Received: 15 February 2019 | Revised: 27 June 2019 | Accepted: 26 August 2019

DOI: 10.1111/jfr3.12567

ORIGINAL ARTICLE

CIWEM Chartered Institution of Water and Environmental Management | Journal of Flood Risk Management | WILEY

Land raising as a solution to sea-level rise: An analysis of coastal flooding on an artificial island in the Maldives

Sally Brown[1,2] | **Matthew P. Wadey**[1,3] | **Robert J. Nicholls**[1] | **Ali Shareef**[4] | **Zammath Khaleel**[4] | **Jochen Hinkel**[5,6] | **Daniel Lincke**[5] | **Maurice V. McCabe**[7]

[1]School of Engineering, University of Southampton, Southampton, UK

[2]Department of Life and Environmental Sciences, Faculty of Science and Technology, Bournemouth University, Poole, UK

[3]Bournemouth, Christchurch and Poole Council, Civic Centre, Poole, UK

[4]Ministry of Environment, Green Building, Malé, Republic of Maldives

[5]Global Climate Forum (GCF), Berlin, Germany

[6]Division of Resource Economics, Albrecht Daniel Thaer-Institute and Berlin Workshop in Institutional Analysis of Social-Ecological Systems (WINS), Humboldt-University, Berlin, Germany

[7]School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK

Correspondence
Sally Brown, School of Engineering, University of Southampton, Boldrewood Innovation Campus, Burgess Road, Highfield, Southampton SO16 7QF, UK.
Email: sb20@soton.ac.uk

Funding information
Seventh Framework Programme, Grant/Award Numbers: IMPACT2C: Quantifying projected impacts under 2°, RISES-AM-Contract ENV-2013-two-stage-603396; European Union Seventh Framework Programme, Grant/Award Number: FP7

Abstract

The Maldives (land elevation approximately 1 m above mean sea level) is often associated with the threat of rising sea levels. Land scarcity due to population pressure is also a major issue. In the late 1990s a new 1.9km^2 1.8 m high artificial island, Hulhumalé was created for urban expansion, including an allowance for sea-level rise. This paper assesses flood exposure through an extreme water level scenario on Hulhumalé taking into account sea-level rise and analyses potential adaptation options to extend island life. Results indicate that overtopping is likely to occur with 0.6 ± 0.2 m of sea-level rise, with more severe, widespread flooding with 0.9 ± 0.2 m of sea-level rise. If the Paris Agreement goals are met, flooding is not anticipated this century. However, under a non-mitigation scenario, flooding could occur by the 2090s. Building seawalls 0.5, 1.0, and 1.5 m high could delay flooding for 0.2, 0.4, and 0.6 m of sea-level rise, respectively. Land raising has been successful in Hulhumalé in reducing flood risk simultaneous to addressing development needs. Whilst new land claim and raising can be cost-effective, raising developed land provides greater challenges, such as timeliness with respect to infrastructure design lives or financial costs. Thus the transferability and long-term benefits of land raising requires further consideration.

KEYWORDS

adaptation, defence, flooding, island, land claim, sea-level rise

1 | INTRODUCTION

Sea-level rise has the potential to threaten the very existence of low-lying atoll nations such as the Maldives, Kiribati, and Tuvalu (Barnett & Adger, 2003; Giardino, Nederhoff, & Vousdoukas, 2018; Nicholls et al., 2007; Nicholls & Cazenave, 2010;Nurse et al., 2014 ; Wong et al., 2014). Flooding is likely to increase in the future unless adaptation is undertaken (Nurse et al., 2014; Wong et al., 2014). To date, many scientists, engineers, and policy makers have questioned how small, low-lying nations, many of which are remote and have a limited resource base, will cope with future sea-level rise (Nurse et al., 2014). Yet many islands are coping with coastal flooding today.

One nation at high risk of flooding, particularly as sea-level rise, is the Maldives, Indian Ocean (Figure 1a) (Hinkel et al., 2018; Khan et al., 2002; Wadey, Brown, Nicholls, & Haigh, 2017; Woodworth, 2005). Natural atoll islands are well known to change shape due to over washing (flooding) resulting in sedimentation, with some islands increasing in area under these conditions (e.g., Duvat, 2018; Kench, Thompson, Ford, Ogawa, & McLean, 2015). For inhabited islands, flooding is not acceptable leading to the building of defences. In the short term, defences such as sea walls (if well built and maintained) reduce the flood hazard (Betzold & Mohamed, 2017; Sovacool, 2012), but in the long-term, the flood hazard may increase where islands do not naturally accrete sediment, and sea-levels continue to rise (e.g., Giardino et al., 2018; Storlazzi et al., 2018). Raised water levels and increased flood risk can lead to knock-on effects, such as ground water salinisation threatening freshwater availability as the frequency of flooding increases (Storlazzi et al., 2018). Thus, on inhabited atoll islands, radical adaptation options will need to be considered in the future if they are to remain habitable.

One approach, which, to date, has received little comment in the literature is the artificial raising of whole islands (island raising) to appropriate heights to cope with future sea-level rise. Land claim and land raising is where new elevated land is created that is above present typical flood levels or sea levels. Land claim and raising differs to land reclamation which implies the land once belonged to the sea, or where a wetland was drained to form a drier area of land, and subsequently protected, such as by a dike. As well as adapting to flooding, land raising can create land where it is needed, satisfying two needs at once (Nicholls, 2018).

Due to urban migration (Speelman, 2015), space in the nation's capital city, Malé (Figures 1a,b and 2) is scarce. Feeling the population pressure two decades ago, the national government decided that more land was needed. Therefore, a new island, Hulhumalé (Phase 1, 1.9km^2) was created adjacent to Malé from the late 1990s by building up land from the coral reef flat (Figures 1c,d and 2). Raised to approximately 1.8 m above mean sea level (natural Maldivian islands are approximately 1 m above mean sea level), the island was designed with sea-level rise in mind. In 2015, the island was expanded (Phase 2, 2.5km^2), and in 2018 was linked to Malé by a bridge (Figure 1c). Development on Hulhumalé (Phase 1 and Phase 2) is now extremely rapid. Population growth on Phase 1 is high, but basic infrastructure construction is still being undertaken on Phase 2. These investments have been funded through loans and the national government (personal communication with national government). While Malé can experience floods during extreme swell wave events (Naylor, 2015; Pernetta, 1991; Wadey et al., 2017), Hulhumalé has not to date, in part due to its raised height. At the time of design, expert judgement (personal communication with the then Maldivian government engineers) was used to determine an appropriate height allowance to cope with future sea-level rise (which at that time was projected to rise up to a maximum of 1 m by 2100 (Warrick, Le Provost, Meier, Oerlemans, & Woodworth, 1996)). More recent projections suggest a 1 m rise could be exceeded before 2100, and especially beyond 2100 (e.g., Church et al., 2013; Hoegh-Guldberg et al., 2018; Jevrejeva, Grinsted, & Moore, 2014). Hence, it remains unclear how long the 1 m height allowance for Hulhumalé will be effective against sea-level rise and what further adaptation options could extend the island's life. Thus, this paper aims to assess the feasibility of island raising as an adaptation option to cope with future sea-level rise, using a case study of Hulhumalé (Phase 1), Maldives. This will be achieved by:

1. Developing a methodology to determine the impacts of sea-level rise (in Section 2);
2. Determining impacts (flood extent and infrastructure affected) caused by different extreme water level conditions, by assessing what sea-level rise thresholds this could occur at and possible adaptation options (in Section 3);
3. Assessing the feasibility of island raising as a means to adapt to sea-level rise (in Section 4).

The conclusions are presented in Section 5.

2 | MATERIAL AND METHODS

2.1 | Setting and approach

Hulhumalé is protected by vertical sheet-pile walls in the north, west and south facing the North Malé Atoll lagoon. Along the eastern side of the island facing the Indian Ocean there is a sloped seawall protected by sand bags blasted with

