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Angaben zur Veröffentlichung / Publication details:

Singh, Simron, Sabrina Linsmaier, Charvi Choudhary, Lars Wietschel, Aisha Azfa, Dominik Wiedenhofer, Shazla Mohamed, and Andrea Thorenz. 2026. "Material requirements for adapting to climate change in the Maldives." *Scientific Reports* 16: 34955. https://doi.org/10.1038/s41598-026-61428-3.

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Material requirements for adapting to climate change in the Maldives

Singh Simron[1]✉, Linsmaier Sabrina[2], Choudhary Charvi[1], Wietschel Lars[2], Azfa Aisha[3], Wiedenhofer Dominik[4], Mohamed Shazla[5] & Andrea Thorenz[2]

Small Island Developing States (SIDS) are on the frontlines of climate change, making adaptation increasingly urgent. This growing challenge is driving the implementation of reactive hard engineered adaptation measures, which can be distinguished by two major strategies: shoreline protection such as breakwaters, groynes, and revetments, and the other by reclaiming and raising land. While these measures may mitigate the immediate impacts of climate change, they demand significant quantities of materials - much of which are imported - potentially exacerbating systemic risks and creating long-term lock-in effects. Herein, we analyze material requirements for climate adaptation in the Maldives from the year 2000 to 2100. The Maldives are a low-lying island nation with ~0.5M inhabitants and an average height of one meter above sea level, susceptible to rising seas and wave surges. Using GIS-based material stock and flow analysis, we quantify materials required for the two hard adaptation strategies: shoreline protection and the reclamation and raising of islands that depend on large-scale seabed dredging and material imports. Possible future material requirements are estimated by scenario modelling considering sea level rise (SLR) and political responses. Results indicate that hard-engineering adaptation projects are highly resource-intensive and reinforced by further adaptations to rising seas, as well as greater wave exposures. This escalating cycle of material demand for climate adaptation in the Maldives is driving material lock-in effects which amplifies economic risk and perpetuate import dependencies.

Keywords Climate adaptation, GIS-based material stock and flow analysis, Socio-metabolic risks, Small island developing states – SIDS, Maldives

Small Island Developing States (SIDS) are sites of multi-hazard and cascading risks. Contributing less than 1% to global greenhouse gas (GHG) emissions, they are disproportionately affected by the impacts of climate change[1–3]. Threats such as sea-level rise, extreme weather events, and environmental degradation are exacerbated by their smallness, geographical isolation, limited resources, and tight socio-ecological coupling, where small or single events can set in motion a series of cascading impacts. As a result, SIDS serve as early warning systems for global climate trends and are often referred to as a global barometer of climate change[4].

The climate change exposure of SIDS is reflected in their ranking on the *Notre-Dame Global Adaptation Index* (ND-GAIN), which identifies them as 10 out of the 19 most climate-exposed countries[5]. Between 1970 and 2020, SIDS incurred collective losses amounting to US$153 billion from weather-, climate-, and water-related hazards, which emphasizes the consequences of converging intrinsic and climate-change-related vulnerabilities[6]. These losses have led to significant financial challenges, with 40% of SIDS now burdened by unsustainable debt levels and public debt ratios exceeding 40% of GDP in 70% of these nations[7]. Adapting to climate change is currently resulting in additional expenses for many SIDS. According to the 2024 Adaptation Gap Report, SIDS have the highest per capita adaptation finance needs globally, amounting to 3.4% of their collective GDP[8].

Sea-level rise is one of the most crucial aspect of escalating climate change impacts for SIDS, driving the need for adaptation. The IPCC report states that adaptation strategies to prevent key-risk #5 (i.e., the destruction of settlements and infrastructure), are hard (shoreline) protection, accommodation and advance, migration, and ecosystem-based measures[9]. In this article, we focus on the Republic of Maldives, a low lying reef atoll state in the Indian Ocean. Maldives is particularly prominent, since it has a long history of consolidating the dispersed

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population, along with implementing hard shoreline protection, land reclamation, and land raising for adaptation and development purposes[10]. The Maldives decided to prioritize adaptation through extensive expansion of shoreline protection, including breakwaters, groynes, and revetments coupled with land reclamation and island raising[11–13] (see Methods for their definitions). Implementing engineered measures requires substantial material, financial, and technological resources – all of which are scarce on SIDS. Consequently, they rely heavily on imports for construction materials, which are increasingly threatened by volatile global supply chains, rising transportation costs, and geopolitical challenges.

In this article, we quantify the Maldives' current and future material needs (from 2000 to 2100) for adaptating to sea-level rise (SLR) under various warming scenarios. We address the following research questions:

1. What are the current and future material requirements for islands like the Maldives to adapt to rising seas?
2. What systemic risks are associated with material lock-in effects in the Maldives as a result of adapting to SLR?

To answer these questions, we draw on resource-use accounting methods from the interdisciplinary field of industrial ecology to quantify the material stocks and flows associated with SLR-associated adaptation[14–16]. Industrial ecology is a field of research that offers a biophysical reading of the economy by tracking resource-use through socio-and-industrial systems in space and time, to improve resource efficiency and to reduce environmental impact.

For the Maldives, publicly available data was used to quantify material demand for engineered adaptation measures. For shoreline protection, including breakwaters, groynes and revetments, we use technical specifications and the spatial dimensions of these constructions, and for land reclamation we retrieve new land areas from satellite imagery and a mean material intensity from literature. Materials accumulated as so-called "in-use material stocks" were quantified up to 2024, as well as typical technical lifetimes for each construction.

Using 2024 as our baseline, we derive scenarios that aim to draw different possible futures for the Maldives' material needs. The results are presented as (a) *Scenario 1*, where no further adaptation or new construction is needed, except to maintain existing constructions as of 2024, (b) *Scenario 2*, that includes active adaptation solely in response to rising seas, and (c) *Scenario 3*, that is motivated by proactive expansion to meet adaptation as well as development needs. To account for SLR, we calculate annualized material requirements following the bathtub approach. We calculate material stocks and flows using dynamic, stock-driven "bottom-up" modelling[17,18], from the year 2000 to 2100. Eventually, we discuss their environmental impacts qualitatively. For the expert reader, we point to the Methods section, and SI-A for definitions, methodological details, and codes used in this study.

Study context

Socio-economic overview and climate threats in the Maldives

The Maldives encompasses an area of 115,300 km^2, of which however only 1% is land. Scattered across roughly 1,500 coral islands[19], it is among the flattest and most densely populated countries in the world, with an average elevation in the range 0.5 m to 2.3 m above mean sea level[20]. The vast Exclusive Economic Zone (EEZ) of the country with an area of 916,000 km^2 houses 3% of the world's reef area and forms the seventh largest reef system[21]. They are among the richest in the world in terms of species diversity, serving the major economic activities. The reefs surrounding the islands also have a critical function in the form of coastal protection[22].

The population of the Maldives is approximately half a million, of which 41% resides in the Greater Malé area, while 62% of the 198 inhabited islands recording fewer than 1,000 residents[23–25]. The economy is heavily reliant on tourism, which contributes 22.5% to GDP, followed by transportation and communication at 12.8%, while fisheries and agriculture account for only 2.4% and 1%, respectively[26]. The country imports most of its food, energy, construction materials, and consumer goods with a value of imported goods summed up to US$ 4,074 billion in 2023. With the exception of sand, all construction materials are imported, amounting to US$ 548 billion in 2024, mainly from India, China, and the United Arab Emirates[27].

Climate change poses significant threats to the Maldives, where especially rising sea levels endanger its many low-lying islands, of which 80% are less than one meter above sea level[28,29].

According to the Country Climate and Development Report (CCDR) for the Maldives, major climate change impacts include sea level rise induced coastal inundation, increased frequency of extreme flooding events, and coastal erosion[30]. Flooding incidents following periods of intense rainfall is demonstrating an increasing trend, with over 1,200 households directly affected in 2024[31]. Moreover, the severity and frequency of observed erosion incidents have increased over the years. Rising sea levels also leads to salt-water intrusion affecting the shallow ground water lenses threatening the limited fresh water resources available. The surrounding coral reefs are at risk due to gradual warming of sea water leading to coral bleaching, alongside pressures from human induced pollution, limiting the islands' ability to accumulate sand[30]. Due to the atoll structure, some islands, particularly those on ocean-facing rims are directly exposed to long-period swell waves from the Indian Ocean, while lagoon-facing areas are relatively sheltered[32,33]. Islands that are highly exposed to wave action experience more frequent and intense inundation, especially during monsoon seasons and high tides. Sea-level rise compounds the effect with wave energy penetrating further inland, increasing flooding risk even in areas that were previously not exposed.

Past and current efforts in adapting to climate change in the Maldives

Responding to this climate crisis, the Maldives over the past three decades has adopted various adaptation strategies, largely focused on hard-engineering solutions. Our analysis includes breakwaters, groynes and revetments, which clearly can be ascribed as hard shoreline protection, and land reclamation projects[34]. Seawalls are not taken into account, as our method does not allow a distinction from quay walls, which are an integral component in port construction and thus constitute a development measure.

Here we provide contextual information on some of the key climate change adaptation efforts in the Maldives over the last three decades. Our assessment bases on the state owned *Maldives Transport and Contracting Company* (MTCC), which is heavily involved in shoreline protection and and dredging activities[35]. Based on a detailed documentation on all implemented shoreline protection and land reclamation and raising projects by MTCC, the majority of projects were conducted between 2015 and 2023. From 2015 onwards, there was a marked increase in the use of revetments[35] (Figure 1), which are particularly effective for deflecting waves and stabilizing shorelines[36]. We additionally observe a consistent usage of breakwaters across all years, likely due to their versatility, durability, and suitability for both onshore and offshore applications.

While shoreline protection by breakwaters, groynes, and revetments along with the adaptation and development measures of island reclamation and raising have been a feature since the 1990s[23], documented projects lack critical details on protection type, material, and cost. The *Population and Development Consolidation Program* (PDC) launched in 1997 can be seen as an important starting point for SLR-adaptation in the Maldives[23], that was aimed to consolidate the country's population to limited islands. The reason for this was to concentrate and facilitate access to employment opportunities and essential social services, while also optimizing the cost and the use of infrastructure[37]. In other words, the PDC's approach to centralize population and optimize geographic space was in effect balancing development with the Maldives' unique environmental constraints. Consequently, our analysis focuses exclusively on trends since 1997 until 2024, a period marked by societal changes, and both internal and external pressures, as indicated by socio-economic and environmental relevant events shown in Fig. 1.

