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Land reclamation e adattamento ai cambiamenti climatici alle Maldives: valutazione delle trasformazioni degli habitat sull'isola di Magoodhoo (Atollo di Faafu)

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Abstract. For low-lying small islands, land reclamation enables development through new land for housing, infrastructure, and tourism while also functioning as an adaptation strategy to counter sea-level rise. Simultaneously, marine biodiversity delivers crucial protective ecosystem services to island communities. Focusing on the micro-scale case study of Faafu-Magoodhoo in the Republic of the Maldives, where a massive land reclamation project tripled the island's landmass for socio-economic and environmental purposes, the paper demonstrates how efforts to create new land to protect against climate change have unexpected side effects on local ecosystems, raising crucial questions on how to monitor these changes in order to limit and compensate for them. Using two years of drone-collected data, we document the major impacts of the reclamation project on coastal ecosystems, including the loss of 7.7 hectares of seagrass meadows and 2.33 hectares of coral reefs - significantly reducing the marine environment's capacity for carbon sequestration and natural coastal protection against climate stressors.

Through an interdisciplinary approach that bridges adaptation studies, human geography and coastal geomorphology, this paper reveals the often-overlooked environmental and geographical costs of land reclamation in the Maldives, highlighting the potential of Uncrewed Aerial Vehicles (UAVs) to monitor them. The study critiques short-term, infrastructure-driven responses to sea-level rise and calls for a re-evaluation of reclamation as a sustainable adaptation measure. Furthermore, it advances actionable recommendations for policymakers and practitioners, aiming to support more ecologically informed and socially equitable adaptation pathways in the Maldives and other climate-vulnerable small island nations.

Keywords: climate change adaptation, small islands, Maldives, land reclamation, UAVs.

Riassunto. Per le piccole isole, la *land reclamation* supporta lo sviluppo attraverso la creazione di nuove aree per l'edilizia abitativa, le infrastrutture e il turismo, funzionando al contempo come strategia di adattamento per contrastare l'innalzamento del livello del mare. Allo stesso tempo, la biodiversità marina fornisce servizi ecosistemici di protezione fondamentali per le comunità insulari. Concentrandoci sul caso di studio dell'isola di Faafu-Magoodhoo, nella Repubblica delle Maldive, dove un imponente progetto di *reclamation* ha triplicato la superficie dell'isola per scopi socio-economici e ambientali, il presente contributo dimostra come gli interventi volti a creare nuova terra come misura adattativa possano avere effetti collaterali inattesi sugli ecosistemi locali, sollevando questioni cruciali su come monitorare tali cambiamenti al fine di limitarli e compensarli.

Utilizzando due anni di dati raccolti tramite *Uncrewed Aerial Vehicles* (UAV), documentiamo i principali impatti del progetto sugli ecosistemi costieri, tra cui la perdita di 7,7 ettari di praterie di fanerogame marine e 2,33 ettari di barriere coralline - una riduzione significativa della capacità dell'ambiente marino di sequestrare carbonio e di fornire protezione naturale contro gli stress climatici.

Attraverso un approccio interdisciplinare che integra gli studi sull'adattamento, la geografia umana e la geomorfologia costiera, l'articolo mette in luce i costi ambientali e geografici spesso trascurati della *land reclamation* alle Maldive, evidenziando il potenziale degli UAV per monitorare tali dinamiche. Lo studio critica le risposte infrastrutturali a breve termine all'innalzamento del livello del mare e invita a una rivalutazione della *reclamation* come misura di adattamento sostenibile. Inoltre, propone raccomandazioni operative rivolte a decisori politici e operatori del settore, con l'obiettivo di promuovere percorsi di

adattamento più ecologicamente consapevoli e socialmente equi, tanto alle Maldive quanto in altri piccoli stati insulari vulnerabili ai cambiamenti climatici.

Parole chiave: adattamento ai cambiamenti climatici, piccole isole, Maldive, *land reclamation*, UAV.

