SOUTH ASIA

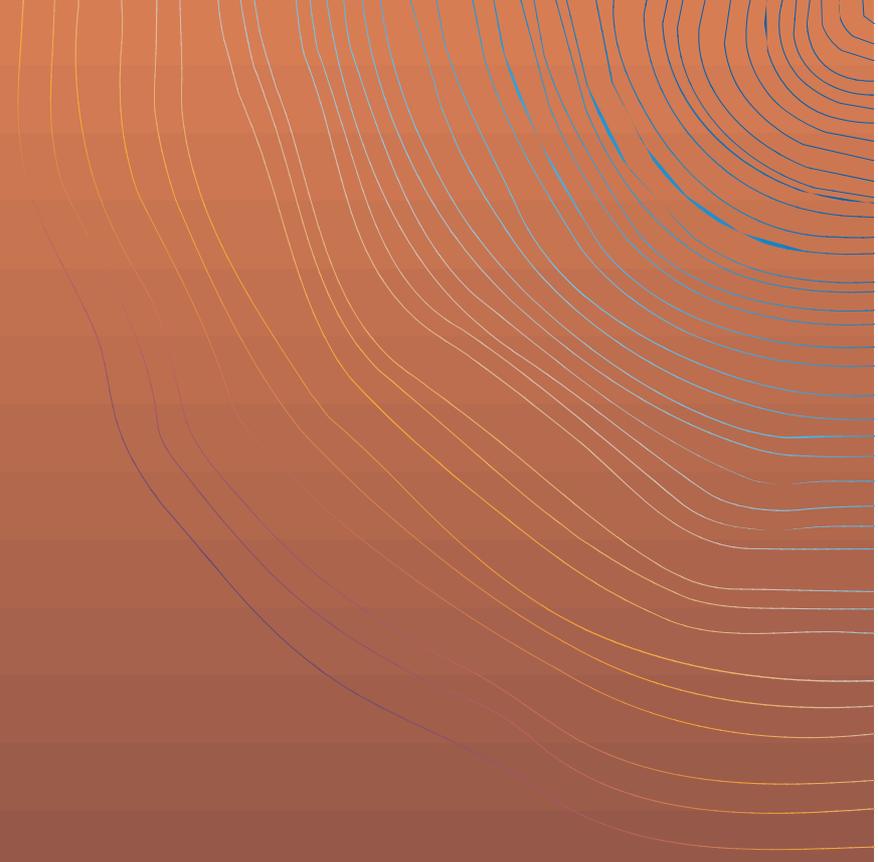# MALDIVES

World Bank Group

Quantitative Risk Assessment of Sea Level Rise-Induced Coastal Flooding in Maldives

Background paper of the Maldives Country Climate and Development Report

October 2024

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Acknowledgements

1. Introduction

Sea level rise is a key threat for Maldives given its low-lying elevation, high levels of economic activity along the shoreline, and societal dependency on coastal ecosystems. Between 1993 and 2015, sea level rise rates of 3.4 mm per year have been observed along the Maldives coastlines, comparable to the global average (Heger et al., 2024). Although the projected sea level rise is highly uncertain, most scenarios show that sea level rise could be between 0.2 – 0.35 meter (m) by 2050 and 0.5 and 1.0 m by the end of the century. The Maldives is particularly sensitive to sea level rise given that an estimated 72 percent of the land has an elevation of 1.5 m above mean sea-level or less (Heger et al., 2024). On top of that, most of the islands' population and economic activity are concentrated near the shoreline and depend critically on coastal ecosystems. For instance, 36 percent of all buildings are located within 100 m from the shoreline, while 71 percent of buildings are located within 200 m (Section 3 below).

As part of the Maldives' Country Climate and Development Report (World Bank Group, 2024), a quantitative risk assessment was carried out to understand the magnitude and hotspots of sea level rise-induced coastal flooding. This paper provides a technical description of the methodology behind, as well as additional deep-dives of the quantitative risk assessment.