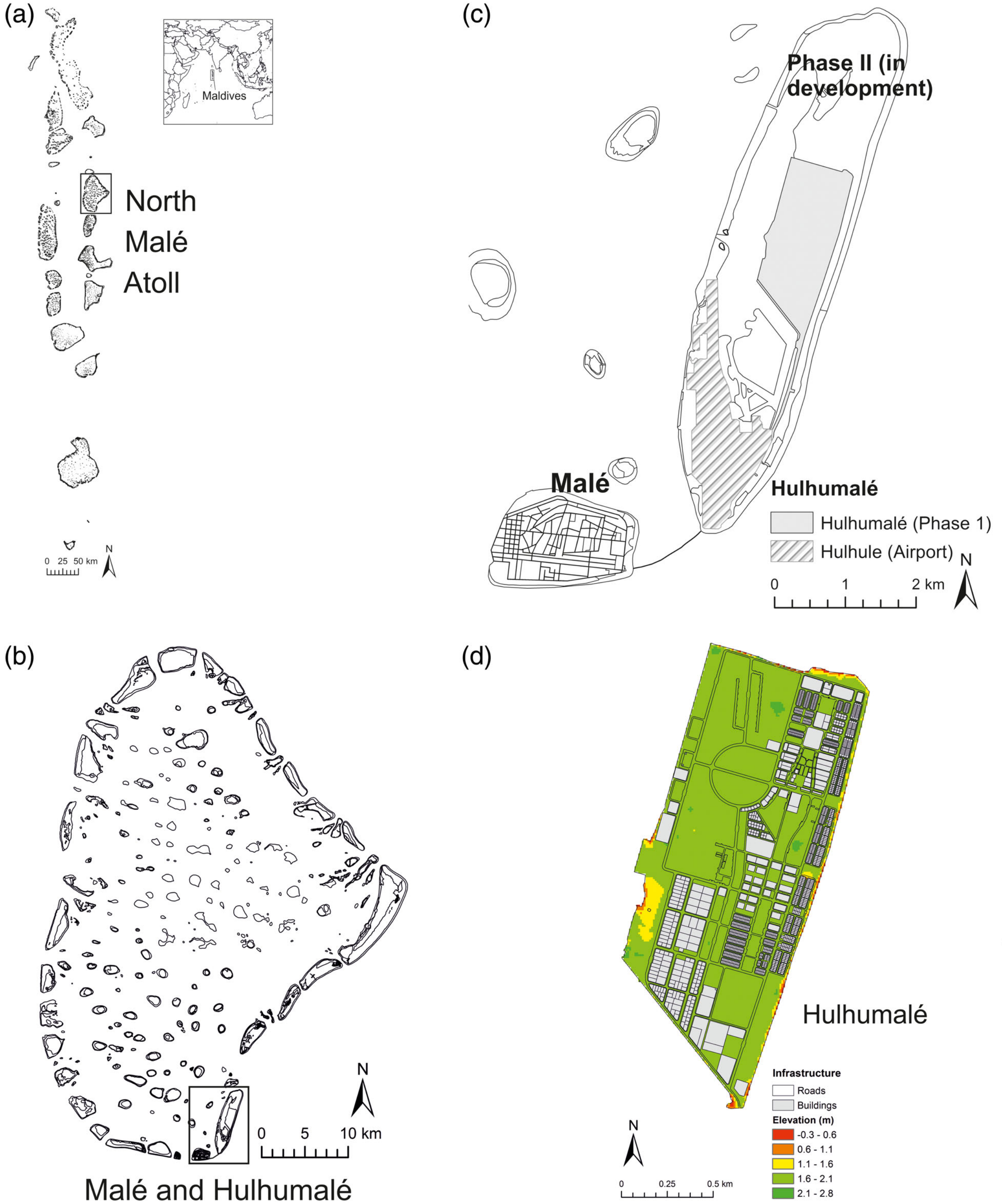

FIGURE 1 Geography of Hulhumalé, Maldives. (a) Location of North Malé Atoll (inset, location of Maldives in the Indian Ocean), (b) Location of Malé and Hulhumalé within North Malé Atoll; (c) Setting of Malé and Hulhumalé with connecting bridge; (d) Infrastructure and land elevation on Hulhumalé (Phase 1). Outline data courtesy of Ministry of Environment and Energy and the Hulhumale Development Corporation

concrete and a nourished beach (Figure 2b). In places the seawall is showing signs of damage (Figure 2b). The nourished beach varies in width from approximately 5 to 20 m along the eastern frontage, and remains relatively stable due to the protective reef. Sand was dredged from within Malé Atoll (personal communication with the Maldivian government). Land use along the eastern side of the island is mostly residential and guest houses (Hulhumalé

FIGURE 2 (a) The heavily engineered coast around Malé showing a sea wall protected by armour units. (b) The coastal defence structure on the eastern side of Hulhumalé

Development Corporation, 2016). On the western side, there are industrial and shipping activities. The island is virtually flat at 1.8 m above mean sea level (1992–1993). The main potential flooding mechanism is overtopping of defences that occurs due to a combination of high water levels (surge and tides), gravity waves such as energetic swell and other cyclonic fluctuations in mean sea level (Church, White, & Hunter, 2006; McCabe, Stansby, & Apsley, 2013; Wadey et al., 2017).

Energetic swell waves are known to generate flooding in the Maldives (Khan et al., 2002; Wadey et al., 2017). A historical analysis of flooding plus discussions with Maldivian scientists (including co-authors A.S. and Z.K.), indicated extensive flooding has occurred twice in Malé over the last 40 years (see Wadey et al., 2017). Due to restrictions in data availability, the only event where comprehensive wave data was available based on a hindcast analysis was from 15th to 17th May 2007 (Wadey et al., 2017). During this event, long-period energetic swell waves generated 5,600 km away in the Southern Ocean approached the Maldives in two separate events over a period of several days, coinciding with the middle of the spring tidal cycle (Wadey et al., 2017). This event was used as a "design storm" for the analysis of possible overtopping and flooding (see Wadey et al., 2017), including the addition of sea-level rise scenarios.

2.2 | Data

To analyse flood risk through time, the design storm was simulated (based on data from Wadey et al., 2017) with the addition of sea-level rise, with overtopping calculated, and then projected onto Hulhumalé. Six data sets were required: (a) significant wave height and period; (b) mean sea level, tides and surge data; (c) bathymetry; (d) defence type and elevation; (e) island topography; and (f) location of infrastructure (Figure 3).

Until very recently, there were no wave buoys or long-term observations recording significant wave heights and periods around the Maldives. Therefore, hindcast data was used, generated from WAVEWATCH III (NOAA–NCEP, 2014), a global ocean surface wave model (e.g., Tolman, 2009). A time series was downloaded from the Indian and Southern Oceans at 3-hour temporal resolution from 2005 to 2014. The nearest data point to Hulhumalé was analysed as shown in Wadey et al. (2017). The data is deemed sufficiently reliable as data analysis of the timing and approximately magnitude of events and their location matched media and official reports (see Wadey et al., 2017). The hindcast data from May 2007 indicated a mean significant wave height of 2 m and wave periods of up to 20s (with 15 s waves not uncommon for a week surrounding the event, see Wadey et al., 2017). This data was used in the overtopping model for the duration of the storm event. Following Holden (2008), wave set-up is accepted to be approximately 20% of the offshore significant wave height, an important flood mechanism at this location which would be implicit within the numerical overtopping simulations.

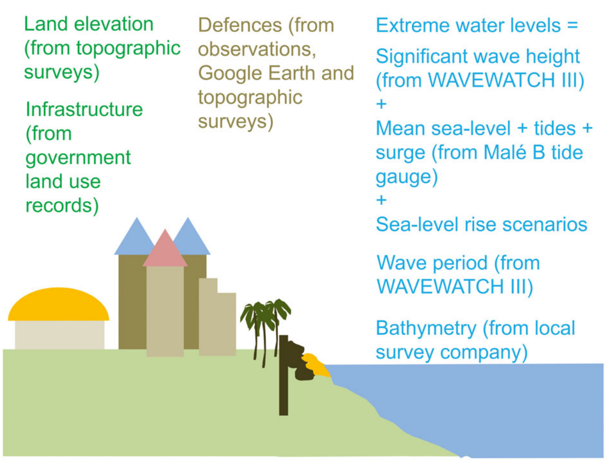

FIGURE 3 Data sets used in this analysis

Extreme water levels were extracted from the nearest tide gauge station to Hulhumalé, the Malé-B gauge, located adjacent to the airport. It recorded hourly still water levels from 1989 to present (UHSLC, 2015). Over a thirty-day period, changes to mean sea level are in the order of centimetres (Wadey et al., 2017). Surges did not exceed 0.25 m in the recording period, and skew surges did not exceed 0.15 m (Wadey et al., 2017). There is also a semi-diurnal tide, with a mean spring range of 0.76 m (Woodworth, 2005), which is an important component of extreme water levels and flooding potential (Wadey et al., 2017). Hence, these extremes are combined when analysing the maximum water level during the design storm conditions in the overtopping model (Section 2.3).

Bathymetric data was only available for the 1,500 m eastern side of the island, up to 550 m offshore. This was in the format of 0.5 m vertically spaced contour lines, and augmented with beach elevation from a differential Geographical Positioning System survey. The shallow reef environment extends to approximately 150 m offshore and is approximately up to 3 m lower than the average land level (see Appendix A1, Figure A1). The reef then rises to a ridge slightly above mean sea-level, before declining at a vertical rate of 0.05 m per 1 m horizontally for 200 m, then steepening to 0.25 m per 1 m horizontally for a further 200 m. Thus depths of 50 m are typically found 400–500 m offshore, and thereafter continue to rapidly deepen.

Coastal defence data was provided by the government, and from observations during a site visit, Google Earth and topographic data. Topographic data was generated through a differential Geographical Positioning System survey from February to April 2013. A digital elevation model of 10 m resolution was created using 8,706 point measurements along roads and coastal defences, by interpolating elevation via the natural neighbour method between measurement points in the Geographical Information System (Figure 1d). Infrastructure data at the time of the study was provided by the Ministry of Engineering and Environment (Figure 1d), and observed on a site visit. This is a snapshot of the dynamic situation on a rapidly developing island.

Finally, to combine data, all datums were checked and referenced to the Maldivian datum of mean sea level (June 1992–June 1993). There is an approximately 1 m difference between the land level and mean sea-level datums.

2.3 | Methods

To determine possible flooding from a swell wave event with additional sea-level rise, a series of discrete scenarios were analysed using the following methodology (further details are in the Appendix):

- A one-dimensional Shallow-water and Boussinesq (SWAB) numerical model (McCabe et al., 2013; McCabe, Stansby, & Apsley, 2011; Stansby et al., 2013) was used to simulate the propagation of nearshore waves and overtopping volumes under extreme conditions for 2 hr, which allowed the modelled sea to produced peak overtopping conditions. Tides were subsequently included into the model simulations. This used input data from extreme water levels (based on the May 2007 storm conditions and duration) bathymetry and topography and wave period. For further details, see Appendix A1.
- Once overtopping volumes were calculated, these were input to a two-dimensional simulation of flooding, based on the topographic data to predict flood extent and depth. This used the LISFLOOD-FP inundation model (Bates, Horritt, & Fewtrell, 2010), with overtopping volumes input at 10 m intervals along the eastern boundary of the island. The eastern side was selected as it is the most exposed to the open ocean (as opposed to the western side which faces into the atoll), and hence there is greater probability that it will be subject to long-period waves which could induce flooding (see Appendix A2).
- The flood extents were then overlaid onto the infrastructure layer in a Geographic Information System to count infrastructure at risk from flooding (see Appendix A3).

Results are presented for overtopping volumes, area and buildings affected (Figure 4) and flood spread (Figure 5). For analysis purposes, the extent of temporary flooding is divided into three categories, where the geographical area of flooding may be limited or widespread:

1. Nuisance flooding: where flooding is predicted adjacent to the south-east shoreline to low depths (<0.2 m). About 0.2 m of average flood depth was selected as a threshold as this is common in the capital today, and causes disruption, but not significant damage. Depths greater than this can cause damage to the building fabric, as noted for urban floods (whatever the cause) elsewhere in the literature (e.g., Kaspersen & Halsnæs, 2017; Penning-Rowsell, 2015; Penning-Rowsell et al., 2005; Zhou, Mikkelsen, Halsnæs, & Arnbjerg-Nielsen, 2012).
2. Hazardous flooding: where flood depths are predicted to be greater than 0.2 m and cover 50% of the island. Here, flooding would be particularly hazardous on the eastern side due to the greater than average depth and rate of flow over the present defences.
3. Life threatening flooding: where flood depths are predicted to be greater than 0.6 m. In the wider literature, Penning-Rowsell et al. (2005) indicates that for any location, flood depths greater than 0.6 m can be considered life threatening.