1. Introduction

The effects of the climate crisis are increasingly, and unevenly, experienced worldwide. Small island populations are among the most exposed to climate change extreme events, among which sea-level rise, coastal erosion, and more intense tropical cyclones represent significant threats (IPCC 2023)¹. Therefore, planning for adaptation strategies that could help sustain livelihoods in their countries is a priority for small island governments (Robinson 2020). The creation of new land through reclamation practices has some potential for Small Island States (SIS) and several administrations are presenting it as a “realistic alternative to widespread assumptions about forced migration and ultimate national abandonment” (Brown et al. 2023, 1). Land reclamation projects become part of broader infrastructure interventions that promise to adequately respond to climate change adaptation needs while ensuring possibilities for economic growth and prosperity² (Nakayama et al. 2022; Chee et al. 2017). Land reclamation in SIS acts as a *promising infrastructure*³ (Anand et al. 2018): it embodies the promise of modernity, progress, and a safer future for small island populations, despite its multiple socio-environmental and economic challenges. Indeed, reclaiming land from the ocean “negatively impacts coastal and marine ecosystems, including reefs and mangroves, which compromises the protection services that they deliver to island communities through wave energy attenuation and sediment supply and may impact the long-term sustainable adaptive planning” (IPCC 2023, 2052; Duvat, Magnan 2019). While it may offer immediate risk reduction or economic advantages, reclaiming land can simultaneously exacerbate existing vulnerabilities, create new ones, or lock in unsustainable development trajectories (Magnan et al. 2016; Schipper 2020). Land reclamation can also be harmful to low-lying island communities and ecosystems (Duvat et al. 2017), as already shown by cases in Seychelles and Mauritius, where it has had profound and detrimental shoreline effects (Duvat 2009). Yet, land reclamation is still considered the go-to practice in policy. Therefore, it is crucial to identify and unpack its multiple - paradoxical - implications for climate change adaptation. To this end, we will examine it as a contested advance measure⁴ of adaptation in the Maldives, where large-scale land reclamation and infrastructure projects have been underway for the past four decades⁵ despite growing documented risks to biodiversity and the disruption of natural coastal processes (Duvat 2020). The Maldives is recognised as a *rare global seagrass bright spot* (Floyd et al. 2024), providing a crucial case study for examining land reclamation’s ecological impacts (Rotini et al. 2020; Macreadie et al. 2024). We therefore argue that comprehensive time-series monitoring of land reclamation projects is crucial to assess their impact on climate-sensitive environments⁶ (Dryden et al. 2020). UAV surveys can collect data over the area of interest at

¹ An 11-36% reduction is estimated in the volume of fresh groundwater lens of the small atoll islands (area < 0.6 km²) of the Maldives due to SLR (IPCC 2023, 2045).

² While reclamation is particularly prevalent in urban areas of East Asia, the Middle East, and Southeast Asia, followed by Western Europe and West Africa and that is undertaken mainly for port expansion, residential/commercial and industrial uses, 70% of recent reclamation has occurred in areas identified as potentially exposed to extreme sea-level rise by 2100 (Sengupta et al. 2023).

³ In Tuvalu, the creation of terrestrial space through land reclamation represents “a means of buying the atoll state time and space to adapt to climate change, as well as serving as adaptive measure in its own right” (Saddington 2025, 449).

⁴ “Advance: advancing the shoreline through the creation of new elevated land” (IPCC 2023, 2049).

⁵ Land raising examples remain scarce in the Maldives, thus questioning the role of reclamation as adaptation (van der Pol et al. 2023).

⁶ Remote sensing data serve as a primary source of information, providing a comprehensive view of the inland and coastal environments involved in reclamation processes (Vitousek et al. 2023; Avtar et al. 2020). These studies typically use satellite imagery (Chaves et al. 2020), such as the free data from the Sentinel and Landsat platforms (Hedley et al. 2018), which are part of the ESA (European Space Agency) and NASA (National Aeronautics and Space Administration) space programmes. However, the limitations of using these data are primarily related to their spatial resolution, which is not

centimetre-level resolution, allowing researchers to focus their data collection efforts only during optimal weather conditions (Hamylton 2017). The use of UAVs or drones for data collection and processing through the application of photogrammetry-based techniques and Object-Based Image Analysis (OBIA) classification algorithms increases the speed of monitoring and mapping activities (Fallati et al. 2020; Ventura et al. 2018). In the next sections, we analyse drone-collected data from the ongoing land reclamation project on Magoodhoo Island (Faafu Atoll).

Through a micro-scale approach, we look at an ongoing reclamation project in Faafu-Magoodhoo⁷ island to map - using high-resolution drone imagery collected over a two-year period - the main changes occurring at the coastal and marine biodiversity level and assess the type and magnitude of those changes. By quantifying the environmental damages of this measure on intertidal biodiversity, we show the importance of integrating drones as monitoring tools throughout the reclamation process and recommend their application in environmental management and biodiversity conservation and restoration measures. The paper is the outcome of broader interdisciplinary research consisting of analysing socio-environmental micro-scale effects of national adaptation and development policies in the Maldives and extensive fieldwork from February 2022 to February 2024 using Uncrewed Aerial Vehicles (UAVs) in Magoodhoo (Faafu Atoll) where two reclamation projects are underway: the expansion of the island settlement and coastal protection, and the construction of a domestic airport. We collected drone data to depict the main effects of the project on the local coastal ecosystems, e.g. seagrass meadows and coral reefs, and provide further recommendations to practitioners and policymakers. Our analysis demonstrates that the project has reshaped the structure of the island and its surroundings, severely compromising the protective functions of coastal and marine ecosystems through wave energy attenuation, sediment supply and, more broadly, their contribution to climate change mitigation. By using a micro-scale approach (the island of Faafu-Magoodhoo), we provide data on both the limits and the potential for reclamation as adaptation in the Maldives with the aim of contributing to a growing scholarship on this topic in climate-vulnerable and spatially constrained places such as low-lying small islands and areas. By understanding the associated impacts, we highlight land reclamation risks and develop some recommendations for better governance of marine and coastal management (specifically for evaluation and monitoring of climate change adaptation measures) in the Maldives and other SIS.