2. Asset database

The analysis starts with constructing an asset database of the 514 residential and tourism islands. All datasets are sourced from open-source databases and therefore may not have a full coverage. The asset types included are roads, buildings (residential, commercial, industrial), airports, ferry terminals, education facilities, health facilities, and hospitals. Table 1 shows the source data, the spatial unit, and the maximum reconstruction costs used for the capital stock assessment. This provides us with a geospatial database of assets, including their capital stock value. The total estimated capital stock is around US$24.5 billion.

Table 1 Overview of the asset datasets used for the country physical damage analysis

Asset	Source	Spatial unit	Asset value
Roads[1]	OpenStreetMap (OSM)	Linestring	US$1.2 million/km for primary and secondary roads US$0.6 million/km for other roads
Building[2]	Google building footprints	Polygon	US$800/m^2
Ferry terminals	OpenStreetMap	Polygon	US$1500 /m^2
Airport	OpenStreetMap	Polygon	US$3000 /m^2
Education facilities[3]	OpenStreetMap	Point	US$3 million per facility
Health facilities[4]	Healthsites.io	Point	US$2.5 million per facility
Hospitals	Healthsites.io	Point	US$20 million per facility

3. Building distance to coastline

The next step is to evaluate the distance of each of the approximately 150,000 buildings in our dataset to the coastline of the island it is located on (Figure 1). According to this analysis, 35.9 percent of all buildings are located less than 100 m from the coastline, 71.1 percent are located less than 200 m from the coastline and 98.4 percent of buildings are located less than 500 m from the coastline.

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[1] This category includes primary, secondary, tertiary, trunk, and residential roads and highways as per OSM classification.

[2] This category refers to all buildings in the country, which include residential, commercial, industrial, education facilities, healthcare facilities, government buildings, prayer buildings, and other critical facilities.

[3] This category includes universities, schools, colleges, kindergartens, and other education centers.

[4] This category includes clinics, doctor practices, and pharmacies.

Figure 1 Fraction of all buildings located within a certain distance from the coastline of the island the building is located.

4. Exposure analysis of assets

To understand the total economic values of the assets exposed, the location of assets is overlaid with coastal inundation extents for different severity of coastal flooding. To do this, the analysis makes use of the FATHOMv3 coastal inundation maps for the Maldives[5]. At the time of the analysis, three return periods were available (1-in-10, 1-in-100, and 1-in-1000 years) for the present (2020 baseline) and four future time slices (2030, 2040, 2050, 2080). The future time slices cover three climate scenarios (SSP1-RCP4.5, SSP2-RCP6.0, and SSP5-RCP8.5), which include sea-level rise projects that drive future coastal flooding.

FATHOMv3 uses a 2D hydrodynamic model (LISFLOOD-FP) to predict inundation depth and extent, forced by water levels, tides, waves and dynamic topographic changes. It should be noted that cyclone-induced flooding is not well captured by this dataset. For the Maldives, this is less important given its close location to the equator that makes it not prone to cyclones. The Digital Elevation Model (DEM) used is called FABDEM, which is a corrected version of the CopernicusDEM and found to be the superior global-coverage DEM with high spatial resolution. To look at the future, sea-level rise projections from the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change are included for different future emission scenarios, which are used to adjust the flood maps derived. All grid cells with a flooding of 10 cm or less are removed to avoid including small scale flooding that does not cause disruptions or damages.

Figure 2 below shows the asset exposure as a percentage of the national asset base, either expressed in number of assets (education, hospital), area (airports, buildings) or length (roads). Different levels of inundation are assessed: small inundation (0.2m, lighter color), moderate inundation (0.5m, moderate shading) or more extreme inundation (1m, darker color). Building exposure reaches levels of 5 percent of all building assets, with a similar exposure found for hospitals. However, education facilities have a much higher exposure, reaching up to 5-20 percent of all assets. Road exposure reaches levels of 5 percent of the total asset length, with airport areas being relatively well protected given their high elevation.