The 2004 Indian Ocean tsunami was a setback to the Maldives in terms of economic losses and revitalization of the economy. The tsunami highlighted the extreme vulnerability of the Maldives' ports and harbours, telecommunications, and water systems. The event resulted in a 33% decline in visitor numbers in 2005[44], with damages to transport infrastructure estimated at US$ 20.3 million[45], and over US$ 230 million to tourism infrastructure and businesses, with a total asset loss estimated at 62% of the nation's GDP[44].

We also observe that the losses together with the decline in revenue from tourism, aligns with the inactivity in adaptation initiatives in the post-tsunami period between 2004 and 2012[46]. A pivotal shift occurred in 2015, when climate adaptation efforts in the Maldives accelerated. Recognizing the urgent need for action, the government introduced policy frameworks and climate change adaptation surveys, signaling a shift in political and policy priorities. During this time, the country also identified a critical need for internal and external funding, leading to the establishment of the *Maldives Green Fund*, increased international support and securing financing such as the *Green Climate Fund* by 2019[47]. As a result, the number of projects for shoreline protection grew rapidly, peaking in 2020 at 42 projects.

The second pillar of the Maldivian adaptation model emphasizes land reclamation as a strategy to increase available land, while also mitigating the impacts of sea level rise[36]. Land reclamation especially refers to the horizontal extension of land (claiming land from the sea), serving development goals such as harbor development and housing of population[23,36]. The vertical enhancement by raising islands is also considered land reclamation

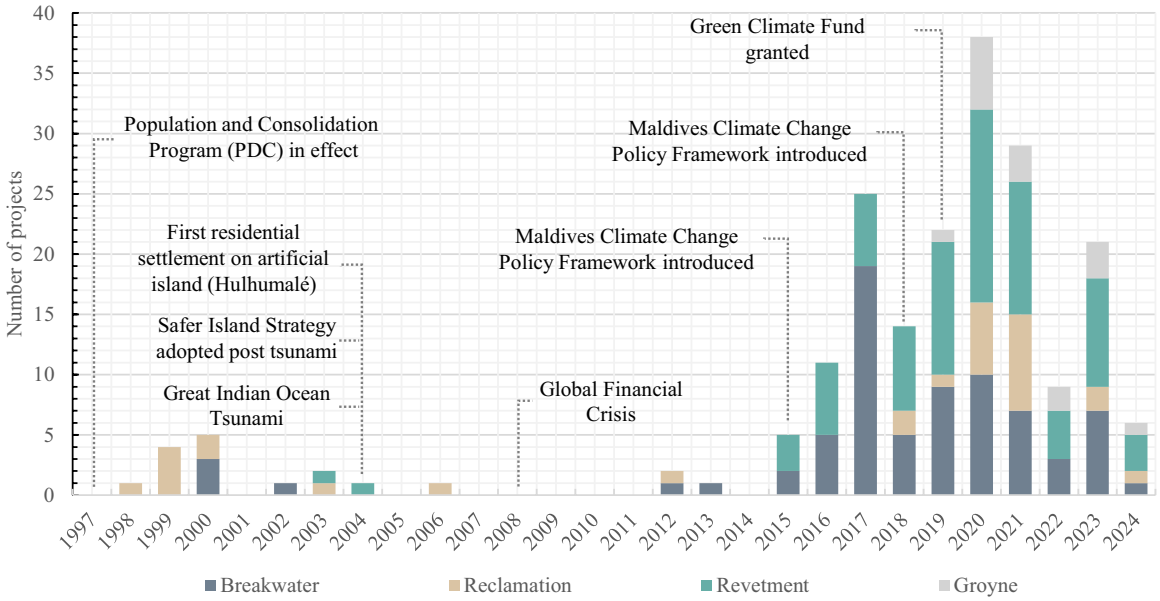


Fig. 1. Number of implemented shoreline protection and reclamation projects by type and year, as documented by the state-owned MTCC. In addition to the projects documented by MTCC, there may have been other projects for which, however, no structured information is available. The graph also includes relevant socio-economic and environmental events. Data for 2024 was collected in Aug-2024, hence includes projects that were active and documented up till Aug of that year. For updated project numbers see[35]. A detailed description on the shoreline protection types and land reclamation and raising including the relevant materials can be found in Table 1,2. Sources: [25,35,46,47].

and particularly serves SLR adaptation[11,34,48]. Whether land reclamation projects serve climate adaptation or development goals is contested. This debate has arisen due to unclear funding sources, that is, who should pay for these projects, the international community, or the island nations themselves.

Our position is that land reclamation projects may serve both goals: climate adaptation as well as development[11]. Even when land reclamation is exclusively accomplished for development goals, the implementation of hard shoreline protection is required due to the inability of artificial shores to accrue sediments[36,48–50]. In this sense, reclaiming land has been a driver for hard shoreline protection demanding additional reinforcement and finances to implement those. Moreover, SLR-associated raising of reclaimed land can be considered as an adaptation measure[11,36,49].

As the narratives of development and adaptation are tightly entangled in SIDS contexts, we consider land reclamation (advance and island raising) at the very least, an important driver for shoreline protection, and hence an adaptation strategy. A notable initiative in the Maldives is Hulhumalé, a reclaimed island designed to accommodate housing and infrastructure. It is built elevated to protect against the projected sea level rise until 2100 with outer edges 2 meters above todays level and thus serves both development and adaptation needs[51,52].

Based on satellite imagery evaluation, among the atolls, Kaafu (Northern and Southern Malé Atoll) stands out, with a remarkable total land expansion of approximately 8 km^2 - a 48% relative increase to 2019 area - most of which occurred in 2024 (see also SI - A Section "Results", Supplementary Fig. 1). This atoll, home to the nation's capital city Malé and major urban centers of Hulhumalé and Villimalé, has seen significant reclamation driven by the growing demand for residential, tourism, and industrial space. Similarly, Seenu (Addu), the second most urbanized atoll, has seen significant reclamation efforts, including the Addu City project, which created approximately 200 hectares of artificial land for housing and infrastructure[53] (see SI – A, Section "Results" for an overview of land expansion). Other atolls, including Ghaafu Dhaalu, Laamu, and Alifu Alifu, also experienced significant land area increases, particularly in 2024, reflecting the country's expanding tourism industry. Additionally, while area changes for Haa Alifu, Shaviyani, and Haa Dhaalu atolls are quite large, there are discrepancies due to reliance on the lower resolution of Landsat-8 data. A yearly analysis signals the accelerated pace of reclamation efforts in 2023 and 2024, particularly in urbanized regions.

Results

In this section we present the results of material demands for adapting to rising seas in the Maldives, based on three pathways, and as briefly mentioned in the Introduction: (a) *Scenario 1*, where no further adaptation or new construction is needed, except to maintain existing constructions as of 2024. Given the rapid shoreline protection development of the recent years and the ongoing SLR, we consider this scenario rather unlikely. Scenario 1 serves as benchmark for Scenario 2 and 3 which consider a future expansion. (b) *Scenario 2* includes active adaptation by increasing heights of existing hard engineered measures and reclaimed land in response to rising seas. This scenario assumes that existing shoreline protection measures will be maintained and adapted to rising sea levels, but no new projects will be initiated. Scenario 2 thus demonstrates that past decisions regarding shoreline protection will continue to require resources in the future if they are to remain effective. (c) *Scenario 3* is motivated by continuing land reclamation and fortification by shoreline protection to meet development and adapatation needs (see Table 1). The last decades show a trend toward a growing population in the Greater Malé Area[20,54]. Based on the historic trend, ground observations, and national predictions on further population increase in the Greater Malé Area in the coming four decades[55], we assume future reclamation projects taking place exclusively in the Greater Malé Area. Detailed information on the modelling and growth assumptions can be found in the scenario description of the Methods. The three are informed and derived based on socio-political context, as well as by *Shared Socio-economic Pathways* (SSP) as defined by IPCC's Sixth Assessment Report on climate change[56,57] on future SLR (for details, see Methods).

How much materials are currently stocked in the Maldives that support climate adaptation, and how much more will be needed simply to maintain these? (Scenario 1)

Based on data retrieved from MTCC, material stocks grew slowly (increase of ~1 kiloton) between 2003 and 2015, (Figure 2), reflecting a low number of shoreline protection projects during that period (consistent with Figure 1). However, between 2015 and 2020 we see a 17-fold growth, from less than 10 kt to nearly 160 kt in the same period. Between 2020 and 2024, approximately 90 kt of materials were added to existing stocks, reflecting a surge in shoreline protection projects. This period also coincided with significant geopolitical activity, marked

#	Assumption	Maintenance	Expansion	Uncertainty
Scenario 1	Observed number of shoreline protection projects and reclaimed land area stays constant until 2100; in-use stocks are maintained	Maintenance of in-use shoreline protection (SP) & land reclamation (LR)	No further expansion in existing SP and LR to adapt to sea-level rise (SLR)	No uncertainty considered
Scenario 2	SP and LR are vertically adapted to forecasted SLR until 2100. No additional adaptation measures in the future; maintenance of in-use stocks	Maintenance of in-use shoreline protection & land reclamation	Expansion of SP and LR by SLR (SSP1-1.9 to SSP5-8.5)	Inclusion of SLR uncertainty range per SSP-scenario
Scenario 3	SP and LR are vertically adapted to forecasted SLR until 2100. Additional LR around Malé including associated shoreline protection in the coming decades until 2100 with decreasing intensity. No further LR in other atolls. In-use SP and LR and future additions to stocks are maintained	Maintenance of in-use & future additions in shoreline protection & land reclamation	Expansion of SP and LR by SLR (SSP1-1.9 to SSP5-8.5) Conservative forecast on further land reclamation around Malé region + shoreline protection	Inclusion of SLR uncertainty range per SSP-scenario

Table 1. Derived scenarios.

