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Decision-support for land reclamation location and design choices in the Maldives

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ABSTRACT

Land reclamation in the Maldives is widespread. Current land reclamation practices, however, lack a systematic approach to anticipate sea-level rise and do not account for local flood risk differences to inform location and design choices. To address these limitations, this paper applies two decision-support tools: a hazard threshold analysis, and a cost-benefit analysis. Both tools produce site-specific estimates of land elevations or flood defence heights but do so for different goals. The hazard threshold analysis identifies hazard-based solutions that meet an acceptable flood probability for an intended lifespan without follow-up actions by reliability optimisation. The cost-benefit analysis identifies risk-based solutions using dynamic programming. We apply both tools to two land reclamation sites, a newly reclaimed airport island and a land extension of an inhabited island, in the Maldives. We find that total hazard-based heights for long-term planning horizons are highly uncertain, with local height differences of up to 1.9 m across sea-level rise scenarios by 2100. Risk-based Island elevations, in contrast, differ much less across scenarios, offering a practical advantage for decision-making. However, land reclamation choices on location, land elevation and investment in flood protection are not only driven by hazard-related aspects, such as reef characteristics, swell exposure, and sea-level rise, but also by estimates of exposed assets, reclamation, and flood protection costs. Taken together, the two decision-support tools are helpful for improving adaptation decisions and are also applicable in other small island regions.

1. Introduction

Land reclamation in small island regions is controversial due to its potential to increase coastal risks, hard adaptation path dependencies, and detrimental environmental impacts (Mycoo et al. 2022). Yet, its practice is widespread, and the creation of new land is also considered as an adaptation pathway to sustain atolls under changing mean and extreme sea-levels (Brown et al. 2023). For small island regions, ubiquitous flood protection of atoll islands will be difficult due to economic and financial constraints to effectively

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protect hundreds of inhabited islands. These constraints might explain why some studies have suggested that international migration could become inevitable if flood or wave overtopping frequencies become too high to sustain habitation (Barnett and Adger, 2003; Yamamoto and Esteban, 2017; Storlazzi et al., 2018). However, such studies tend to overlook key adaptation options for small island regions, such as targeted flood protection strategies (MEEW, 2007), and land reclamation.

Especially for densely populated atolls, land reclamation may be feasible in technical, financial, and economic terms (Hinkel et al., 2018). Artificial islands can be designed with a sea-level rise (SLR) allowance, which means that such islands are reclaimed with a higher elevation in anticipation of SLR. This offers a better starting point to adapt to rising sea-levels in comparison to natural atoll islands whose natural capacity to accrete vertically is often impeded by human activity (Duvat 2020). A SLR allowance is formally defined as the vertical distance that keeps the expected flood frequency constant under a SLR scenario at a moment in the future as compared to today (Hunter et al., 2013). In the Maldives, more than 80% of the land area is less than one metre above current mean sea-level (MEE, 2017). The islands are therefore prone to increasing flood risk due to SLR, especially when coral reefs, which reduce wave impact and provide sediment to the islands, e.g., for natural accretion, degrade due to increasing ocean temperatures. The local occurrence, timing and rate of reef degradation is highly uncertain (van Woessik et al., 2015; Yates et al., 2017; Perry et al., 2018). Yet, even under a low 1.5 °C global warming scenario most tropical coral reefs that exist today could disappear (Hoegh-Guldberg et al., 2018) and the natural geomorphological responses of atoll islands under accelerating SLR are unlikely to further accommodate human settlements (Tuck et al. 2019).

So far, the Maldives have not primarily reclaimed land to adapt to SLR. Rather, land has been reclaimed across the archipelago to address current land use needs. The largest land reclamation project in the Maldives is Hulhumalé, which was reclaimed to alleviate population pressure in the capital, Malé (Brown et al., 2020). The Maldives have recently completed the second phase of this project with a target population of a hundred thousand people (World Bank, 2020). Next to Hulhumalé, various island extension projects for residential land use have been completed (MEE, 2017). Land has also been reclaimed for non-residential land use purposes, for example for airports and harbours (Duvat, 2020), tourist resorts, for example Reethi Rah (Riyaz and Ali, 2004), waste management, and even industrial land use.

The current Maldivian practice for reclaiming new artificial islands follows a non-binding guideline to reclaim land at a level of 1.5 m to 1.8 m above current mean sea-level (MEE, 2015). This guideline is based on a tidal component of 0.6 m and 1.0 m of SLR (Gusmann and Hinkel, 2021). The current practice for land extension projects is to reclaim the land at the same or a similar elevation as the existing land to avoid drainage problems.

These land reclamation practices have three limitations. First, the recommended reclamation heights do not consider the full range of plausible SLR futures. While a 1.5 m to 1.8 m elevation is higher than the average island elevation, global mean sea-level is likely to rise by 0.6–1.1 m under RCP 8.5 by the end of the century (Oppenheimer et al., 2019), whilst high-end estimates exceed two metres (Bamber et al., 2019). Second, the recommended heights do not systematically include SLR based on total water levels (Lambert et al. 2020). Whereas storm surges are small in the Maldives (<0.25 m), remotely generated energetic swell events under spring tide have been key drivers of flooding in the Maldives (Wadey et al., 2017). Local wave exposure, however, greatly differs across the archipelago (Amores et al., 2021). Third, monetary exposure and flood vulnerability are not considered in current practice. As a result, the current land reclamation practices are inadequate to meet the looming coastal adaptation challenge and potentially produce costly path dependencies if artificial islands would need to be abandoned prematurely. To improve current land reclamation practices, coastal managers in the Maldives require decision-support tools that can help to determine location and height of land reclamation projects.