Three conclusions can be drawn from this analysis: first, flooding in Maldives is not very severe in terms of flood depth, with only small fraction of assets experiencing flood levels of 1 m or more. This will have an impact on the physical asset damages to the assets. Second, the locations of certain assets are more sensitive to flood frequency. Hospital exposure is relatively insensitive, whereas education buildings are more sensitive to the flood frequency. However, a general observation can be made that the sensitivity is relatively low given the small difference in storm surges generated during 1-in-10-year events versus more extreme ones. Third, the exposure of assets varies. Assets that are more scattered

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[5] https://www.fathom.global/product/global-flood-map/

across islands and distributed within island boundaries (buildings, roads) are less exposed. Education buildings are clustered in a small number of places, which are exposed to coastal flooding. On the other hand, the airports of Maldives are highly elevated and hence less affected by coastal flooding.

Figure 2 Asset exposure to coastal flooding for three return periods and four time horizons[6]

[6] The colors indicate the scenarios (blue: SSP126, green: SSP245, red: SSP585) and the shading indicates the exposure to >0.2m (light shading), >0.5m (medium shading) and >1.0m (dark shading). See Table 1 for the definition and scope of each of each exposure class.

Scenario
Base — SSP2-RCP4.5
SSP1-RCP2.6 — SSP5-RCP8.5

Exposure level (m)
>0.2 >0.5 >1.0

5. Physical asset damage analysis

To translate exposed assets into physical asset damages, the analysis uses, per asset type, fragility curves that translate a given flood depth into the fraction of the asset value damaged (Figure 3). For example, if a building is exposed to 1 m of flooding, then based on the fragility curve below the fraction of damage to the building would be around 0.3 (or 30 percent). Therefore, if the building's replacement value is for example US$2 million, a 1 m of flooding would cause US$0.6 million (=0.3 x US$2 million)

worth of damages assuming one wants to rebuild the building to its initial state. This mathematical operation is performed to all assets in the country to calculate the total damages from a given flood event. The fragility curves used are based on existing curves developed for the Asian context (Huizinga et al., 2017). This can help us translate flood exposure of physical assets into subsequent economic costs, and consequently the total capital stock that is damaged.

Figure 3 Flood fragility curves adopted in this study for the different asset types

Figure 4 below shows the share of national capital stock that is affected by coastal flooding, and the equivalent damage value associated with that. As can be seen, the capital stock damaged for the 1-in-10-year event increases from US$0.42 billion in 2020 to US$0.69 – 0.80 billion in 2050. For the 1-in-100-year event, this value increases from US$0.55 billion in 2020 to US$0.82 – 0.94 billion in 2050, whereas for the 1-in-1000-year event, this value goes from US$0.67 billion to US$0.96 – 1.07 billion between 2020 and 2050. It should be noted that under all these scenarios, no additional adaptation efforts are included in the analysis.

Figure 4 Capital stock damaged by coastal flooding for different event severities[7]

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[7] Top row: capital stock damages in relative terms (as a percentage of the total asset stock). Bottom row: capital stock damages in absolute terms (in billion US$)

Two observations can be made; (i) the fraction of national capital stock damaged is only a small percentage of the total capital stock (e.g., just slightly above 2 percent under a 1-in-100-year event in the current climate); and (ii) the difference in asset damages between the 1-in-10 year event and the 1-in-100/1000 year event is relatively small.

The first observation can be explained by the fact that a large share of Maldives' capital stock is concentrated on a few islands that are already elevated higher than the extreme water levels during storm events. The second observation aligned with the results from a detailed hydrodynamic modelling for the Maldives, which showed limited difference in flood depths between a 1-in-10-year event and a 1-in-100 year event (Amores et al., 2021). In particular, the maximum water levels could be around 0.75m above tides for a 1-in-10-year event and 0.9m above tides for a 1-in-100-year event (Amores et al., 2021). It should be kept in mind that the flood model used only simulates inundation dynamics based on extreme water levels (that is, land will inundate if water levels are above land elevation). However, in the Maldives, inundation can also happen due to the overtopping of flood protection infrastructure (e.g., embankments), especially for large swell waves hitting the islands. These dynamics are not captured and hence may underestimate some of the inundation extent (see the Limitations section for further elaboration). In general, even parts of the islands that do inundate do only so for small water depths, hence not causing full damages to the exposed assets. As such, results should be interpreted with caution and more detailed hydrodynamic models are needed to capture inundation dynamics properly.

