Pathways to sustain atolls under rising sea levels through land claim and island raising

Sally Brown*[1,2], Robert J Nicholls[2], Alan Bloodworth[3], Oliver Bragg[1,4], Audrey Clauss[1], Stuart Field[1], Laura Gibbons[1,5], Milda Pladaitė[1,6], Malcolm Szuplewski[1], James Watling[1], Ali Shareef[7], Zammath Khaleel[7]

*Corresponding author. Email: sb20@soton.ac.uk Tel: n/a

1. School of Engineering, Faculty of Engineering and Physical Sciences, Boldrewood Innovation Campus, Burgess Road, Southampton. SO16 7QF. UK.

2. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich Research Park, Norwich. NR4 7TJ. UK.

3. TEDI-London, Building 11, Quebec Way, London, SE16 7LG. UK.

4. Jacobs, 2 Colmore Square, 38 Colmore Circus Queensway, Queensway, Birmingham B4 6BN.

5. JBA Consulting, 35 Perrymount Road, Haywards Heath RH16 3XE.

6. Brussels, Belgium

7. Development Advisory Services Pvt Ltd, Malé, Maldives.

ORCID ID:

Sally Brown: 0000-0003-1185-1962

Alan Bloodworth: 0000-0002-9082-477X

Robert J Nicholls: 0000-0002-9715-1109

Zammath Khaleel : 0000-0003-1512-4244

List of abbreviations:

AMSL: Above mean sea-level

MSL: Mean sea-level

SIDS: Small island developing States

SLR: Sea-level rise

Keywords:

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Abstract:

Low-lying atoll nations (e.g., the Maldives, Kiribati, Tuvalu, Marshall Islands) are highly vulnerable to climate change, especially sea-level rise. Stringent climate change mitigation will slow but not stop sea-level rise, which will continue for centuries, mandating additional long-term adaptation. At the same time, urbanisation is concentrating population in a few centres, especially around capital islands which creates additional pressure as most atoll nations are 'land-poor'. This paper demonstrates how structural adaptation using land claim and island raising can be utilised within an adaptation pathway approach to sustain enough islands and land area above rising sea levels to satisfy societal and economic needs over multiple centuries.

This approach is illustrated using the Maldives, especially around the capital and its environs (Greater Malé). Raising, expanding and connecting 'urban' islands can provide multiple benefits. Significant developments have already occurred in Greater Malé and further developments there and for other urban centres in the Maldives are expected. Migration to

urban centres, especially Malé, is widespread and this adaptation approach assumes this trend continues, implying many other islands are depopulated or abandoned. Tourism is core to the Maldives economy and tourist islands require a different ambience to urban islands. They could be sustained with sympathetic soft engineering reinforcing the natural processes that produce atolls. While land advance and island raising provides a technical solution for sea-level rise, any application must also address the additional policy, human, physical, engineering and economic/ financial challenges that are raised. Nonetheless, by aligning adaptation through land advance/raising with existing development trends, atoll nations have the potential to persist and prosper for many centuries even as sea levels inevitably rise. This provides a realistic alternative to widespread assumptions about forced migration and ultimate national abandonment. The lessons here may find wider application to other small island settings and even mainland coasts.

1. Introduction

Despite pledges of climate change mitigation and aspirations for temperature stabilisation, sea-level rise (SLR) poses long-term threats to small islands, including atolls, world-wide (Hoegh-Guldberg *et al* 2018, Li *et al* 2020, Nicholls *et al* 2018, Mycoo *et al* 2022, Oppenheimer *et al* 2019), as even small rises in sea level threaten island life (Storlazzi *et al* 2018). Small island developing States (SIDS) are often considered to be the most vulnerable setting to be affected by climate change and SLR (Magnan *et al* 2022). However, islands are diverse in morphology, slope and elevation (National Geographic, 2022, Nunn *et al* 2016, Mycoo *et al* 2022) resulting in an island classification of:

- Continental, e.g. land masses once connected to the mainland, diverse topography.
- Tidal, e.g. low-lying flat bars, connected to the mainland only at low tide.

- Barrier, e.g. low, flat sediment deposited parallel to the mainland.
- Volcanic, e.g. high, and flat or steep volcanic deposits, distant from other land.
- Raised limestones, e.g. high or low, steep sided with flat top.
- Coral reef, e.g. low, flat atolls.
- Composite, e.g. alternating volcanism and uplift.
- Artificial, e.g. built for trade, transport, real estate, defence, tourism.
- Floating, not commonly considered in present classifications, but an emerging concept/approach to create space or an alternative means of living

For high or steep islands, only the island rim may be physically affected by SLR, but the ramifications could be felt island wide, as is the case on low islands. Adaptation to SLR is needed. For islands of a scale of several kilometres and of higher elevation, traditional measures such as sea-walls and beach nourishment are appropriate. However, for smaller low-lying islands at the scales of hundreds of metres such as atolls, the entire island may be at risk from SLR, so dramatically different adaptation approaches are needed. This leads to the widespread pessimistic view of ultimately forced migration and abandonment of individual low-lying atolls and even whole countries being the ultimate response, and the creation of islander climate change refugees (Barnett and Adger 2003, Biermann and Boas 2010, Constable 2017, Farbotko and Lazrus 2012, McLeman 2018). Such a pessimistic view is reinforced by the discourse within the international community and global media (McMichael *et al* 2019).

There has been significant debate as to whether climate change related migration is a means to adapt, or a failure to adapt (Lietaer and Durand-Delacre 2021, McMichael *et al* 2019, Vinke *et al* 2020), which could when crossing international borders lead to refugee status. However, if implemented appropriately to decrease vulnerability, ‘migration as adaptation’ (i.e. orderly governance, positioned as a positive or anticipatory response) may be seen as a way to build resilience (Black *et al* 2011), especially over long time scales. Furthermore, relocation of villages and migration could be implemented with support at global and national levels, importantly combined with community level consideration of the locality, time and design of moving (McMichael *et al* 2019). Sobczak-Szelc and Fekih (2020) argue that migration does not need to be a measure of last resort and could be used as part of wider socio-economical change. In addition, migration within and between islands is a longstanding and widespread phenomena due to a range of economic and social factors. This needs to be considered, as otherwise the processes and outcomes linked to climate and SLR may be considered too simplistically (Speelman *et al* 2021, Wilmsen and Webber 2015) and have potential to create new problems. For example, planned migration may be viewed as a means to adapt, where creative mobility (e.g. in response to labour markets, e.g. Barnett and McMichael 2018) can result in movement of people across countries. Thus, migration can be an anticipation of change allowing for the orderly movement of people based on social networks and a diversification of livelihoods, whilst reducing exposure to a hazard (Bettini, 2017, McMichael *et al* 2019).

For an atoll, which is the most vulnerable small island setting, planned displacement off the atoll may be seen as a means of last resort when other in situ adaptations fail, as a strong attachment to people's homelands remains (Barnett, 2017, Laurice Jamero *et al* 2017). Barnett (2017) asks 'if the loss of atolls can be avoided…[by a] vastly more creative and committed approach to adaptation' as it is wrong to give up efforts (e.g. for cultural, dignity and ethical reasons) in securing the rights of people to continue to live on atolls. Successful adaptation involves ownership of the solution: This involves adaptation undertaken by atoll people, not done for them (Barnett, 2017).

IPCC (2019) and Magnan *et al* (2022) consider the risk of SLR to urban atolls in the year 2100 evidenced through a burning embers diagram. Even assuming a maximum potential in situ adaptation response to SLR, they argue that the levels of risk remain high, conforming to the pessimistic view already discussed. This paper challenges this perspective with a more optimistic approach, based on linking adaptation and development trends in atoll nations. The ideas presented provide a framework where island societies can and should take ownership of their future under rising sea levels. It focuses on technical and environmental perspectives but acknowledge that significant social, political and cultural debate, including ethical dimensions is also required to determine adaptation futures. In detail, it presents an alternative vision for the future of atoll nations based on adaptation via strategic land claim (hereafter called 'advance') and/or island raising (hereafter called 'raise') (Oppenheimer *et al* 2019). Island raising was proposed as a response to SLR for small islands in the first global cost estimate of SLR by Dronkers *et al* (1990), but subsequently has seldom been considered systematically in the literature until Oppenheimer *et al* (2019). This is despite a long history of land advance for development purposes around the world's coasts, with Asia dominating in the last few decades (Sengupta *et al* 2020, Sengupta *et al* in review). As such, raising and advancing are emerging means of adapting to SLR that are consistent with current practice. Given that the need for new land is usually associated with highly populated areas, the main focus here is on urban areas, although the approach could be applied anywhere. To explore this approach in depth, a case study of the atoll nation of the Maldives is presented. The Maldives is selected as it is already undergoing transformational changes as a nation due to rapid urbanisation and tourism development, including advance and the building of completely new islands to create space for development. Lessons learnt here could be applied to adapting to SLR in other atolls or islands, and more widely. Thus, the goal of this paper is to determine how novel methods of land raising and advance can provide a transformative adaptation approach for SLR for atoll nations that could be effective in the long term (i.e. over multiple centuries). This will be achieved by:

(i) Assessing the background of environmental change in atoll environments (Section 2);

(ii) Developing and applying a methodology to adapt to SLR utilising land raising and advance using a case study of the Maldives (Section 3);

(iii) Discussing the challenges and implications of land advance and raising in adaptation (Section 4).

2. Environmental change and development in atoll nations

2.1 Natural change

With SLR, reefs will need to grow simultaneously to survive, including allowance for wave effects. It is important to distinguish between (i) natural atolls with low population densities and (ii) protected atolls with higher populated densities (figure 1). While the former are much more numerous, the later account for a significant and growing proportion of national population, usually reflecting urbanisation around capital islands (Speelman *et al* 2021). Natural atolls (figure 1a) are morphologically dynamic so that they do not simply drown with SLR; rather during extreme inundation (flood) events, they can accrete sediment vertically around the island edge or expand laterally (Kench, 2012, Kench *et al* 2018). The future ability of reefs worldwide to accrete at a sufficient pace to respond to SLR is a subject of significant debate amongst scientists (e.g. Kench *et al* 2018, Masselink *et al* 2020, Storlazzi *et al* 2018), especially where faster rates of SLR are projected than we have seen in the past. Measurements show that atolls have expanded their land area in the past decades despite regional SLR in these areas being twice that of global-mean trends (Kench *et al* 2018). Conversely, on protected atolls defences reduce inundation (hereafter referred to as flooding) and inhibit morphological responses in both the vertical and horizontal dimensions as they are not able to accrete naturally (Betzold and Mohamed 2017, Kench, 2012, Sovacool, 2012) (figure 1c). Simultaneously, the perceived safety of defences reinforces development and urbanisation in a well-known positive feedback loop (MacDonald *et al* 2012, White 1945), elevating residual risk through increased exposure and hazard under failure.