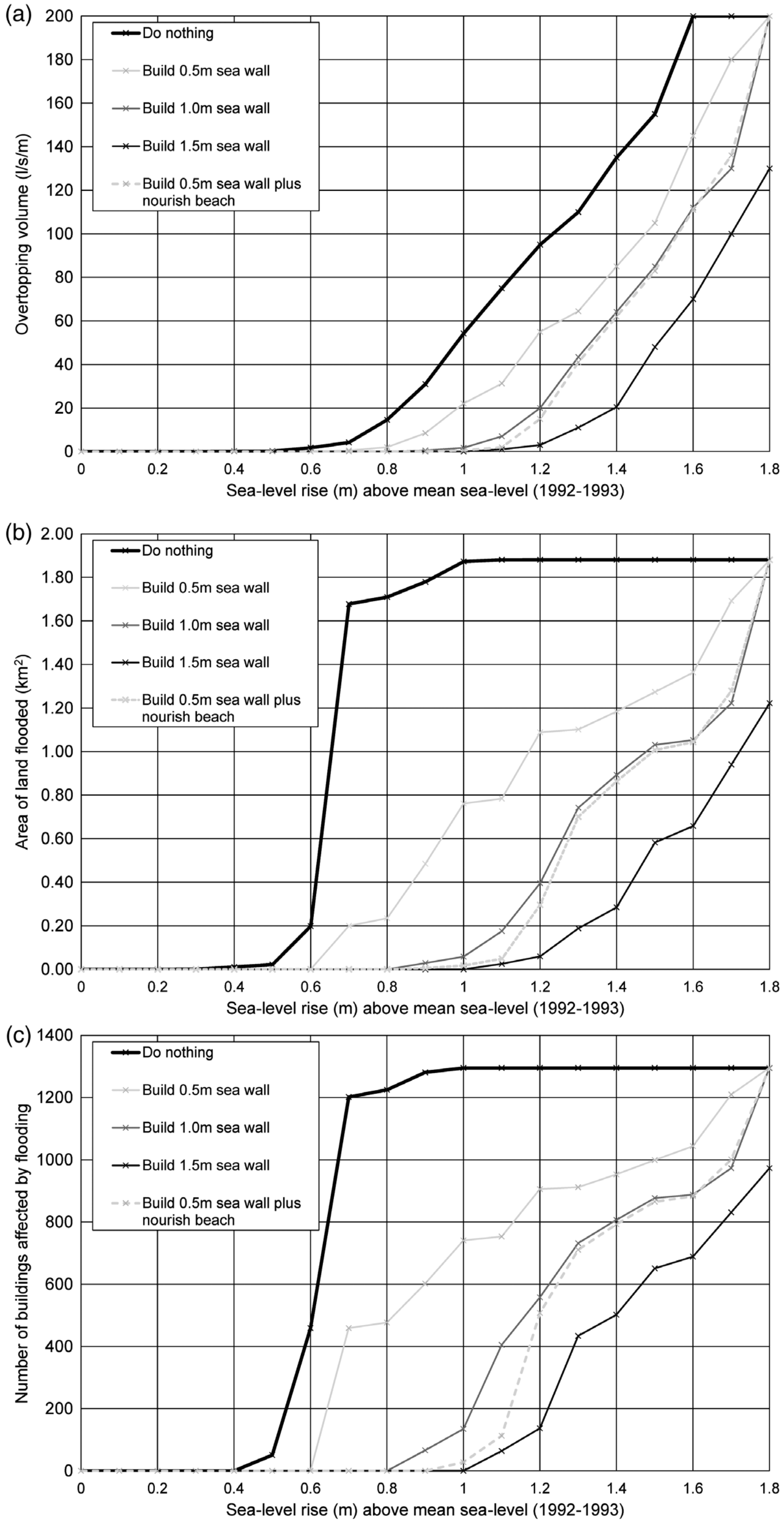

FIGURE 4 Flood extent on Hulhumalé for the baseline with sea-level rise scenario and with adaptation options (a) Overtopping volumes; (b) area affected by flooding; (c) number of properties affected

2.4 | Scenarios tested

Conditions tested are noted in Table 1. These included differing magnitudes of sea-level rise (up to 1.8 m in increments of 0.1 m), rates of reef growth with respect to sea-level rise (following Perry et al., 2018 as with fast rates of rise, reef growth may be able to keep up with sea-level rise), roughness (a default friction value of 0.01 and then increased to take account of actual conditions), and types of protection (through beach nourishment and sea walls).

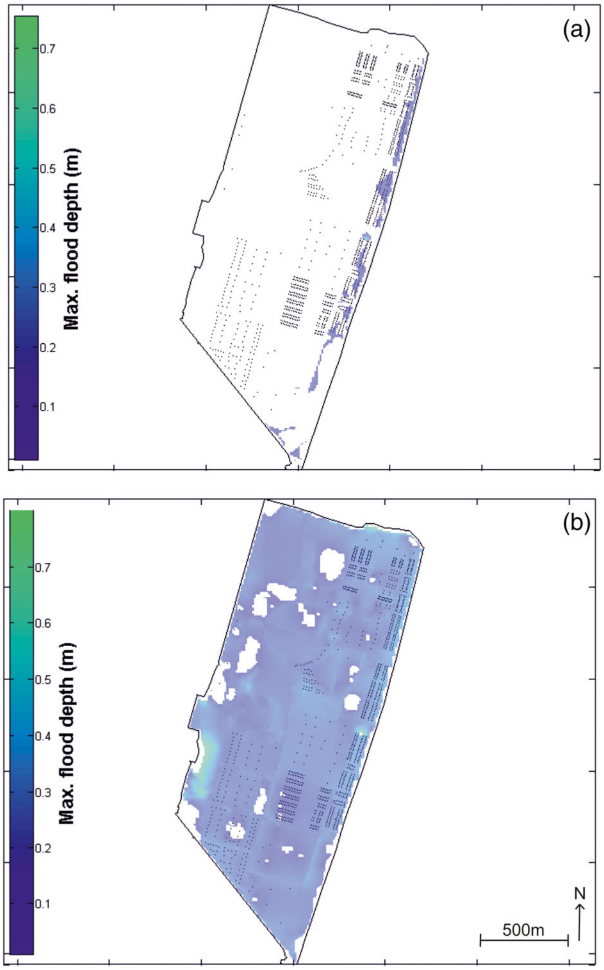

FIGURE 5 Flooding on Hulhumalé associated with sea-level rise and wave conditions of the extreme swell wave event of May 2007. Examples of flooding extent with baseline conditions with approximately (a) 0.6 m; and (b) 0.9 m of sea-level rise

TABLE 1 Adaptation and sensitivity scenarios tested for future flooding in Hulhumalé

Scenario name	Conditions tested: With reef growth	Standard bed roughness	Adaptation assumptions
Baseline	No	Yes	No change
With adaptation	No	Yes	Seawall height increases by 0.5 m
	No	Yes	Seawall height increases by 1.0 m
	No	Yes	Seawall height increases by 1.5 m
	No	Yes	Seawall height increases by 1.5 m, plus beach nourishment
Sensitivity	With SLR	Yes	No change
	Half the rate of SLR	Yes	No change
	No	Increase in friction	No change
	No	Yes	Loss of beach material

Abbreviation: SLR, sea-level rise.

3 | IMPACTS

Firstly, the baseline scenario followed the procedure outlined in Section 2.3 considering today's conditions (Section 3.1). This was then repeated considering up to 1.8 m of sea-level rise above the 1992–1993 datum. Second, various adaptation scenarios were tested (Section 3.2). Thirdly, sensitivity tests were undertaken to consider uncertainty concerning bed roughness and reef growth (Section 3.3).

3.1 | Baseline

Under today's physiological and engineering conditions, with approximately 0.1 m of sea-level rise since the 1992–1993 datum, SWAB did not generate any overtopping, indicating that the present defences are sufficient (Figure 4a, solid black line). This agrees with observations during the design storm event of May 2007 (e.g., UN Office for the Coordination of Humanitarian Affairs, 2007). Thus Hulhumalé was built sufficiently high to withstand extreme events in the near term.

When considering the same conditions but with sea-level rise, SWAB predicts overtopping starts with approximately 0.6 m of sea-level rise (at around 2.0 L/s/m of water overtopping the eastern boundary). This overtopping leads to temporary flooding from extreme water level conditions only. Model runs from LISFLOOD indicate that limited overtopping occurs adjacent to the south-east shoreline to a mean depth of 0.1 m resulting in nuisance flooding (Figure 5a). The model projects that 50% of the island could be temporarily flooded with 0.65 m of sea-level rise (and approximately 4.0 L/s/m of water overtopping the eastern boundary), but flood depths remain below 0.2 m (Figure 4). The eastern side of the island is most severely affected as this is the modelled source of the waves. In practice, flooding may also occur in the eastern side of the island which is of similar elevation, but less exposed to long-period waves. When sea levels rise to 0.9 m, LISFLOOD-FP indicated flood depths increase to nearly 0.2 m, with the flood extent covering approximately 90% of the island and threatening over 1,200 buildings (Figures 4b,c and 5b). With 1 m of sea-level rise the entire island could be extensively flooded, with floods on average, greater than 0.2 m deep. If flooding was initiated on the western side of the island, an industrialised area, park land and open space would be projected to be affected rather than local apartments. As building is continuing on Hulhumalé, the number of assets exposed and potential affected will increase with time.

3.2 | Baseline with adaptation options

Around Malé, sea walls are an essential form of defence (Figure 2a), and similarly they could be used to defend Huhumalé against extreme events should sea levels rise to sufficiently threaten the island. In SWAB, sea wall heights of 0.5, 1, and 1.5 m were constructed on top of the present defences. No reef growth was assumed, and the standard bed roughness was maintained. The resulting flooding is shown in Figure 4 (solid grey lines). Initial overtopping at nuisance level (equating to 2.0 L/s/m of overtopping as shown in Figure 4a) is delayed by approximately 0.2 m (for the 0.5 m sea wall), 0.4 m (for the 1 m sea wall), and 0.6 m (for the 1.5 m sea wall) of sea-level rise. This is lower than the actual additional height of protection offered due to wave run-up and interaction at the sea wall. Thus, building a seawall delays the onset of flooding compared with the baseline scenario and can potentially buy significant time before other measures are required.

A further method to reduce overtopping is increasing beach volumes to encourage wave attenuation. A further hypothetical scenario assessed the benefits of 60,000 m^3 of beach nourishment above present day extreme water levels along the eastern coast in conjunction with a 0.5 m sea wall (Figure 4, dotted grey line). The volume and area of flooding had a similar effect to reducing the area flooded to a similar magnitude to a 1.0 m high sea wall. Thus nourishment is also an effective way to reduce risk, whilst increasing the aesthetic properties of the defence.