We begin by outlining essential background on the Maldives, with specific attention to large-scale land reclamation initiatives and their impact on biodiversity. The study area, methodological framework, and data collection procedures are then presented. The core of the paper is dedicated to the presentation and analysis of the primary results, culminating in a comprehensive discussion of key findings and offering targeted recommendations for future research, policymaking, and practice.

2. Background: Reclaiming Land in the Maldives

The Maldives is an archipelago in a double chain of coral atolls extending across the central Indian Ocean for over 860 km from north to south and 80 to 120 km from east to west (Fig. 1a). The archipelago, which consists of approximately 1,192 small, low-lying coral islands grouped into 26 natural atolls, has the seventh-largest reef system in the world - the largest in the Indian Ocean (Ministry of Environment and Energy - MEE 2016). Small size, low elevation and unconsolidated

suitable for studying benthic communities in certain small-scale coral reef areas such as the Maldives, and secondarily to the adverse environmental and operational conditions that can occur during surveys, including cloud cover, high water's turbidity, breaking waves, limited access, and costs.

⁷ Magoodhoo hosts the MaRHE Center (Marine Research and Higher Education Center), a research outpost of the University of Milan-Bicocca active in the region since 2010 to carry out research and educational activities in the fields of environmental science, marine biology, tourism science and human geography (Montano et al. 2012; Saponari et al. 2018; Fallati et al. 2020; Cerri et al. 2024; Ruggieri et al. 2025; Siena et al. 2026). The MaRHE Center collaborates with the Maldivian Ministry of Fisheries, Marine Resources and Agriculture to blend technology, development and sustainability for protecting the natural environment and enhancing quality of life in the Maldives. Over the past decade, MaRHE researchers have conducted long-term monitoring activities focused on the coral reef environments surrounding the island. This extensive research was made possible thanks to the presence of the MaRHE Center in Magoodhoo, which provided essential logistical and research support on site.

material make atoll islands at risk of flooding and coastal erosion, especially under climate change⁸ (Duvat 2020). Over 80% of the Maldives' landmass is less than a metre above sea level with many settlements and critical infrastructures being less than 100 metres from the ocean, making it exceptionally vulnerable (Ministry of Environment and Energy - MEE 2015a). Over the past few decades, the archipelago has experienced significant changes primarily due to climate change, particularly sea-level rise, and human-induced disturbances (Malatesta et al. 2021).

The Maldives has widely adopted land reclamation and coastal protection structures in almost all inhabited islands to reduce land shortages and enhance socio-economic development through infrastructures like ports and airports to boost connectivity and tourism⁹ (Republic of Maldives 2006; Kench 2012; Naylor 2015; Duvat, Magnan 2019). In 2015, the national government stated that “the Maldives would not be at its current level of development without reclamation” (Ministry of Environment and Energy - MEE 2015b, 60), suggesting that land reclamation would increase in the coming years. Currently, there are 15 ongoing airport development projects to be completed within the next 2-3 years (Fig. 1b; Tab. 1) with the aim of “facilitating smoother travel, stimulating tourism and bolstering economic development” (Ministry of Economic Development and Trade 2024, 1).