In recent decades it has been increasingly recognised that coastal erosion and flooding are interconnected by sediment exchange and its control on inundation (Dawson *et al* 2009, Nicholls *et al* 2015), including on coral atolls (Masselink *et al* 2020). There is a need for the natural *accretion* of sediments to raise land elevation, especially around the edge of the island (e.g. East *et al* 2018, Kench *et al* 2018, Perry *et al* 2018), with faster rates of SLR (figure 1b). For densely populated atolls where this process is suppressed or excluded, a human-induced mechanism is required to artificially raise islands to cope with SLR.

2.2 Engineering change

Raising existing areas and advancing land can reduce risk, particularly where infrastructure is yet to be built (figure 1d). Land advancing in urban areas has been widely practiced for centuries where land is scarce, such as in coastal cities and ports. In recent years, Asia has been globally dominant in this practice (Sengupta *et al* 2020). This is also true in land-scarce atolls, such as the Maldives (Aslam and Kench 2017, Bisaro *et al* 2019, Duvat 2020, Duvat and Magnan 2019), where it has been a key element of wider national development trends and goals. In the mid 2000s, the Maldives' Population Consolidation programme advanced land seawards to provide space and modern infrastructure and utilities to support larger populations on selected islands (Ministry of Planning and National Development 2007). Similarly, the Safer Island programme, prompted by the 2004 Indian Ocean tsunami raised selected islands (and provided improved infrastructure) to both develop the islands and lower tsunami risk (Riyaz and Park 2010). This allowed for a small number of islands to increase their resilience to SLR as a by-product of development and tsunami risk mitigation. The National Spatial Plan 2020-2040 (pers comm M. Imad) indicates five 'Urban Centers' across the Maldives as clusters of growth to complement growth in and around Malé -- the capital city. This includes an emphasis on advancing land to promote development.

2.3 Future change and development

Despite mitigation pledges following the Paris Agreement (United Nations 2015), there are large uncertainties in the future rates of SLR, depending on future emissions and how the climate and especially the large ice sheets respond to the resulting warming (Fox-Kemper *et al* 2021, Hoegh-Guldberg *et al* 2018, Oppenheimer *et al* 2019, van de Wal *et al* 2022). Importantly, whilst mitigation significantly reduces future SLR, some SLR cannot be avoided and so adaptation remains essential. The greatest uncertainties into the magnitude of future SLR occur in the second half of this century and beyond, leaving valuable time to plan and instigate an adaptation strategy. This raises the prospect of integrating the strategies of adapting to SLR with development, consistent with present trends and societal aspirations, and advancing and raising land to provide safe space for development. Thus, we propose an adaptation pathway approach (Haasnoot *et al* 2013, Haasnoot *et al* 2019) largely based on engineered land advance and raising to allow selected islands to adapt to SLR, consistent with present development policies and trends. This considers land use and function, as adaptation is highly specific to these needs (Magnan and Duvat 2020).

3. Land raising and advance and adaptation pathways: Application to the Maldives

3.1 Setting of the Maldives

We focus on the highly urbanised capital city of Malé, capital of the 1,190 low-lying atoll islands of the Maldives, and adjacent urban islands as case studies (figure 2). The mean spring tidal range at Malé is 0.76m (Woodworth 2005), with a semi-diurnal regime and strong diurnal inequalities. Storm surges are relatively small, especially near the Equator. Tide gauge records from 1991 to 2015 indicate a rise of 3.46±0.25mm/yr for Malé (Wadey *et al.* 2017). Flooding typically is associated with long period energetic swell waves originating to the south (Harangozo 1992), such as seen in April 1987 and May 2007. Malé is elevated to approximately 1.2m above mean sea-level (AMSL), with variations ranging between 1 and 2 m, according to a topographic map by Pernetta (1989) with reclaimed land generally being of lower elevation. At nearly 2km^2, its population has grown significantly over the last few decades, and according to the 2014 census, houses approximated 103,000 people or 38% of national population (Ministry of Finance & Treasury 2018, Speelman 2015). The population continues to grow with in excess of 250,000 people registered or residing there (Avas 2021), via increasing density accomplished in part via higher buildings. To address land scarcity and population pressure (Naylor 2015, Pernetta 1989), approximately 0.5km^2 of land has been advanced since the 1970s (a 33% expansion). As no further expansion of Malé is practical due to large water depths, the new larger (4.3km^2) island of Hulhumalé was constructed in two phases in 1997 and 2015 by building onto the reef flat around the small atoll 3.5km north-east of Malé (Bisaro *et al* 2019, Ministry of Planning and National Development 2007). It was designed as two islands (one per phase), both approximately 2m AMSL (with a range of 1.1m to 2.6m according to a topographic survey reported by Brown *et al* 2020, with most of the island being very flat at around 2m elevation). This is 0.8 m above typical elevation on Malé, with the aim of adaptation to both tsuanami risk and SLR (pers comm M Aslam). The total planned population is nominally 160,000 (Hulhumale Development Corporation 2015), but this could increase if urbanisation pressures around Malé continue to grow. A bridge opened in 2018 between Malé and Hulhumalé, improving links and integrating these urban areas. The success of this bridge has led to the Greater Male Connectivity Project, signed in 2021, which will consist of a bridge and causeway link between Malé and islands of Villingli, Gulhifalhu and Thilafushi to the west. This is the largest ever infrastructure project in the Maldives and will promote further urban development on these islands. By 2050, about 475,000 people (or 52% of national population) are expected to live on Malé and Hulhumalé (Ministry of Finance & Treasury 2018), continuing historic urbanisation trends and providing further pressure for new land and/or higher buildings (Speelman 2015). Thus, the Maldives is developing rapidly.

Other major urban areas in the Maldives will also see significant land advance, such as Addu Atoll in the south. Many other islands in the Maldives have a single function, such as agriculture, rural living, port facilities, energy storage or tourism, and this is how they are often described.

3.2 Background to adaptation pathways

Adaptation pathways are sequences of linked actions that can be enacted as conditions change (Barnett *et al* 2014). Typically starting with a series of low regret adaptation actions, a range of further adaptation options could be taken over time depending on how conditions change, including recognising relevant triggers. These triggers could take many forms, such as being rates or magnitudes of SLR, engineering design standards, space and material availability, population density, cost-benefit, social acceptability and economic productivity (Haasnoot *et al* 2019). An opportunity tipping point is noted where an adaptation option is required to reduce flood risk. When an option is no longer viable or effective, an adaptation tipping point occurs. Thus, adaptation options evolve creating new opportunities. While pathways often start with conceptual design, to be applied in practice they have to consider the management process and comprise deliverable measures and actions. Active adaptation pathway processes include the UK Thames Estuary 2100 plan (Ranger *et al* 2013), Bangladesh Delta Plan 2100 (General Economics Division 2018) and the Dutch Delta Programme in the Rhine-Meuse delta (Bloemen *et al* 2019, Delta Programme 2014). These active plans combine support of top-down (e.g. national governments) and bottom-up (e.g. local government and communities) players, where all strive for an overall agreed goal (typically to manage long-term flood risk, combined with other goals such as development). Whilst engineers and scientists can define what is physically possible in the adaptation space, it is the socio-political players and people who must live with the outcomes that need to make a decision about the exact pathway itself. In this paper we focus on the structural adaptation measures to develop the technical measures, and acknowledge that the socio-political dimensions would require further development. These wider challenges (the next step on decisions related to adaptation pathways) are discussed in Section 4.

The adaptation pathways generated for the Maldives in this paper consider structural adaptation, combined with support systems common within flood risk engineering. The focus is on three urban islands and their inter-relationship: Malé, Hulhumalé and a third hypothetical higher island (that here is called Abadhah-Malé) that could be created like Hulhumalé, or via an advance/raise of existing islands such as Villingli, Gulhifalhu and Thilafushi. Pathways are presented for each island based on the modelling of flood risk conditions. This considered the effects of SLR and potential flooding under energetic swell wave events, which constitute the major climate hazard as they are exacerbated by SLR. A design event based on the significant flooding that occurred nationwide in May 2007 is used, modelled with other oceanographic input parameters (for details, see Wadey *et al* 2017 and Brown *et al* 2020). This was selected as it is the first major flood event where all the data required for a flood impact assessment is available from hindcast data, including linking to future SLR scenarios. Elevation data was provided by the Maldivian government (Ministry of Home Affairs 2001) and from a survey undertaken especially for previous research (Brown *et al* 2020), plus consultancies. Overtopping and flood extent were assessed using overtopping models (Shallow-water and Boussinesq - McCabe *et al* 2013 and EurOtop - EurOtop 2007) and a flood spread model, LISFLOOD-FP (Bates *et al* 2010) under different SLR scenarios. Flood events were modelled for Hulhumalé (Brown *et al* 2020), with further exploratory modelling runs using the same methods for Malé and Abadhah-Malé under similar oceanic conditions, which consider their differing elevations.

3.3 Methods of adaptation options and pathways for case studies

The methodological approach is presented for the two case studies analysed.

Case I: Heavily urbanised capital city

For case (I) we consider the evolution and potential inter-relationship of three urban islands (1) Malé (which experiences periodic flooding today - Wadey *et al* 2017), (2) Hulhumalé (which will experience flooding by the 22nd century or beyond - Brown *et al* 2020 and Wadey *et al* 2017) and (3) Abadhah-Malé, to be constructed at a higher elevation than Hulhumalé, further delaying the emergence of flooding issues due to SLR.

To develop generic adaptation pathways for set coastal archetypes (e.g. urban area adjacent to an estuary), Haasnoot *et al* (2019) considered the (i) management aim; (ii) adaptation options for selected impacts (iii) thresholds for instigating an option and terminating it (an opportunity tipping point), including physical, social and economic reasons to adapt; and (iv) how adaptation options may be sustained with future SLR given thresholds for adaptation. To build an adaptation pathway for the islands in Case I, each component of the Haasnoot *et al* (2019) approach is considered.

Firstly, the management aims for each island are (1) to avoid flooding due to SLR and (2) provide safe land for development. Flooding occurs periodically due to energetic swell wave conditions coinciding with high water levels (Wadey *et al* 2017). Periodic flooding, although causing damage, may be acceptable if the event occurs infrequently. However, the frequency and depth of flooding increases over decadal to centennial timescales as still water levels rise, raising flood risk. With time, flood water will be progressively unable to drain back into the sea due to lack of hydraulic head, enhancing damage. To some extent, this is already occurring on Malé as the island is surrounded by seawalls and tetrapod defences, buying time although ultimately these defences will be overwhelmed too frequently, requiring new adaptation responses. As Hulhumalé (Brown *et al* 2020) and Abadhah-Malé are built at higher elevation relative to sea level, the risk of flooding is not yet a real threat.