3.3 | Sensitivity tests and study limitations

These results present a first attempt to project flood risk on Hulhumalé, Maldives. However, due to data and resource limitations, there remain key uncertainties in the approach, so sensitivity tests were undertaken. With respect to the baseline scenario (Section 3.1), this included testing:

- Reef growth: This was assumed to keep pace with sea-level rise (e.g., following observations of Camoin et al., 1997 and for low rates of sea-level rise by Perry et al., 2018), and a scenario of half the rate of sea-level rise;
- Friction: Where an increased surface roughness was assumed impeding the propagation of the flood wave (where model input changed from 0.01 to 0.015). For instance, this could be because of vegetation or buildings;
- Erosion of beach material: Where the beach profile was flattened back to the coastal slope.

The outcomes are described in Table 2. These tests highlight the main sensitivities firstly being the presence of the beach and subsequently the slope around the foreshore, and secondly friction and reef growth. Due to the flatness of the island, the greatest relative sensitivities occur for the lower rates of sea-level rise. When these uncertainties were combined, it meant that flooding to a depth of 0.1 m may occur at 0.6 ± 0.2 m of sea-level rise.

Additional limitations were noted:

- Longshore variation in bathymetry on the eastern side. This has the potential to vary rates of overtopping, delaying overtopping by 0.3 m of sea-level rise. Visibly, bathymetry does vary longshore on the eastern side and around the island, but a lack of data meant that this could not be thoroughly tested. Hence a representative profile was used.
- Uncertainty in wave conditions. A finer resolution temporal data set would also provide a more precise record of events. To test this sensitivity on the baseline scenario, the significant wave height was increased from 2 to 3 m (which described conditions further south in the Maldives, as noted in Wadey et al., 2017). This resulted in extensive flooding of the whole island at 0.7 m of sea-level rise, 0.2 m lower than the baseline scenario. In the future more detailed wave modelling is recommended supported by the country's first wave buoy which was installed in 2015.
- Drainage and roughness. First-hand accounts of flooding due to swell waves on other islands indicates that flood waters did not cover whole islands. For example, at GDh. Fiyoari (in the southern Maldives), flood waters travelled up to 61 m (200 ft) inland. Eye witness accounts suggested the water level was 0.6 m (2 ft) above normal land levels (National Disaster Management Centre,

TABLE 2 Sensitivities tested in the overtopping model

Sensitivity parameter	Variation	Magnitude of variation of overtopping volume
Reef growth	Same rate of sea-level rise	Decreased by ~5%
	Half the rate of sea-level rise	Decreased by ~15%
Friction	Rougher	Decreased by ~10%
Beach material	Loss of original beach material	Increased 1.5–1.8 times

2007). Thus, on Hulhumalé it is unlikely that the entire island will flood, even under the most extreme conditions. Drainage into the soil is one factor that may reduce flooding.

4 | CAN LAND RAISING BE A SOLUTION TO RISING SEA LEVELS?

4.1 | Land raising on Hulhumalé

One baseline scenario and four adaptation scenarios, under future sea-level rise have been analysed for potential flooding conditions for Hulhumalé. Results indicate nuisance flooding under swell wave conditions (from May 2007) that occur roughly once every 20 years (Wadey et al., 2017) to a mean depth of 0.1 m (but up to 0.2 m), could result with 0.6 ± 0.2 m sea-level rise. After 0.6 m of sea-level rise, flooding under swell conditions could become much more extensive and deeper.

The timing of impacts have been synthesised in Figure 6 by analysing the outputs described in Section 3 with climate change scenarios from Goodwin, Brown, Haigh, Nicholls, and Matter (2018) which align with the Paris Agreement (United Nations, 2015). About 0.6 m of sea-level rise is projected to occur in 2155 (2095–2300 for the 5th to 95th percentile of uncertainty) for a 1.5°C mitigation scenario, 2130 (2090–2230) for a 2.0°C mitigation scenario, and 2090 (2070–2110) for RCP8.5. This indicates that to avoid flooding under the extreme conditions considered in this analysis, adaptation could be required before the end of the century. A 1.8-m rise in sea-level could totally submerge the island during a swell event unless protection is provided, similar to the defences seen in Malé today (as shown in Figure 2a). This level is not projected by 2300 for the 1.5°C scenario (95th percentile), but is projected in 2280 for the 2°C scenario (95th percentile). For RCP8.5, a 1.8-m rise in sea-level is projected at around 2160 (2130–2215).

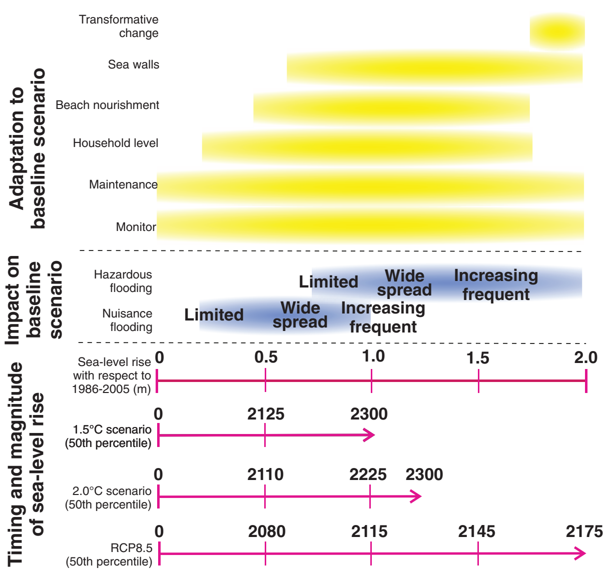

FIGURE 6 Magnitude of timing of sea-level rise, impacts, and adaptation on the baseline scenario with sea-level rise on Hulhumalé

Land raising (include claiming land when raised from the sea bed) for new development is also economically viable. For example, from informal and formal interviews and local data (e.g., Hulhulmalé Development Corporation, 2017; Ministry of Environment and Energy, 2015) in Hulhumalé (Phase 1), Bisaro, de Bel, Hinkel, Kok, and Bouwer (2019) indicated total investment costs for Phase 1 (i.e., since the start of construction, the reclamation and associated infrastructure, such as water and sanitations systems, but not the cost of building residential blocks) of US$32 million. These costs include dredging, where sand costs approximately US $8/m^3 cubic meter for Phase I. In contrast, income revenue from housing (sale, lease, and taxes) for the government, can be hundreds of millions of dollars (e.g., long-term land lease of US$830 million and land acquisition fees of US$15 million from 2016 to 2025). Land raising of existing islands (or mainland areas) would be much more costly compared with new land raising as existing infrastructure (including that underground) would need to be refitted, or at least its renewal timed to when a building is renewed. However, to be effective large expanses of land would need raising, which could take decades or longer, unless it is strategically, logistically, and financially coordinated.

Hulhumalé is successful as it serves a dual purpose of serving an expanding population in a rapidly developing country, whilst adapting to sea-level rise. The relatively low additional sand volume costs with respect to its additional height (approximately 1 m) compared with other islands, are a worthwhile preventative investment in flooding compared with dikes which take up space, require maintenance, and have residual risk. Additionally, land raising is ascetically pleasing and allows direct access to the sea. Whilst future flood or adaptation costs on Hulhumalé are unknown, when building a new island (projected to last more than a century), it makes sense from an engineering perspective to make it resilient against known flood hazards. These risks may differ or throughout the lifetime of the island. Importantly, by addressing future flood risks now, problems are not stored up for the future. This provides confidence for the government, businesses and individuals living and working on Hulhumalé.

Land raising has provided one solution for sea-level rise on Hulhumalé, but this will still not withstand the highest rises in sea-level over time into a second century, particularly if rapid sea-level rise occurs. Thus additional forms of adaptation will become essential on Hulhumalé. These could form a series of possible approaches, such as monitor, warn and cope with the aftermath of a flood rather than protect (Figure 6). Another decision could be for household level protection only, such as flood gates or barriers on doors, to cope with nuisance flooding. Beach nourishment (in parallel with tourist need) and sea-walls would reduce flooding and potentially extend the design life of the island. Ultimately though with rising sea levels, more transformative approaches of further land raising would be required, despite the difficulties of raising a developed island.

Overall, land raising on Hulhumalé has been successful as it has allowed for a relatively smooth transition of urbanisation due to the proximity from one island to another. The 2018 bridge between Malé and Hulhumalé has enabled further transition, and aligns with the nation's ambitious development goals. This includes expansion of housing, improved living conditions and opportunities for growth from external income sources. Thus, socio-economically, land raising has been successful, and serves a dual purpose in adapting to sea-level rise and allowing development.

4.2 | Land raising in other islands

Land raising is not a new concept or approach but has been applied for very different reasons in Hulhumalé, compared with historical needs. Raising islands has been undertaken traditionally to help reduce exposure to flooding, such as Halligen islands, Wadden Sea, which contain small mounds on which dwellings were constructed (Grimm, Wöffler, Bachmann, & Schüttrumpf, 2012). Traditionally, land raising has been used for the creation of new land (e.g., for ports) or to protect against floods, such as in swampy conditions on waterfront cities in the United States (Colten, 2018a, 2018b), or more recently in east Asia for industrial or residential reasons (Martín-Antón, Negro, del Campo, López-Gutiérrez, & Esteban, 2016). However, the reasons for its use today have evolved. Islands are often land-poor, with flat land often required close to the coast for access or industrial reasons. As nations develop, land claim is increasingly common (e.g., Singapore, Mahé [Seychelles], Hong Kong [China]), but needs to be undertaken to a height sufficient enough to avoid flooding today and in the future. Land raising can been seen as a form of "attack" as if undertaken successfully and seaward of existing land, land claim can effectively act as a dike and offer protection for a much larger area. Claiming land or islands including aggregate extraction brings many challenges (UNEP, 2014), including environmental concerns, legal implications (as seen with new islands in the South China Sea), or aggregate resource constraints (as found with sand availability in Singapore). Additional concerns include pollution threats (e.g., if dredged material is used for reclamation without appropriate sampling and testing for contamination) or potential changes in natural erosion or accretion processes. Additionally, as experienced in the Maldives, if new land claim is at a higher elevation than the existing land, drainage of water may subsequently flood the older land. Where land is claimed but not raised high enough (e.g., Malé) flooding can still result. If land raising is to become a successful adaptation option, these implications need to be fully considered or where sensible, numerically modelled from the outset.