While there are studies that analysed flood risks in the Maldives, there is a lack of tailored methods that can provide optimal land reclamation height and flood defence choices for coastal managers under SLR. For example, Amores et al. (2021) generate a regional wave data set and demonstrate that it can be used for local flood hazard analysis of land reclamation projects. However, the local flood hazard analysis does not tell the coastal manager which combination of land elevation height and coastal defence height to choose, given the intended land use and built environment on the island. Computationally intensive 2D wave propagation models are also not very suitable to do so, as this requires the analysis of many alternatives. A step in the direction towards determining optimal land reclamation heights is put forward by the rapid flood hazard assessment method in Amores et al. (2022), which could also be considered for local optimisation purposes. However, it does not account for flood exposure. This is a crucial component of flood risk to determine the initial elevation choice of a land reclamation project. Brown et al. (2020) consider this setting and include flood wall options for Hulhumalé. However, in this case the location and elevation of the island (Hulhumalé) were already given. What is needed

Table 1
Different methods for determining elevations of new artificial islands.

Method	Maldivian guideline	Hazard threshold analysis	Cost-benefit analysis
Policy goal	Not stated	Meet acceptable flood probability throughout project lifespan	Select economically efficient land reclamation strategies
Outcome	Fixed design heights (1.5–1.8 m above datum)	Hazard-based design heights	Risk-based design heights
Aspects of flood risk considered	None	Flood hazard	Flood hazard, monetary exposure, and flood vulnerability
Information on risk intolerance	None	Acceptable maximum flood probability	Social discount rate
Costs considered	No	No	Yes

are decision support tools to inform location and design choices of land reclamation projects. To address these limitations, this paper develops two decision-support tools for land reclamation projects to select appropriate land reclamation locations (hazard threshold analysis) and to determine optimal land elevation and protection choices (a cost-benefit method) and illustrates them with two cases from the Maldives. The two cases are a newly reclaimed artificial island for an airport near Ha.Hoarafushi located in the North of the Maldives and an urban land extension on Gdh.Madaveli in the South of the Maldives.

2. Methods

Table 1 shows how the current Maldivian guideline for elevations of new artificial islands differs from the two decision-support tools used in this study. These tools aim to estimate how high artificial islands, or their flood defences should be under a given hazard-based or a risk-based policy goal. The hazard threshold analysis (HTA) estimates hazard-based island elevations or flood defence heights and is introduced in Section 2.1. The cost-benefit analysis (CBA) identifies risk-based solutions and is introduced in Section 2.2. The latter accounts for land reclamation costs and flood protection costs and expected flood damages.

Both methods estimate flood probabilities now and in the future under SLR. For this, the following inputs are applied: wave information (H_s for different return periods), seabed information (1D bathymetric profiles), some island configurations (island height, flood protection) and SLR scenarios. For an island configuration, waves are simulated without and with a rise in mean sea-level to estimate conditional flood probabilities. The aim of both methods is different: HTA answers the question: How long does an island with a given height last under a given scenario? Whereas CBA answers the question: What would be an efficient island height now in a given scenario, if flood protection will be added in the future? The methods thereby provide complementary insights on the differences in heights across these two aims.

2.1. Hazard threshold analysis

Fig. 1 presents our HTA method for land reclamation projects. The aim is to meet a maximum acceptable annual flood probability (P_{ACC}) throughout the intended lifespan of a land reclamation project. This method either produces estimates of the minimum land elevation of an artificial island (x_1) without flood defences or the height of a flood defence (x_2) on an island without future upgrades. The hazard-based solution is found where the estimated annual flood probability (P_f) under a SLR scenario in year T (SLR_T) is equal to the maximum annual flood probability. In this paper, this is done numerically by increasing either x_1 or x_2 in steps, which are denoted by Δx .

The HTA starts from a range of inputs used to perform 1D wave simulations. In Step 1, idealised 1D profiles for different island configurations are generated. This step requires bathymetric profile data and the specification of island and flood defence slopes, bottom friction coefficients and a porosity coefficient of the optional flood defence.

In Step 2, mean sea-level, tide, and offshore sea forcing conditions for the wave simulations are specified and applied. The latter inputs include offshore significant wave heights for a selection of significant wave heights (H_s) for some return periods and corresponding peak periods (T_p); see Case study and Data. No specific SLR scenarios are applied in this step, but rather a wide SLR interval (0.0–3.5 m) is approximated in small (dmslr = 0.1 m) mean sea-level steps. The upper value of this range relates to a plausible high-end global mean sea-level scenario under RCP 8.5 by 2200 or the median under RCP 8.5 by 2300 provided by the SROCC (Oppenheimer et al. 2019). The stepwise sea-level approximation enables the analysis of flood probabilities for different island heights (h) and defence heights (dh) under specific SLR scenarios of multiple assessments without the need to run 1D simulations for every SLR scenario. Table 2 lists wave simulation runs used to illustrate the methods. The number of simulations increases in the number of

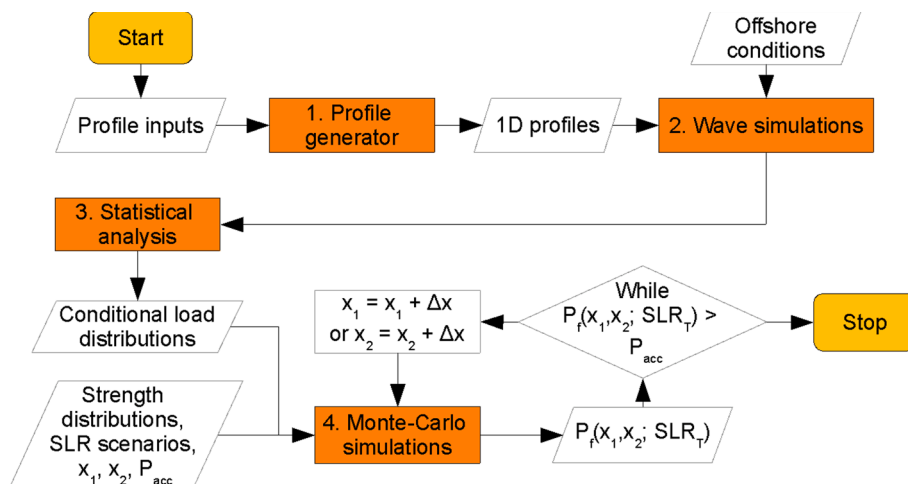


Fig. 1. Overview of hazard threshold analysis method to estimate minimum land reclamation elevation (x_1) or flood defence height (x_2).