Secondly, Haasnoot *et al* (2019) categorised adaptation options under the umbrella of accommodate, protect and retreat categories from Dronkers *et al* (1990). Due to the large number of adaptation options available, options were combined where they had a similar function (e.g. wave dissipation structures including natural or artificial structures that decrease wave energy, including breakwaters and wetlands). This helped reduce the complexity in the adaptation pathways that were generated. A similar approach is taken for the Maldives, where the options are condensed into protect and accommodate categories. Major adaptation options were compiled by reviewing a wide range of common coastal engineering and adaptation literature (Dronkers *et al* 1990, Haasnoot *et al* 2013, Klein *et al* 2001, Linham *et al* 2010, Nicholls *et al* 2007, Wong *et al* 2014). For each island, 15 adaptation options were considered (Table 1, columns 1 and 2), combining options with similar functions. Some options such as flood gates, glass walls, underground or water storage were not considered, as they are unsuitable, did not align to the goal to extend an island's life (i.e. flooding in an extreme event with SLR would be inevitable and would overwhelm defences and/or significant disruption) or were so small in scale that they could be incorporated into everyday strategies (Arnall and Kothari 2015).

The 15 options were classified into protect, accommodate, migrate and raise/advance (Dronkers *et al* 1990, Oppenheimer *et al* 2019). Oppenheimer *et al* (2019) and Bongarts Lebbe *et al* (2021) also considered ecosystem-based adaptations, but these were not used as it is not appropriate for highly urban atolls. Furthermore, structurally, *horizontal* retreat is not necessary over long-time periods and short time scales as raise/advance is a viable alternative. However, local ‘between-island’ migration in a planned manner is considered here. This is not ‘retreat’ as no large-scale or international migration is needed and this could be considered as accommodation via advance and raise practices (see Section 4). As the focus of the pathways is on structural adaptation to deem what is possible not plausible (see Section 4), behavioural or societal adaptations (apart from warning systems which support the structural options presented) were not considered.

Thirdly, Haasnoot *et al* (2019) stated that thresholds for instigating an adaptation option, and opportunity tipping points for terminating it, were dependent on engineering design conditions, space and material availability, cost-benefit conditions, social acceptability and economic productivity. The adaptation options presented in Table 1 were assessed against these thresholds. As geographically remote island settings are considered here, greater emphasis was given to the magnitude and rate of SLR, present and future population density, design life and space and material availability (Duvat and Magnan 2019, Haasnoot *et al* 2013, Kwadijk *et al* 2010, Ministry of Housing and Environment, 2011, Nurse *et al* 2014). Thresholds for options were debated between the authors and local coastal engineers, particularly considering a Maldivian perspective (from co-authors AS and ZK) of what is culturally and socially acceptable.

Fourthly, adaptation options were considered with respect to future SLR. Long centennial (100+ year) timescales were considered for adaptation options as SLR operates over this scale. This enables a full range of adaptation scenarios associated with SLR to be analysed. Whilst acknowledging, generating and implementing an adaptation pathway is challenging even for the 21st century, the multi-centennial outlook provides opportunities to consider what is possible, that is, relevant to the long-term sustainability of low islands under progressively rising sea levels (Oppenheimer *et al* 2019). Other trends need to be considered where possible. For socio-economic change it was simply assumed that current development trends continue, to illustrate the process as these are highly uncertain. An adaptation pathway for a mitigation and a non-mitigation SLR scenario (Fox-Kemper *et al* 2021) was analysed per island (See Section 3.4). To bring the islands together, and to stretch thresholds of adaptation further, aligning them with development goals, a multi-island adaptation pathway was produced (see Section 3.4) for the capital city region, including migration between the islands as needed (when other forms of adaptation could no longer manage the risks - McMichael *et al* 2019).

Case II: Whole country based on islands with a dominant land use

Outside Malé and the other urban islands, the Maldives has a diverse range of land uses and therefore needs different pathways to adapt and sustain these uses (or possibly abandon them in some cases). Due to their small size, islands are often designated as having a set, main purpose. Previous classifications have considered ecological perspectives and drivers of land use change (e.g. Fallati *et al* 2017, Steibl *et al* 2021), such as urban (including tourism and reclamation), infrastructure, lagoons or natural land use cover. Islands were classified (VROM 2001) via land use and island function based on satellite imagery, observations and discussions within the author team. Eight uses (and island types) were identified: agricultural, energy, heritage, natural, port, rural, tourism, and urban. Natural islands are uninhabited, whereas rural islands contain scattered dwellings or villages. As the focus on this paper is on land advance and raising, plus the associated movement of people, natural and heritage islands have not been analysed here and would require further research as they evolve essentially naturally.

The remaining six land use types were grouped into four classes (i) agriculture, rural housing; (ii) port, energy; (iii) urban development including housing and industry and (iv) tourism. These four classes are important as they exhibited similar temporal and spatial characteristics in terms of adaptation approach. They were each analysed in terms of engineering design conditions, space and material availability, cost-benefit conditions, social acceptability and economic productivity (Haasnoot *et al* 2019). For example, a tourist island has a rapid payback time of around five years, a timescale where the impacts of climate change are not considered a risk (Becken *et al* 2011). Hence, there is high economic productivity and appropriate cost-benefit conditions, space to build and engineering design possibilities, but low social acceptability for hard structural solutions unless they are aesthetically pleasing. This means it is financially viable for land raising/advance to take place (particularly when timed at the end of a multi-decadal lease period).

Options were considered by island function. These were then combined to determine how different island functions can support each other, often reinforcing current practice, following movement patterns established in Case I. Due to the complexity of variables affecting natural processes plus land advance and raising with respect to SLR, connections between island types are discussed, rather than the thresholds and opportunity tipping points themselves.

3.4 Key findings

Key findings for both cases are explored below.

Case I: Heavily urbanised capital city

Figure 3 illustrates the adaptation options and tipping points with SLR in Malé. This figure (like figure 4 and figure 5) provides an illustration and plan of current and/or future adaptation measures. Illustrated in the first column are stylised adaptation options, divided into four categories of protect, accommodate, raise/advance and migrate. Horizontally in pale grey, there is a linear scale of SLR, topped with the time periods of when that SLR could occur depending on scenario. The magnitude of SLR that is suitable in terms of end and start points for each stylised adaptation option is shown through a coloured rectangle. Today, Malé is largely protected by breakwaters and tetrapods built after the 1989 floods (Wadey *et al* 2017). But as the city extends to the reef edge, space for further protection upgrade is limited unless land within the city is sacrificed, and the residual risk given failure of the protection is growing. Upgrades to present protection will help (e.g. breakwater raising), but cannot be a long-term solution, as flooding associated with an extreme wave event is projected to occur with 0.4m of SLR (e.g. to minimum hydraulic head – see Methods). With rises in excess of 0.5m, accommodation to more frequent flooding becomes the main option available to adapt. When sea-levels rise more than 1.2m (according to Fox-Kemper *et al* 2021, after 2100 or significantly beyond), Malé may need to be abandoned as coastal flooding becomes too frequent. Information systems are improving emergency response (for example, a Facebook severe wave warning service commenced in 2015 - Facebook 2016, with Twitter and Viber messaging becoming more popular) and this could be developed further, potentially reducing damage and risk to life. However, this only buys time before flooding becomes more routine. Ultimately, Malé as presently configured will need to be abandoned (or fundamentally reconfigured).

On Hulhumalé (Phase I) (figure 4), overtopping and inundation analysis indicated that under the most severe swell wave conditions recorded to date (approximately every 20 years), occasional flooding could commence with approximately 0.6m of SLR (Brown *et al* 2020). Hence, little adaptation is needed until this rise occurs. Then further protection, such as sea walls, may be required, as unlike on Malé there is sufficient space around the coastline to build them. However, adaptation must fit with wider development and the government's vision, so seawalls are not suitable all around the island as they degrade natural aesthetics and restrict tourist areas. Thus, in touristic areas on the island, adaptation measures could include a dike (or wide embankment) due to the space available, potential multi-functional use and likelihood to be more aesthetically pleasing. This could protect for up to 1.4m of SLR, but beyond this future protection is limited due to the spatial footprint required for dike construction given the current infrastructure on the island. This means that with 1m of SLR, Hulhumalé will be in a similar situation to Malé today. At this point, accommodation of more and more frequent flooding becomes a major response. Forward planning, such as raising land or buildings as part of redevelopments and when new ones are constructed, would buy time. With 1.8m of SLR, the island may have to be abandoned (or fundamentally reconfigured).

Drawing lessons from Malé (the need for improved drainage, space for buildings and land advance due to urbanisation) and Hulhumalé (advantages of space, investment opportunities, island elevation), Abadhah-Malé (figure 5) is raised to about 6 m elevation, optimised for cost, design life and to withstand multi-metre SLR. While the island is built to about 6m here, this is illustrative and the allowance is a variable which could be adjusted as desired. Before SLR, localised beach and harbour access would be needed, particularly for tourism and transportation. Hence island topography and associated infrastructure could be designed to roll back with SLR, or with greater access such as the artificial beaches used today augmented by temporary barriers where flooding is a threat. With respect to pluvial flooding today, there is some risk tolerance for this at present, but this may well decrease as widely observed with development and rising living standards, leading to expectations of higher defence standards than Malé and Hulhumalé. Allowing for this and further population consolidation (particularly if other islands in the Maldives are abandoned), areas are included for tourist use, which is a major economic sector today. Given uncertainty in future SLR, set-back zones were included in case future protection measures need to change.

Figure 6 illustrates an adaptation pathway that includes island advance and raising, plus population migration between the three islands (figure 3, figure 4 and figure 5) as needed. As sea levels rise, adaptation shifts from simultaneous protect and accommodate, to accommodate, to cope with more frequent and larger floods and ultimately migration to another island, following the suitability of options described in Table 1. Each island (figure 3, figure 4 and figure 5) has physical (e.g. level of protection, set-back space) and social (e.g. acceptability of the magnitude and frequency of floods determined by local people, councils or government) thresholds of living with SLR. These thresholds were determined from the model results and comparing the height of the land and SLR (see table 1). When these thresholds are reached, the population migrates to a new higher island, leaving the original island uninhabited and available to be raised and reoccupied in the future. Once raised, migrants from the next lowest island move to the raised island when needed. Transport links are key, and the initial focus has been on ferry links reflecting the traditional Maldivian approach. However, bridge links are now being demonstrated (e.g. Malé to Hulhumalé) and are advantageous in easing population movement, so the principles outlined here might be applied in different ways to sets of islands linked by bridges – e.g., abandoning and raising parts of individual islands. This movement is theoretical, but consistent with current trends in the Maldives. These pathways illustrate the possibilities should society wish to use them, providing a feasible way for Greater Malé to continue to prosper and grow in the future under rising sea levels.