Raising existing islands where there is substantial infrastructure on is costly and logistically challenging. Land raising is most effective when a defined area is simultaneously raised, so that the entire area reduces flood risk. If single building plots are raised (such as when a building reaches the end of its life and is demolished), flood risk is only reduced for that one property. As seen in HafenCity, Hamburg, Germany, a different range of flood proofing (e.g., plinths, raised buildings, and raised streets) may be required as the whole area may not be able to raised simultaneously (HafenCity Hamburg GmbH, 2019). Demolishing buildings, and associated underground infrastructure (e.g., communication cables, sewage) before the end of their lives to raise an area, could lead to high costs. Hence it is more sensible to raise islands to a sufficient level today to sustain the island for centuries.

Land raising can be most successful, where there are win–win situations, which help to overcome this issue, such as demonstrated here with population pressure in Malé/Hulhumalé, or through the Maldivian Safer Islands programme, where islands have been selectively raised as a form of tsunami protection (Riyaz & Park, 2010) and development purposes (e.g., a harbour or water or sewage facilities have been added as it is cost-efficient to do so when there is a larger population base). Land reclamation and raising (to 2 m above the highest measured sea-level) of 3.3 km^2 of land in response to sea-level rise is also in the early stages of consideration on the Temaiku Bight, Kiribati (Jacobs, 2018). Similar to the Maldives, this development helps to simultaneously address issues such as development, urbanisation, water supply, as well as flood adaptation. In both these examples raising islands allows communities to be sustained in one location, which has significant cultural importance.

The design of land claim and raising creating islands raises questions of the appropriate height allowance over time. Ideally, all the factors that contribute to flood hazard (e.g., sea levels, waves, surges, tides) and exposure (e.g., land use, defences) need to be considered. A more probabilistic approach which analyses these uncertainties would be useful to inform future projects. This should also arguably consider a large allowance for sea-level rise—the larger the allowance, the longer no further action will be required. Guidance on the trade-offs in this decision need to better developed.

In natural environments, land raising such as through sediment dispersion is a proxy for natural sediment processes, and can provide benefits of changes to land use or agricultural uses. Thus raising islands, in a similar manner to raising land in non-island environments (e.g., due to subsidence or sediment starvation due to dike building), provides opportunities but ultimately needs time planning and investment, which can be particularly challenging for developing nations. Additionally consideration is required for the secondary effects of sea-level rise such as groundwater salinisation, which could limit the sustainability of islands.

5 | CONCLUSIONS

Sea-level rise threatens low-lying atoll nations such as the Maldives. This paper has taken a novel approach by assessing how claiming and raising land on one island, Hulhumalé, in response to land scarcity while adapting to sea-level rise has been beneficial in reducing long-term flood risk and aiding development. Based on a flood assessment of the artificial island of Hulhumalé, Maldives including the effects of sea-level rise, it is concluded that:

1. Land claim at an appropriate level provides multiple opportunities to reduce flood exposure in vulnerable locations.
2. Hulhumalé is built sufficiently high to be safe from flooding under present extreme still water level conditions, and with these conditions combined with wave events (based on an analysis from a design storm from past extensive floods). Limited flooding (<0.2 m flood depth) may occur on the eastern side of the island (the main overtopping area modelled) with 0.6 ± -0.2 m of sea-level rise, with the flood extent (and > 0.2 m flood depth) becoming more extensive with 0.9 ± 0.2 m of sea-level rise. This indicates that Hulhumalé is likely to be safe from flooding during the 21st century, as long as sea-level rise is less than 0.6 m.
3. As sea-level rise will continue for many centuries, further adaptation options would need to be sought to extend the life of the island. For greatest efficiency, this may involve assessing combinations of protection options.
4. Monitoring sea-level rise is important so that future adaptation is timed in an appropriate and effective manner.
5. To ensure the long-term survival of low-lying islands, adaptation may need to be radically different to today. Land claim and island raising offers the opportunity to save vulnerable islands and societies, but this requires forward planning as retrofitting land claim is logistically challenging and more costly. Consideration of other knock-on impacts, such as ground water salinisation is essential to ensure islands remain sustainable places to live.
6. Land claim also has the opportunity to support urbanisation and enhance cultural links between new and existing islands, thus aiding other development opportunities.

ACKNOWLEDGEMENTS

S.B., R.N., A.S., Z.K., J.H., and DL received funding from the European Union Seventh Framework Programme FP7/2007–2013 under grant agreement no. 282746 (IMPACT2C: Quantifying projected impacts under 2°C of warming). S.B., M.W., R.N., J.N., and D.L. received funding from the European Union Framework Programme through the grant of the budget of the Collaborative Project RISES-AM-, Contract ENV-2013-two-stage-603396. The authors are grateful to Land and Marine Environmental Resource Group (La Mer), Maldives for providing the bathymetry data used in this research, and to numerous students who helped in the early stages of the analysis of this data. Data for Figure 4 is located in the Appendix A4. Data for other figures is not publically available due to commercial sensitivities. Sea-level data was freely downloaded from the University of Hawaii Sea Level Centre (http://uhslc.soest.hawaii.edu/) and WaveWatch III data from the NOAA/National Weather Service National Centers for Environmental Prediction Environmental Modelling Center Marine Modelling and Analysis Branch (http://polar.ncep.noaa.gov/waves/download.shtml). We thank Sandy Bisaro for help on land claim valuation. S.B. helped design the study, led the work, wrote the paper, and analysed the data. M.W. undertook the modelling and data analysis, assisted by M.M. M.W. and M.M. helped write the Appendix, with M.W. writing parts and creating figures of the manuscript taken from earlier project reports. R.N. helped design and co-ordinate the study. A.S. and Z.K. set up the research problem, collated/commissioned the data and led the fieldwork. R.N., J.H., and D.L. helped with the study analysis and fieldwork. All authors commented on the manuscript text.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

New data generated is available in the appendix. Table A1 provides data for Figure 4. Data for other figures is not available due to data sensitivity and/or commercial issues.

ORCID

Sally Brown https://orcid.org/0000-0003-1185-1962

REFERENCES

Barnett, J., & Adger, W. N. (2003). Climate dangers and atoll countries. *Climatic Change*, *61*, 321–337.

Bates, P., Trigg, M., Neal, J., Dabrowa, A. (2013). LISFLOOD-FP. Code release 5.9.6 (online). Retrieved from https://www.bristol.ac.uk/media-library/sites/geography/migrated/documents/lisflood-manual-v5.9.6.pdf.

Bates, P. D., Dawson, R. J., Hall, J. W., Horritt, M. S., Nicholls, R. J., Wicks, J., & Hassan, M. A. A. M. (2005). Simplified two-dimensional numerical modelling of coastal flooding and example applications. *Coastal Engineering*, *52*(9), 793–810.

Bates, P. D., Horritt, M. S., & Fewtrell, T. J. (2010). A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology*, *387*, 33–45.

Betzold, C., & Mohamed, I. (2017). Seawalls as a response to coastal erosion and flooding: A case study from Grande Comore, Comoros. *Regional Environmental Change*, *17*, 1077–1087.

Bisaro, A., de Bel, M., Hinkel, J., Kok, S., & Bouwer, L. (2019). Leveraging public adaptation finance through urban land reclamation: Cases from Germany, The Netherlands and the Maldives. *Climatic Change*. https://doi.org/10.1007/s10584-019-02507-5

Camoin, G., Colonna, M., Montaggioni, L., Casanova, J., Faure, G., & Thomassin, B. (1997). Holocene sea level changes and reef development in the southwestern Indian Ocean. *Coral Reefs*, *16*, 247–259.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., … Unnikrishnan, A. S. (2013). Sea level change. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), *Climate change 2013: The physical science basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1137–1216). Cambridge and New York, NY: Cambridge University Press.

Church, J. A., White, N. J., & Hunter, J. R. (2006). Sea-level rise at tropical Pacific and Indian Ocean islands. *Global and Planetary Change*, *53*, 155–168.

Colten, C. E. (2018a). Raising urban land: Historical perspectives on adaptation. In J. Day & J. Erdman (Eds.), *Mississippi delta restoration. Estuaries of the world* (pp. 135–142). Cham: Springer.

Colten, C. E. (2018b). Raising New Orleans: Historical analogs and future environmental risks. *Environmental History*, *23*(1), 135–142.

Duvat, V. (2018). A global assessment of atoll Island planform changes over the past decades. *WIREs Climate Change*, *10*, e557.

Giardino, A., Nederhoff, K., & Vousdoukas, M. (2018). Coastal hazard risk assessment for small islands: Assessing the impact of climate change and disaster reduction measures on Ebeye (Marshall Islands). *Regional Environmental Change*, *18*(8), 2237–2248.

Goodwin, P., Brown, S., Haigh, I. D., Nicholls, R. J., & Matter, J. M. (2018). Adjusting mitigation pathways to stabilize climate at 1.5°C and 2.0°C rise in global temperatures to year 2300. *Earth's Future*, *6*(41), 601–615.

Grimm, C., Wöffler, T., Bachmann, D., & Schüttrumpf, H. (2012). Risk management in coastal engineering: Applied coastal research projects for northern Germany, *14*, 53–55.

HafenCity Hamburg GmbH (2019). *Flood-secure bases instead of dikes: Safe from high water in HafenCity*. Retrieved from https://www.hafencity.com/en/concepts/flood-secure-bases-instead-of-dikes-safe-from-high-water-in-hafencity.html.

Harangozo, S. A. (1992). Flooding in the Maldives and its implications for the global sea level rise debate. In P. L. Woodworth, D. T. Pugh, J. G. DeRonde, R. G. Warrick, & J. Hannah (Eds.), *Sea level changes: Determination and effects Geophysical Monograph* (Vol. 69, pp. 95–99). Washington, DC: American Geophysical Union.

Hinkel, J., Aerts, J. C. J. H., Brown, S., Jiménez, J. A., Lincke, D., Nicholls, R. J., … Appeaning Addo, K. (2018). The ability of societies to adapt to twenty-first-century sea-level rise. *Nature Climate Change*, *8*, 570–578.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., … Zhou, G. (2018). Impacts of 1.5°C of global warming on natural and human systems. In V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al. (Eds.), *Global warming of 1.5°C*. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Chapter3_Low_Res.pdf.

Hoeke, R. K., McInnes, K. L., Kruger, J. C., McNaught, R. J., Hunter, J. R., & Smithers, S. G. (2013). Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change*, *108*, 128–138.