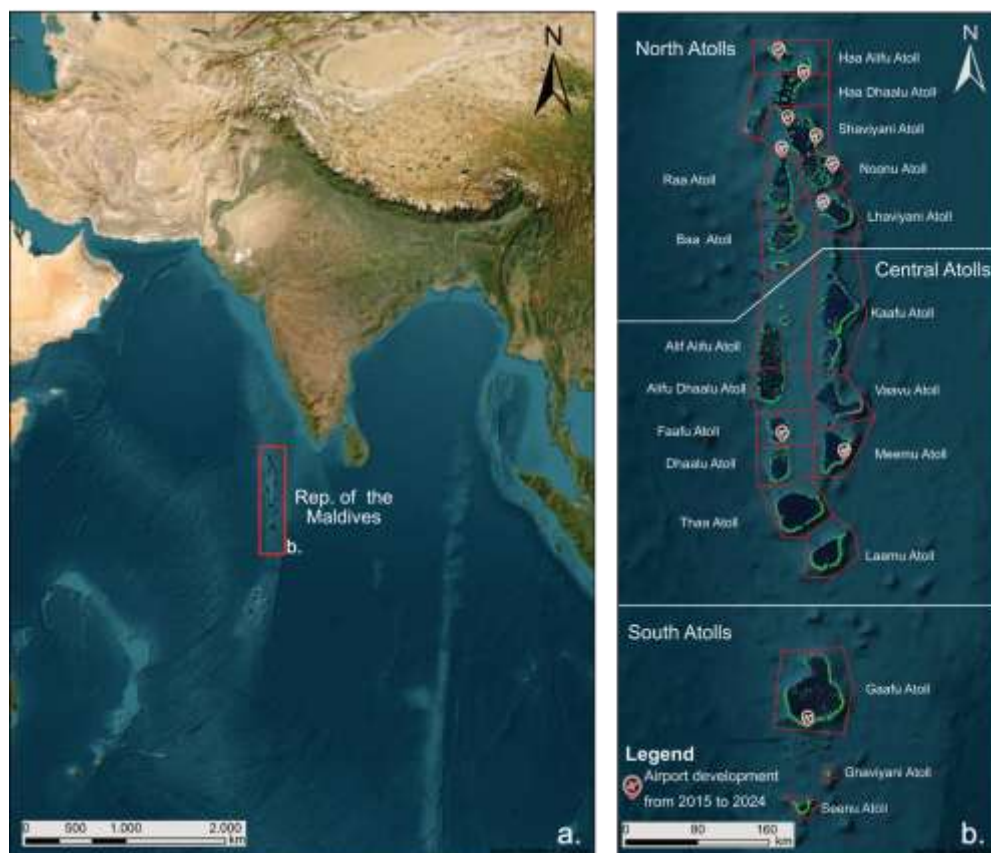


Figure 1. (a) Republic of the Maldives, located in the Indian Ocean southwest of the Indian subcontinent. (b) Zoomed-in view of the entire archipelago, with the approximate boundaries of the administrative atolls marked in red and the airport development projects approved across the country in 2015-2024. Source: Esri, World Imagery, ArcGIS Online Basemaps, <https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08feb2a9>.

⁸ Under Gayoom’s presidency, first official policies of relocation to decrease population dispersion were elaborated (Gussmann, Hinkel 2021) but relocation plans as climate change responses have officially been abandoned in favour of land reclamation policies.

⁹ The previous government led by Ibrahim Mohamed Solih (2018-2023) announced a policy to provide 20-30-minute speedboat transfers to airports across the country: “Our goal is to build an airport every 20-30-minute distance between residential islands. As the airports are developed, as the seaplane network is expanded, and the isolated islands linked via the RTL ferry service, greater opportunities will open for local tourism” (<https://en.sun.mv/78027>).

Table 1. The list of the Environmental Impact Assessments (EIAs) conducted by the Environmental Protection Agency (EPA) - renamed to Environmental Regulatory Authority (ERA) in 2025 - from 2015 to 2024 concerning airport development projects in the Maldives. Most of the projects have been completed, some of them are in progress and/or nearing completion. Source: Authors' elaboration using data from the Environmental Regulatory Authority (ERA), <https://www.era.gov.mv/reports.html>.

EIA Submission Year	Atoll	Island	Project
November 2017 (EIA)	Haa Dhaalu Atoll	Kulhudhuffushi	Airport development project
March 2017 (EIA)	Shaviyani Atoll	Funadhoo	Residential area and airport area reclamation
November 2017 (EIA)	Noonu Atoll	Maafaru	Airport development project
July 2018 (EIA)	Gaafu Atoll	Faresmaathodaa	Airport development project
June 2018 (EIA)	Haa Alifu Atoll	Maafinolhu	Domestic Airport Development project
August 2018 (EIA)	Lhaviyani Atoll	Madivaru	Airport development project
November 2022 (EIA)	Raa Atoll	Alifushi	Airport development project
December 2022 (EIA)	Faafu Atoll	Magoodhoo	Magoodhoo land reclamation for the airport development and shore protection
	Meemu Atoll	Muli	Airport development project

Engineering interventions, such as land reclamation and shoreline armouring can be observed throughout the country: since 2000, the Maldives has added 37.50 km² of land area¹⁰, modifying the shape, the size and the potential of many islands (Holdaway et al. 2021; Esteban et al. 2019). Over the past decades, the geography of the Maldives has been reshaped through land reclamation: 93.5% of inhabited islands and 79.2% of resort islands have experienced expansion due to this practice and/or the effects of engineered structures (Duvat 2020). The Land Use and Land Cover (LULC) maps produced by Fallati et al. (2017) showed an increase in land reclamation within lagoons near inhabited islands resulting in environmental damage to the reef habitat. Indeed, this development path has strained the country's blue natural capital¹¹ - which offers the first important protection services against disasters and sea-level rise - and key economic sectors such as tourism - depending on the country's blue natural capital (Schmidt di Friedberg, Malatesta 2022) - and fisheries¹² (World Bank 2024).

