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

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Abstract

The Maldives (land elevation approximately 1m 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 2m 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±0.2m of SLR, with more severe, widespread flooding with 0.9±0.2m of sea-level rise. If the Paris Agreement goals are met, flooding is not anticipated this century, but under a non-mitigation scenario, flooding could occur by the 2090s. Building seawalls 0.5m, 1.0m and 1.5m high could delay flooding for 0.2m, 0.4m and 0.6m 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: sea-level rise, adaptation, flooding, island, defence, land claim

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 and Adger 2003; Nicholls et al. 2007; Nicholls and Cazenave 2010; Nurse et al. 2014; Wong et al. 2014; Giardino et al. 2018). Flooding is likely to increase in the future unless adaptation is undertaken (Wong et al. 2014; Nurse 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 rises, is the Maldives, Indian Ocean (Fig 1a) (Kahn et al, 2002; Woodworth 2005; Wadey et al. 2017; Hinkel et al. 2018). 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. Kench et al. 2015; Duvat 2018). For inhabited islands, flooding is not acceptable leading to the building of defences. In the short term, defences such as sea walls reduce the flood hazard (Sovacool 2012; Betzold and Momhamed 2017), 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 (Fig 1a, Fig 2a) 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 (Fig 1c, Fig 1d, Fig 2b). Raised to approximately 2m above mean sea-level (natural Maldivian islands are approximately 1m 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 (Fig 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 (Pernetta 1991; Naylor 2015; 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 1m by 2100 (Warrick et al. 1996)). More recent projections suggest a 1m rise could be exceeded before 2100, and especially beyond 2100 (e.g. Church et al. 2013; Jevrejeva et al. 2014; Hoegh-Guldberg et al. 2018). Hence, it remains unclear how long the 1m 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:

(i) Developing a methodology to determine the impacts of sea-level rise (in Section 2);
(ii) 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);
(iii) 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 concrete and a nourished beach (Fig 2b). In places the seawall is showing signs of damage (Fig 2b). The nourished beach varies in width from approximately 5m to 20m 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 Development Corporation 2016). On the western side, there are industrial and shipping activities. The island is virtually flat at 1.8m 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, tides), gravity waves such as energetic swell and other cyclonic fluctuations in mean sea-level (Church et al. 2006; McCabe et al. 2013; Wadey et al. 2017).

Energetic swell waves are known to generate flooding in the Maldives (Kahn et al. 2002; Wadey et al. 2017). A historical analysis of flooding plus discussions with Maldivian scientists (including co-authors AS and ZK), 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 5,600km 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: (i) significant wave height and period; (ii) mean sea-level, tides and surge data; (iii) bathymetry; (iv) defence type and elevation; (v) island topography; and (vi) location of infrastructure (Fig 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 2m and wave periods of up to 20s (with 15s 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.

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 0.25m in the recording period, and skew surges did not exceed 0.15m (Wadey et al., 2017). There is also a semi-diurnal tide, with a mean spring range of 0.76m (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 1,500m eastern side of the island up to 550m offshore. This was in the format of 0.5m vertically spaced contour lines, and augmented with beach elevation from a differential Geographical Positioning System survey. The shallow reef environment extends to approximately 150m offshore and is approximately up to 3m lower than the average land level (see Appendix A1, Figure A1.1). The reef then rises to a ridge slightly above mean sea-level, before declining at a vertical rate of 0.05m per 1m horizontally for 200m, then steepening to 0.25m per 1m horizontally for a further 200m. Thus depths of 50m are typically found 400-500m offshore, and thereafter continue to rapidly deepen.

Coastal defence data was provided by the government, 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 10m 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 (Fig 1c). Infrastructure data at the time of the study was provided by the Ministry of Engineering and Environment (Fig 1c), 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 1m 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 1-dimensional Shallow-water and Boussinesq (SWAB) numerical model (McCabe 2011; McCabe et al. 2013; Stansby et al. 2013) was used to simulate the propagation of nearshore waves and overtopping volumes under extreme conditions for 2 hours, 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 2 dimensional simulation of flooding, based on the topographic data to predict flood extent and depth. This used the LISFLOOD-FP inundation model (Bates et al., 2010), with overtopping volumes input at 10m 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 long period waves which could induce flooding (see Appendix).
- 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 (Fig 4) and flood spread (Fig 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 southeast shoreline to low depths (<0.2m). 0.2m of average flood depth was selected as a threshold as this 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. Penning-Roswell et al. 2005; Zhou et al. 2012; Penning-Roswell 2015; Kaspersen and Halsnæs 2017).