Holden, J. (2008). *Physical geography and the environment* (2nd ed.). Harlow: Prentice Hall.

Hulhumalé Development Corporation (2016). *About Hulhumalé*. Retrieved from https://hdc.com.mv/hulhumale/.

Hulhumalé Development Corporation. (2017). *Invest in Hulhumale. Maldives housing development Corporation*. Hulhumalé, Maldives: Maldives Housing Development Corporation.

Jacobs (2018). *Jacobs presents sea level rise strategy at United Nations climate change conference*. Retrieved from https://www.jacobs.com/news/106/jacobs-presents-sea-level-rise-strategy-at-united-nations-climate-change-conference.

Jevrejeva, S., Grinsted, A., & Moore, J. C. (2014). Upper limit for sea level projections by 2100. *Environmental Research Letters*, 9, *104008*. https://doi.org/10.1088/1748-9326/9/10/104008

Kaspersen, P. S., & Halsnæs, K. (2017). Integrated climate change risk assessment: A practical application for urban flooding during extreme precipitation. *Climate Services*, *6*, 55–64.

Kench, P. S., Thompson, D., Ford, M. R., Ogawa, H., & McLean, M. F. (2015). Coral islands defy sea-level rise over the past century: Records from a Central Pacific atoll. *Geology*, *43*(6), 515–518.

Kennedy, A. B., Chen, Q., Kirby, J. T., & Dalrymple, R. A. (2000). Boussinesq modelling of wave transformation, breaking and runup. I: 1D. *Journal of Waterway Port Coastal and Ocean Engineering*, *126*(1), 39–47.

Khan, T. M. A., Quadir, D. A., Murty, T. S., Kabir, A., Aktar, F., & Sarker, M. A. (2002). Relative sea level changes in Maldives and vulnerability of land due to abnormal coastal inundation. *Marine Geodesy*, *25*, 133–143.

Larsen, J., & Dancy, H. (1983). Open boundaries in short wave simulations - a new approach. *Coastal Engineering*, *7*, 285–297.

Madsen, P. A., & Sorensen, O. R. (1992). A new form of the Boussinesq equations with improved linear dispersion characteristics. Part 2. A slowly varying bathymetry. *Coastal Engineering*, *18*, 183–204.

Martín-Antón, M., Negro, V., del Campo, J. M., López-Gutiérrez, J. S., & Esteban, M. D. (2016). Review of coastal land reclamation situation in the world. *Journal of Coastal Research, SI*, *75*, 667–671.

McCabe, M. (2011). *Modelling nearshore waves, runup and overtopping*. (PhD thesis). University of Manchester, UK.

McCabe, M., Stansby, P. K., & Apsley, D. D. (2011). Coupled wave action and shallow-water modelling for random wave runup on a slope. *Journal of Hydraulic Research*, *49*(4), 515–522.

McCabe, M. V., Stansby, P. K., & Apsley, D. D. (2013). Random wave runup and overtopping a steep sea wall: Shallow-water and Boussinesq modelling with generalised breaking and wall impact algorithms validated against laboratory and field measurements. *Coastal Engineering*, *74*, 33–49.

Ministry of Environment and Energy. (2015). *Guidance manual for climate risk resilient coastal protection in the Maldives*. Malé: Maldives Ministry of Environment and Energy, UNDP, GEF.

Munk, W. H., Miller, G., Snodgrass, F., & Barber, N. (1963). Directional recording of swell from distant storms. *Philosophical Transactions of the Royal Society of London. Series A*, *255*, 505–584.

National Disaster Management Centre (2007). *Joint rapid assessment report on sea swell affected areas conducted by the Government of the Maldives, UN and IFRC – 19th May 2007*. National Disaster Management Centre: Republic of the Maldives. Retrieved from http://reliefweb.int/sites/reliefweb.int/files/resources/4BD33F2621419994C12572E5004D7DFE-Full_Report.pdf.

Naylor, A. K. (2015). Island morphology, reef resources, and development paths in the Maldives. *Progress in Physical Geography*, *39*(6), 728–749. https://doi.org/10.1177/0309133315598269

Nicholls, R. J. (2018). Adapting to sea-level rise. In Z. Zommers & K. Alverson (Eds.), *Resilience: The science of adaptation to climate change* (pp. 13–29). Oxford: Elsevier.

Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science*, *328*, 1517–1520.

Nicholls, R. J., Wong, P. P., Burkett, V. R., Codignotto, J. O., Hay, J. E., Mclean, R. F., … Woodroffe, C. D. (2007). Coastal systems and low-lying areas. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 315–356). Cambridge: Cambridge University Press.

NOAA/National Weather Service National Centers for Environmental Prediction (2014). *Environmental modeling center marine modeling and analysis branch [online]*. Retrieved from http://polar.ncep.noaa.gov/waves/download.shtm.

Nurse, L., McLean, R., Agard, J., Briguglio, L., Duvat, V., Pelesikoti, N., … Webb, A. (2014). Small islands. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, et al. (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Contribution of working group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1613–1654). Cambridge and New York, NY: Cambridge University Press.

Penning-Rowsell, E. (2015). A realistic assessment of fluvial and coastal flood risk in England and Wales. *Transactions of the Institute of British Geographers*, *40*, 44–61.

Penning-Rowsell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J., … Fernandez-Bilbao, A. (2005). *The benefits of flood and coastal risk management: A manual of assessment techniques*. London: Middlesex University Press.

Pernetta, J. C. (1991). Cities on oceanic islands: A case study of male, capital of the republic of the Maldives. In R. Frassetto (Ed.), *Impact of sea level rise on cities and regions. Proceedings of the first international meeting 'cities on water', Marcilio, Venice, December 11-13, 1989*.

Perry, C. T., Alvarez-Filip, L., Graham, A. J., Mumby, P. J., Wilson, S. K., Kench, P. S., … Macdonald, C. (2018). Loss of coral reef growth capacity to track future increases in sea level. *Nature*, *558*, 396–400.

Riyaz, M., & Park, K.-H. (2010). "Safer Island concept" developed after the 2004 Indian Ocean tsunami: A case study of the Maldives. *Journal of Earthquake and Tsunami*, *4*(2), 135–143.

Sovacool, B. K. (2012). Perceptions of climate change risks and resilient Island planning in the Maldives. *Mitigation and Adaptation Strategies for Global Change*, *17*, 731–752.

Speelman, L. H. (2015). *Empirical analyses of migration in small islands: The role of environmental and social factors*. (PhD thesis). University of Southampton, UK.

Stansby, P., Chini, N., Apsley, D., Borthwick, A., Bricheno, L., Horrillo-Caraballo, J., … Yan, K. (2013). An integrated model system for coastal flood prediction with a case history for Walcott, UK, on 9th November 2007. *Journal of Flood Risk Management*, *6*(3), 229–252.

Storlazzi, C., Gingerich, S. B., van Dongeren, A. P., Cheriton, O. M., Swarzenski, P. W., Quatatert, E., … McCall, R. (2018). Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, *4*(4), EAAP9741.

Tolman, H.L., (2009). User manual and system documentation of WAVEWATCH III TM version 3.14. Technical note, MMAB Contribution, **276**. http://nopp.ncep.noaa.gov/mmab/papers/tn276/MMAB_276.pdf.

UHSLC. (2015). *Data, products, and software*. Honolulu, Hawaii: University of Hawaii Sea Level Center. http://uhslc.soest.hawaii.edu/

UN Office for the Coordination of Humanitarian Affairs. (2007). *Coastal flooding OCHA situation report no. 3 [online]*. Maldives: UN Office for the Coordination of Humanitarian Affairs.

UNEP (2014). *Sand, rarer than one thinks*. UNEP Global Environmental Alert Service. Retrieved from https://www.srf.ch/content/download/5093676/69243700/version/2/file/UN_Sand_Mining.pdf

United Nations. (2015). *Adoption of the Paris Agreement*. United Nations Framework Convention on Climate Change [online].

Wadey, M., Brown, S., Nicholls, R. J., & Haigh, I. (2017). Coastal flooding in the Maldives: An assessment of historic events and their implications. *Natural Hazards*, *89*(1), 131–159.

Warrick, R. A., Le Provost, C., Meier, M. F., Oerlemans, J., & Woodworth, P. L. (1996). Changes in sea level. In *Climate change 1995. The science of climate change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 359–405). Cambridge: Cambridge University Press.

Wong, P., Losada, I., Gattuso, J., Hinkel, J., Khattabi, A., McInnes, K., … Sallenger, A. (2014). Coastal systems and low-lying areas. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, et al. (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 361–409). Cambridge and New York, NY: Cambridge University Press.

Woodworth, P. L. (2005). Have there been large recent sea-level changes in the Maldive Islands? *Global and Planetary Change*, *49*(1), 1–18.

Yoon, S. B., & Choi, J. W. (2001). A note on extension of fully dispersive weakly nonlinear wave equations for rapidly varying topography. *Coastal Engineering Journal*, *43*(3), 143–160.

Zhou, Q., Mikkelsen, P. S., Halsnæs, K., & Arnbjerg-Nielsen, K. (2012). Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *Journal of Hydrology*, *414-415*, 539–549.

How to cite this article: Brown S, Wadey MP, Nicholls RJ, et al. Land raising as a solution to sea-level rise: An analysis of coastal flooding on an artificial island in the Maldives. *J Flood Risk Management*. 2020;13 (Suppl. 1):e12567. https://doi.org/10.1111/jfr3.12567

APPENDIX

A1. OVERTOPPING MODEL

Figure A1 indicates a typical bathymetric profile for Hulhumalé. The focus on this study has been on the eastern side of the island where the overtopping modelling took place as this part of the island is most exposed to the open ocean and long-period waves which may induce flooding. The text in red in Figure A1 indicates the different future conditions tested according to the magnitude of sea-level rise and adaptation conditions (see Appendix A2)

Significant wave height, period, duration of design storm, still water, and extreme water level conditions (as described in Wadey et al., 2017) were extracted from data sources as described in Section 2.2. These were input, along with bathymetry data into a semi-implicit shallow-water and Boussinesq (SWAB) numerical model (McCabe, 2011; McCabe et al., 2013; Stansby et al., 2013). A typical profile of the SWAB model is shown in Figure A2.