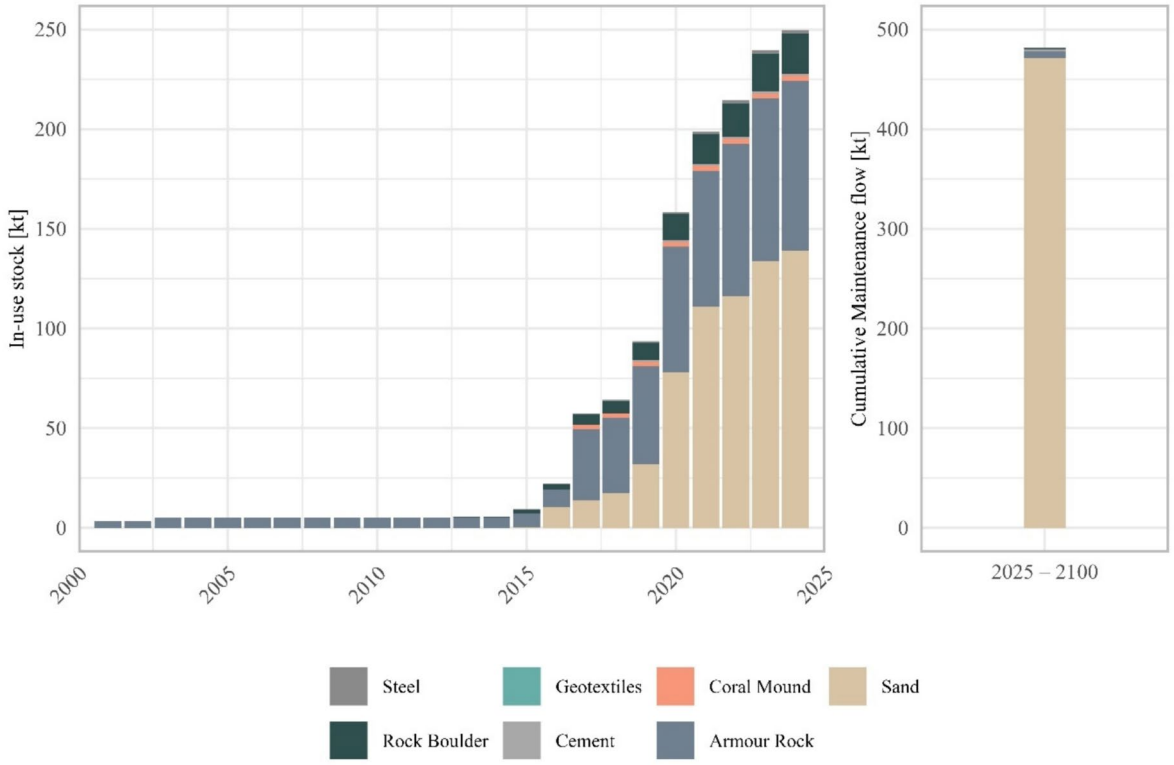


Fig. 2. In-use stocks for shoreline protection from 1998 to 2024 (left), and cumulative maintenance flows from 2025 to 2100, aggregated over each material type (right).

by Chinese and Indian investments in the development of Phase 2 of Hulhumalé (2015–2018) and the Greater Malé Connectivity Bridge (2019–2024) respectively.

Maintenance and upkeep requirements during this time were relatively modest, amounting to just 59 kt over four years, and reflect in the gross addition to stocks. Looking ahead, maintenance material needs beyond 2024 are projected at 6.4 kt annually, accumulating to 482 kt by 2100 (Figure 2). This demonstrates that resource demand will continue to grow even in the absence of new shoreline protection projects.

A closer look at the material types reveals that sand and armour rock are key components, serving as foundational materials for all shoreline protection types, making up approximately 90% of total in-use stocks in 2024. Therefore, the requirements for sand and armour rock dominates, followed by rock boulder, while steel, coral mound, cement and geotextiles contributed a small share. The share of sand as part of the total material stocks increased from 40% to nearly half from 2016 to 2024 (Figure 2). In-use stocks for land reclamation solely consist of sand and are based on the observed positive land area change from 2019-2024 (~36.7 km^2). Based on average material intensities per square meter and density per cubic meter, the estimated cumulative in-use stock of sand for reclaimed land between 2019 and 2024 is 135,000 kt, exceeding shoreline protection in-use stocks by a factor of 540 (not depicted in Fig. 2). Solely maintaining land reclamation in-use stock would on average require 9,000 kt of sand annually (all underlying assumptions can be found in Methods).

Besides sand, all other material categories for adaptation are imported at high costs, mostly from India, which accounts for one third, China with 28%, and United Arab Emirates with 18% (see Supplementary Fig. 2 and 3). In 2023, earth and mineral intermediates represented the greatest value of gross imports at almost US$ 200 million, including cement, gravel, stones, sand and similar. Following which aluminium and related products accounted for US$ 142 million, iron and steel articles accounting for US$ 121 million, and iron and steel intermediates for US$ 77 million. In the subcategories, stone boulders, steel rods and bars, and aggregates are in terms of import expenses the most important materials. It is not possible to clearly distinguish between imported materials based on their use (adaptation or other construction sectors), wherefore the figures primarily show the significance of the categories and the import dependencies. However, the import volumes clearly exceed the material volumes applied in shoreline protection.

Coral mounds, once used in earlier projects, now represent a minimal share of material usage due to environmental concerns and strict regulations limiting their application[58,59]. It is excluded from maintenance and expansion scenarios, with the assumption that they will eventually be replaced by alternative materials.

What are the material requirements for Maldives to 'stay afloat' by adjusting to sea-level rise? (Scenario 2)

Scenario 2 depicts a future, where already in-use adaptation measures are maintained, and in addition there is some vertical expansion (or raising) in adaptation infrastructure to adjust to the rising seas. Fig. 3 shows in-use stocks, expansion and maintenance flows for shoreline protection (a-c) and land reclamation (d-f), respectively.

Fig. 3a shows the hard-protection in-use stock per material type for SSP2-4.5 and additional projection for SSP1-1.9 and SSP5-8.5 till 2100. For shoreline protection, sand makes up almost half of the stock with 139 kt of sand in 2025, followed by armour rock (85 kt), and rock boulder (20 kt). Cumulative expansion material requirements due to SLR from 2025 till 2100 depend on the selected SSP scenario, varying from around 25 kt (SSP1-1.9) to 52 kt (SSP5-8.5) (Fig. 3b), which is distributed over an average annual quantity of 0.5 kt/year following SSP2-4.5. Cumulative material requirements for maintenance from 2025 to 2100 make up the majority of total inflows across all SSP scenarios, at approximately 8 kt/year.

Fig. 3d shows the disproportionally higher material stocks for land reclamation, with roughly 206,000 kt of sand in 2025. Materials for expansion (Figure 3e) accumulate at an average of 101,500 kt by 2100 (ranging from 64,600 kt to 144,500 kt over all SSP scenarios). Maintenance requirements result from balancing the erosion with

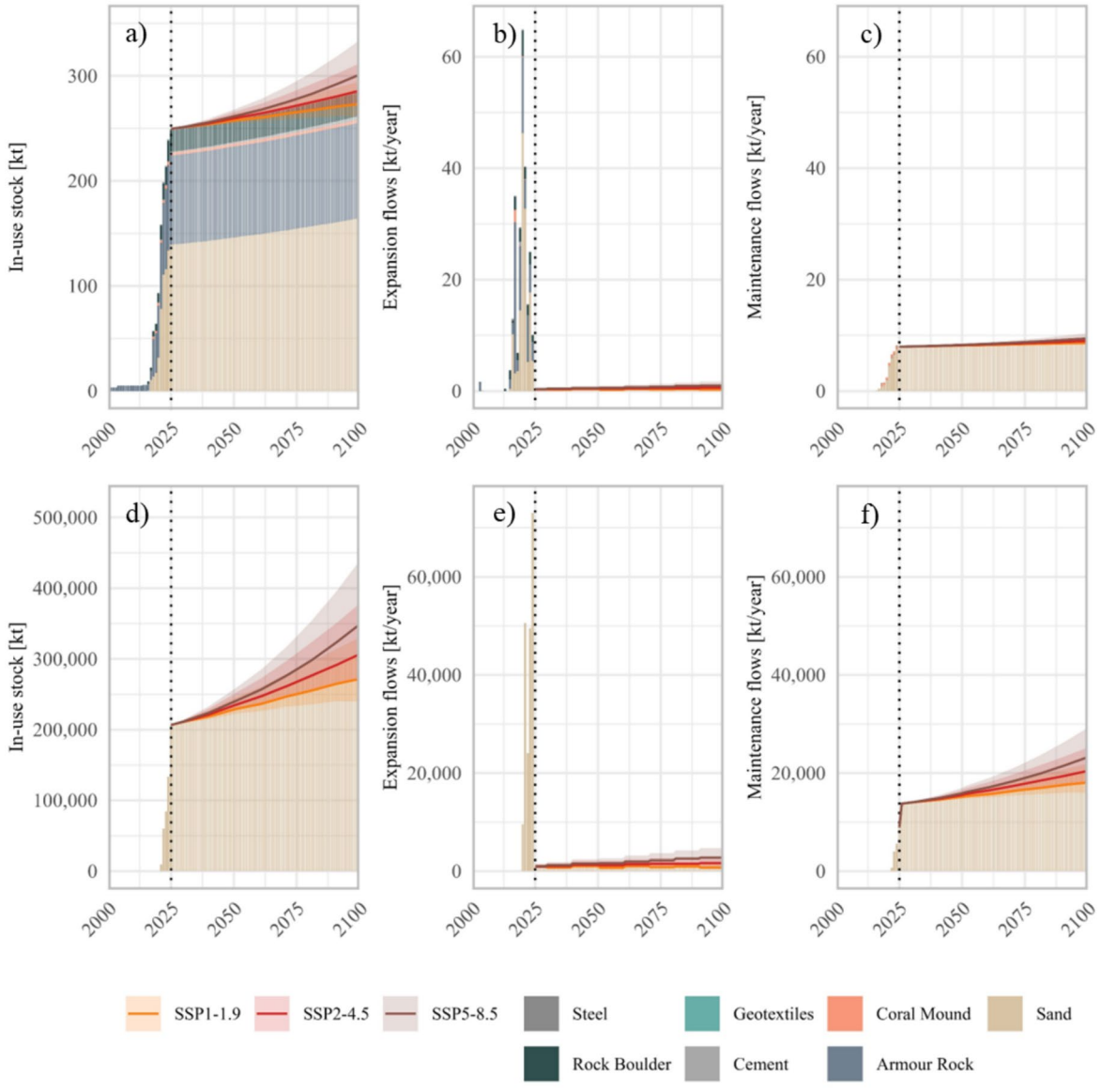


Fig. 3. Material stocks and flows for Scenario 2 from 2000 till 2100, following SSP2-4.5, and including predictions for SSP1-1.9 and SSP5-8.5. (**a**) and (**d**) In-use stocks for shoreline protection measures and land reclamation, respectively, per material type. (**b**) & (**e**) Expansion flows for shoreline protection and land reclamation, respectively. (**c**) & (**f**) Annual expansion flows for shoreline protection and land reclamation, respectively. Bars with less opacity indicate projected information. Please note that 2025 in-use stock is shown as observed data, as it is the sum of observed in-use stocks and expansion requirements from 2024.

constant sand replenishment, which for the Maldives is as high as 20% of the original volume every three years[50]. Therefore, just maintaining newly reclaimed land adds up to almost 1.5 times (148%) the 2025 in-use stocks. These striking volumes indicate a potential lock-in effect caused by exceeding land reclamation projects. By 2100 then, cumulative maintenance requirements range from 1,200,000 kt (SSP1-1.9) to 1,340,000 kt (SSP5-8.5). Furthermore, the material requirements for hard adaptation and land reclamation differ by a factor of almost a thousand. And with faster degradation through sediment transportation, the maintenance requirements of reclaimed land are also massive compared to shorline protection; together the former makes up approximately 99.9% of total material requirements.