Table 2

The setup for wave simulations with three input variables used in this study.

Island height (m), defence height (m)	Sea-level (m)	Extreme sea-level event Hs (m), Tp (s)
h_{\min}	0 + maxTide	10-year event
h_{\min}	0 + maxTide	100-year event
h_{\min}	0 + maxTide	1000-year event
h_{\min}	dMSLR + maxTide	10-year event
h_{\min}	dMSLR + maxTide	100-year event
h_{\min}	dMSLR + maxTide	1000-year event
h_{\min}	2*dMSLR + maxTide	10-year event
h_{\min}	SLRmax + maxTide	1000-year event
$h_{\min} + dh$	0 + maxtide	10-year event
h_{\max}	SLRmax + maxTide	1000-year event

**Fig. 2.** Illustration of an artificial island with a flood defence.

variables and their levels. For example, Table 2 illustrates that the number of simulations is equal to the number of island configurations $((h_{\max} - h_{\min})/dh + 1) \times$ the number of mean-sea level bins $(SLR_{\max}/dMSLR + 1) \times$ number of extreme sea-level events (10-year event, 100-year event, 1000-year event).

In Step 3, a statistical analysis is performed. Surges are disregarded for this particular case, because surges are rather small in the Maldives (Wadey et al. 2017). Tide could not be convoluted, and high spring tide point estimates (maxTide) are used instead. Extreme water levels at the artificial island are analysed, i.e., mean sea-level + tide (+surge) + wave set-up, the total water level distribution of the water level maxima of a wave simulation, and the occurrence of inundation as defined by inundation depths, overland flow velocities or discharge rates. Conditional load distributions are estimated for each mean sea-level bin. In this study, one extreme water level variable is used as a single load variable (van der Meer et al., 2009; Dupuits et al., 2017). We derive these probability distributions by solving for the parameters of annual generalised extreme value distributions with the simulated extreme sea-levels at the coast from conditional 1/10, 1/100 and 1/1000-year swell events for cases without inundation. Wave effects at the island structure for specified island configurations are investigated separately by estimating empirical distributions of total water levels (Stockdon et al., 2006). Critical exceedance values are endogenously determined from simulations with border cases of inundation from a flood definition.

In Step 4, load and strength distributions are numerically combined to estimate flood probabilities in a reliability optimisation procedure that uses Monte-Carlo simulation with Latin Hypercube Sampling; see McKay et al. (2000). We define islands as unbreakable structures that can only fail by wave overtopping or overflow (Fig. 2). The optional flood defence is associated with a variety of failure modes, which can be represented by an appropriate strength distribution function. To illustrate the method, we apply a lognormal strength distribution function to represent the coastal flood defence and derive the parameters from its height (Dupuits et al., 2017). The reliability optimisation procedure stops when either a minimum land elevation or a minimum flood defence height for an island with a given elevation is found that meets the flood standard. No unique solution exists to meet a flood standard: the minimum flood defence height to meet a flood standard depends on the island elevation.

2.2. Cost-benefit analysis

The CBA method identifies an efficient “reclaim & protect” strategy: an island elevation combined with an optional flood defence that can be upgraded over time. One can interpret this strategy as an initial investment size choice that can neither be delayed nor reversed, which is combined with a sequence of protection options for reducing future damages that can be delayed. The solution is found where the total costs of reclaiming land, flood protection and flood damages, are minimised. In this setup, the initial land reclamation choice accounts for future SLR through the anticipation of resulting future trade-offs between protection costs and expected damages.

Consider a cost function to reclaim land I_1 that can be estimated without detailed land reclamation cost data:

$$I_1(x_1) = b_1 + p_1 A x_1 \quad (1)$$

This function distinguishes between fixed costs (b_1) and variable costs ($p_1 A x_1$). Fixed costs do not depend on the island elevation (x_1), such as planning costs and the cost of sand that is needed to fill up the reef below datum. The variable costs are assumed to linearly increase in sand volume applied above datum, which is equal to the land area A multiplied with the island elevation. The price of sand (p_1) is assumed to be constant.

The cost function of a flood defence depends on its type and height (Jonkman et al., 2013). For a sea dike or similar flood defence, we use a linear cost function. This function includes a fixed cost component (b_2), as one cannot raise flood defences yearly or at least not in an economically efficient way (van Dantzig, 1956; Kind, 2014; Eijgenraam et al., 2017). We will denote the height of the flood defence in year t by $x_{2,t}$, which is a state variable. The height increment is denoted by $u_{2,t}$, which is a decision variable. We apply the following linear flood protection cost function:

$$I_2(x_{2,t}, u_{2,t}) = b_2 + b_3 u_{2,t} + b_4 x_{2,t}, \text{ if } u_{2,t} > 0 \quad (2)$$

This function assumes that the variable costs increase linearly in both the height increment choice and the total height of the flood defence ($b_3 > b_4$).

