysis using the erosion hazard subindex as one criterion next to other criteria selected by stakeholders including critical infrastructure, economic activity, per capita income and the potential to house additional people that may resettle to the island from riskier places as sea-level rise progresses.

Results of this new ranking method show that among the top-ranked islands are many regional centres, with S.Hithadhoo, the second largest settlement in the Maldives, ranking highest. But top-ranked islands also include less populous islands such as Filladhoo, HA.Uligamu, ADh. Mandhoo and HA.Mulhadhoo, all of which offer a large potential to house additional people if sea level rise accelerates.

The co-creation process was evaluated positively by the users for several reasons, including that they were involved from the start of the project, that they could determine the actual problem to be addressed (i. e. the prioritization of erosion management), and that they were able to participate in the technical project meetings held in Europe. Mutual understanding was furthermore fostered by the conduction of joint field campaigns to collect data, as well as training sessions on wave modelling. All insights gained, and feedback received, was directly incorporated into the co-creation processes to make sure that user-needs can be met.

While the resulting index can not be directly transferred to another context, because it incorporates the preferences of the Maldivian stakeholders, the erosion hazard subindex and the multi-criteria analysis can be applied to address erosion prioritisation problems in other atoll islands. Furthermore, the general building blocks of the methodology applied such as the co-creation process, index development and the clean separation between objective and subjective aspects, are generic and provide useful guidance for climate service development aiming at addressing adaptation prioritisation problems in other contexts.

Practical Implications.

Climate policy makers and practitioners need to prioritise resources for adapting to climate change. This is particularly true for low to middle income countries. One important policy question for governments with limited resources is to prioritise which adaptation problem in which location to address first. Such prioritisation in climate adaptation in a low and middle income context is challenging specifically for two reasons. First, data for modelling climate related risks and supporting prioritisation is often scarce, and so are resources for gathering this data. Detailed surveys cannot be conducted in each location and pragmatic choices need to be made on how environmental risks are to be assessed. Second, objective aspects relating to the biophysical processes causing climate risk and subjective aspects relating to preferences, adaptation goals and policy priorities are often tightly intertwined.

So far there is few literature that has addressed adaptation prioritisation problems. This paper contributes to filling this gap and provides guidance on the process of co-creating prioritisation methods together with a worked example on how stakeholders and researchers did so for the Maldives, a low-lying atoll island nation in the Indian Ocean, consisting of around 1,200 islands of which 187 are currently inhabited. Specifically, we present the co-creation of an index for prioritising investments in coastal erosion measures. Due to scarce land and high population densities, coastal erosion of inhabited islands is a major concern for the Maldivian society. Hence, addressing erosion is a key responsibility of the Maldivian government and, in particular, its Ministry of Environment, Climate Change and Technology. As many islands experience coastal erosion, the Ministry must prioritise among islands.

Indices are widespread and specifically suited methods for situations in which decisions must be made with limited resources in data-scare contexts, as is often the case for prioritization decisions, specifically in low and middle income countries. Prioritisation generally considers multiple criteria and many cases that can not be modelled in detail due to a lack of data and limited resources. In the Maldives example presented here, prioritization addresses 185 inhabited islands. It would be impossible to gather detailed data and implement proper hydro- and morphodynamic models assessing all processes relevant to coastal erosion in each island. While indices can not fully capture the complexity of atoll island erosion, they provide an alternative approach in situations in which decisions need to be made no matter what, as is the case for island prioritization for erosion management in the Maldives. Hence, the challenge index development addresses is to use available data, and state-of-the-art understanding of atoll island erosion, in existing decision making processes.

The co-created approach consists of two nested indices in order to cleanly separate between the objective factors that drive erosion hazard and subjective preferences of those taking the decision and being affected by it. The first index aggregates biophysical drivers of erosion (wave energy, reef width and reef health) through expert judgement into an erosion hazard subindex. This erosion hazard subindex is then used together with other criteria considered to be important by stakeholders (i.e., critical infrastructure, economic activity, per capita income and the potential to house additional people that may resettle to the island in question from riskier places as sea-level rise progresses) in a participatory Multi-Criteria Analysis (MCA), implemented through the method of Analytical Hierarchy Process (AHP).

While the resulting nested index can not be directly transferred to another context, because it incorporates the preferences of the Maldivian stakeholders, the erosion hazard subindex and the multi-criteria analysis can be applied to address erosion prioritisation problems in other atoll islands. Furthermore, the general building blocks of the methodology applied such as the co-creation process, index development and the clean separation between objective and subjective aspects, are generic and provide useful guidance for climate service development aiming at addressing adaptation prioritisation problems in other contexts.

CRediT authorship contribution statement

Jochen Hinkel: Conceptualization, Methodology, Formal analysis, Investigation, Supervision, Project administration, Funding acquisition. **Manuel Garcin:** Conceptualization, Methodology, Formal analysis, Investigation, Visualization. **Geronimo Gussmann:** Conceptualization, Methodology, Formal analysis, Investigation, Visualization. **Angel Amores:** Methodology, Formal analysis, Investigation. **Constance Barbier:** Investigation. **Alexander Bisaro:** Methodology, Formal analysis, Investigation. **Gonéri Le Cozannet:** Funding acquisition, Investigation. **Virginie Duvat:** Funding acquisition, Investigation. **Mohamed Imad:** Investigation. **Zammath Khaleel:** Investigation. **Marta Marcos:** Investigation. **Rodrigo Pedreros:** Investigation. **Ali Shareef:** Investigation. **Ahmed Waheed:** Investigation.

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

Data will be made available on request.

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