What if land reclamation grows in the Greater Malé Area? (Scenario 3)

Scenario 3 displays a possible future, where land reclamation projects increase in the Greater Malé Area. Retrospectively, from 2019 to 2024, the share of Kaafu's land area to its total reef area (excl. lagoons) increased from 6.90% to 8.75%. In 2024, 2.15% of Kaafu's reef area is protected and therefore not considered for prospective expansion. Excluding protected areas, some 355 km^2 would be available for land reclamation in 2024. By 2100, Scenario 3 would lead to a share of 9.60% land area of Kaafu's reef area (excl. lagoons). Our considerations are depicted in Fig. 4.

In addition to simply piling up sand, we assume, based on data retrieved from ArcGIS, that onshore breakwaters and revetments stabilize newly reclaimed land by an average of 0.35 m per added shoreline meter, followed by nearshore breakwaters (0.07 m) and groynes (< 0.01 m). Fig. 5 shows the material stocks associated with land reclamation projects, differentiated by the total material demand, which is clearly dominated by sand for reclamation itself (Fig. 5a-c), and the materials associated for fortification only (Fig. 5d-f).

The high material stocks in 2025, shown in Fig. 5a, particularly result from great expansion rates in 2024. Based on a time-series fitted logistic growth model and the assumption of further projects only be realized in



Fig. 4. (**a**) Map of the Maldives (left). (**b**) Kaafu atoll, scope of Scenario 2 (right). Reef area, land area of 2024, protected reef area and excluded zones are shown. 1) zooms in to Kaashidhoo, 2) to Malé and Hulhumalé, 3) to Guraidhoo, to allow a closer look on the geographical conditions. The squares in the top right corner allow a comparison of total area per category. Source: Background map[60], Data sources[19,61,62].

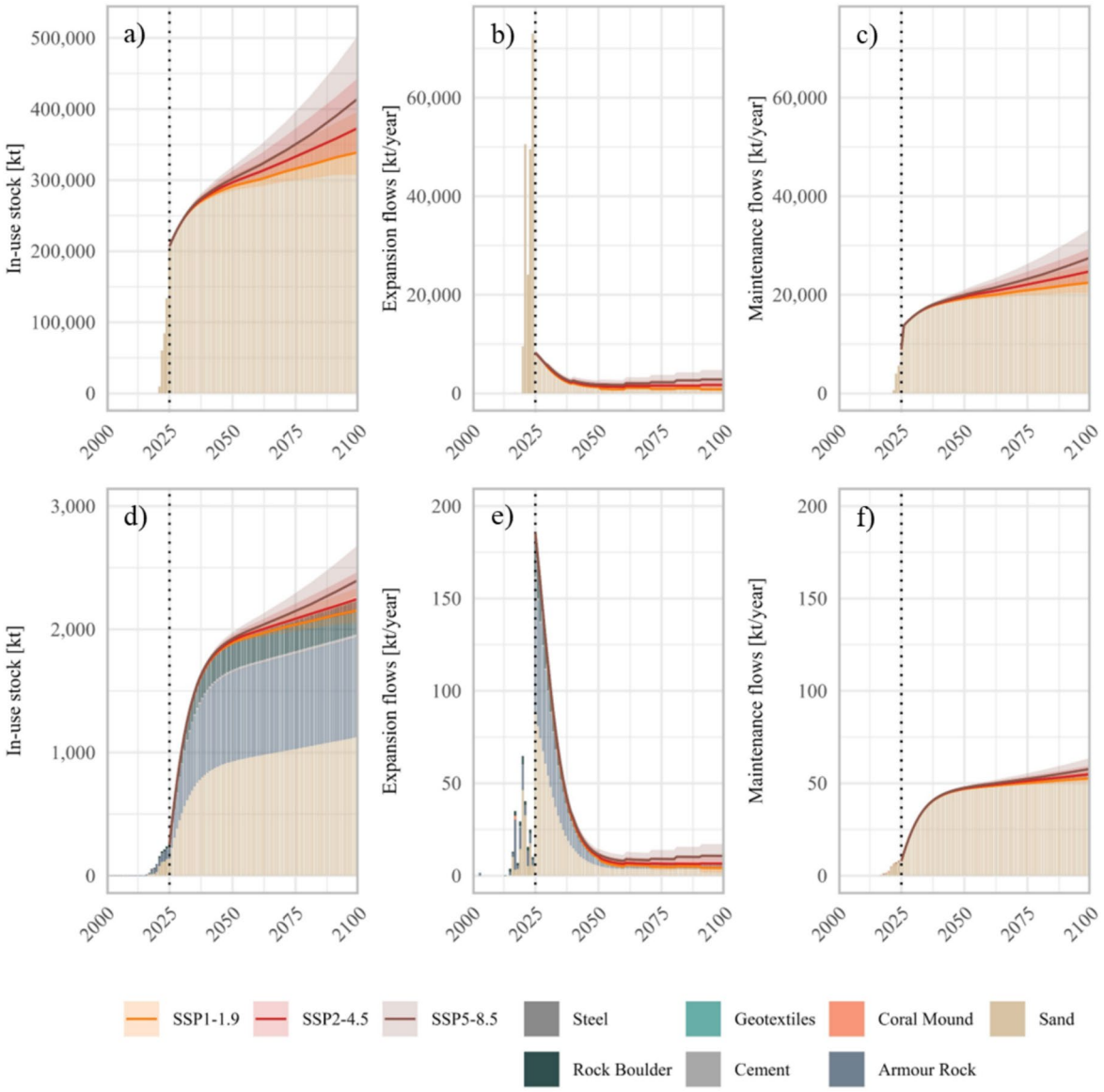


Fig. 5. Material stocks and flows for Scenario 3, following SSP2-4.5. (**a**) In-use stocks for land reclamation. (**b**) Expansion flows for land reclamation and associated fortification. (**c**) Maintenance flows for fortified land reclamation. (**d**) In-use stocks, (**e**) Expansion flows and (**f**) Maintenance flows for fortification respectively. Ribbons represent 5th to 95th percentile ranges of the respective SSP scenario. Bars with less opacity indicate projected information. Please note that 2025 in-use stock is shown as observed data, as it is the sum of observed in-use stocks and expansion requirements from 2024.

the Greater Malé Area, expansion drops from 2025 onwards, resulting in a mean annual expansion flow of 2,220 kt for SSP2-4.5 (Fig. 5b). Comparing SSP1-1.9 and SSP5-8.5 for Scenario 2 with the same SSPs of Scenario 1 respectively, the cumulative expansion demand is 1.5 to 2 times higher. Therefore, maintaining the current stock will, in sum, have required about 1,556,994 kt by 2100, which exceeds the current and future in-use stock. This translates to 20,487 kt/year of mean annual maintenance requirements (Fig. 5c). Fig. 5d shows annual in-use stocks for hard shoreline stabilization measures associated with expanding land reclamation, which gradually taper out towards 2100. Compared to Scenario 1, the predicted mean annual material demand for expansion of shoreline protection is 55 times higher with 26.4 kt/year (following SSP2-4.5). Maintaining associated shoreline protection structures will on average require 46 kt/year of mixed materials, mainly sand followed by armour rock and rock boulder.

Comparing different SSPs and percentile ranges, in-use stocks for fortified land reclamation projects in 2100 may vary from 307,681 kt (SSP1-1.9, 5th percentile) to 504,607 kt (SSP5-8.5, 95th percentile) (Fig. 5a). While ranges of expansion requirements in 2050 differ by 1,661 kt (975 kt SSP1-1.9 5th percentile, 2,636 kt SSP5-8.5 95th percentile) in 2100, the difference accounts for 4,744 kt, showing impacts of accelerating SLR in SSP5-8.5 and increasing uncertainty in the future (Fig. 5b and 5e). Along with increasing expansion and in-use stocks in

the future, total maintenance requirements in 2100 vary from 20,425 kt to 33,452 kt for SSP1-1.9 and SSP5-8.5, respectively (Fig. 5c).

Discussion

Building resilience or accumulating socio-metabolic risk (SMR) in the Maldives?

In recent years, the "adaptation to climate change" in SIDS emerges as yet another critical service that is increasingly delivered by resource-intensive strategies. Oftentimes, in response to crises or external shocks, interventions focus on short-term, symptomatic solutions, leading systems into what can be described as a "socio-metabolic trap"[63]. For example, the 2004 tsunami that devastated the Maldives triggered a surge in shoreline protection projects between 2016 and 2020, creating long-term lock-in effects of 6.4 kt of material demand per year for maintenance, or 482 kt by 2100.

As sea-level rise will continue in the decades to come, larger adaptation stocks require greater flows of materials to maintain and operate them, creating a reinforcing feedback loop that has been termed the "stock-flow-service" (SFS) nexus[64]. The predicted extension demands are sensitive to SLR, with reclaimed land and shoreline protection requiring 2,100 kt of sand, and 22.2 kt of construction materials for each additional centimeter SLR respectively. Malé is roughly one meter above current sea level, which under certain wave conditions already causes periodic flooding, a threat that grows with every additional centimeter of SLR[51]. If global warming continues at today's pace, SLR unequivocally further accelerates after 2050 and could reach 1.01 m by 2100 and 1.88 m by 2150 in the very high emissions scenario SSP5-8.5, and even higher levels of 2 to 5 m cannot be ruled out until 2150 due to limited understanding of ice-shield processes[56,57].

We find that simply maintaining the already existing hard shoreline protection requires steady material inflows, with a majority that has to be imported. Even with Scenario 2 wherefore projections are solely based on an adjustment to rising seas, it is estimated on an average 101,500 kt of material stocks will be accumulated by 2100. Merely maintaining newly reclaimed land could require six times as much as the projected 2025 in-use material stocks. Similarly, under Scenario 3, under the conservative SSP2-4.5 SLR, on average 20,487 kt annually material inflow can be expected for only maintaining and repairing the already existing stock. Expansion to keep flooding probability constant adds another 26 kt annually. While erosion of recently reclaimed land will require constant replenishment volumes of roughly 20,440 kt annually, and another 2,193 kt/year for keeping up with advancing sea levels.