Raising of land is the only way to guarantee that coastal flooding will not occur with SLR, as dikes and other defences are always associated with residual risk (Oppenheimer *et al* 2019). However, a policy of advancing and raising islands can only be effective when the movement of people between raised islands is undertaken in a managed way, allowing for wider development issues (e.g. inclusion of utilities, drainage, housing) and acceptability of the need to change. Two of the three urban islands in Figure 6 could house two thirds of the current national population at present urban densities. If higher buildings are permitted following current development trends, two islands could house the entire national population. This leads to a cycle of (i) abandoning and (ii) raising infrastructure, whilst the population moves to a new island, (iii) settles and (iv) stays, until higher sea levels threaten again and the cycle repeats (figure 7). While the details need to be determined (e.g. design island height, anticipated and observed rate of SLR), allowing flexibility and innovation, this provides an adaptive approach for the urban area of 'Greater Malé' that can continue far into the future even with large amounts of SLR. Once the principle of strategic island raising is accepted (particularly where this aligns with development trends), consultation with the Maldivian population would be essential to allow the design of this approach to be tuned to local needs and wishes.

Sea levels are projected to continue to rise for centuries, but rates remain highly uncertain depending on future emissions, climate sensitivity and ice sheet response (Fox-Kemper *et al*

2021, Oppenheimer *et al* 2019, van de Wal *et al* 2022). For current population levels and low rates of SLR, the building of Abadhah-Malé may not be required until 2150 and Abadhah-Malé could be raised less or more than suggested here – buying different amounts of time (continued population growth following current trends will trigger an earlier need to advance and create Abadhah-Malé or similar due to the ‘need for living space’ driver rather than the adaptation driver). Thus, advance and raise provides an opportunity to reverse the apparent adaptation lock-in of simply reinforcing and raising Malé’s seawalls, and create land as needed for development.

Case II: Whole country based on islands with a dominant land use

The Maldives has changed rapidly over the last few decades due to development and internal migration, especially around the capital city (Speelman 2015; World Bank 2022). If this continues the country will look very different in 50-100 years compared with today. Thus we demonstrate that if adaptation aligns with present and future development, and builds flexibility, it can provide development opportunities and improved livelihoods (figure 8). For example, the need for space means new islands can be built, and these can be raised sufficiently high to cope with centennial-scale SLR.

Figure 8 illustrates adaptation approaches due to SLR for islands with a dominant land use type. SLR will affect agriculture (figure 8(a) to (d)) and rural islands (figure 8(e) to (h)) that have minimal protection and ability to afford artificial defence (Nunn *et al* 2021), or these activities may no longer be considered ideal for livelihoods, leading to abandonment. Accommodation (e.g., changing crops, planned migration, desalinated water supply, importing food) is often already the norm. Rural islands may be raised if the population can be concentrated on one island to make it financially viable (albeit this may occur in the distant future, see Section 4) or where revenue could be generated (Bisaro *et al* 2019). As a planned accommodation method, existing rural to city migration could be reinforced (figure 8, pink arrow).

Large port facilities and energy infrastructure (figure 8(i) to (l)) are estimated to require just two islands nationally, protected to high standards or enhanced through raise or advance, and this would be economically affordable. Whilst building new islands is relatively cheap, replacing infrastructure is more costly (Bisaro *et al* 2019) so this needs to consider the infrastructure's lifetime, and long-term SLR (figure 7(j) and (l)).

Urban islands (figure 8(m) to (p)) are likely to consider advance or raise when protect and accommodate approaches have been exhausted (figure 6 and figure 7). As illustrated here, maintaining two of three islands provides a simple solution to sustain the capital, if well connected with food supplies and desalinised water (as is already the norm in urban islands today). In this scenario, the third island allows for the planned and slow movement of people, a decision taken by choice, rather than it being an enforced process. The more general principle is that island advance and raise greatly increases adaptation options in an acceptable way to Maldivian society.

Tourist islands (figure 8(q) and (r)) that have not been subject to land advance may be morphologically compared with agriculture or rural islands, but economically to urban areas as they generate large revenues: Pay-back times of investment are typically less than 10 years (Becken *et al* 2011). More costly adaptations can ensue: sea walls, and especially soft measures of beach nourishment, land raising and advance, as well as infrastructure renewal (figure 8(q)). As islands are leased to operators for a few decades, response will be controlled more by extremes and erosion (which can often occur on short timescales), rather than SLR. Over time, if flooding or erosion is too severe, alternative islands may be designated or created as tourist islands or new islands constructed (figure 7(r)), particularly where coral reefs which attract tourists are not projected to experience coral bleaching during extreme sea temperature events (Hoegh-Guldberg 2011, Hoegh-Guldberg *et al* 2018, Schuhmacher *et al* 2005, Shakeela and Becken 2015). Furthermore, as tourists are expecting islands to look 'natural', emulating natural processes (e.g. Masselink *et al.* 2020) will be increasingly important as the pace of SLR quickens. Hence, changes in preferred tourist areas and tourist preferences would seem almost inevitable, providing another key change factor to consider (see Section 5). Thus, adaptation is possible across land use types that is consistent with existing development trends and driven by choices made by the Maldivian population.

4. Discussion

Section 3.4 presented an illustrative technical approach of land advance/raising and adaptation pathways that would allow an atoll nation such as the Maldives to persist in the long term, but it did not consider the wider practicalities. Successful adaptation solutions also need to consider policy, human, wider physical/engineering and financial/economic challenges (Hinkel *et al* 2018, Duvat *et al* 2022; Magnan *et al* 2022), driven by local choice. This section deliberates those multiple challenges and how they may be overcome. It also considers how island advance/raising is being used more broadly as a means to serve to a range of needs.

4.1 Policy challenges

Land raising/advance through an adaptation pathways approach will not be successful unless appropriate socio-political-financial policies are established from the top-down and bottom-up perspectives (figure 9), including aligning with wider development needs. To achieve this, broad stakeholder support is needed so that the adaptation goal is widely shared and collective. This increases the potential to develop and sustain a pathway approach through shared values, ownership, investment, learning and monitoring (figure 9, middle box) to allow future choice, even at a cost today. Within the Maldives, long-term SLR risk is acknowledged by all, but more pressing development needs take precedence today. Social (Barnett *et al* 2014), governance (Bosomworth *et al* 2017), ecological (van Ginkel *et al* 2020) and physically orientated (Rosenzweig and Solecki 2014) events including SLR, plus disasters (e.g. 2004 Indian Ocean tsunami – Riyaz and Park 2010), act as trigger mechanisms and tipping points where a change in approach is possible. Steps of change need to be planned for balanced with the known risks and regularly communicated to stakeholders so they do not appear as a surprise.

4.2 Human challenges

Migration can be seen as a means to adapt or as a failure to adapt in situ (Lietaer and Durand-Delacre 2021, McMichael *et al* 2019, Vinke *et al* 2020). This raises questions of scale, and whether land advance/raising and associated movement of people restricts loss and damage as the population is contained within one country, or whether migration is a product of loss and damage as people move away from their homes to another island. As Mayer (2017) states, loss and damage arises not due to the migration outcome itself, but the circumstances in which it occurs, such as where there are inadequate frameworks to protect migrants and the receiving communities. For example, the Maldives has used population consolidation through the Safer Islands programme (Riyaz and Park 2010) in response to tsunami threats and to improve infrastructure. This reduced risk, prevented potential future loss and damage and aligned with development plans. However, it is not without financial and human cost, such as socio-political integration (Shaig 2008). Government-led relocation no longer features in policies (Gussmann and Hinkel 2020). Furthermore, to reduce loss and damage, movement between islands would need to effectively manage losses in land tenure, political representation, cultural decline, identity, education, and employment represented challenges, language, place names, customary practice, tradition, cultural obligations of land custodianship and solidarity that bind people and place, as these factors have been found to cause challenges in other migrating nations (e.g. Adger *et al* 2013, Donner 2015, Jarillo and Barnett 2022, Mortreux and Barnett 2009). Cultural factors are particularly important, including land, relocation and religion being key factors determining or hindering the want or need to migrate (Oakes 2019). Where finances and legal abilities allow relocation (Oakes 2019), preservation of language, diet and existing communities (Heslin 2019) within the area that migrants move to is critical, as is support for receiving communities to enable integration. Movement between islands with land advance/raising needs to be planned to align positively with other needs and gain societal acceptance, thus minimising loss and damage.

4.3 Physical and engineering challenges

The non-human adverse impacts of land advance/claim are noted in Table 2. For advance/raising to be successful, adverse impacts need to be overcome or significantly mitigated. For example, artificial reefs have previously been considered in the Maldives

(Clark and Edwards 1994, Clark and Edwards 1999), but their success is subject to debate (Higgins *et al* 2022). Around the Maldives and Indian Ocean more generally, the ability of reefs to respond to observed SLR is site specific, depending on sediment supply (East *et al* 2018) and rates of SLR (Perry *et al* 2018). Additionally, although land may be advanced in one location today, rising temperatures may make the island less desirable to live on. Hence, constructed islands should be no larger than natural islands, to allow the cooling benefit of sea breezes across the entire island.

Groundwater volume and quality is a key resource on atolls. The height of groundwater is dependent on changes in precipitation, evapotranspiration, waves and SLR. It can be near the surface rising and falling with the tide (Kane and Fletcher 2020; Oberle et al 2017), especially during spring tides where localised ponding may result (Beaven et al 2017). Storlazzi et al (2018) projected that due to SLR and wave dynamics on reefs, saltwater flooding from overwash events would become more common, reducing the ability of aquifers to recover between events, thus leading to salinisation of groundwater. Reduced freshwater can lead to challenges on land for drinking water and the ability of agriculture and other day-to-day activities to survive. However, as seen on urban and tourist islands today, especially those undergoing development, imported, desalinised and rain water are essential in everyday living, with desalinisation plants increasing from two in around 2002 to 39 in 2018, plus others on tourist islands (Ibrahim 2002, Moosa 2021). With more challenging groundwater conditions, this could become commonplace, including on islands with lower population densities, thus reserving groundwater for other essential activities.