Monetary damages in case of flooding can be defined by the share of the total monetary flood exposure E_t that is lost under an extreme water level h for an island with land elevation x_1 :

$$d(h, x_1) = v_l(h, x_1) E_t \quad (3)$$

The fraction lost is specified by a depth-damage function (v_l) for intended land use l . For example, flood vulnerability of a local airport may be different from residential or touristic land use. For simplicity, inundation depths are assumed to follow a bathtub model, i.e., inundation depth is $h - x_1$, which represents a homogeneous inundation depth for small islands that are approximately flat. The expected flood losses L are defined as the product of flood probability and flood consequences, where the flood probability densities are conditional on mean sea-level at time t (m_t), and the expected flood losses for a given extreme event h depend on island height (x_1) and flood defence height at time t ($x_{2,t}$). Construction time will be ignored, such that $x_{2,t+1} = x_{2,t} + u_{2,t}$. Discrete deterministic dynamic programming (Eijgenraam et al., 2017) is applied to find optimal flood defence height increments u_2 for an island with height x_1 . Let us write the cost-to-go function V as follows:

$$V(x_1, x_{2,t}, m_t) = \{I_2(x_{2,t}, u_{2,t}) + L(x_1, x_{2,t} + u_{2,t}, m_t) + \beta V(x_1, x_{2,t+1}, m_{t+1})\} \quad (4)$$

Where the annual discount factor is denoted by $\beta < 1$.

Finally, define $C_{def}^*(x_1) = V(x_1, 0, 0)$. These are the total discounted expected costs of an optimal flood defence strategy for island height x_1 at $t = 0$. The present value of the total costs for the optimal island height choice follows from:

$$C_{tot}^* = \{I_1(x_1) + C_{def}^*(x_1)\} \quad (5)$$

The optimisation of reclaim and protect strategies can be summarised as follows. First, a land elevation is selected. This is followed by a sequence of flood defence height choices over time. We use a finite time horizon, and the problem is, therefore, solved backwards: The optimal flood protection strategies are determined for given island heights, and then the optimal island height is identified that minimises the present value of the total costs (C_{tot}^*).

2.3. Case studies and data

The decision-support tools were applied to two case study sites: a new artificial island that has been reclaimed near Ha.Hoarafushi located in the North of the Maldives for the construction of a local airport, and an urban land extension case at Gdh.Madaveli in the South of the Maldives (Fig. 3). Both locations are exposed to South-Western swell waves and waves that are generated by the Indian Monsoon.

Table 3 shows median estimates of conditional 10, 100 and 1000-year significant wave heights (Hs) and peak periods (Tp) of nearby grid-points for South-Western swell (SW swell; 209°) of Wavewatch III simulations, downscaled from a global wave reanalysis (Amores et al., 2021). This swell direction is the most frequent in the Maldives. All 1D simulations were performed under spring tide conditions, mean sea-level + 0.5 m for Ha.Hoarafushi and + 0.6 m for Gdh.Madaveli (Wadey et al., 2017). Wave propagation from deep waters to the shoreline was performed using the phase-resolving numerical model SWASH (Zijlema et al., 2011).

Five bathymetric profiles were collected for Ha.Hoarafushi airport, and three profiles for Gdh.Madaveli. These were used to generate idealised 1D profiles with different island configurations. Fig. 3 provides an example. A cubic spline interpolation was used to address missing reef data. A maximum reef crest height of - 0.7 m below current mean sea-level was assumed. The profiles with the shortest distance to the fore reef were selected to estimate flood probabilities. Profile changes were not modelled in this work; see Discussion. The following Manning bottom friction coefficients were applied. For the reef flat and crest, a value of 0.035 was used based on Green et al. (2018). For the remainder of the seabed including foreereef, a default value of 0.025 was used (Dilmen et al., 2018).

Wave set-up values at the shoreline were extracted from the wave simulation data. Total water levels of simulated events were analysed by estimating empirical distributions (Stockdon et al., 2006). Point estimates of these distributions were used to estimate load distributions of extreme water levels. Specifically, probability threshold values were obtained from border cases of flooding for island configurations that - under a given mean sea-level - produced discharge rates near the minimum design wave overtopping magnitude of flood defences (MEE, 2015). The difference between the island height and extreme sea-level without swash was used as a point estimate of the critical height of the wave effect of the simulated event. It corresponds to a probability threshold value of the empirical distribution.

Table 4 summarises the regional SLR scenarios used in this study to estimate flood probabilities in year 2100 under regional low-