Starting from the late 1990s the creation of new elevated land in the Maldives has been framed as an adaptation measure to sea-level rise¹³, described as having “high engineering resiliency [...] to climate change impacts (i.e.: increase its floor level height etc. by dredging more material etc.)” (Ministry of Environment and Energy - MEE 2015b, 25). However, no explicit mention of reclamation as adaptation can be found in the *National Adaptation Programme of Action* (NAPA)¹⁴, which states that land reclamation has put critical infrastructures under pressure on some islands since it “have caused settlements and associated infrastructure to be located close to the coastline” (Republic of Maldives 2006, 24). The *Survey of Climate Change Adaptation Measures in the Maldives* (Ministry of Housing and Environment, UNDP 2011) provides an early reference to land reclamation as an adaptation strategy, noting that it can support climate resilience when newly reclaimed land is elevated to reduce coastal flooding risks. Similarly, the Maldives' *Nationally Determined Contribution (NDC) Implementation Plan* (Ministry of Environment and Energy - MEE 2018)

¹⁰ The amount of lagoon and reef areas modified for land reclamation purposes was estimated at more than 10 km² in 2015 according to the 2015 National Biodiversity Strategy and Action Plan of the Maldives (NBSAP) (MEE 2015d).

¹¹ As stated by the World Bank Country Environmental Analysis “The ability of the nation to adapt to the future sea-level rise is heavily dependent on this ecosystem service, and whether the new sand amounts produced and deposited are enough to outpace SLR” (World Bank 2024, 11).

¹² Over the years, the Maldives' financing of infrastructure - mostly built on reclaimed land - has contributed to the deterioration of the country's fiscal and debt stability (World Bank 2024).

¹³ See Muizzu 2024.

¹⁴ An updated version of the NAPA is expected to be published in 2025.

emphasises that land reclamation should be integrated with measures to raise land elevation and strengthen shoreline protection, particularly on vulnerable inhabited and resort islands.

Current land reclamation practices in the Maldives are guided by the non-binding *Guidance Manual for Climate Risk Resilient Coastal Protection* (Ministry of Environment and Energy - MEE 2015b), which recommends elevating reclaimed land 1.5-1.75 metres above current mean sea level and implementing robust protective measures. However, projections of sea-level rise between 0.6 and 1.1 metres by 2100 (Oppenheimer et al. 2019) suggest these elevations may be insufficient. Moreover, without adequate protection, land reclamation can generate short-term environmental impacts, such as severe erosion during and after construction. New land must be assessed in terms of its impact on coastal processes and natural systems (Ministry of Environment and Energy - MEE 2015c), yet many projects still replicate existing elevation levels to prevent drainage issues. A notable exception is Hulhumalé, raised two metres above sea level and currently the country's largest reclamation initiative (Chase-Lubitz 2024).

Despite policy recommendations in key documents like the *National Strategy for Sustainable Development* (Government of Maldives, UNEP 2009) and the *Strategic Action Plan 2019–2023* (Government of Maldives 2019), a specific regulatory framework¹⁵ for land reclamation is still lacking. This gap undermines environmental safeguards and hinders efforts to reduce induced hazards and enhance island habitability and quality of life (World Bank 2020). Several land reclamation projects have been criticised for ignoring environmental laws, disregarding site-specific conditions, and causing habitat destruction and biodiversity loss (Human Rights Watch - HRW 2023). This is a major concern for development, risk reduction and adaptation strategies in the Maldives. The *National Biodiversity Strategy and Action Plan* (NBSAP) (Ministry of Home Affairs, Housing and Environment 2002) already warned that “the reefs¹⁶ of the Maldives, high in diversity and low in abundance, are especially sensitive to over-exploitation”. By undermining these ecosystems, reclamation projects may deliver short-term economic gains at the expense of long-term ecological security and adaptive resilience. The updated NBSAP (Ministry of Environment and Energy - MEE 2015d) set ambitious goals for restoring impacted ecosystems and achieving near-zero loss of coral reefs, seagrass beds¹⁷, and mangroves¹⁸ by 2025 - targets that appear increasingly out of reach amid accelerated coastal development. The EPA, operating under the Ministry of Environment, Climate Change and Technology, lacks adequate capacity for monitoring and enforcement¹⁹. As HRW (2023, 7) noted, “Planning ministry reclamation projects arrive preapproved before any EIA is carried out”, raising concerns about transparency and accountability. Moreover, there is little recourse or compensation for communities adversely affected by these developments.

3. Study Area, Data and Methodology

Magoodhoo is located on the south-western rim of Faafu Atoll (Fig. 2a; 3°4'49.08"N, 72°57'57.19"E). Faafu Atoll, 70 nautical miles far from Malé City, the capital city of the Maldives, has a total of 23 islands of which 5 islands are inhabited: Nilandhoo, Dharanboodhoo, Magoodhoo, Bilehdhoo and Feeali. Major income sources in the atoll, inhabited by about 4,800 people (Maldives Bureau of Statistics 2022) include fishing and agriculture, construction, public and tourism sectors. As part of a state-led urbanisation strategy, land reclamation has been implemented across the majority of the atoll's inhabited islands to address infrastructure shortfalls and facilitate tourism growth. Currently,

¹⁵ The only exception is represented by the Regulation on Dredging and Reclamation (2013/ R-15), which “prevents dredging or land reclamation on environmentally sensitive areas hence preventing anthropogenic stress on the coastal dynamics of vulnerable areas” (UNFCCC 2015).