Unrestrained material growth and unsustainable resource-use patterns undermine system resilience over time. Specific configurations of material stocks, and flows within a socio-economic system accumulate "socio-metabolic risk" (SMR)[63]. SMR resembles circulatory health problems in humans, constraining a system's ability to withstand shocks and adapt to changes. The magnitude of these risks depends not only on the volume of material flows but also on the composition and quality of the materials, which collectively define the metabolic profile of a society. For instance, several small and remote island states like the Maldives rely heavily on critical resources as imports, such as metals, minerals, and fossil fuels, transported through complex and vulnerable supply chains susceptible to disruptions from even minor perturbations. Consequently, distinct and shifting patterns of resource use influence the degree of SMR, potentially impacting the system's ability to maintain its social metabolism and deliver critical services effectively.

SMR is not only biophysical but also manifests in the system as social risks. Resource-use patterns may be influenced by and in turn ignite geopolitical tensions creating dependencies, human displacement, and loss of livelihoods resulting in social conflicts with local communities[52,65]. A recent example of this conflict was witnessed in Hanifaru Bay where a plan to reclaim about 13.59 hectares of lagoon and sea in Baa Atoll triggered controversy. The government said the project was cancelled in response to public outcry, as many local residents of Dhonfanu island were not consulted[66].

Moreover, the resource-intensive nature of shoreline protection measures comes at an overwhelming cost. In 2016, the Govt. of Maldives estimated US$ 8.8 billion for shoreline protection measures across the inhabited islands[67]. This was likely an underestimation, since in their 2024 report to UNFCCC under the Paris Agreement, international climate finance received in 2022 alone was US$ 6.2 billion (40% as loans), or 125% of the country's GDP, in addition to domestic sources[68]. Nearly 90% of these investments are used towards critical infrastructure, including coastal protection[69]. In addition, the "global phenomenon" of coastal reclamation[70] will lead to increased demands for embankment and fortification materials and eventually inducing higher costs to purchase those materials, ultimately exacerbating the issue.

The world bank estimates debt service payments housing projects on newly reclaimed land to average US$ 40 million per year until 2028 (World Bank, 2022), but the revenues generated from land reclamation projects (through land sale and taxes) will not be sufficient to cover these debts[71]. A crucial insight here is that current development pathway is fiscally unsustainable. There are significant public expenditure risks faced by the Maldives. This is an important lesson for the Maldives and any other SIDS going down this path.

Implications of land reclamation: addressing the twin goals of development and adaptation

The "reclamation-fortification island model" adopted in the Maldives – for both development and adaptation - exemplifies a socio-metabolic trap. They create "lock-in effects" characterized by dependence on external technologies, high-interest loans, and continuous imports of construction materials for maintenance and repairs[72]. Estimated using remote sensing data, we find that land reclamation since 2019 has proceeded at remarkable speed, requiring massive sand quantities for creating new land.

The State employs different models for land reclamation and climate adaptation projects depending on geographic locality. In Greater Malé Area, where land value is high, a capitalist model is used, whereby state-owned enterprises are involved across acquiring funds for land reclamation, physical development, land sales and commercial leasing. In contrast, both types of projects in outer islands including airports, harbours, ports

and land extension works are carried out through a Public Investment model financed solely through the national budget[71].

Nonetheless, land reclamation projects are reported to have significant socio-environmental costs from seabed mining, including damaging coral reefs and coastal areas that are critical for natural adaptation to rising sea levels[34], as well as loss of local livelihoods. A report by Human Rights Watch (2023)[73] argued that poorly regulated reclamation and dredging on islands including Kulhudhuffushi and Addu Atoll have resulted in extensive environmental degradation. The report documents severe impacts on coral reefs, mangrove ecosystems and wetland areas, with negative consequences on local fisheries, agriculture, freshwater availability, and community livelihoods. On Kulhudhuffushi, for example, 70% of the mangrove habitat was buried to build a new airport displacing people and destroying natural resources.

Large parts of Hulhumalé - that is both a development and adaptation project - have been reclaimed in recent years with SLR scenarios up to 2100 in mind, resulting in a structure with outer edges 2 meter above the today's level, wherefore coastal flooding is not yet likely[51,52]. This was largely influenced through the lived experience of 1987 sea surge and flooding event that partially inundated Malé. Incremental costs associated with incorporating adaptation features (such as land raising and installing shoreline protection features) to Hulhumalé were estimated about 10 percent of the total project costs[11].

Due to the required fortification, possible future projects similar to Hulhumalé would depend heavily on large volumes of imported construction materials, as well as external financial and technological resources. Besides in-situ dredging, official trade data indicates considerable sand imports of more than 5 Mt since the beginning of the 21st century, mainly stemming from India and Malaysia[27]. Beyond official data, illegal sand mining is a severe issue in India, wherefore shipped volumes might even be higher[74].

Scenario 3 assumes drastically decreasing land reclamation speed compared to the observed period 2019 to 2024 by incorporating predictions on additional projects only in the Greater Malé Area. Sand is obtained by seabed dredging close to the reclaimed land, where the operations have severe impacts on affected marine ecosystem[52,75]. Even though sand is geologically an abundant resource and global scarcity is unlikely, regional scarcity due to overexploitation, and conflict with local communities can be a limiting factor for Maldives adaptation efforts[76]. This raises concerns on the long-term sustainability and affordability of maintaining these structures, particularly in a context where climate risks threaten tourism revenues and international funding remains uncertain[42].

Land reclamation activities are said to be mostly driven by underlying political and economic motives. Recent land reclamation activities in the Maldives, particularly those pursued after the 2015 constitutional amendments enabling foreign entities to hold land rights, could directly be attributed towards political agendas of incoming governments[77,78]. This is demonstrated by the fact that all incoming governments since the adoption of the first democratic constitution in 2008 have pursued various land reclamation projects to fulfil electoral pledges around housing, coastal protection and economic development.

More recently, land reclamation activities have also been linked with intensifying regional geopolitics, particularly with regard to Chinese and Indian interests to increase their presence in the Indian Ocean. Much of the finance from both China and India were in the form of non-concessional loans secured through sovereign guarantees, putting the Maldives in a precarious fiscal situation. As of 2022, publicly guaranteed debt in the Maldives was calculated at US$ 6.1 billion or 125% of the country's GDP[68]. This excessive spending towards land reclamation and shoreline protection projects without adequate reference to environmental regulations, public consultations, long term vision and fiscal sustainability have thus resulted in growing public discontentment and tension surrounding such projects.

Conclusions

For SIDS, land scarcity presents a significant development challenge that impedes effective socio-economic development. Theoretically, recent advancements in land reclamation and dredging technologies such as the ability to develop raised artificial islands that are fortified against current and future climate impacts, offers a reliable, technology-based solution to respond to the unique development challenges faced by small island states[71]. Yet, in practice, the ability of these nations to achieve this uniformly across widely dispersed islands with small population bases is neither economically nor technologically feasible. Both land reclamation and hard shoreline protection adaptation measures involve significant costs, which most SIDS are unable to generate. They also require access to adequate technologies, capacities and specialised skill sets.

What does this mean for global resource extraction – with all the associated consequences? Global material extraction has tripled in the past 50 years and human material stocks exceeded all living biomass in 2020 by mass[79,80]. Extraction is expected to further increase by 60% by 2060, from 100 to 160 billion tons annually[80]. We believe the increase will be significantly higher as material requirements for adaptation have not yet been considered by any study to our knowledge. Beyond that, resource extraction and transportation come at massive energy demands, most of which is covered by fossil fuels, thereby contradicting climate change mitigation efforts, which can result in a self-enforcing negative feedback loop.

Furthermore, the volatility of material prices in global commodity markets, coupled with resource scarcity driven by increasing global demand due to population growth, has contributed to a trend of de-globalization. Nations are increasingly prioritizing the retention of their resources for domestic use rather than exporting them. This shift carries significant implications for human and societal resilience, particularly in the context of unregulated and rapid infrastructure development. If geopolitical tensions in the region escalate, this could further disrupt supply-chains of materials. While our analysis does not model this scenario, it could be considered as one of the worst scenarios given the high dependency on material imports for adaptation. In this regard, current practices amplify exposure to socio-metabolic risks, a concern that is especially acute in climate-vulnerable SIDS where resource dependencies and environmental sensitivities compound existing challenges.

While Maldives remains our focal case, this is also the first study of its kind to estimate resource demands for any country for coastal adaptation to rising seas, thereby filling a critical gap in industrial ecology research and adaptation science. Through this analysis, we offer an empirical basis to highlight the existing socio-metabolic trap, and risks related to current responses to adapt to climate change in the Maldives. However, the question remains – what options are there to address these risks? We believe the solutions lie locally. Small islands have a long and demonstrated history of adapting to extreme weather and climate change impacts, yet little attention has been paid to evidence of past and present adaptation responses[81]. At this critical stage in history, we would hope local politics will initiate a process of inclusive national consultation that takes both the past and the future into account in order to develop possible alternatives.

As a final note, we would describe all estimations on current shoreline protection adaptation stocks as conservative, since they exclusively base on published MTCC projects, which is the biggest - but not the only - company responsible for adaptation projects on the Maldives. Also, projections on future inflows are rather conservative, since we do not assume any additional shoreline protection expansion for already existing islands. For land reclamation, we only assume further projects in the Greater Malé Area with the associated fortification requirements. Even with these conservative estimates, the consequences for Maldives are significant in terms of their future resource needs and associated impacts. This calls for accelerated global efforts to streamline climate financing, knowledge transfer and provide technical support to small island nations, who are the least responsible for global greenhouse gas emissions[82] but one of the most affected geographies in the world.

Methods

Geographical scope

Geographical scope of the work is the Republic of Maldives. The study aims to estimate material requirements for hard engineered infrastructure, including breakwaters, revetments, groynes and reclaiming and raising land. (see Table 2 for definitions) to adapt to climate change.

Methodological approach

An overview of our methodological approach can be visualized in Fig. 6 that highlights the main steps in the quantification. This includes:

- The parameter compilation for estimation of land reclamation based on remote sensing, estimation of the stock-flow dynamics parameters (lifetimes, maintenance requirements). It also includes information from 1998 to 2024 on hard-protection in-use stocks based on reports from MTCC. Literature, geometry, and remote sensing-based estimation of material intensities per adaptation measure.
- Calculation of retrospective in-use stocks based on gathered parameters.
- Parameter compilation and estimation for future scenarios, including SLR scenarios and upcoming potential projects. Calculation of stock-flow dynamics resulting in scenario-wise prospective expansion and their maintenance for each adaptation measure until 2100.
- Material requirement calculation per adaptation measure, year and scenario. Preparation of resulting scenario-wise annual material inflows and in-use stocks.