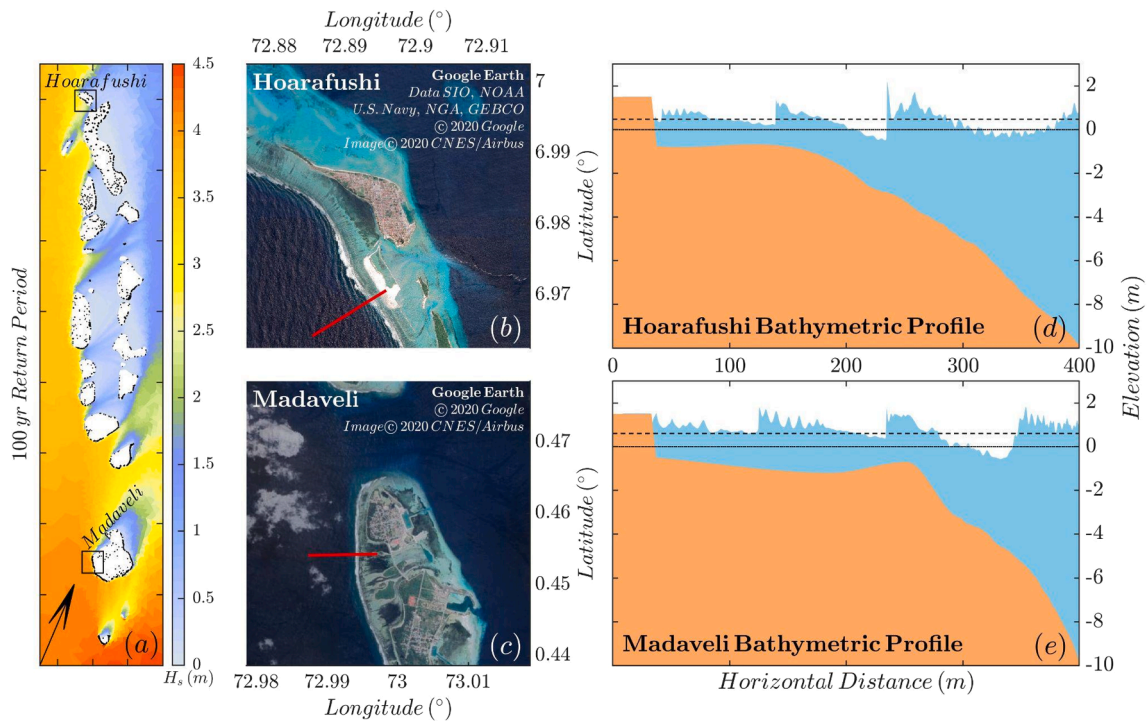


Fig. 3. Case study locations. Panel (a) shows the 100-year return level values of significant wave heights for SW swell across the Maldivian archipelago. Panels (b) and (c) show satellite imagery of the two case study sites Ha.Hoarafushi and Gdh.Madaveli. Panels (d) and (e) show the idealised 1D profiles of both islands with an elevation of + 1.5 m above current mean sea-level without flood defence. There, the horizontal solid lines represent present-day (zero) mean sea-level and dashed lines correspond to an increment of 0.5 m of mean sea-level.

Table 3

Significant wave heights and peak periods applied (source: Amores et al. (2021), SW swell).

Return period	Ha.Hoarafushi Airport			Gdh.Madaveli South-West		
	10-year	100-year	1000-year	10-year	100-year	1000-year
Hs (m)	2.3	2.6	2.8	3.5	4.0	4.3
Tp (s)	19.6	20.4	21.7	19.6	20.4	21.7

Table 4

Summary of regional SLR scenarios (m) used in this study for y2100; probabilistic interpretations are used for the Monte-Carlo simulations.

Scenario	RCP 2.6			RCP 8.5		
	5%	50%	95%	5%	50%	95%
Low-end	0.17	0.35	0.52	0.52	0.76	0.99
IPCC SROCC: Gaussian interpretation	0.30	0.47	0.66	0.64	0.91	1.24
High-end	RCP 2.6 / L			RCP 8.5 / H		
	0.30	0.62	1.27	0.62	1.16	2.61

end scenarios (Le Cozannet et al., 2019), a Gaussian interpretation of the IPCC SROCC scenarios (Oppenheimer et al., 2019), and high-end scenarios that combines the regional IPCC SROCC scenarios with regionally corrected expert-elicited ice sheet contributions of Bamber et al. (2019) under the 2 °C (L) and 5 °C (H) scenarios. The interpolated 5–95% values of the low-end and high-end scenarios were applied as partial SLR probability distributions (van der Pol and Hinkel, 2019). These scenarios were not available for each year till y2100. The CBA therefore only applied a Gaussian interpretation of the regional IPCC SROCC scenarios till 2100. For the terminal condition of the CBA, the probabilistic scenarios were extrapolated till year 2200 with long-term global SLR scenarios (Oppenheimer et al., 2019).

CBA is a data-intensive method. To demonstrate our method, several flood risk assumptions were made to address data gaps. Specifically, a fixed cost share of 40% for land reclamation was assumed to derive the fixed investment cost component (b_1) and the variable cost of sand (p_1 ; 5.0 USD per m^3). The latter estimate was obtained from the variable share of the total costs to reclaim Ha.

Hoarafushi Airport (4.3 million USD), the island elevation (u_1 ; 1.5 m), and the reclaimed land area (A) of 34.6 ha (CAPA 2019). The total planned reclaimed land area at Madaveli-South is 10.0 ha (MHE, 2012). For flood defences, a fixed unit cost share of 32% was assumed based on Dutch experience (Eijgenraam et al., 2017). A flood defence of 1.7 km length was considered for Ha.Hoarafushi Airport to effectively protect the island in the future. The flood defence at the reclaimed land at the South-West of Gdh.Madaveli would have a length of 0.472 km (MHE, 2012). An extra flood defence at the western side of the island of 0.8 km was considered for the analysis. An initial cost estimate of 1.6 million USD per kilometre was used for both cases. Total flood defence costs were assumed to increase with 30% per metre height increase. A lognormal strength distribution, and a constant Coefficient of Variation of 0.2 was assumed to represent coastal flood defence failure (Dupuits et al., 2017).

Little information is available about monetary exposure and vulnerability of small domestic airports. To our knowledge, depth-damage functions for small domestic airports are currently lacking in the literature. Although some have argued that small airports are completely invulnerable to flooding (Vanneuville et al., 2006), flood damages can arise from damaged aeroplanes and buildings on site (Stokoe et al., 2011), as well as destabilised runways (Douglas and Lawson, 2003). In this work, a road infrastructure depth-damage function (Huizinga et al., 2017) was adopted to represent flood vulnerability of the airport. This function, for example, assumes that 37% of the monetary exposure is lost for a flood depth of one metre. A conservative estimate of monetary exposure of 6 million USD was applied, which is the replacement value of the main runway infrastructure of Ha.Hoarafushi airport (MTCC, 2019).

An island that is extended with reclaimed land will be represented as a floodplain with two segments. The weakest link determines the flood probability, which implies that a flood defence is added to protect the island if the elevation of the reclaimed land is higher than the island elevation. Monetary flood exposure at the island and the proposed land reclamation areas at Gdh.Madaveli was estimated with a locally adjusted capital-per-capita multiplier approach (Hallegatte et al., 2013). In a first step, it was assumed that the population density on the reclaimed land would directly converge to the population density of Gdh.Madaveli. The population density at the end of 2014 was 1821 people (NBS, 2017) per 33.8 ha. This gives an initial population exposure estimate of 539 people on the reclaimed land. In a second step, initial monetary flood exposure was estimated by multiplying average annual per capita income at atoll-level, which was 2693 USD for Gaafu Dhaalu in 2016 (NBS, 2016), with total population exposure at the island and the reclaimed land, and a capital-per-capita multiplier of 2.8 (Hallegatte et al., 2013). The stylised depth-damage function of Hinkel et al. (2014) was adopted to represent flood vulnerability of residential areas, which for example assumes that 50% of the monetary exposure is lost for a flood depth of one metre. For both case studies, future local monetary exposure was estimated with national Shared Socio-economic Pathway scenarios of the Maldives (Riahi et al., 2017). Annual economic growth rates till 2100 were obtained from a piecewise cubic interpolation of the 5-year scenario development of the Gross Domestic Product, and long-run economic growth rates were assumed to be constant between 2100 and 2200. Damages and investment costs were discounted at a real annual discount rate of 5%.