6. Exposure analysis of island landmass

Similar as with the exposure analysis in Section 4, the analysis estimates the island surface area that is exposed to coastal flooding. The analysis uses 0.5 m as threshold for facing some level of disruption to the affected landmass. This step is done separately for the residential islands (Figure 5 top) and the tourism islands (Figure 5 bottom).

Several observations can be made. First, under the current climate, the share of landmass exposed to at least 0.5 m of flooding under current climate is around 2-3 percent for residential islands and 3-4 percent for tourism islands. These numbers are expected to increase by around 0.5-2 percentage points in 2050.

Second, tourism islands are almost twice as flood-exposed compared to the residential islands. It is hard to understand what is driving this, given the large number of islands (each island may have different explanations of driving factors), the accuracy of the elevation model, and the different mechanisms that drive coastal flooding in Maldives. For instance, the islands in the west of the country are more prone to extreme water levels compared to those in the east (Amores et al., 2021). On top of that, some islands are only 100-200 m wide, whereas others are 1 km wide, making it hard to comprehend what is driving the results.

Third, the amount of land inundated for a 1-in-10-year event is comparable to a 1-in-1000 event, and in both cases are relatively small, indicating that the storms in Maldives are relatively mild. Sea-level rise is a bigger driver of coastal flooding compared to storm severity.

Fourth, the increase in capital stock damages across the different time horizons is larger than the increase in landmass flooded. This indicates that most of the increase in capital stock damages is caused by increasing flood depth and not the increase in flood extent.

Figure 5 Share of island area facing inundation of more than 0.5 m from coastal flooding[8]

7. Island level asset damages

Alongside the national capital stock damages, this report also evaluates the island specific capital stock damages. This report focuses on the residential islands only, leaving us with 189 islands in our analysis. Figure 6 shows the top 30 most affected islands for the present-day scenario and the three future scenarios in 2050. As can be observed, three islands have capital stock damages of over US$100 million at present. This increases to over US$150 million in 2050, with the largest future capital stock damages in Hanimaadhoo island, followed by Hithadhoo and Dharavandhoo.

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[8] Top row: residential islands. Bottom row: tourism islands.