(2) Hazardous flooding: where flood depths are predicted to be greater than 0.2m 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 0.6m. In the wider literature, Penning-Roswell et al. (2005) indicates that for any location, flood depths greater than 0.6m can be considered life threatening.

2.4 Scenarios tested

Conditions tested are noted in Table 1. These included differing magnitudes of sea-level rise (up to 1.8m in increments of 0.1m), rates of reef growth with respect to sea-level rise (following Perry et al. (2018) 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).

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 1.8m 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 0.1m of sea-level rise since the 1992-1993 datum, SWAB did not generate any overtopping, indicating that the present defences are sufficient (Fig 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 0.6m of sea-level rise (at around 2.0l/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 0.1m resulting in nuisance flooding (Fig 5a). The model projects that 50% of the island could be temporarily flooded with 0.65m of sea-level rise (and approximately 4.0l/s/m of water overtopping the eastern boundary), but flood depths remain below 0.2m (Fig 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 0.9m, LISFLOOD-FP indicated flood depths increase to nearly 0.2m, with the flood extent covering approximately 90% of the island and threatening over 1200 buildings (Fig 4b,c and Fig 5b). With 1m of sea-level rise the entire island could be extensively flooded, with floods on average, greater than 0.2m 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 (Fig 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 0.5m, 1m and 1.5m 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 Fig 4 (grey lines). Initial overtopping at nuisance level (equating to 2.0l/s/m of overtopping as shown in Fig 4a) is delayed by approximately 0.2m (for the 0.5m sea wall), 0.4m (for the 1m sea wall) and 0.6m (for the 1.5m 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 60,000m^3 of beach nourishment above present day extreme water levels along the eastern coast in conjunction with a 0.5m sea wall (Fig 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 1.0m 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 0.1m may occur at 0.6±0.2m 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 0.3m 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 2m to 3m (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 0.7m of sea-level rise, 0.2m 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 61m (200 feet) inland. Eye witness accounts suggested the water level was 0.6m (2 feet) above normal land levels (National Disaster Management Centre, 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 stop or lessen 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 initial nuisance flooding under swell wave conditions (from May 2007) that occur roughly once every 20 years (Wadey et al. 2017) could occur with 0.6±0.2m sea-level rise to a mean depth of 0.1m (but up to 0.2m). After 0.6m of sea-level rise, flooding under swell conditions could become much more extensive and deeper.

The timing of impacts have been synthesised in Fig 6 by analysing the outputs described in Section 3 with climate change scenarios from Goodwin et al. (2018) which align with the Paris Agreement (United Nations 2015). 0.6m of sea-level rise is projected to occur in 2155 [2095-2300 for 5^{th}-95^{th} percentile] 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 1.8m 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 Fig 2a). This level is not projected by 2300 for the 1.5°C scenario (95^{th} percentile), but is projected in 2280 for the 2°C scenario (95^{th} percentile). For RCP8.5, a 1.8m rise in sea-level is projected at around 2160 [2130-2215].

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. Ministry of Environment and Energy 2015, Hulhulmalé Development Corporation 2017) in Hulhumalé (Phase 1), Bisaro et al. (accepted) indicated total investment costs (i.e. reclamation and associated infrastructure, such as water and sanitations systems) 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), can be hundreds of millions of dollars. 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 development country, whilst adapting to sea-level rise. The relatively low additional sand volume costs with respect to its additional height (approximately 1m) 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 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 (Fig 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, socioeconomically, 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 et al. 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, b), or more recently in east Asia for industrial or residential reasons (Martin-Antón et al. 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 sufficient 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 design 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, raised streets) may 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 design 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 and 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 2m 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 (<0.2m flood depth) may occur on the eastern side of the island (the main overtopping area modelled) with 0.6±-0.2m of sea-level rise, with the flood extent (and >0.2m flood depth) becoming more extensive with 0.9±0.2m 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 0.6m.
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.

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