3. Results

3.1. Benchmark results

Our benchmark results illustrate that artificial islands in the Maldives are projected to need increasing flood protection in the future due to SLR. Fig. 4 illustrates this for the reclaimed airport island at Ha.Hoarafushi for two hypothetical elevation choices of 1.6 m and 2.0 m above datum without flood protection. The latter choice would postpone the moment that flood protection is needed by four decades in this particular case. For example, Fig. 4 shows that estimated conditional annual flood probabilities for an island elevation of 1.6 m above datum without flood protection already exceed the assumed probability threshold in the next decade. For an island

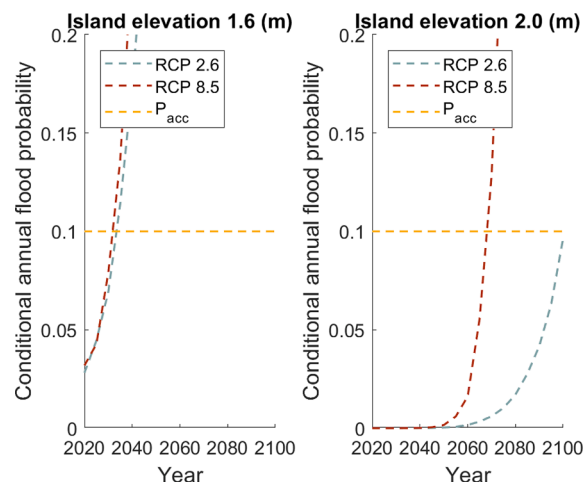


Fig. 4. Conditional flood probability estimates over time for the Ha.Hoarafushi Airport site assuming island elevations of 1.6 m and 2.0 m above datum without flood defences under regional SLR scenarios (IPCC SROCC RCP 2.6 and RCP 8.5: Gaussian interpretation), high tide (+0.5 m), no reef growth and H_s estimates of SW swell (209°).

Table 5

Long-term estimates of hazard-based island and flood defence heights (m) assuming a 1.6-meter island elevation with a flood defence ($T = 2100$, $P_{acc} = 1/10$, lognormal strength and $CV = 0.2$).

SLR scenario	Ha.Hoarafushi Airport		Gdh.Madaveli South-West	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
IPCC SROCC: Gaussian interpretation	2.04	2.79	2.71	3.35
Low-end (5–95%)	1.86	2.44	2.52	3.05
High-end (5–95%)	2.50	3.76	3.05	4.24

elevation of 2.0 m, no additional flood defences would be needed till the end of this century for the applied SLR scenario under RCP 2.6 or only after half a century under RCP 8.5. Note that for the purposes of this study key uncertainties beyond SLR are excluded, and that unconditional flood probabilities may be lower than the conditional ones shown. The latter have been used as conservative estimates, as unconditional flood probabilities could not be estimated without estimates of the likelihood of the different directions.

3.2. Hazard threshold results

Our HTA results demonstrate that some locations are more suitable for land reclamation than others. To illustrate this, fixed land elevations of 1.6 m were applied to both case study sites in an HTA. The results in Table 5 suggest that for the assumed flood defence and a long-term planning horizon till 2100, flood defence heights of 0.4–2.2 m would be needed for Ha.Hoarafushi Airport, and 0.9–2.6 m for Gdh.Madaveli SW. The latter location is therefore less suitable for land reclamation from a flood hazard perspective due to the higher swell exposure and the limited distance between the reclaimed land and the forereef in both cases. Without flood protection, lower island elevations up to a few decimetres would be needed than the values shown in Table 5. Yet, these long-term estimates are higher than the land elevations in the current guideline.

Table 5 illustrates two key problems of the hazard-based approach. First, it shows that an arbitrary island elevation must be specified to estimate optimal hazard-based flood defence heights. In other words, the HTA cannot give an answer whether to reclaim land at a lower elevation with a flood defence or at a higher elevation without flood defence. Second, the case studies illustrate that low-end to high-end SLR uncertainty ranges result in very wide uncertainty ranges of optimal hazard-based heights across SLR scenarios with differences up to almost two metres for a planning horizon till 2100. In summary, HTA can be used to obtain insights in local flood hazard differences for site selection but provides limited decision information on how to invest.

3.3. Cost-benefit results

Risk-based height estimates of the reclaimed land areas range from 1.83 m to 1.89 m for Ha.Hoarafushi Airport and from 2.74 m to 2.77 m for Gdh.Madaveli (see Table 6). These height differences across sites are partly explained by the local flood hazard differences, and partly by the differences in flood consequences. For both cases, the CBA results suggest that it is optimal to add flood protection to the reclaimed land in the future rather than to invest in a lower island with initial flood protection. Provided that any neighbouring land is equally protected, a higher reclamation height permanently reduces the expected flood damages over time as compared to the same total height of a lower island or land extension with a flood defence. This damage reduction outweighs the additional initial reclamation costs. For example, for Ha.Hoarafushi the reclamation costs are approximately 5 million USD for an island with an elevation of 1.8 m, whereas the additional costs of reclaiming land with a higher elevation are larger than of adding a higher initial flood defence ($p1A > b3$).