Principles of stock-driven dynamic MFA were followed, considering inflows based on consolidated project information and observed land area increases. In-use stocks based on the cumulative expansion of material inflows; for the years 1998 – 2024 based on documented data for adaptation projects, and for the years 2025 – 2100 the calculations were based on scenario-wise expansion projections. Outflows were considered implicitly through the use of the leaching method[83].

The adaptation measures were distinguished between land reclamation and shoreline protection types (refer to Table 2 for definitions), each following a distinct method for data collection and processing.

For further information on how material stocks and flows were calculated for used materials listed in Table 2, see Supplementary Table 5,6,7.

Adaptation measure	Definition	Common materials	Source
Breakwater	Used across all types of islands, these structures are designed to protect shorelines by disrupting wave energy. They are for shore stabilizing and preventing erosion, especially close to land-based developments, and act as a physical barrier. Breakwaters can either be implemented onshore, or offshore close to the shoreline.	Sand-cement bags, coral mounds (in earlier years), armour rock (recent development)	86,87
Groyne	Shore-perpendicular structures extending into the lagoon above high-water levels, designed to trap sand along the shoreline and mitigate erosion. Design is often based on trial-and-error, with aesthetic adaptations like circular heads common in resort areas.	Geobags, rock boulders, sand-cement bags	86,87
Revetment	Normally constructed in high energy zones – usually on the ocean-ward side beach using interlocking or overlapping material – they are a sloped, armouring structure serving as a direct measure to prevent erosion and beach retreat.	Coral mounds (in earlier years), rock boulder, sand-cement bags, concrete interlocking blocks	86,87
Land reclamation and raising	Process of restoring land that has been eroded, expanding existing land, or creating new artificial land, through the process of sand dredging; includes horizontal and vertical land expansion. Shoreline protection measures accompany reclamation to secure and fortify the new land. Referred to as 'land reclamation' or 'reclaiming land' and 'raising land', 'island raising' or 'land raising'.	Sand and backfill	23,52

Table 2. Definitions and commonly used materials for climate adaptation measures covered in the analysis.

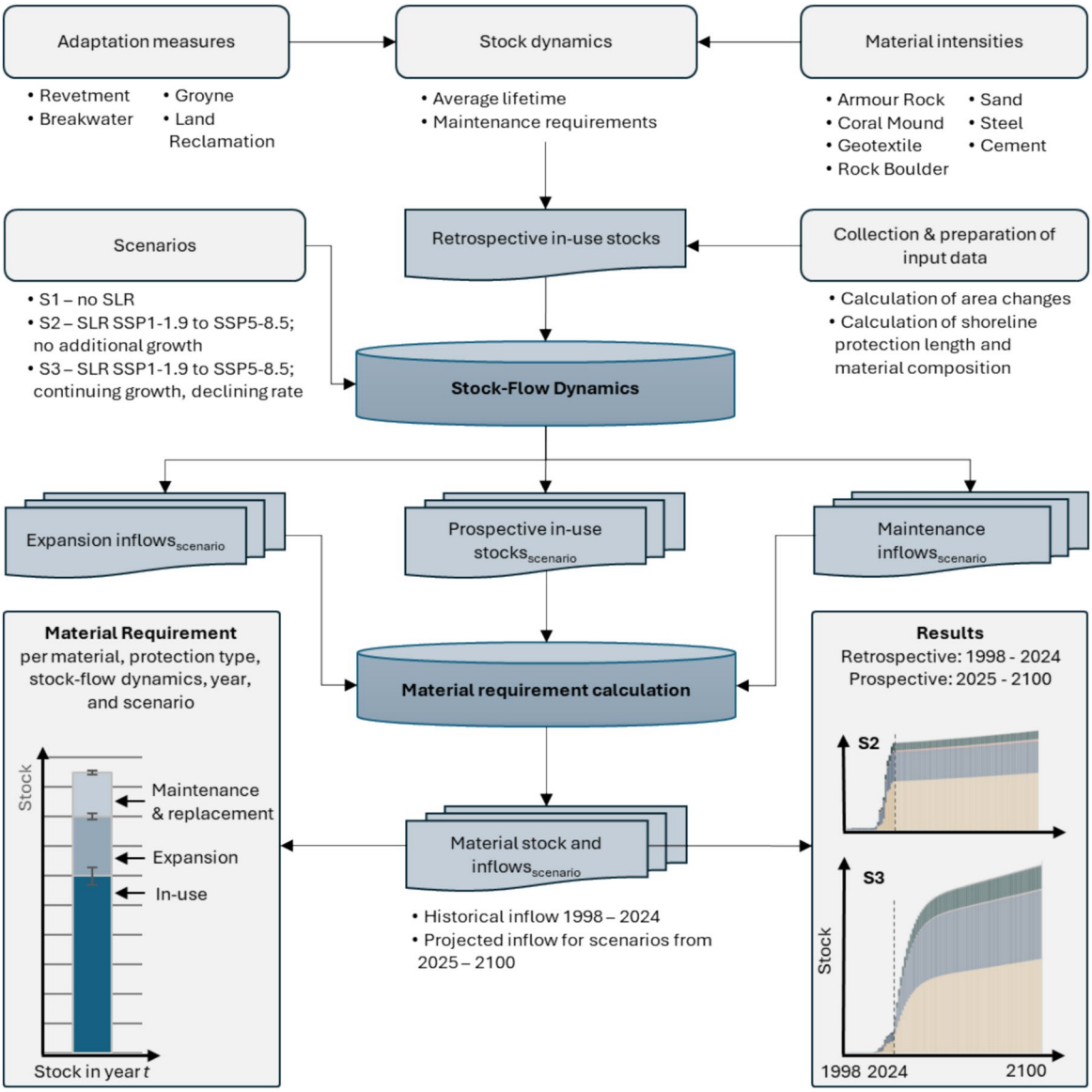


Fig. 6. Methodological approach (based on[84,85]). Grey boxes show information included in the model. Flow boxes show calculated results, with layers indicating different scenarios considered. Cylinders demonstrate calculation processes. Arrows represent logical relationships between the shapes. Please note that the diagram is representative and mathematical relations are not fully addressed in this figure.

Stock dynamics

Maintenance requirements were modelled using the leaching method[83], in which outflows are modelled as a constant fraction of the stock.

$$\frac{\mathrm{dIU(t)}}{\mathrm{dt}} = \mathrm{inflows\,(t)} - \mathrm{outflows(t)} \tag{1}$$

In formula 1, inflows consider expansion and maintenance flows of the year t, minus the outflows in the same year, which are approximated as the material demand for maintenance. In total, in-use stock changes with the annual expansion flows. In the original method, the fractional probability is constant across all adaptation measures, however we modified this approach by calculating distinct maintenance factors based on adaptation measure, their average lifetimes and the specific material under consideration. Lifetime is not considered for End-of-Life outflow calculations. Maintenance factors were primarily obtained from the Maldives Climate Adaptation Survey[36], and were calculated based on the percentage of the original material or cost required per maintenance round (POC) and the maintenance frequency (MF).

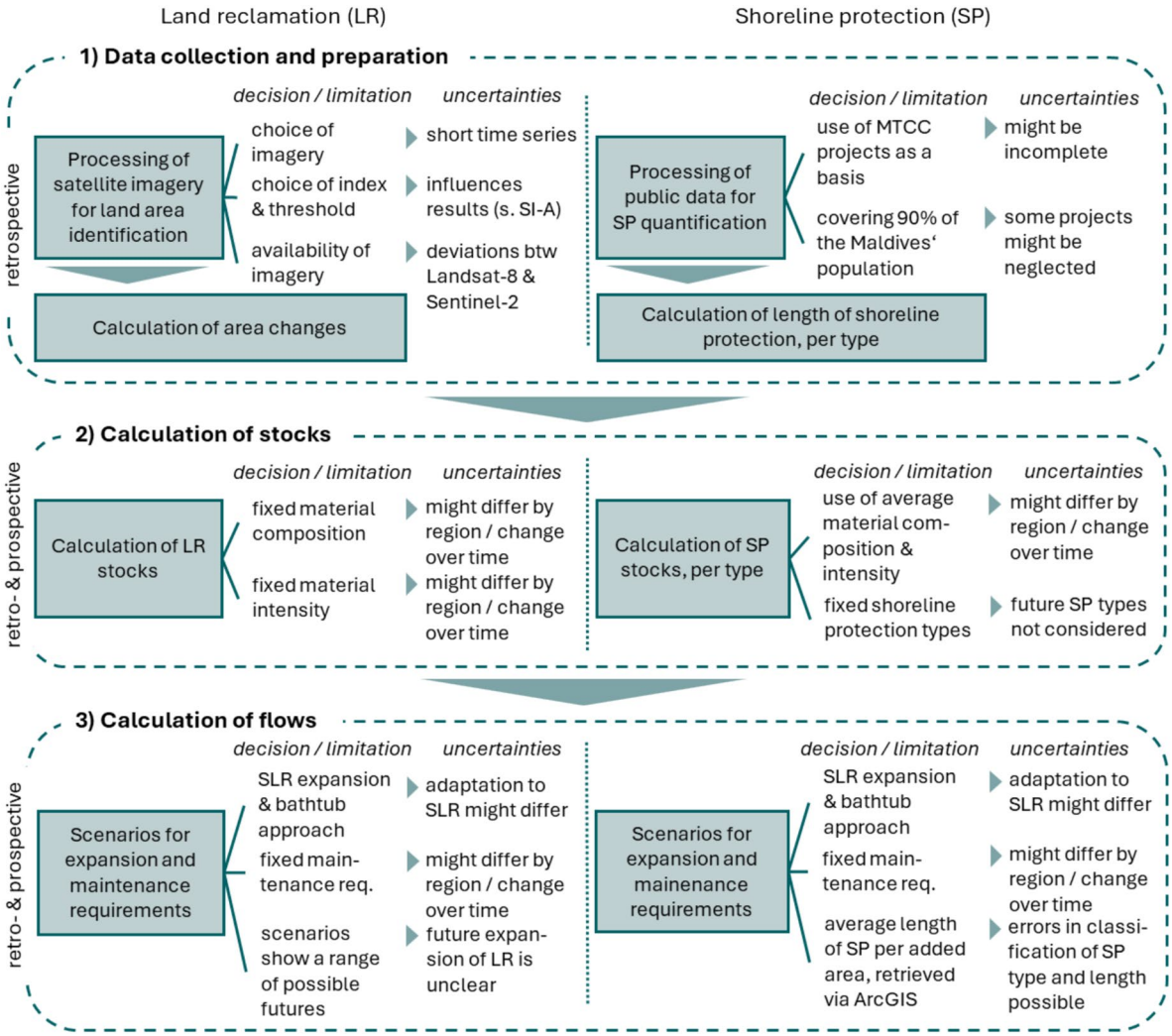


Fig. 7. Limitations and uncertainties within the methodological approach, for land reclamation and shoreline protection, respectively. Boxes display main processing and calculation steps; connections point out where decisions and assumptions have been made.