Figure 6 Top 30 islands in terms of capital stock damaged in absolute terms (US$) during a coastal flood event of different severities across different scenarios
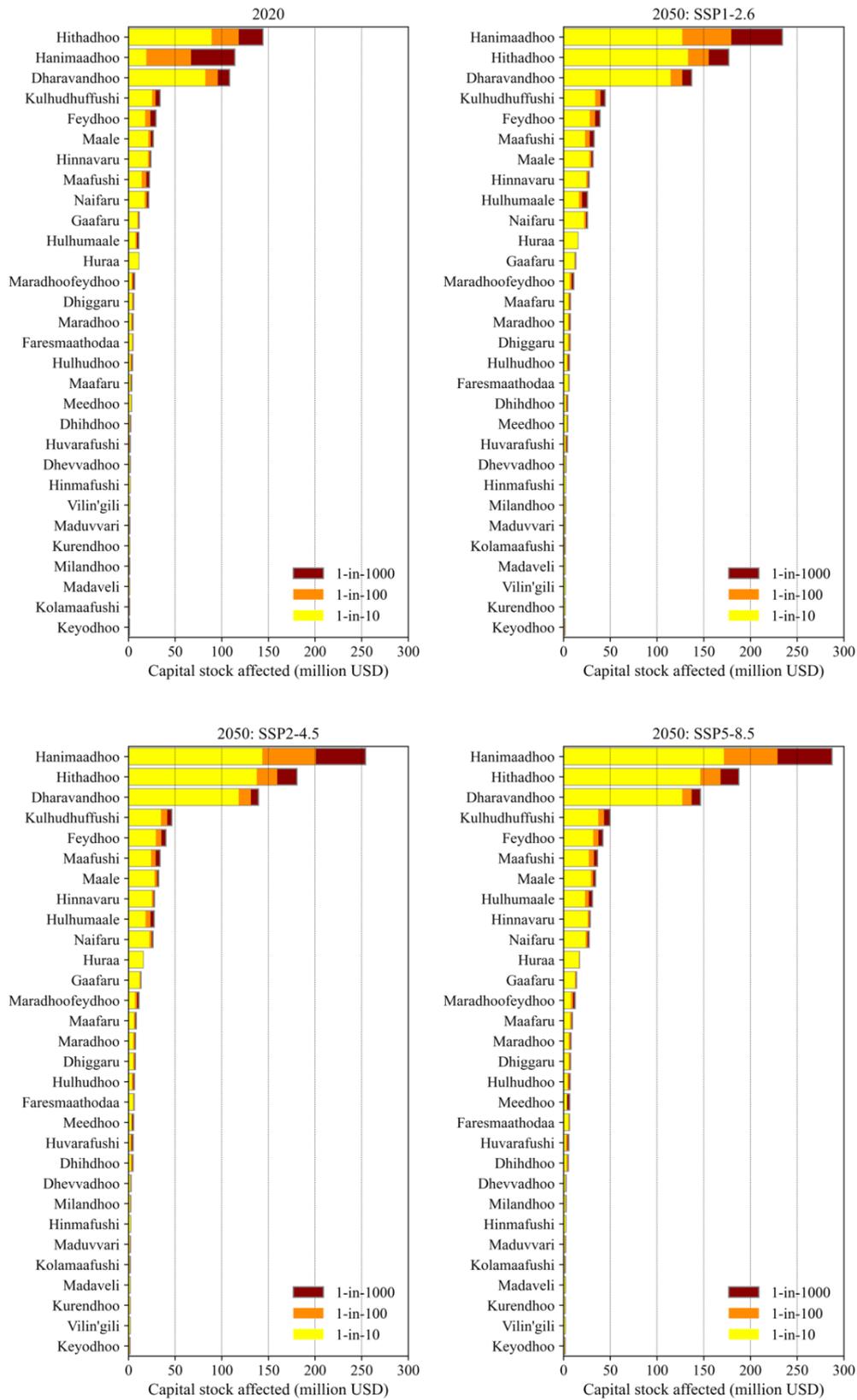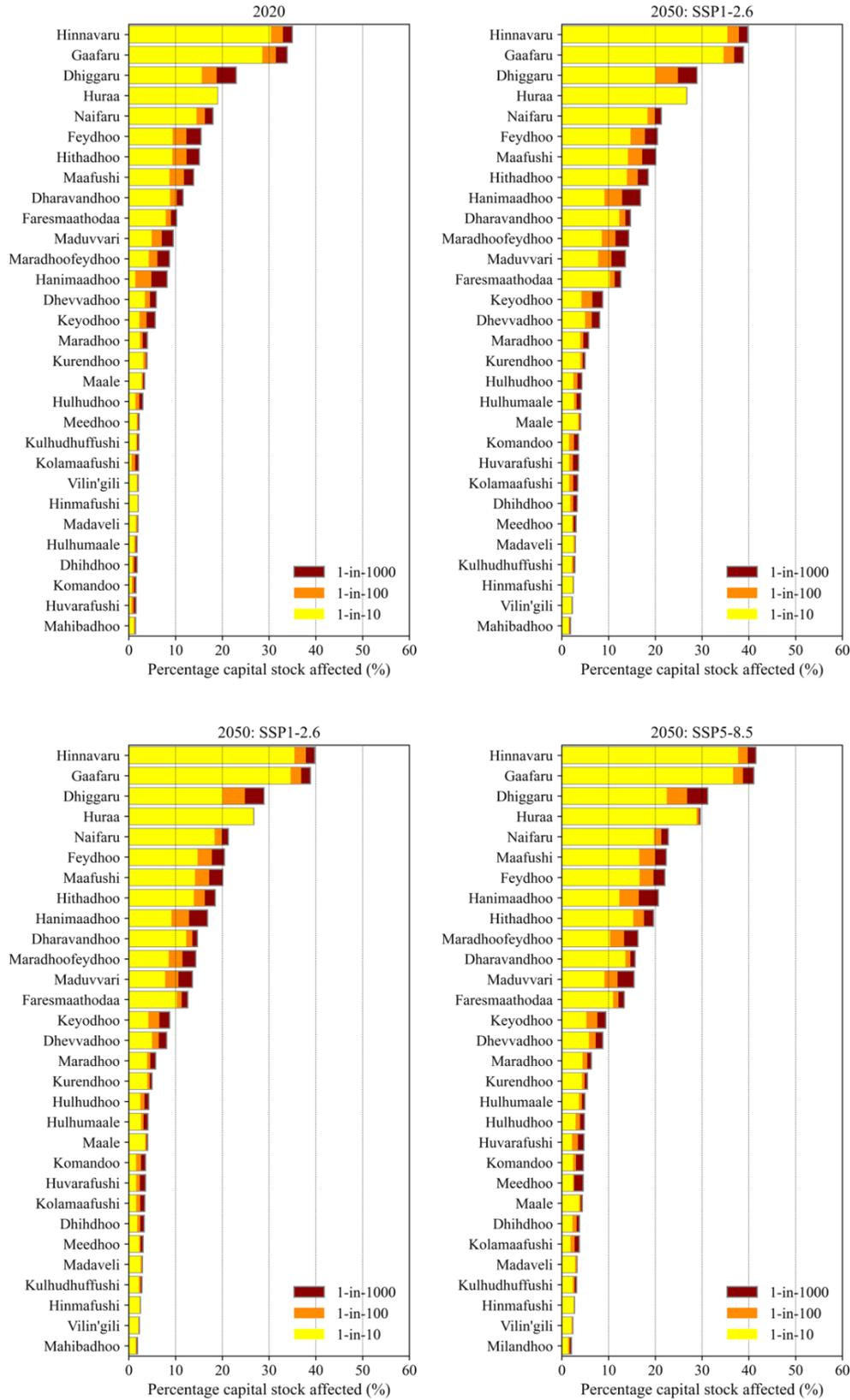
Figure 7 Top 30 islands in terms of capital stock damaged in relative term (as a percentage of total asset stock) during a coastal flood event of different severities across different scenarios