Land reclamation elevations vary much less across both RCP and SSP scenarios than optimal hazard-based heights across RCP scenarios alone. This is due to the future additional flood protection investments, the similarity of SLR scenarios across RCPs in the coming decades, and discounting of future benefits. For example, the differences amount to only a few centimetres for both cases under RCP 2.6 and 8.5 if only the Gaussian interpretation of the IPCC SROCC scenarios is considered. In contrast, the timing and size of future optimal flood protection investments varies significantly across scenarios: higher SLR and socioeconomic scenarios are associated with earlier investment and higher flood defences.

The case study results of the CBA also suggest that it is efficient for both cases to invest in reclaimed land that is sufficiently high today to reduce current annual flood probabilities to small values ($<10^{-4}$) due to the anticipation of SLR. Whereas the HTA required

Table 6

Estimates of risk-based island elevations and flood defence heights under IPCC SROCC-Gaussian SLR scenarios and local exposure growth from SSP scenarios ($\delta = 0.05$).

SLR scenario	Ha.Hoarafushi Airport		Gdh.Madaveli South-West	
	RCP 2.6	RCP 8.5	RCP 2.6	RCP 8.5
SSP scenario	SSP1	SSP5	SSP1	SSP5
island elevation (m)	1.83	1.89	2.74	2.77
flood protection height (m)	0.52	0.86	0.48	0.80
flood protection year	2070	2061	2084	2066

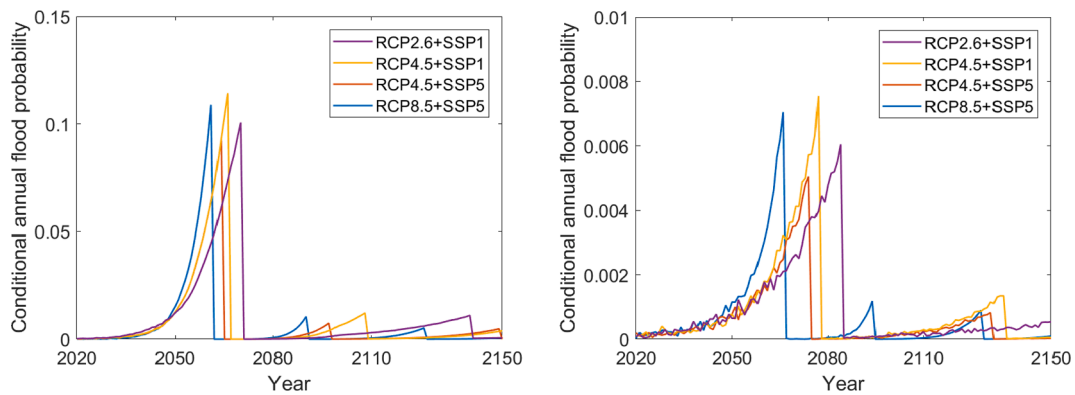


Fig. 5. Conditional flood probabilities of risk-based strategies under spring tide and four scenarios ($N = 40000$) for Ha.Hoarafushi Airport (left panel) and Gdh.Madaveli South-West (right panel).

the specification of an acceptable flood probability threshold and planning horizon, the CBA has identified optimal risk-based flood protection levels and optimal planning horizons till follow-up investments. Fig. 5 illustrates that for Ha.Hoarafushi airport risk-based maximum annual flood probabilities are estimated at 0.09–0.11 till 2061–2070. These relatively high values are explained by the modest initial flood exposure and the limited flood vulnerability (Section 2.3). For residential land use at Gdh.Madaveli, risk-based maximum annual flood probabilities would be estimated at $5.1\text{--}7.5 \times 10^{-3}$ till 2066–2084. The CBA also finds that risk-based maximum flood probabilities for both cases are projected to decrease, in the order of a factor 10, between the first and the second round of investments in flood protection due to the projected increase in monetary exposure. The first flood protection investment takes place between 2050 and 2090, depending on the scenario. The timing of follow up investments are also displayed in Fig. 5: The conditional flood probabilities drop to values close to zero after an investment in flood protection.

4. Discussion

From a decision perspective, land reclamation offers a unique coastal adaptation opportunity. Typically, land elevations and existing flood exposure are given when initial coastal flood impacts are assessed. This is not the case when new artificial islands are reclaimed, allowing coastal managers to choose an adequate location and design of land reclamation projects. This study, however, highlights that one must carefully think about where and how to reclaim land for the intended land use. For decision-making, local differences in flood hazard, projected exposure and vulnerability are too large to be able to work with fixed design height policies. Quantitative decision-support tools, as the ones developed in this study, are therefore indispensable to make informed decisions about appropriate locations, land elevations and flood protection.

While the HTA is good for obtaining insights in local flood hazard differences for site selection, this method cannot provide unambiguous solutions on hazard-based land reclamation choices. This is due to the presence of deep SLR and other uncertainties that by definition do not come with probabilities (Kwakkel et al., 2010). This also holds true to a lesser degree for the applied CBA method that equally combines simulation with optimisation techniques. Deep uncertainties hinder the application of optimisation methods in general, and especially CBA has been frequently criticised in a context of climate change adaptation for this reason (Kunreuther et al., 2013). For example, it is unlikely but possible that the future does not look like any of the scenarios we used here, e.g., if ice-sheet stability in Antarctica deteriorates quicker than anticipated (Oppenheimer et al., 2019). However, the numerical results illustrate that for the particular case of land reclamation, the initial land elevation decision is much less sensitive to SLR uncertainty in a CBA as compared to a hazard-based approach, because CBA accounts for the possibility to add adaptation measures in the future and associated damage and protection cost trade-offs over time. Of course, there are complementary strategies to understand these uncertainties that were beyond the scope of this work, including a sensitivity analysis of key uncertainties, or the application of alternative or complementary methods from the robust decision-making literature e.g., combining Real Option Analysis and Dynamic Adaptive Policy Pathways to generate a robust decision method that can be applied in contexts of deep uncertainty like Stroombergen and Lawrence (2022) have demonstrated for cases in New Zealand. Moreover, approaches with multiple objectives that also consider the risk of decreasing freshwater availability due to groundwater salinization and the associated need for desalination plants and pumps may be useful as well for decision-making in the atoll-context (Alsumaiei and Bailey, 2018). Nevertheless, using the HTA and CBA approaches together, as done in this work, aids decision-making by demonstrating how land reclamation choices can differ based on either the same inputs (SLR scenarios) or different inputs like planning horizons in the case of an HTA, or exposure and vulnerability estimates for the planned land use and project size, and discounting preferences in the case of a CBA.