¹⁶ Coral relocation is occasionally practised (EPA 2023a), but data on post-transplant survival remain limited (Ferse et al. 2021).

¹⁷ Seagrass ecosystems - essential for oxygen production, carbon sequestration, sediment stability, coastal protection, food source and nursery habitat for important fish species and biodiversity (Hastings et al. 2020) - are increasingly threatened by land reclamation. Yet, these ecosystems are under-studied.

¹⁸ Mangroves - important carbon sinks and coastal buffers - have historically been undervalued and are often lost to land reclamation or used as waste disposal sites in the Maldives.

¹⁹ Information gained through interviews and informal chats with key informants during fieldwork in February 2024.

a land reclamation project for an airport development is being implemented in Nilandhoo, only 8 km away from Magoodhoo²⁰.

Magoodhoo's original size - prior to the ongoing reclamation - covered less than 0.36 km² with a length of 1 km, a maximum width of 0.27 km, and a perimeter of 2.4 km (Leoni et al. 2021). The island has a population of 825 people (Maldives Bureau of Statistics 2023). A port was built on the northwest side of the island between 2015 and 2016 (Fig. 2b), with a reclamation project that increased its area by 10% (Duvat, Magnan 2019).

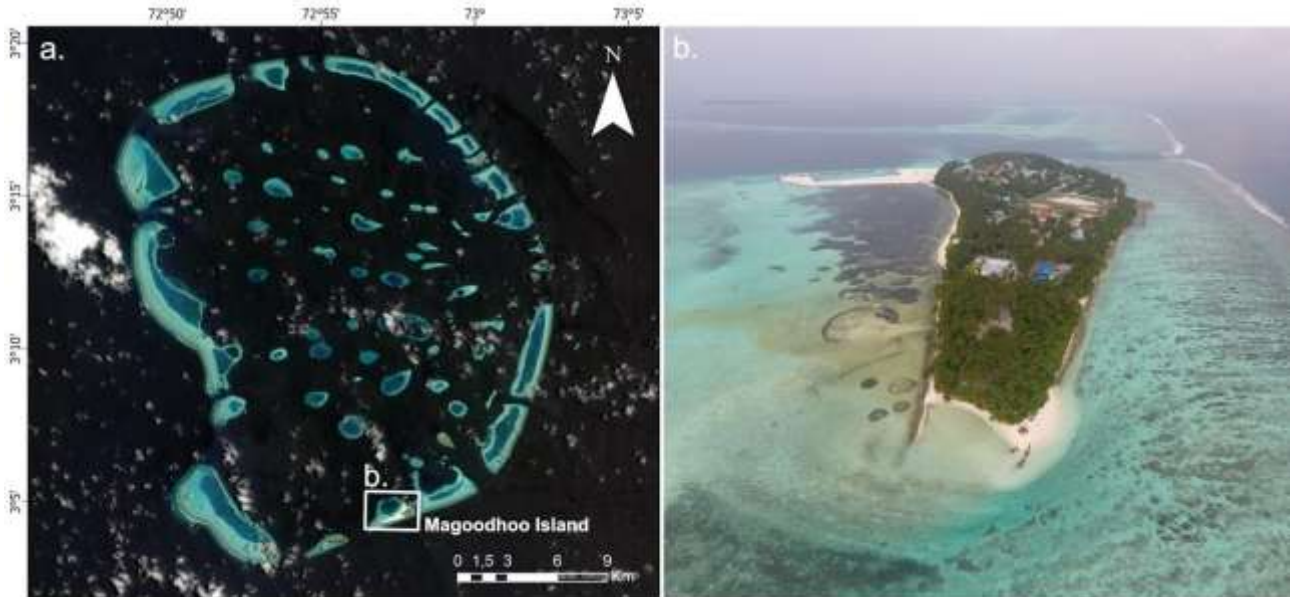


Figure 2. (a) Overview of the study area from satellite, showing Faafu Atoll with Magoodhoo highlighted in the white box; inset: drone image of Magoodhoo. (b) Drone image of the island at the beginning of 2017 (February). Source: elaborated by Fallati.