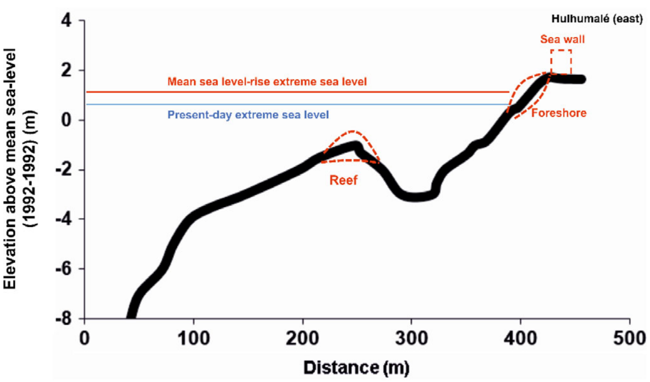

FIGURE A1 Typical bathymetry on the eastern shore of Hulhumale

SWAB uses a Boussinesq modelling approach allowing for the breaking of a wave and its propagation over the surf zone, and the lagoon area where the water is deeper than the immediate reef edge. It simulates nearshore waves, run-up, and overtopping. SWAB has previously been used and tested against field data and wave flume tests for sites in the United Kingdom (McCabe et al., 2013). Overtopping comparisons have been in the "bounds of accuracy" of what might be expected, given the inherit uncertainty of datasets used.

To determine the volume of overtopping per metre run, SWAB solves the continuity equation (Equation (A1.1)) and momentum equation (Equation (A1.2)) of Madsen and Sorensen (1992):

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}=0. \tag{A1.1}$$

$$\begin{aligned}\frac{\partial (hu)}{\partial t}+\frac{\partial \left(hu^2\right)}{\partial x} &= -\mathrm{gh}\frac{\partial h}{\partial x}-\mathrm{gh}\frac{\partial z_b}{\partial x}-\frac{\tau_b}{\rho} \\ &+\left\{\left(B+\frac{1}{3}\right)d^2\left(\frac{\partial^3 (hu)}{\partial x^2 \partial t}\right)+Bgd^3\frac{\partial^3 \eta}{\partial x^3}\right. \\ &\left.+d\frac{\partial d}{\partial x}\left(\frac{1}{3}\frac{\partial^2 (hu)}{\partial x \partial t}+2Bgd\frac{\partial^2 \eta}{\partial x^2}\right)\right\}_{pre-break} \\ &+\left\{\frac{\partial}{\partial x}\left(h(\nu+\nu_e)\frac{\partial u}{\partial x}\right)\right\}_{post-break.}\end{aligned} \tag{A1.2}$$

where: B = constant that controls the linear dispersion characteristics; d = still-water depth (m); g = gravitation acceleration (m/s); h = water depth (m); t = time (s); u = horizontal depth-averaged velocity, in the x-direction (m/s); ν = kinematic viscosity of water (m^2/s); ν_e = wave breaking eddy viscosity (m^2/s); x = location in profile or grid domain (m); z_b = bed level above datum level (m); η = Free surface level above datum level (m); ρ = water density (kg/m^3); τ_b = bed shear stress (N/m^2).

The Boussinesq terms are the pre-breaking part on the second line of Equation (A1.2). Madsen and Sorensen (1992) determined that a value of B = 1/15 gives the best linear dispersion characteristics. The breaking of waves is expected to occur when the wave height to water depth ratio exceeds 0.6 (McCabe, 2011; McCabe et al., 2013). In the surf zone, the pre-breaking Boussinesq terms are set to zero giving the nonlinear shallow-water equations. A post-breaking horizontal diffusion term is also applied (the third line of Equation (A1.2)), similar to the method in Kennedy, Chen, Kirby, and Dalrymple (2000).

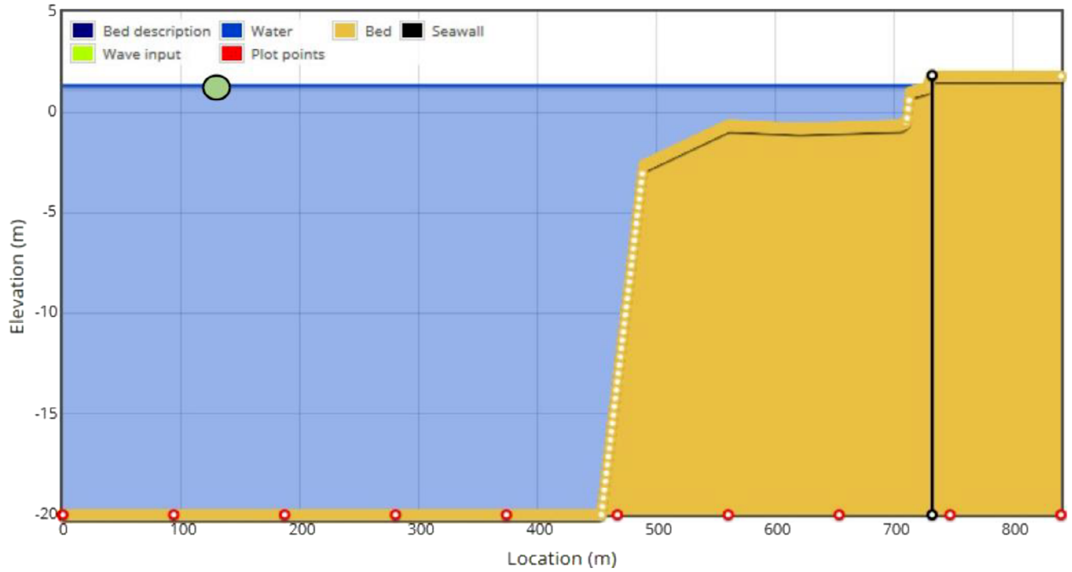

FIGURE A2 Example of the profile and user interface of the SWAB model. The bed along the x-axis is flattened at 450 m for modelling purposes only. The elevation on the y-axis represents the datum above mean sea level (1992–1993). The black vertical line represents the location of the sea wall

The nonlinear shallow water equations do not take account of the impact force imposed by a sea wall when a jet (or wave) of water impacts against a wall in the x-direction. If a jet of water with velocity u_{jet} is reflected backwards at the same speed (possible with a recurve wall) then the force imposed by the wall on the water, F_{wall}:

$$F_{\text{wall}} = 2\rho A u_{jet}^2. \quad \text{(A1.3)}$$

where: A = Cross-sectional area of the jet of water (m^2) F_{wall} = Force imposed by the wall on the water (N); u_{jet} = Water velocity in the horizontal direction (m/s); ρ = water density (kg/m^3).

In reality, when a wave impacts against a seawall, the flow is directed upwards as well as seawards and the following term is applied to the momentum Equation (A1.2), at cell i, located at the wall:

$$F_{wall,i} = \frac{k_{wall} h_{F,i} u_i^2.}{\Delta x} \quad \text{(A1.4)}$$

where: $F_{\text{wall},i}$ = force per water density per unit bed area, imposed on the flow (m^2/s^2); i = cell, as represented in the model; k_{wall} = empirical constant; $h_{F,i}$ = water depth in front of the wall (but less than the height of the wall itself) (m); u_i = horizontal water velocity impacting the wall (m/s); Δx= cell size (m).

The value of k_{wall} is likely to be a function of the profile of the wall, although $k_{\text{wall}} = 0$ when the flow is directed seawards (i.e., away from the wall). McCabe et al. (2013) found $k_{\text{wall}} = 1.0$ gave good overtopping volumes for a particular recurve wall, and this value was used for this study.

The SWAB model solves these equations using a one-dimensional semi-implicit finite-volume method. Input waves are applied within the model domain, using a method similar to that of Larsen and Dancy (1983). Reflected waves are absorbed by a sponge layer, using the method of Yoon and Choi (2001). Further details on the SWAB solver are provided by McCabe et al. (2013).

The model has various options for incident wave type including the generation of random waves with a JONSWAP spectrum (McCabe, 2011). This ensures at least one wavelength is provided for the offshore sponge layer, and waves are non-breaking at the wave input location. The wave depth to wavelength ratio at the input location is in the range of 600 m offshore, which is acceptable for the model equations. An onshore collection tank for overtopping water is also provided, so that it was assumed that water does not drain back into the sea. To some extent this is realistic of actual conditions given the flatness of Hulhumalé.

The model provides overtopping volumes as a time series of overtopping volumes: the cumulative volume of water passing over the seawall. This is based on the flow passing over the wall. Figure A3 illustrates an overtopping run using SWAB.

A2. FLOOD SPREAD MODEL

To translate the one-dimensional SWAB outputs (which were used to generate an overtopping volume time series) to two-dimenstional simulations of flooding, an inundation model, LISFLOOD-FP (Bates et al., 2010), was used. LISFLOOD-FP utilises raster "storage cells" where each grid cell represents the local topography. For each flood

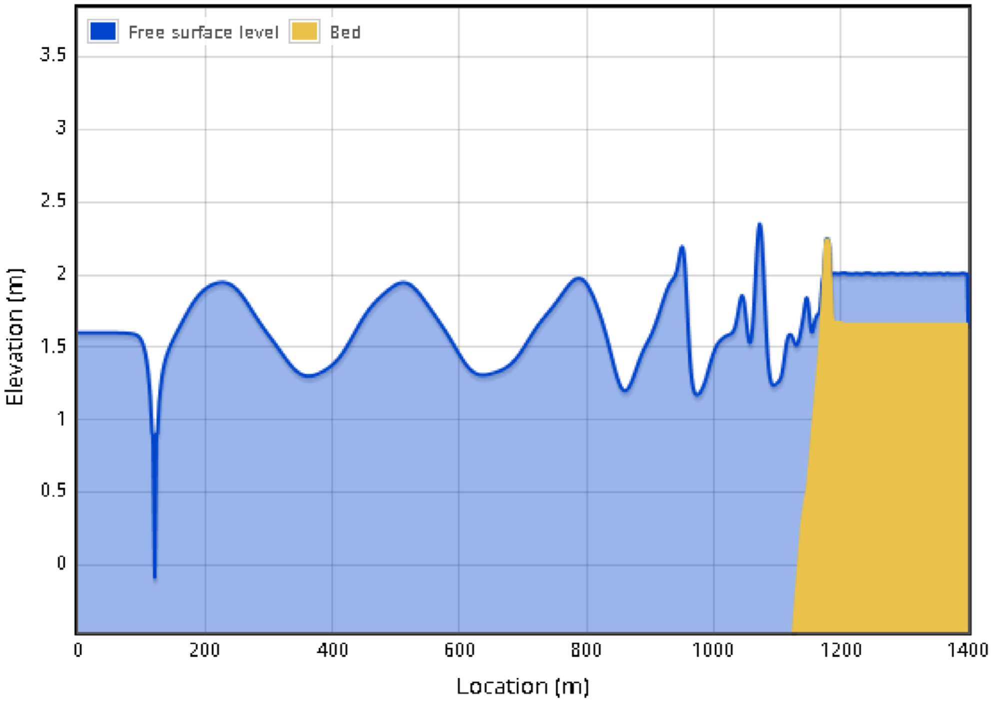

FIGURE A3 An example of wave generation and overtopping during a typically SWAB run