Nevertheless, freshwater availability is essential to consider in the long-term outlook and could have a greater impact of livelihoods than flood events themselves. Modelling studies of

Maldivian islands indicate the freshwater lens reduces in size more and has greater variability with SLR in small islands than in large islands (Alsumaiei and Bailey 2018), and is also worse for small islands during the dry season (Bailey et al 2014). Reclaimed land can have higher permeability than naturals sands, leading to larger variations in salinity and greater inundation (e.g. as found in Tuvalu by Nakada et al 2011). Hence, rising sea levels pose a threat to freshwater in atolls worldwide (Bosserelle et al 2022) which could be intensified in artificial settings, leading to a greater reliance on imported or desalinised water.

Designing islands presents engineering challenges, such as potential consolidation, sand type and availability, sedimentation patterns and scour, with consideration of transportation between islands needed. For example, a greater number of bridges connecting islands could increased vehicle use and this needs to be considered. Whilst sand is an increasingly precious resource (Bendixen *et al* 2019; 2021), atolls have large sand reserves, and developing dredging technology to access deeper water depths will increase these resources further, subject to environmental impact assessments. Sand also has the potential to be imported. There is scope for much further technical innovation. For example, rather than abandoning islands, can islands and their infrastructure be designed to be raised with SLR, potentially avoiding the need for migration? Similarly, floating islands (Drummen and Olbert 2021, Flikkema *et al* 2021, Proetzel 1983, Souravlias *et al* 2020, Tamis *et al* 2021) might be explored with similar benefits.

4.4 Financial and economic challenges

Innovative funding and financing methods are needed (Hinkel *et al* 2018). This could comprise levies on hotel stays, sand use and international flights (with the dual aim to reduce emissions), or higher prices for buying advanced or claimed land. As SIDS develop, their higher adaptation costs need to be continually recognised whilst noting the detrimental effect if adaptation is not fully financed. Growing and urbanising populations allow for concentration of wealth, and thus pooling of finance to adapt to SLR. As climate impacts emerge, adaptation needs will become apparent in ways not seen today. For instance, rising sea temperatures and coral bleaching and mortality will likely profoundly change the Maldives' tourist industry. Pressure on emissions from flights could reduce European tourists, but allow increased tourism from south Asia as flight distances are shorter. Thus financing adaptation needs to be suitable for the present and over longer timescales, when conditions may be quite different.

4.5 Adapting islands

Land advance/raising can be applied more widely, including in other atolls (for example, in Tarawa, Kiribati - Watkin *et al* 2019 and the Marshall Islands - Letman 2018) and other island types (see Section 1). Table 3 illustrates how islands (typically less than 1km in length) have been used as part of development, typically for transport needs (e.g. deep sea ports and airport runways) and for tourism (e.g. marinas). Presently, none appear to primarily use land advancing solely as a means to protect against SLR, although this may be integrated into the design. Hence, as with Hulhumalé, solutions to SLR are a by-product of development needs, and through land advance have great potential to be integrated into coastal management.

4.6 Islands as adaptors

More diverse adaptation solutions are needed in coastal areas as demand for adaptation grows (Magnan *et al* 2022). Creating and raising islands as the means to adapt has the potential to dissipate waves and act as artificial barriers. Figure 10 indicates how islands can be used as defence structures along urban coasts. These configurations are largely theoretical, and extensive modelling and analysis will be needed to minimise adverse environmental impact. However, some of these ideas are starting to appear in practice, such as the planned creation of Lynetteholm island, Copenhagen in Denmark (BBC 2021). In delta regions, sand is used to nourish existing islands or wetlands, to reduce local erosion and flooding in the wider delta. For example, Scofield Island, Mississippi Delta, Louisiana has undergone nourishment to create land (Erwin *et al* 2007, Prosser *et al* 2022,), improve habitat and act as a protective measure to those exposed (Benedet and Pierro 2019, Joffrion *et al* 2015). Maintenance and construction of new islands is likely to feature more in the future with SLR and other pressures.

5. Conclusion

Atolls as geomorphic features and their populations are dynamic. There has long been a significant mobility of population associated with island life. More recently, as seen globally, rural to urban migration in the Maldives has increased, especially to the capital island. This development trend is likely to continue regardless of climate change. Growing population densities mean more space is needed in urban areas and a common solution to this is land advance (claim) – and with the recognition of sea-level rise (SLR), a trend towards raising as a means to adaptation.

Atolls change morphologically in time and space, with floods depositing sediments that allow island height to increase. Inundation via flooding promotes this process which allows reefs to respond to observed SLR. Climate mitigation will slow but not completely stop rising sea levels, so adaptation is also essential. To survive under SLR, islanders could enhance Nature's response by raising and advancing land. By aligning with development strategies as sea levels rise, raising and advancing land can lead to dual wins. This could create habitable space, especially if planned in the long term following an adaptation pathway approach. To an extent, this has already started around the capital of Malé through the building of the new island of Hulhumalé, and our conceptual ideas illustrate the potential of this approach if applied systematically to the Maldives or elsewhere.

This paper presents a starting structural adaptation framework for atoll adaptation using land raising and advance. In addition to the technical aspects the policy, human, physical and engineering, financial and economic dimensions must be considered to ensure the approach is appropriately designed and implemented, and ultimately successful. The ideas presented here are a starting point and provide a development and adaptation blueprint for island communities to develop innovative and positive solutions that have the potential to allow them to remain on these islands for many centuries. The approach includes local human mobility (i.e., migration) as a key component to allow raising to occur. Nonetheless, land advance/claim provides an approach for Maldivians to remain in the Maldives as sea levels rise over centuries, provided that they wish to do so.

For development and economic reasons, the number of artificial islands globally is growing, so experience in the Maldives illustrates a wider trend. Thinking more broadly, artificial islands have the potential to be built high enough to withstand SLR, and also provide/sustain protection, such as acting as breakwaters/barriers for the mainland. By taking account a broader range of human interventions and non-climatic drivers of change, this radically alters the IPCC's (2019) burning embers perspective that impacts of SLR will be very high in corals, although with reduced environmental quality. However, this island raising concept is not a reason not to mitigate for climate change and further efforts are essential to reduce risks. Atoll nations, such as the Maldives may not drown with SLR as often perceived by the media, and with transformational adaptation can remain a thriving nation long into the future, albeit a reshaped one compared to what exists today. Island raising and advancing thus provides a positive future for island nations and expands the adaptation and development options far into the future.

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Author Contributions

SB, AB and RJN designed the research question, based on input from AS and ZK. OB, AC, SF, LG, MP, MS and JW undertook most of the research (which SB and RJN further developed) and led the background, methods and results surrounding Case I. SB wrote the manuscript with input from RJN, with further contributions from all authors.

Competing Interests statement

The authors do not have any competing interests. This article presents an illustrative example for moving between islands to cope with SLR, and is not part of Maldivian government policy. This work was undertaken at the University of Southampton by all authors except AS and ZK. It does not reflect the views of subsequent organisations that all authors have moved to.

Data availability

No new data was generated in this paper. Model inputs that are freely available and not commercially sensitive can be found in Wadey et al. (2017) and Brown et al. (2020).

Ethics statement

Not applicable.

Figures

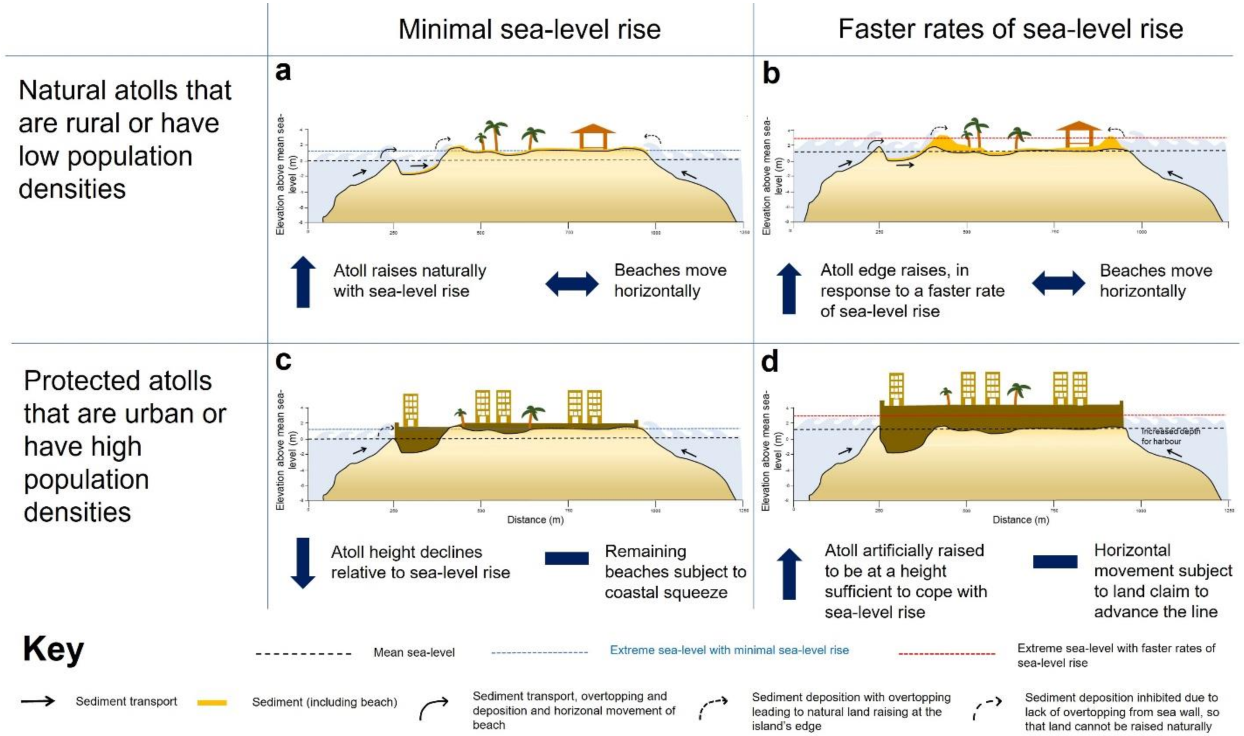


Figure 1. Stylised view of island evolution over the coming decades for natural and protected islands and its relationship to population density. Raising on the edges of rural islands occurs periodically with overtopping and sea-level rise, especially with higher levels of SLR projected, whereas raising in urban islands would occur in larger, discrete steps.