Following two EIAs conducted in 2019 and 2022 respectively, a major project, *Land reclamation for airport development and shore protection at Magoodhoo, Faafu Atoll*, was approved in December 2022²¹ (Environmental Protection Agency - EPA 2022), with an additional EIA commissioned and approved in 2023 (Environmental Protection Agency - EPA 2023b), due to technical information gaps found in the previous documentation. The project entails the reclamation of 47.8 hectares of land - comprising 17 hectares designated for housing and related activities, and 30.8 hectares allocated for the construction of a domestic airport. As of mid-2024, the project is reported to be approximately 50% complete. The EIAs highlight several environmental concerns during the construction phase, notably increased sedimentation from backfilling operations, degradation of marine biodiversity, and alterations to local hydrodynamics. Despite these documented risks, the 2022 EIA concludes that the overall long-term impact is expected to be positive, citing anticipated socioeconomic gains “for the locals, transportation sector, and economy of the Maldives” (Environmental Protection Agency - EPA 2022, 13). The fieldwork in Magoodhoo Island aimed to identify and assess coastal and habitat changes due to the land reclamation project. Following the mass coral bleaching event of 2016, systematic monitoring of reef functionality around Magoodhoo began in January 2017, coinciding with the initial phases of port construction. This long-term ecological assessment has been instrumental in tracking the condition and resilience of these highly vulnerable ecosystems. As part of the ongoing research related to the current land reclamation project, a comprehensive image dataset was compiled, comprising high-resolution drone imagery collected between November 2022 and early 2024. These visual records capture the sequential phases of reclamation and provide a critical basis for assessing coastal and marine habitat changes over time (Fig. 3).

²⁰ See Ganic 2026.

²¹ The 2022 EIA was based on data collected by the Maldives Transport and Contracting Company (MTCC) in October/November 2022, which is the same company in charge of the project.



Figure 3. Overview of Magoodhoo from drone images highlighting the various stages of land reclamation around the island. (a) provides an overview of the entire island in 2017, clearly showing the bare land resulting from the initial reclamation for building the harbour (2016/2017). Images (b), (c), and (d) highlight the various stages of the reclamation process from October 2022 to February 2024. Source: elaborated by Fallati.

DJI quadcopters, specifically the Phantom 4 and Mavic 3 Enterprise, were selected for data collection. These drones are lightweight, portable, and can fly efficiently at low altitudes to capture high-quality ground resolution imagery. Furthermore, their simple take-off and landing procedures make them an excellent solution for low-altitude and short-distance surveys (Bonali et al. 2019). The metadata of the captured images, which includes information such as shutter speed, aperture, ISO (International Organization for Standardization), and GPS (Global Positioning System) coordinates (x, y, and z), are recorded in an EXIF (Exchangeable Image File Format) file. The surveys were designed in the areas of interest using ground station software, which enabled planning all aspects of the drone mission in detail, including generating flight paths, setting camera parameters, and checking data acquisition directly on the controller screen. Fixed flight and image acquisition parameters were established for all surveys. Similar environmental conditions were selected for all surveys to collect relevant data for comparison over time. Data were collected along the three main areas affected by the reclamation project: seagrass meadow in the north-west, reef flat in the south-east zone and sandbank in the south-west (Fig. 4).



Figure 4. Magoodhoo before the beginning of the land reclamation and shore protection project in 2022. The dotted lines indicate the areas affected by the reclamation monitored through time (2022-2024) with UAV surveys. Source: Esri, World Imagery, ArcGIS Online Basemaps, <https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9>.

All images captured by the drone were analysed using Agisoft Metashape (<https://www.agisoft.com/>), using structure from motion (SfM) technology (Jiang et al. 2020). The image processing workflow consisted of four main steps: photo alignment, dense point cloud generation, Digital Terrain Model (DTM) creation and orthomosaic generation. Photo alignment was performed using a high accuracy setting to detect and match key points across overlapping images, allowing the reconstruction of camera positions and the generation of a sparse point cloud. This step also included an initial optimisation of camera parameters to improve internal and external orientation. Dense point cloud generation was subsequently carried out using a moderate depth filtering setting, which provided a balance between point density and noise reduction, ensuring a reliable representation of the surveyed surface. A DTM was then derived from the dense point cloud after the classification and removal of non-ground points. This step allowed the extraction of a surface model representative of the underlying terrain morphology. Finally, an orthomosaic was generated by projecting the original images onto the DTM, resulting in a georeferenced, high-resolution raster product with uniform scale and minimised geometric distortions. The use of Real-Time Kinematic (RTK) correction improved the georeferencing accuracy and ensured consistency among multi-temporal surveys. The orthomosaics obtained from UAV surveys were analysed and classified using Trimble eCognition Developer 10.3 (<https://geospatial.trimble.com/en/products/software/trimble-ecognition>). This software helped analyse the orthomosaics to produce comparable benthic coverage maps. OBIA algorithms were used following the methods described in previous studies for both satellite and UAV data (Fallati et al. 2020; Ma et al. 2017). A multi-resolution segmentation algorithm based on homogeneity criteria was applied to the high-resolution orthomosaics, with the image layer weights set equally for all three bands. The optimal scale parameter found was 300, with a shape value of 0.1 and a compactness value of 0.5. Following the segmentation process, well-defined samples as training areas were used for the supervised classification. The benthic coverage polygons were exported as a shapefile in the ArcGIS 10.8 environment to compare the impact of the reclamation over time, create maps, and estimate the loss of benthic habitat due to the project (Fig. 5).