In a similar fashion, Figure 7 shows the top 30 islands affected but in relative terms. At present, 10 islands have over 10 percent of their capital stock exposed to coastal flooding. In 2050, this can

increase to 13 islands. The two most affected islands (Hinnavaru and Gaafura) can lose around 40 percent of their capital stock during a single extreme flood event.

The island-level capital stock damages are then compared to the Coastal Vulnerability Index (CVI) developed for each island (Heger et al., 2024). It should be noted that the CVI is constructed such that the size of the islands does not strongly determine whether the CVI is high or low. However, the island-level damage estimates do scale with the size of the island, with larger islands generally having higher absolute damage values and smaller islands having higher relative damage estimates (damages as share of capital stock). As a result, the alignment of the damages estimates and CVI is mild. The Spearman rank correlation coefficient between the CVI and the 1-in-100-year absolute and relative damage estimates are 0.30 and 0.33, respectively, for 2020 and 0.28 and 0.31, respectively, in 2050 (SSP2-RCP4.5).

8. Atoll level asset damages

Alongside the national capital stock damages, this report also evaluates the atoll specific capital stock damages (Figure 8 and Figure 9). A few atolls are driving the capital stock damages, including Lhaviyani, Seenu, Baa and Kaafu, all around 10 percent or more of their asset stock affected 2050 during a single extreme event. In other words, it should be kept in mind that there are clear differences in coastal flood vulnerability of the different atolls in Maldives, driven by island characteristics, the concentration of assets, and the hydro-meteorological forces that drive storm surges.

Figure 8 Capital stock damaged per atoll during a coastal flood event of different severities across different scenarios, in absolute terms (US$)

Figure 9 Capital stock damaged per atoll during a coastal flood event of different severities across different scenarios, in relative terms (as a percentage of the total asset stock)

9. Expected Annual Damages

In the final step, the Expected Annual Damages (EAD)[9] are calculated by taking the integral of seven return periods (RPs) and assuming that no damage occurs at a 1-in-1 year event (RP1; while our lowest

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[9] EAD is the expected damage incurred by flooding in each year, calculated by probabilistically averaging the probable maximum damages of flood events of different severities (e.g., from 1-in-10-year event to 1-in-1000 year event). Note that the assessment

return period is RP5). The EAD at present is estimated to be almost US$200 million, which is around 2.65 percent of GDP (Table 2). In 2050 under SSP2-RCP4.5, this number can increase to US$426 million, or 5.7 percent of GDP (present-day GDP)[10].

However, the assumption of the existing flood protection level is critical in estimating the EAD, in particular given the relatively flat loss-exceedance curve (that is, damages at lower RPs are in the same order of magnitude as for higher RPs). For a flat loss-exceedance curve, the damages from lower RPs would statistically weigh more heavily in the EAD calculation.

For instance, in Table 2 below, this report looks at the same results but under different assumptions of present-day and future flood protection standards (between 1 and 10 years). This highlights two things; (i) the assumption of existing protection level can make a huge difference in the risk estimates, up to a factor 2.4 when assuming protection at RP5 compared to RP1, (ii) when considering adaptation, it becomes clear that large economic benefits can be derived under relatively mild adaptation efforts (protecting against future 1-in-5 to 1-in-10 year events), with a large diminishing return. As such, information on island-level flood protection (beyond elevation levels) is required to refine the risk estimates.

Table 2 Expected Annual Damages in 2020 and 2050 (SSP2-RCP4.5) under different assumption of present-day and future flood protection standards

PROTECTION LEVEL (YEARS)	EAD IN 2020 (US$ MILLION PER YEAR)	EAD 2050 (US$ MILLION PER YEAR)
1	198.8	426.3
2	148.0	258.9
5	82.8	150.3
10	47.3	79.3

10.   Limitations

This analysis is based on best available national level datasets, but has several inherent limitations that should be acknowledged, including:

- Exposure datasets are based on publicly available data sources and could be refined using official country infrastructure datasets.
- Local flood protection measures are not included in the underlying flood models. This may lead to an overestimation of the flooding. However, it is likely that adequate flood protection measures exist only in some of the more populated and bigger islands.
- The future climate change scenarios do not take any further policy action into consideration (e.g., changing land-use or adopting asset-level/building-level flood adaptation measures), and should purely be considered as "what if" scenarios.
- The hydrodynamic model used considers the interaction of waves, storm surges and tides, and the inundation dynamics caused by storm water levels exceeding land elevation. However,

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assumes that flooding takes place across all islands simultaneously, which is highly unlikely. Moreover, the storm conditions that drive extreme water levels differ across atolls (Indian monsoon, swell waves, etc), making it unlikely that extreme water levels occur at all islands at once.

[10] The result is within a similar magnitude with the stress-testing done my IMF which projects direct damages of up to 3.4 percent in mid-century (IMF, 2023) and with a global-scale assessment that predicts around 7 percent of EAD in 2050 (Vousdoukas et al., 2023)

inundation from temporary overtopping or overwash, in particular due to long swell waves, are not properly accounted for. This may underestimate flood extent and depth.

- The impacts of coral reefs on flood inundation are not properly accounted for in the hydrodynamic modelling framework, which may slightly overestimate flood inundation.

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