Material intensities

Material intensities (MIs), representing the volume of material (m^3) used per unit of adaptation measure, were documented to support stock calculations. Shoreline protection measures and land reclamation material intensities are expressed in m^3/m and m^3/m^2, respectively. Total mass requirements were calculated using the mass per cubic volume (kg/m^3). Dimensions and cost per length of the materials were used for expansion calculations in Scenario 2 and 3.

The data was consolidated from a variety of sources, including academic papers, consultant reports, construction schematics, product manuals, and grey literature. Maldives-specific data was prioritized, with the primary sources of material information being the Maldives National Adaptation Survey[36] and the JICA Planning Survey Report[50]. When Maldives-specific data was unavailable, data from comparable low-lying coastal areas was used, such as coastal communities in India and other islands within the Indian Ocean. Any variations in MI were noted based on material-specific characteristics such as usage, composition, and grade/type. These variations were consolidated by averaging the MI values. Refer to Fig. 7, under "Data Method and Limitations", for further information regarding the uncertainties resulting from the data collection and analysis process.

Scenarios

Inclusion of sea-level rise

Natural reef islands can adapt to rising sea levels through coral-derived sediment, wave-driven transport, and native vegetation. However, extensively modified islands have often reached "anthropogenic tipping points", losing this adaptive capacity and requiring constant human intervention to manage SLR[72]. Here we model two scenarios based on sea level rise predictions based on the *Shared Socio-economic Pathways* (SSP) as defined by IPCC's Sixth Assessment Report on climate change[56,57]. The SSPs range from 'very low emissions' (1-1.9), to 'low emissions' (1-2.6), 'intermediate emissions' (2-4.5), 'high emissions' (3-7.0) and to very high emissions (5-8.5).

Depending on the emissions pathway, global sea level rise until 2100 will range between 0.384 to 0.88 meters (50^{th} percentile) relative to 1995 – 2014 levels[56,57]. Amores et al.[88] demonstrated through numerical simulations of several Maldivian islands that increasing island and hard-protection heights by an increment equal to the projected SLR effectively maintains current flooding levels, irrespective of wave setup, runup, and overtopping.

Scenario 1
Here, we provide a benchmark estimate of accumulated in-use materials (referred to as 'material stocks' or simply 'stocks') and project the additional quantities required by 2100 for maintenance and repair of these already existing stocks.

Scenario 2
Scenario 2 models an average annual increase of hard shoreline protection and an expansion in reclaimed land area in response to SLR. In practice, this will most probably not happen annually, but over a longer period. Besides SLR related expansion, additional expansion of land or shoreline protection is not considered.

Scenario 3
In Scenario 3, we assume continuing land reclamation in the future, but at a considerably slower pace than in recent years. Regardless of ever-changing governmental strategies to consolidate the population, the last decades show a trend toward a growing population in the Greater Malé Area[20,54]. Based on the historic trend, ground observations, and national predictions on further population increase in the Greater Malé Area by almost 90,000 people in the coming four decades[55], we assume future land reclamation projects taking place exclusively in the Greater Malé Area. The assumed future increase corresponds to approximately the same reclamation area in the upcoming 75 years as what has been observed in the past six years with a saturation towards 2100, using statistical methods to simulate growth functions for future projections.

In addition to material requirements for creating more land (mainly sand from dredging), these reclaimed lands also require hard-protection fortification to reduce sediment erosion, further driving up the material demands. The parameters of the reclamation-fortification nexus are based on a remote sensing derived reclamation-fortification parameter, and turn out to be slightly higher than what has been documented by MTCC for recent years[35], which indicates, that taking MTCC data only rather corresponds to a conservative scenario.

We validated our assumptions, model data inputs and results by drawing on official documents, scientific literature, and ground-truthing by co-authors familiar with local context.

Scenario 2 includes a bare minimum of adaptation requirements by SLR, whereas Scenario 3 draws on current trends in advance, but keeping growth in a conservatively defined limits of expansion.

Collection & preparation of input data
Land reclamation analysis included analyzing satellite imagery for all islands, within the period of 2019 - 2024. For shoreline protection measures, data was consolidated from public information for all residential islands accounting for 90% of the national population for the years 1998 – 2024.

Calculation of area changes
To capture most islands, an automated remote sensing approach was chosen to identify land and water bodies for all islands. First, we compared different datasets (Landsat-8 and Sentinel-2) and indices and juxtaposed the results in challenging regions, for example, where water levels are low and vegetation leads to increasing complexity in land and water differentiation. The $AWEI_{nsh}$ (Automated Water Extraction Index for Non-Shadowed and Humid Areas), a well-established tool developed by[89], worked best for our purposes (for details on index selection, see SI–A)[90]. The calculation of $AWEI_{nsh}$ is[91] shown in Eq. 2:

$$\mathrm{AWEI_{nsh}} = 4 \cdot (\mathrm{green} - \mathrm{SWIR1}) - (0.25 \cdot \mathrm{NIR} + 2.75 \cdot \mathrm{SWIR2}) \quad (2)$$

The index was calculated using the median pixel values annually, to account for and smoothing out natural seasonal variations in land area. Due to significantly higher resolution (10m x 10m) and less noise than Landsat-8, Sentinel-2 data was used. We applied a threshold of -0.25, as testing different values showed that this value allows to differentiate islands situated in close proximity to one another, while also producing less background noise. This case especially occurred in the atolls Gaafu Dhaalu, Gaafu Alifu and Seenu. As Sentinel-2 data was not available for Haa Alifu, Haa Dhaalu and Shaviyani atoll for the years 2019 and 2020, the data was processed using Landsat-8 data as well. Results were extracted using the Google Earth Engine (GEE)[61] code editor (https://code.earthengine.google.com/, and for a detailed code see SI-A).

QuantumGIS software[92] was used for preparation of spatial data and all island data was obtained from the Maldives Land and Survey Authority (MLSA) (https://readme.onemap.mv/). The attribute table of the shapefile contains the atoll, island name, capital, longitude and latitude, island category (residential, tourism, uninhabited, industrial), sector and usage. $AWEI_{nsh}$ results (tif) were merged on a yearly basis and the raster got vectorized. All non-land polygons were deleted and the area (m^2) per polygon was calculated. A visual comparison of 2024 $AWEI_{nsh}$ data with existing island polygons was conducted to identify newly emerged islands not included in the official dataset. If $AWEI_{nsh}$ suggested a new island, the region was compared with the colour imagery in GEE. This was especially the case in the Kaafu atoll (i.e., Malé atoll). For islands built between 2023 and 2024, a new polygon was drawn and if available (via public google maps information) a name added, otherwise, generic names were assigned. After cleansing the raw data, the new polygons and the island's shapefiles were combined

by geographical position. Results were extracted as excel spreadsheets and subsequently got cleansed by RStudio due to:

1) Use of Landsat-8 data for 2019 and 2020 for Haa Alifu, Haa Dhaalu and Shaviyani atoll.
2) Conglomerating islands, as some are too close to neighboring islands or connected.

After cleaning the data, the sum of all polygons per island polygon (fid) was calculated (see SI -A for details).

The results reveal both expansions and reductions in island size, with smaller islands exhibiting significant fluctuations due to natural processes such as erosion, stabilization, and accretion, consistent with findings by Duvat (2020)[23]. In a few cases, this led to disappearance of entire uninhabited small land areas. Since this work investigates resource demands, the study solely focuses on positive land area changes. For a visual comparison on atoll-level area changes, see Supplementary Fig. 1.

Calculation of shoreline protection length and material composition

Data for shoreline protection projects in the Maldives primarily stems from the *Maldives Transport and Contracting Company* (MTCC). Efforts to access data housed by the *Ministry of Construction and Infrastructure* were unsuccessful. To streamline the consolidating of MTCC projects, a representative subset of residential islands was selected for analysis. Population was a key indicator in determining the implementation of shoreline protection[12], wherefore islands covering 90% of the national population were included. Shoreline protection also exists on tourism and industrial islands, however, these projects are funded by private investments[69] and therefore not in the MTCC database. For each residential island, all shoreline protection projects from 1998 onwards were documented, including projects as part of land reclamation efforts. Where available, the project year, costs, status, protection type, length, and materials used were documented.

The MTCC data got transformed into meters of shoreline protection for each type and materials per year and atoll. MTCC records protection components in specific forms (e.g., sand-cement bags) instead of raw material components (e.g., sand and cement). All project costs were inflation-adjusted for annual cost comparisons and for providing necessary inputs for estimating missing data.

Some adaptation projects only provided partial information. Missing data was estimated based on assumptions and existing data preserved trends and relationships. For projects without measurements of protection, the length was back-calculated using the total inflation-adjusted project cost and the cost per length for the specified protection type and material. If no material information was given, a length-based distribution of all materials for the specified protection type was used. On projects without any information, a length-based distribution was used across all types and materials to allocate a proportion of each.

Retrospective in-use stocks

IU was calculated as size of protection (P_s), which is m^2 for land reclamation and m for shoreline protection, times the material intensity (MI_{mat}), multiplied by a conversion factor (CF_{mat}), m^3 to kg, that gives the final IU in kg, where "mat" is the material. For land reclamation, "mat" will only be sand, whereas for shoreline protection, based on the format of available information on existing shoreline protection, stock calculations were performed for the protection components and subsequently disaggregated into raw material requirements using material intensity factors.

IU represents the total of IU across multiple materials in the structure. For further information, see SI - A.

$$\mathrm{IU} = \sum_{\mathrm{mat}} (\mathrm{P_s} \cdot \mathrm{MI_{mat}} \cdot \mathrm{CF_{mat}}) \tag{3}$$

Annual in-use stocks are the accumulated amount of annual expansion, which can also be formulated as the sum of in-use stocks and expansion material requirements of the previous year:

$$\mathrm{IU_t} = \mathrm{IU_{t-1}} + \mathrm{E_{t-1}} \tag{4}$$

For the Scenario 1, IU materials stay constant, as expansion is not considered here.

Prospective in-use stocks

Projection of stocks until 2100 was based on calculating the expansion and maintenance requirements, which varied by each of the two scenarios (Table 1). Scenario 2 was calculated individually for shoreline protection and land reclamation projects, whereas Scenario 3 investigated the relationship between the two adaptation types – calculating the expansion of shoreline protection, given the expansion of land reclamation.