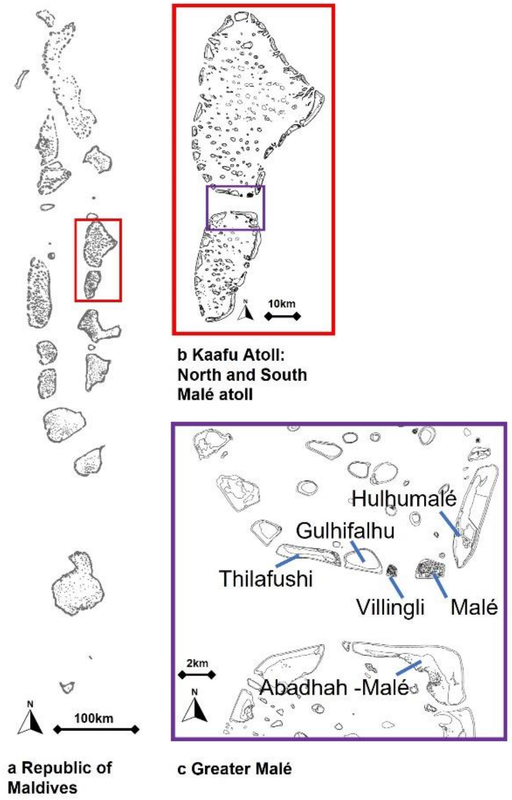


Figure 2. Map of the Republic of Maldives, including locations studied or referenced in this paper. a Republic of Maldives; b Kaafu Atoll; c Greater Malé, including the conceptual island case study of Abadhah-Malé. Outline data courtesy of Ministry of Environment and Energy and the Hulhumale Development Corporation.

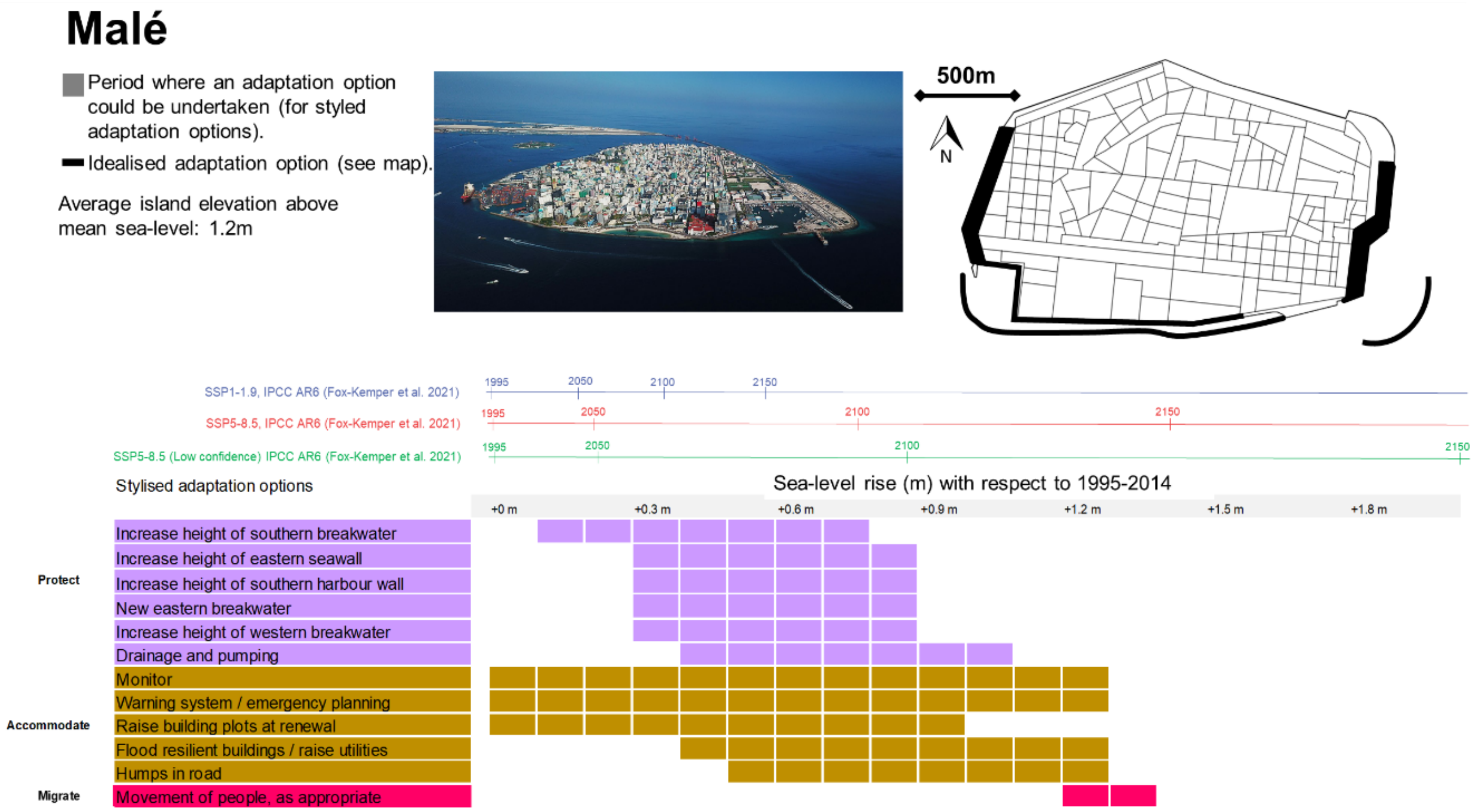


Figure 3. Stylised adaptation options for Malé to adapt to SLR. Photograph: Male, Maldives – 2017. Shahee Ilyas. Reproduced under CC BY 3.0.

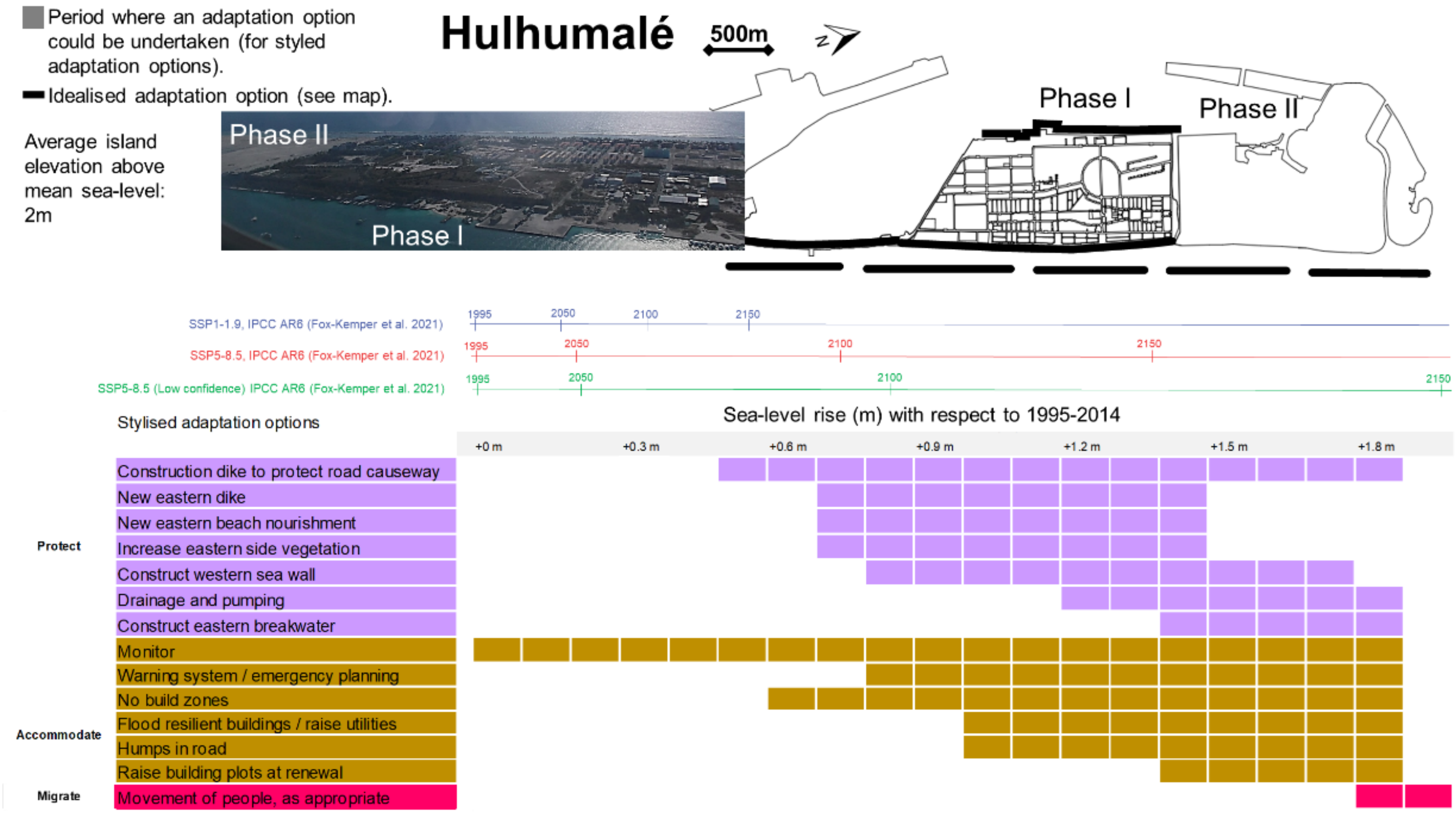


Figure 4. Stylised adaptation options for Hulhumalé to adapt to SLR.