A few limitations are related to 1D wave simulations that underlie both approaches. 1D wave simulations were applied to keep computations tractable within the optimisation schemes of both HTA and CBA (Dupuits et al., 2017). The use of the meta-modelling methods can be envisaged to overcome the computational burden of more advanced simulation methods (Rueda et al., 2016). Uncertainties that were not considered in the 1D wave simulations are reef friction uncertainty (Rosman and Hench, 2011; Green et al., 2018), reef growth uncertainty (Perry et al., 2018), and initial 1D profile uncertainty due to the use of idealised profiles and missing

reef data. Other key uncertainties include model uncertainty of significant wave heights and peak periods (Amores et al., 2021), uncertainty related to the applied flood definition, and tide uncertainty. Tide was not modelled probabilistically due to the insufficient event duration data, and spring tide levels were applied to estimate conditional flood probabilities. This scenario approach may be justified given that flood events that have occurred in the Maldives, have been frequently associated with high spring tides as one of the sources of flooding (Wadey et al., 2017). The assumption of no reef growth was used for the analysis, which could be overly pessimistic under low RCP scenarios (van Woessik et al., 2015). Reefs in the Maldives under RCP 8.5 have amongst others been projected to experience a mean water depth increase of about half a metre by 2100 (Perry et al., 2018). Works in other regions, however, have also suggested that net reef accretion can be negative, which would accelerate rather than reduce relative SLR (Yates et al., 2017). Moreover, the results highlight that any increase in mean water depth is associated with lower wave set-up values at the island but with higher overtopping risk.

CBA is a more data-intensive method than HTA, as it requires additional information on monetary exposure and flood vulnerability, and reclamation and protection costs. A few assumptions were made to address data gaps. Only direct flood damages were considered without reef damages, for which site-specific impact evaluations are required (Erftemeijer et al., 2012). For larger projects, local sand scarcity and associated cost increase may also have to be considered. We further represented an island with a land extension as a non-homogeneous coastal floodplain with two segments, provided that a single swell direction is analysed. However, to account for waves from multiple directions or local differences in existing flood protection, a more detailed CBA with multiple segments might be needed (Zwaneveld et al., 2018). Additional drainage costs were also ignored, which assumes that water freely discharges onto the neighbouring land without costly infrastructure. Moreover, in CBAs of flood protection, investments are often modelled as adaptation options of an incremental nature with a predictable outcome. For further research, alternative methods that consider deep uncertainties and adaptation lock-ins would be interesting to apply in the context of land reclamation, for example by economic valuation of adaptation pathways (Haasnoot et al. 2020).

Another data problem for CBA is that relatively few studies are available that provide complete probabilistic SLR scenarios till 2200 (Garner et al., 2018). For example, the IPCC SROCC provides partial probabilistic regional SLR scenarios till 2100, and global SLR scenarios are available for the year 2300 (Oppenheimer et al., 2019). However, this information has not yet been provided for intermediate years in the next century and has not been translated to the regional level. For dynamic cost-benefit models, the analyst is then left with three choices: (i) use different SLR scenarios, (ii) interpolate the selected SLR scenarios with the available long-term SLR information, or (iii) prematurely cut off the time horizon of the CBA at year 2100. The latter would negatively impact investment in the second half of this century due to missing flood damage estimates after 2100 and was not applied in this research. Lastly, while the use of 1D profiles saves data collection costs (Weaver and Slinn, 2010), further efforts are needed to make the decision-support methods easier to execute for coastal managers to seize their full utility in supporting adaptation decisions.

5. Conclusions

Addressing the lack of tailored methods for determining optimal land reclamation locations and heights under SLR, this paper has developed two quantitative methods and applied them in two case study sites in the Maldives. Using the two methods, we demonstrated how land reclamation heights can differ from flood hazard and cost-benefit perspectives and how these complementary perspectives are helpful for informing coastal managers. The key message of this paper is that generically fixed heights (like the current Maldivian guideline) or hazard-related rules do not produce effective or efficient land reclamation solutions at the local level. The latter requires local insights in both flood hazard and flood consequences, for example driven by planned land use and project size, and in the temporal trade-offs between land reclamation and flood protection costs, and residual damages.

HTA is primarily useful to support the initial site selection for land reclamation. From a flood hazard perspective, sites that are exposed to relatively high waves or that take away much of the protective capacity of the reef are less suitable for land reclamation. The two Maldivian case studies illustrate that local flood hazard differences should not be neglected when land is reclaimed. HTA, however, does not provide much guidance on hazard-based land elevations for long-planning horizons beyond 2050, as the resulting land reclamation heights differ substantially due to deep SLR uncertainty. HTA also cannot provide guidance on which planning horizon to use, on how to define an acceptable flood standard, or whether it is better to invest in a lower island with a flood defence or a higher island without. The developed CBA method, in contrast, can provide insights in these questions from a social welfare perspective. This method, however, comes with higher data requirements on flood exposure, flood vulnerability, reclamation and protection costs, and applicable discount rates. For decision-making, CBA has a practical advantage over HTA in that risk-based island elevation choices taken in the near future, in contrast to flood defence choices, tend to be relatively insensitive to SLR uncertainty. This is due to the anticipation of additional flood protection investments to reduce flood damages in the future and their weights as expressed in present and future values, and the similarity of SLR scenarios across RCPs in the coming decades.

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

Flood hazard data and SLR data used for the HTA is available in the cited references. CBA parameters are provided in [Section 2.3](#).

Code is available upon request from the authors.

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