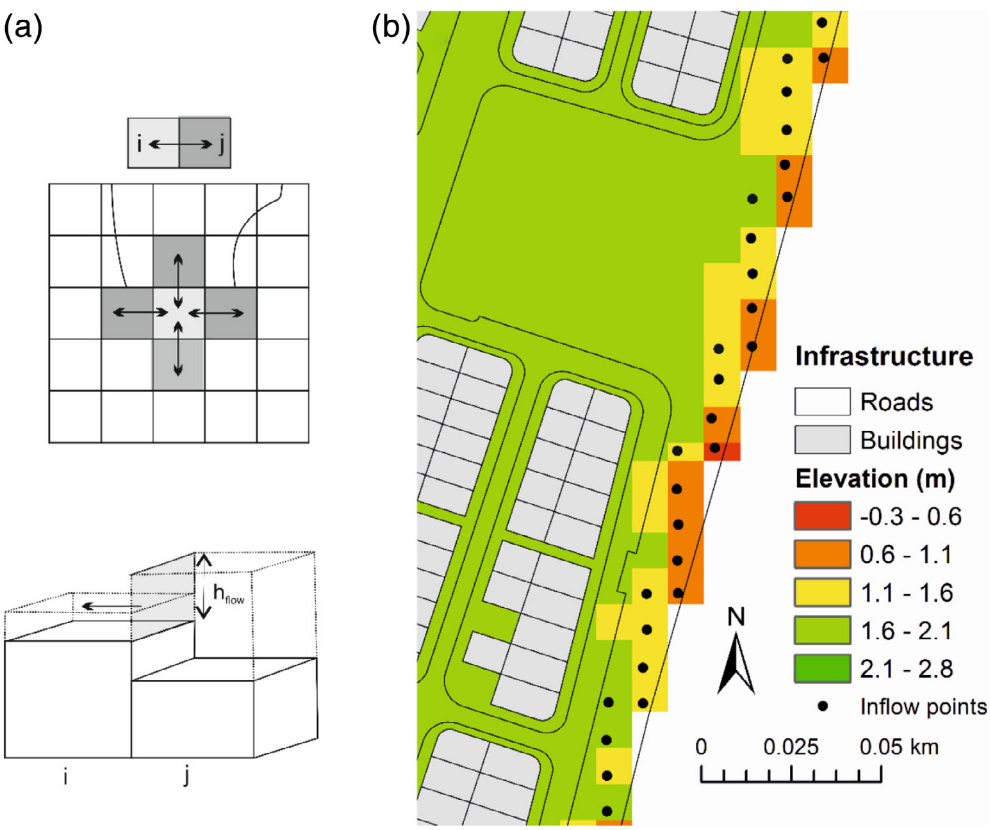

FIGURE A4 Representation of flow due to overtopping using LISFLOOD-FP. (a) Flow between raster cells where the flow depth (h_{flow}) represents the depth through which water can flow between two cells (i, j) and is defined as the difference between the highest water free surface in the two cells and the highest bed elevation (adapted from Bates et al., 2005). (b) Example of boundary inflow points on Hulhumalé

simulation, this was represented by the overtopping volume per cell representing an input into each storage cell at the seaward boundary of the model's digital elevation model (DEM) (known as "inflow points" which are located along the eastern defences on Hulhumalé). When storage cells are full, they flow into adjacent storage cells (Figure A4a). In the Hulhumalé DEM, flood cells are located 10 m apart (Figure A4b). The flow depth (h_{flow}) represents the depth

TABLE A1 Data used to produce Figure 4 indicating the flood extent on Hulhumalé with sea-level rise and different adaptation strategies

	Do nothing			Build 0.5 m sea wall			Build 1.0 m sea wall			Build 1.5 m sea wall			Build 0.5 m sea wall plus nourish beach		
SLR (m)	Volume ($L\ s^{-1}\ m^{-1}$)	Area (km^2)	No. of bdgs	Volume ($L\ s^{-1}\ m^{-1}$)	Area (km^2)	No. of bdgs	Volume ($L\ s^{-1}\ m^{-1}$)	Area (km^2)	No. of bdgs	Volume ($L\ s^{-1}\ m^{-1}$)	Area (km^2)	No. of bdgs	Volume ($L\ s^{-1}\ m^{-1}$)	Area (km^2)	No. of bdgs
0	0	0.0	0	0	0.0	0	0	0.0	0	0	0	0	0	0	0
0.1	0	0.0	0	0	0.0	0	0	0.0	0	0	0	0	0	0	0
0.2	0	0.0	0	0	0.0	0	0	0.0	0	0	0	0	0	0	0
0.3	0	0.0	0	0	0.0	0	0	0.0	0	0	0	0	0	0	0
0.4	0	0.0	0	0	0.0	0	0	0.0	0	0	0	0	0	0	0
0.5	0	0.0	51	0	0.0	0	0	0.0	0	0	0	0	0	0	0
0.6	1.8	0.0	459	0.0	0.0	0	0	0.0	0	0	0	0	0	0	0
0.7	4.2	0.2	1,202	0.5	0.0	459	0	0.0	0	0	0	0	0	0	0
0.8	14.6	0.2	1,225	2.0	0.0	477	0	0.0	0	0	0	0	0	0	0
0.9	31.0	0.5	1,281	8.4	0.0	602	1	0.0	66	0	0	0	0.1	0	0
1	54.2	0.8	1,295	22.0	0.1	741	2	0.0	135	0	0	0	0.5	0	28
1.1	75.0	0.8	1,295	31.3	0.2	753	7	0.0	405	1.0	0.0	64	2.0	0	113
1.2	95.0	1.1	1,295	55.0	0.4	906	20	0.1	558	3.0	0.1	137	15.0	0.3	508
1.3	110.0	1.1	1,295	64.4	0.7	912	43	0.2	732	11.0	0.2	434	41.0	0.7	711
1.4	135.0	1.2	1,295	85.0	0.9	953	64	0.3	807	20.5	0.3	502	62.0	0.9	793
1.5	155.0	1.3	1,295	105.0	1.0	999	85	0.6	877	48.0	0.6	651	83.0	1.0	865
1.6	200.0	1.4	1,295	145.0	1.1	1,044	112	0.7	888	70.0	0.7	689	111.0	1.0	883
1.7	200.0	1.7	1,295	180.0	1.2	1,210	130	0.9	973	100.0	0.9	831	136.0	1.3	1,001
1.8	200.0	1.9	1,295	200.0	1.9	1,296	200	1.2	1,296	130.0	1.2	973	200.0	1.9	1,296

Abbreviation: SLR, sea-level rise.

through which water can flow between two cells, and is defined as the difference between the highest water free surface in the two cells and the highest bed elevation.

When a cell is flooded, water is spread to the adjacent cells by solving a continuity and momentum equation (Equation (A2.1)) in two directions:

$$q_{t+\Delta t} = \frac{q_t - gh_t\Delta t\frac{\partial(h_t+z)}{\partial x}}{\left(1+gh_t\Delta t n^2 q_t/h_t^{10/3}\right)}. \tag{A2.1}$$

where: g = gravity (m/s); h_t = water depth at time, t (m); n = Manning's friction coefficient; q_t = flow per unit width at time, t (m^3/s); t = time (s); x = location in profile or grid domain (m); z = bed elevation (m); Δt = model time step (s).

Water depths were updated at each time step. As explained by Bates, Trigg, Neal, and Dabrowa (2013), there is an adaptive time step option in LISFLOOD-FP to aid stability, which is related to cell size and water depth, as specified in Equation (A2.2). Resultantly the time step used by the solver varies throughout simulations (in the Hulhumalé case study, the time step was predominantly around 1 s, and reducing to near 0.5 s for the higher overtopping simulations). The stability criterion is given by the Courant–Freidrichs–Levy condition for shallow water flows such that the stable model time step, Δt, is a function of the grid resolution and the maximum water depth within the domain:

$$\Delta t_{max} = \alpha\frac{\Delta x}{\sqrt{gh_t}} \tag{A2.2}$$

where: g = gravity (m/s); h_t = the maximum water depth (m); α = a dimensionless coefficient varies between 0.2 and 0.7 used to produce a stable simulation; Δt = model time step (s); Δx = model grid resolution in the direction x (m).

Water level time series at inflow locations were based upon the sea-level time-series of a storm in May 2007 (the total sea water level was mainly affected by tide, with a surge influence, although surges are small in the Maldives as demonstrated in Wadey et al., 2017). However, as the Maldives are not low lying enough to be flooded by extreme still water levels alone (i.e., wave run-up is needed to project sea water onto land) (Wadey et al., 2017), the nation like many other low-lying islands and coastal areas, is well-known to be susceptible to inundation from energetic swell (long-wavelength wind waves). Swell can propagate thousands of kilometres across ocean basins (Harangozo, 1992; Hoeke et al., 2013; Munk, Miller, Snodgrass, & Barber, 1963; Wadey et al., 2017). Therefore this sea-level time-series was also associated with wave overtopping as the basis of a design storm (from conditions in May 2007). It assumed to have a linear relationship with the peak overtopping volume generated from SWAB. This was the only event where records or hindcasts exist where sea level and wave conditions are able to be quantified in relation to a significant flood. Hence, the results from this analysis were checked against local conditions reported at the time. Many of these reported local conditions are described in Wadey et al. (2017).

Outputs from LISFLOOD-FP indicated the area of land flooded and the average depth of flooding. The digital elevation model did not take account of buildings on the island.

A3. INFRASTRUCTURE AFFECTED

Outputs from LISFLOOD-FP were used to assess the infrastructure flooded using a Geographical Information System. The area flooded was overlaid on the infrastructure layer indicating whether or not the 1,295 buildings present on Hulhumalé at the time the research was undertaken were flooded (see Figure 1d in the main text). As rapid development is occurring, the number of buildings exposed and therefore potentially affected would have now increased.

A4. DATA FOR FIGURES

Table A1 provides data for Figure 4. Data for other figures is not available due to data sensitivity and/or commercial issues.