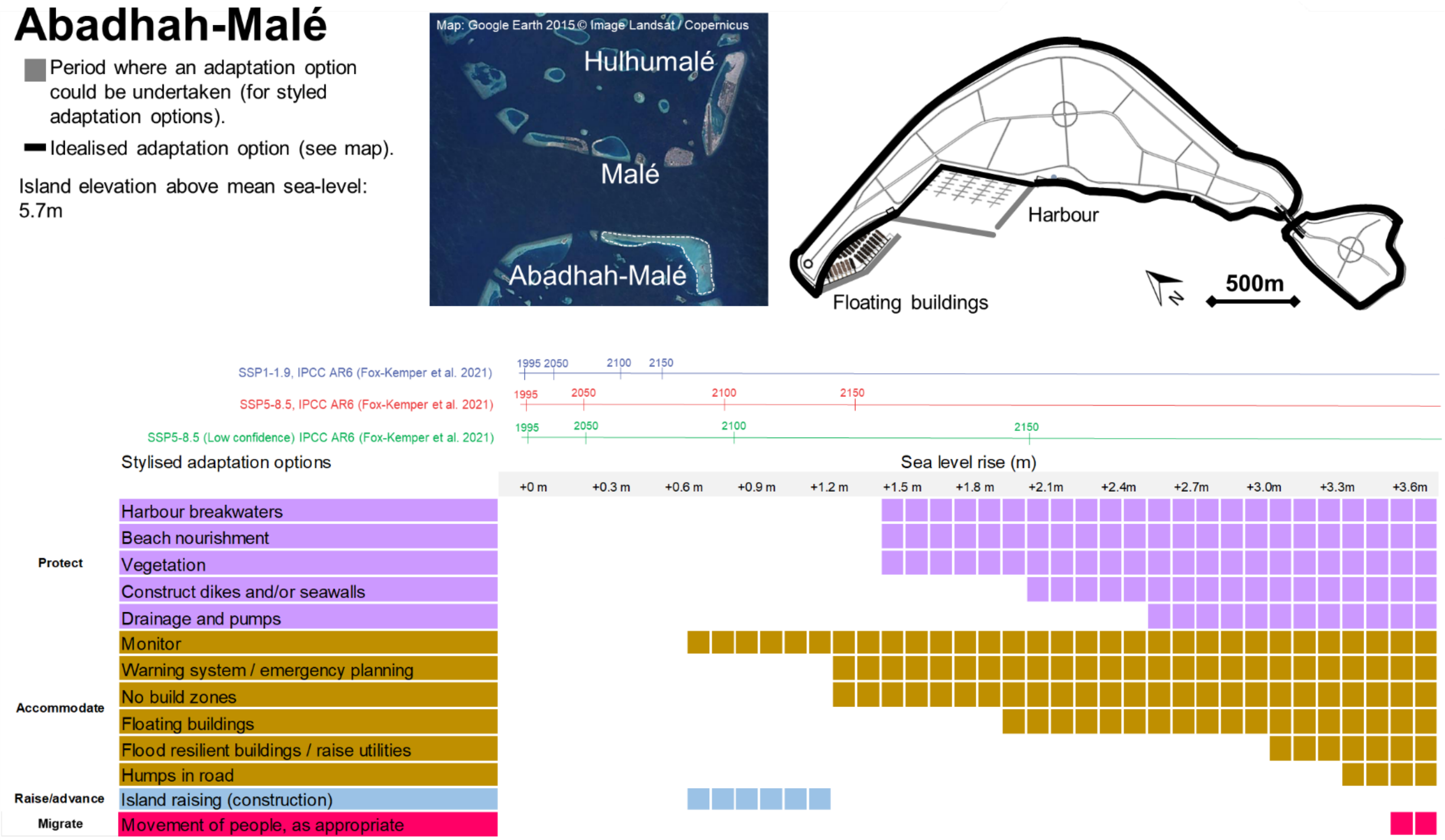


Figure 5. Stylised adaptation options for Abadhah-Malé to adapt to SLR. This is a conceptual island and other locations could be considered such as Villingli, Gulhifalhu and Thilafushi to the west of Malé.

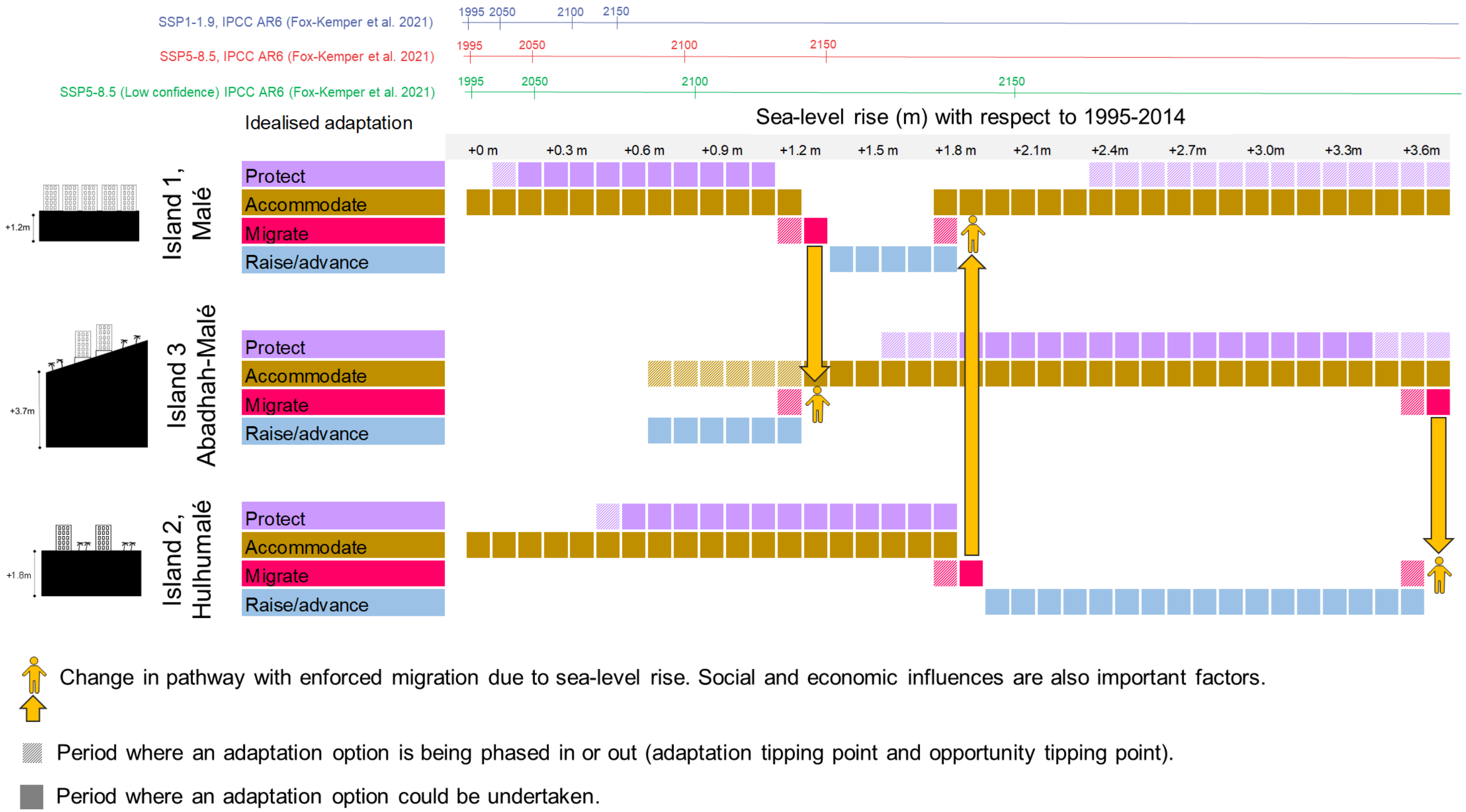


Figure 6. An illustrative adaptation pathway approach with SLR for the capital three-island system (Malé, Hulhumalé and Abadhah-Malé) through land raising and migration between the islands up to about 6m of SLR – the adaptation pathways shown can continue under higher sea levels. Information systems include early warning and transformational adaptation include raise and advance.

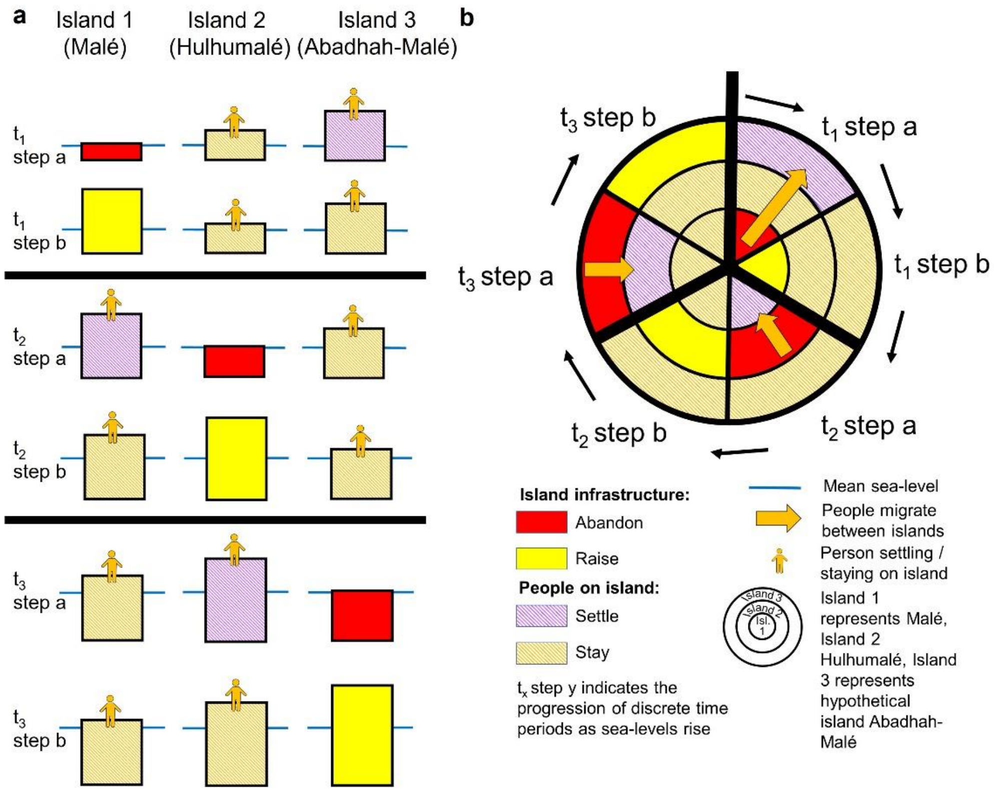


Figure 7. Time evolution of the proposed adaptation pathway for the three islands making 'Greater Malé' which can then repeat if needed. Only two out of the three islands are populated at any one time, whilst the third island is abandoned (uninhabited), then raised. a) Schematic of potential island abandonment, raise, settle (habitation) and stay (habitation); b) The cycle of island raising and population migration through abandon, raise, settle (habitation) and stay (habitation).