For Scenario 3, in addition to analyzing satellite imagery in GEE and QGIS, we retrieved information from ArcGIS satellite imagery on shoreline protection measures. We drew the length for shoreline protection associated with land reclamation as well as the length of the added coastline for at least one island per atoll. The results were compared and completed by MTCC information on land reclamation projects. We then calculated the mean length of added shoreline protection type per gained coastline, also including non-occurrence of shoreline protection measures. As we calculate the scenarios with added areas, we took the ratio of coastline [m] per land area [m^2] from islands in the official shapefile[19]. The calculation of prospective in-use stocks followed Eq. 4.

Expansion inflows

For modelling the changing material demands depending on the SSP SLR scenarios, we followed the bathtub approach[88], where adaptation measures are increased by height. For land reclamation, this means that any area that is being appended, needs to be increased in height by SLR. Similarly for shoreline protection, the additional volume of material is increased based on annualized SLR increase. Calculations for maintenance material demands and in-use stocks are identical for Scenario 2 and 3. Only expansion material requirements differed based on the approaches followed.

Scenario 2

Eq. 5 shows the annual expansion material requirements (E_t) of Scenario 2 with t = year, AC = area change. The SLR is available on decadal aggregation[56,57] and in eq. 6 annualized by the difference between the SLR of the current decade (d) and the decade before divided by 10 years.

$$\mathrm{E_t} = \left(\sum_{2020}^{2024} \mathrm{AC}\right) \cdot \mathrm{SLR_t} \tag{5}$$

$$\mathrm{SLR_t} = \frac{\mathrm{SLR_d} - \mathrm{SLR_{d-1}}}{10} \tag{6}$$

Scenario 3

We assume slowly tapering growth in the Greater Malé Area due to the availability of limited resources (limited reef area, sand, and financial resources), wherefore logistic growth models are suited well[93]. Regarding the saturation value S, we assume twice the atoll size of 2019, which is within the theoretical limit of the atoll area and this assumed saturation seems to be reasonable conservative, since the projection of additionally reclaimed area from 2025 to 2100 corresponds to approximately the same land area that has evidently been reclaimed in the period of 2019-2024 (further information on parameter calculations, see SI - A). For expansion material requirements estimation, the projected area change was calculated from the difference of y_t and y_{t-1}. Land reclamation demands were calculated as follows:

$$\mathrm{E_{t,mat}} = \mathrm{AC_t} \cdot \mathrm{MI_{mat}} + \left(\sum_{2019}^{2024} \mathrm{AC_{observed}} + \sum_{2025}^{t} \mathrm{AC_t}\right) \cdot \mathrm{SLR_t} \tag{7}$$

To account for associated shoreline protection, the "reclamation-fortification" parameters were applied based on the projected area change and the total estimated length of shoreline protection. Shoreline protection expansion due to fortification was calculated using the added length of the protection type in year t ($L_{t,mat}$) multiplied with the known meter-wise material intensity of the structure (MI_{mat}) and converted to kilograms using the factor CF_{mat}.

$$\mathrm{E_{t,mat}} = \mathrm{L_{t,mat}} \cdot \mathrm{MI_{mat}} \cdot \mathrm{CF_{mat}} \tag{8}$$

For SLR adjustment, most calculations used known top widths (T_{mat}) of the structures, the length of the structure, using SLR_t as the height and CF_{mat} to calculate the weight in kilograms.

$$\mathrm{E_{SLR_{t,mat}}} = \mathrm{T_{mat}} \cdot \mathrm{SLR_t} \cdot \mathrm{L_{mat}} \cdot \mathrm{CF_{mat}} \tag{9}$$

The increase in revetments was calculated using the known MI_{mat}, multiplied with the necessary extension of the hypotenuse c (slope), determined based on the Pythagorean theorem and the increase in leg a (height) due to SLR.

Maintenance inflows

To account for the mean maintenance material demand, the average lifetime and associated maintenance requirements (MR) were annualized. We assume that maintenance material requirements for reclaimed land are exclusively based on sand replenishment. The *Maldivian Ministry of Climate Change, Environment and Energy (MCCEE; new name of Ministry)* claims that every three years 20% of the original material requirement is needed to sustain artificial land[1].

$$\mathrm{MR_{t,mat}} = \frac{\mathrm{POC_{mat}}}{\mathrm{MF_{mat}}} \tag{10}$$

$$\mathrm{M_{t,mat}} = \mathrm{MR_t} \cdot \mathrm{IU_{t-1}} \tag{11}$$

Type- and material-specific maintenance requirements were calculated for shoreline protection analogous to land reclamation, but with year-specific maintenance requirements. Calculating maintenance for each shoreline protection involves a per material calculation, as one structure can be composed of multiple materials. This leads to a more complex calculation based on summed M_t for each material within each type of structure. For a more detailed explanation for each protection type, see SI - A. The maintenance calculation for each scenario remains constant, where IU_{t-1} varies depending on expansion calculations for each scenario. For Scenario 1,

the same amount of M_t will be added each year, and for Scenarios 2 and 3, this value will change depending on SLR-adjusted expansion and the expansion of land reclamation.

Other attempted approaches for shoreline protection

As consolidating data from MTCC projects was of a considerable manual effort, prior to resorting to this method, three additional, primarily GIS-based methods were attempted. The first approach identified island archetypes and required manually mapping shoreline protection based on GIS data. The second attempted method followed a statistical approach using a sample of islands and applying retrieved information from satellite imagery on other islands within the same service type. The third approach was based on a machine learning approach combined with verification against MTCC data. Nevertheless, all three methods had significant issues, predominantly because of difficulties to differentiate shoreline protection measures from satellite imagery, as well as susceptibility to errors due to subjective assessment of dimensions.

Data and method limitations

Along the data collection, processing and calculation steps shown in Fig. 6 and described in the previous sections, there are several assumptions made, due to data limitations and uncertainties that need to be considered. Fig. 7 shows decisions made, the main limitations and associated uncertainties with different steps of our method.

Data collection and preparation

Land reclamation *Choice of imagery.* For land reclamation, we chose Sentinel-2 imagery due to higher resolution than Landsat-8. The associated limitation with this decision is, that Sentinel-2 covers only the period from 2019 onwards. Our land reclamation observation hence covers a short period, that is later used as input data for Scenario 3. *Choice of index & threshold.* To identify newly emerged land areas in the chosen satellite imagery, we applied $AWEI_{nsh}$ with the threshold of -0.25. The choice of indicator and threshold affects the accuracy of the results. In SI-A, we further explain why $AWEI_{nsh}$ was chosen and show the sensitivity of the threshold for the land-water mask. The sensitivity analysis shows that the resulting land area can vary from -4% to +7% for the range of -0.40 to -0.10. *Availability of imagery*. For 2019 and 2020, no data is available for the atolls Haa Alifu, Haa Dhaalu and Shaviyani. Therefore, Landsat-8 data was used for the affected areas. This limitation induces an uncertainty in the calculated land area, due to deviations between Landsat-8 and Sentinel-2 data, mostly by reason of different spatial resolutions.

Shoreline protection *Use of MTCC projects as a basis*. For shoreline protection, MTCC data was collected to calculate the length of the respective shoreline protection types. Uncertainties associated with this step might be the incompleteness of MTCC data, as they only cover their own projects. *Covering 90% of the Maldives' population*. Also, only islands covering 90% of the Maldives' population are considered, possibly neglecting a small number of projects.

Calculation of stocks

Land reclamation *Fixed material composition and fixed material intensity*. For land reclamation, we used the same material composition and intensity among all atolls and years. There might be regional and temporal deviations not considered. As satellite imagery was retrieved only for 2019-2024, land reclamation projects prior to 2019 are not considered as in-use stocks, e.g. Hulhumalé. This limitation therefore influences 3) Calculation of flows as well.

Shoreline protection *Use of average material composition & intensity*. For retrospective in-use stocks, we used information on material compositions, if given by the projects. If no information was available, we applied average material compositions and intensities, for retro- und prospective in-use stocks. This assumption does not include local differences or changes in over time. *Fixed shoreline protection types*. Changes in protection types are not considered. Therefore, resource demands for new strategies or technologies that might come up in the future, are neglected.

Calculation of flows

Land reclamation and Shoreline protection *SLR expansion & bathtub approach*. To account for adaptation to SLR, we applied the bathtub approach by raising reclaimed land areas by mean sea-level rise. This approach is simpler than complex approaches including probabilities of flooding. However, based on[88] we chose the bathtub approach as it led to comparable results in the Maldives. Nevertheless, on site adaptation efforts to SLR might work differently. *Fixed maintenance requirements*. Assumptions for maintenance requirements were made, based on literature and public data. We assumed that coral mound is not used as a maintenance material in the future, as the use of coral blocks is strictly regulated[59]. Associated uncertainties concern local differences, changes over time and unpredictable extreme events. *Average length of SP per added area, retrieved via ArcGIS*. For shoreline protection, the type and length of shoreline protection measures was retrieved using ArcGIS, by drawing lines along the structures from satellite imagery and calculating the length. Uncertainties might be errors in classification of SP and minor inaccuracies in the drawing of polylines. *Scenarios show a range of possible futures*. Both Scenario 2 and 3 show possible futures, although it is highly unlikely that this specific future will occur. Scenario 2 outlines the possibility of no further expansion of land area and adapting to SLR by simply increasing the height of SP and LR. Scenario 3, however, assumes there will be future LR projects, especially in the Greater Malé area (see also Section "Past and current efforts in adapting to climate change in the Maldives"). The scope of Scenario 3 is rather conservative, as they do not consider a further rapid expansion of reclamation projects (see also Fig. 5b). How land reclamation projects will continue in the future is highly uncertain, as it is dependent

on different factors, as population growth, infrastructure demands, climate change impacts and policy changes, just to name a few. Major SP projects will develop along with LR, although further expansion without new land reclamation projects is possible. Within Scenario 2 and 3, we show the possible magnitude of SLR impacts, by including 5^{th} – 95^{th} percentile ranges across all SSP scenarios. As for material composition of future flows, we used constant values and did not consider possible reuse of shoreline protection materials.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Received: 15 January 2025; Accepted: 2 July 2026
Published online: 30 July 2026

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Funding
This work falls under the RECOVER project (Grant No. 110158-001), funded by UK aid from the UK government and by the International Development Research Centre (IDRC), Canada, as part of Climate Adaptation and Resilience (CLARE) research programme. The views expressed herein do not necessarily represent those of the UK government, IDRC or its Board of Governors. D. Wiedenhofer was funded by the Austrian Science Fund (FWF) project REMASS (https://doi.org/10.55776/EFP5). S. Linsmaier was funded by the Green Transformatio n initiative of the University of Augsburg (Germany) as part of the Green Research Network BRaVE, supported by the Bavarian State Ministry of Science and the Arts.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-026-61428-3.

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