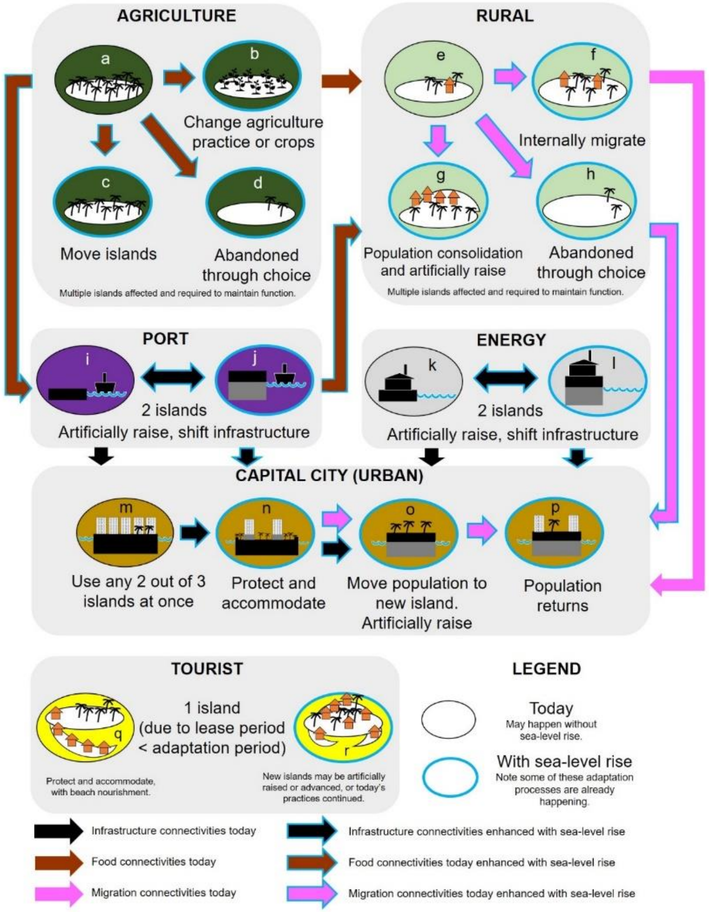


Figure 8. Adaptation approaches due to sea-level rise for islands with a dominant land use type. Collectively, this approach could sustain an entire atoll nation.

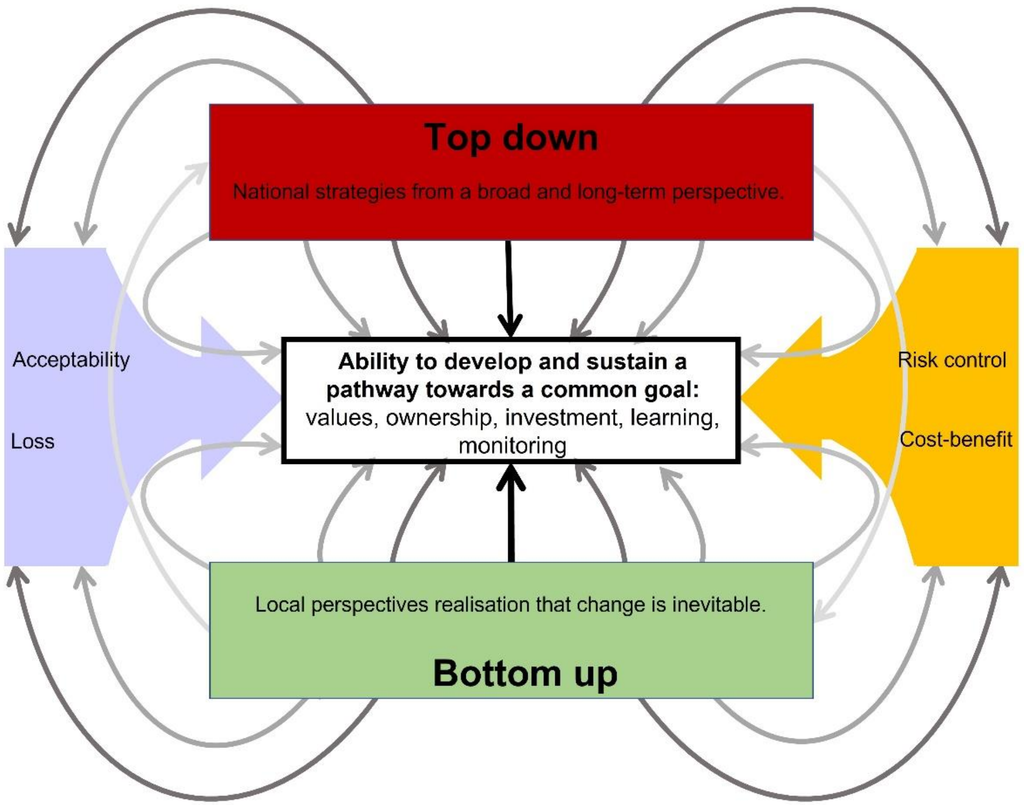


Figure 9. Enabling and sustaining adaptation pathways requires many multiple elements bound by stakeholders as interveners, from the top down and bottom up, balanced with socio-political values. Taking a pathway approach forward spans generations that can benefit from the formation of a common goal that rises above individual and single generation interests.

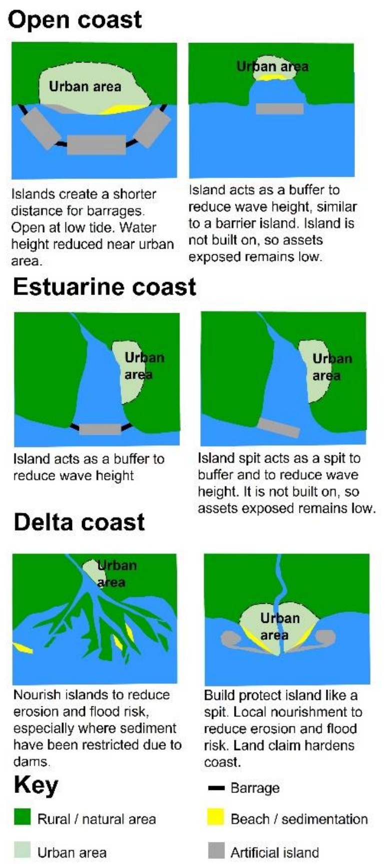


Figure 10. Generalising the approach across a range of geomorphic settings, islands can act as protective features to reduce the affects of wave inundation or sea-level rise. Yellow = Beach nourishment. Grey = Land advanced areas.

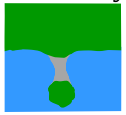
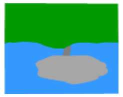
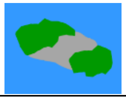
Table 1. Climate change adaptation options in four categories and their adaptation tipping points indicating the start and end point (in terms of SLR thresholds) when an adaptation option may be suitable for each of the three islands. Based on data presented in Brown *et al* (2020).

	Type of adaptation	**Malé**	**Hulhumalé**	**Abadhah-Malé**
Protect	Breakwaters	● (orange)	● (black)	● (red)
	Dikes	-	● (green)	● (red)
	Drainage and pumps	● (orange)	● (black)	● (red)
	Beach nourishment	-	● (green)	● (red)
	Sea walls	● (orange)	● (green)	● (red)
	Vegetation	-	● (green)	● (red)
Accommodate	Raise building plots at renewal	● (orange)	● (black)	-
	Floating buildings	-	-	● (red)
	Flood resilient buildings / raise utilities	● (orange)	● (black)	● (grey)
	Humps in road	● (green)	● (black)	● (grey)
	No build zones	-	● (green)	● (black)
	Monitor	● (orange)	● (orange)	● (black)
	Warning system / emergency planning	● (orange)	● (green)	● (black)
Migrate	Movement of people, as appropriate	● (green)	● (black)	● (grey)
Raise/advance	Island raising	● (black)	● (red)	● (grey)
Key				
-	Adaptation measure not suitable, physically or financially viable			
● (orange)	Possible adaptation measure with 0m-0.5m of SLR			
● (green)	Possible adaptation measure with 0.5-1m of SLR			
● (black)	Possible adaptation measure with greater than 1.0-2.0m of SLR			
● (red)	Possible adaptation measure with greater than 2.0-3.0m of SLR			
● (grey)	Possible adaptation measure with greater than 3.0m of SLR			

Table 2. Non-human potential adverse impacts of land advance/claim from coastlines worldwide.

Topic	Impact	Reference
Habitats and species	Reduced biodiversity footprint Reduced levels of biodiversity Algae blooms Reduction in reef and lagoon area Carbon management	Jones *et al* (2007), Slamet *et al* (2020), Wang *et al* (2014), Zainal *et al* (2012)
Sediments	Siltation Reduced visibility in water column Use of sand resources Sediment movement Pollution and heavy metals	Bendixen *et al* (2019), Flemming and Nyandwi (1994), Lee *et al* (2014), Martín-Antón *et al* (2016), Sovacool *et al* (2015), Smith *et al* (2019), Wang *et al* (2014)
Hydrology and geophysics	Changes in local levels Increased flood risk where advanced land is lower than original Water storage capacity	Healy and Hickey (2002), Liu *et al* (2019)
Engineering	Subsidence (post-advance/claim) Earthquake-related liquefaction	de Mulder *et al* (1994), Martín-Antón *et al* (2016)
Legal	Shipping Sovereignty	de Mulder *et al* (1994), Dolven *et al* (2015), Koh and Lin (2006), Zhang *et al* (2017)

Table 3. Land advance and raising in other island settings. Green indicates original land area, grey land that is advanced or raised, dark grey is a bridge, hashed area is land removed.

Island adaptation	**Terrain**	**Bathymetry**	**Justification for advance and raise**	**Island classification**	**Example**
Joined to mainland via causeway 	Low-high Flat - Steep	Shallow and plentiful space	Raise around land and island rim. Advance to connect to main to island	Tidal, barrier (less likely due to land size v size of causeway), coral, volcanic (shallow depths only)	Ashton, St Vincent and the Grenadines. Tekong Island, Singapore. Victoria, Seychelles.
Bridge to mainland: from artificial island or selective island advance. 	Low-high Flat - Steep	Shallow or deep water	Advance and raise through artificial island. Bridge allow connectivity. Maintains flushing of water and shoreline length for tourism	Tidal, barrier, coral, raised limestone, artificial	Eden Island, Seychelles. Maehara, Shirumichu Park, Japan.
Connection via advance 	Low-high Flat - Steep	Shallow or deep water	Advance and raise to desired level. Ideal for deep sea ports	Tidal, coral, volcanic, raised limestone, composite	Deep Sea port, Shanghai, China. Jurong Island, Singapore
Advance and selectively raise	Low-high Flat - Steep	Shallow water to advance. Deep	Raise around rim in steep islands. Advance has	Tidal, coral, volcanic, raised	Malé, Maldives. Woody, Paracel Islands.

		water raise or limited advance	greater reach in shallow water. Advanced limited to ports or runways in deep water	limestone, composite	Basseterre, Saint Kitts. Forte de France and airport, Martinique. Various in Singapore e.g. Queenstown
Artificial or floating 	Artificial island low and flat	Typically shallow	Raise to create new space for housing, tourism, territory or military reasons	Tidal, coral, barrier, artificial, floating	Palm Islands, Dubai, UAE. Hulhumalé, Maldives. Fiery Cross Island, South China Sea. Busan (proposed), South Korea.
Remove and extend 	Low and flat (could start with natural or artificial island)	Shallow	Remove part of an island and advance seaward with channel to increase coastline length for mooring	Tidal, some coral, floating and artificial	Nanny Cay, British Virgin Islands. Eden Island (after construction), Seychelles

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