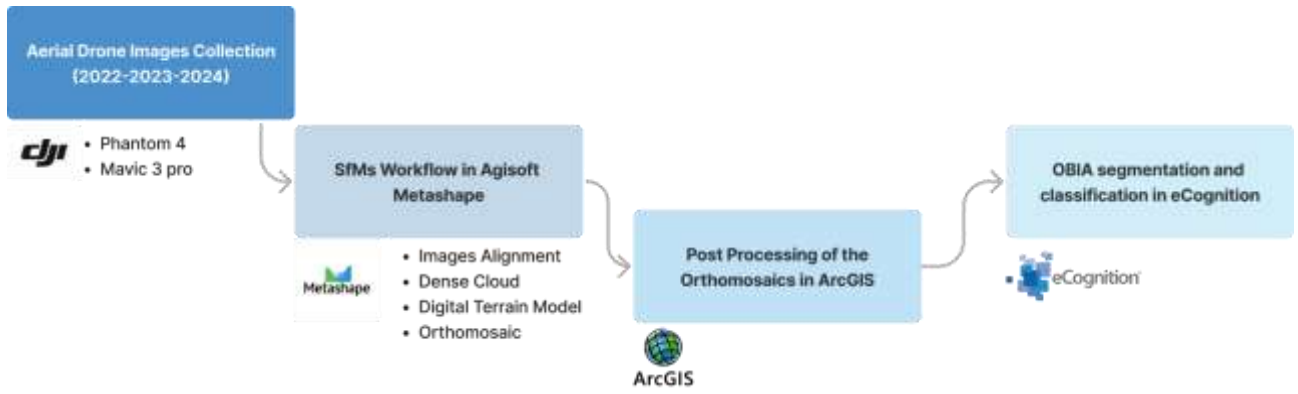


Figure 5. Workflow for drone image acquisition and data processing using various software: Metashape (Agisoft), ArcGIS (ESRI) and eCognition (Trimble). Source: elaborated by Fallati.

To gain a comprehensive understanding of the entire reef system around Magoodhoo, the use of RapidEye satellite imagery was integrated at a resolution of 3 m/pixel and combined with drone data. One of the images (May 2022) served as a basemap for plotting the high-resolution drone orthomosaics, while the others were used to compare the island and its surrounding environments in November 2014, May 2022, and May 2024. All images were downloaded from the Planet Scope web platform (<https://www.planet.com/explorer/>) using a basic educational account.

4. Results

Processing of the UAV imagery resulted in the creation of high-resolution orthomosaics (3.5 cm/px) covering an average of 116 hectares of shallow water environments around Magoodhoo for the years 2022, 2023, and 2024 (Fig. 6).



Figure 6. High-resolution orthomosaics derived from UAV images of Magoodhoo and its nearshore environments, plotted on a satellite basemap with a 3 m/pixel resolution. (a) shows the study area in March 2022, before the beginning of the reclamation work. (b) and (c) show two intermediate phases of the reclamation with work focused on the seagrass area. (d) is the last orthomosaic, produced in February 2024,

highlighting the final step of the reclamation around the island. Source: Image © 2022 Planet Labs PBC, elaborated by Fallati.

The detailed models provide an overview of the dynamics of the benthic communities in relation to the reclamation steps, allowing for low-cost and time-saving surveys. The quality of the data highlights the differences in benthic community expansion between the two years through a visual on-screen comparison of the orthomosaics (Fig. 7).



Figure 7. Close-up of a section of the seagrass meadow to highlight its coverage during the progress of the dredging works. Source: elaborated by Fallati.

Benthic assemblage maps, created using OBIA, delineate the extent of seagrass and coral colonies in specific regions of the three monitored sites. This analysis spans the period from shortly before reclamation commenced to February 2024, encompassing the project's final phases. The initial phase of the reclamation focused on the nearshore area on the northwest side of the island to make way for new settlements (Fig. 7; Fig. 8). A comparison of the benthic maps showed a total loss of 7.7 hectares of seagrass meadows in the northwest lagoon. These meadows were in a healthy condition and were expanding before the reclamation work began (Fig. 8a). They were initially partially covered during the first phase of the work (Fig. 8b) and then disappeared completely after the work was completed (Fig. 8c).



Figure 8. (a). Full extent of the seagrass in March 2022. (b) The same area with the seagrass extent classified and mapped through OBIA analysis. (c) Overlap of the seagrass map, outlined in green, on the same area recorded with a UAV after the reclamation. Source: elaborated by Fallati.

The second phase of the reclamation, starting in February 2023, targeted the southwest side of the island, which is characterised by a reef flat dominated by coarse sediments (sand and coral rubble) and coral colonies, mainly consisting of massive corals such as *Porites*. This area is being developed to accommodate airport facilities and a 1.5 km east-west runway. The UAV survey was only conducted on the reef flat near the western tip of the island, where previous monitoring activities have shown the presence of numerous coral colonies (Fig. 9a). From the results obtained, and the analysis of the benthic composition maps derived from the OBIA analysis (Fig. 9b), it was found that the reclamation activity in this area covered 2.33 hectares of coral (Fig. 9c).

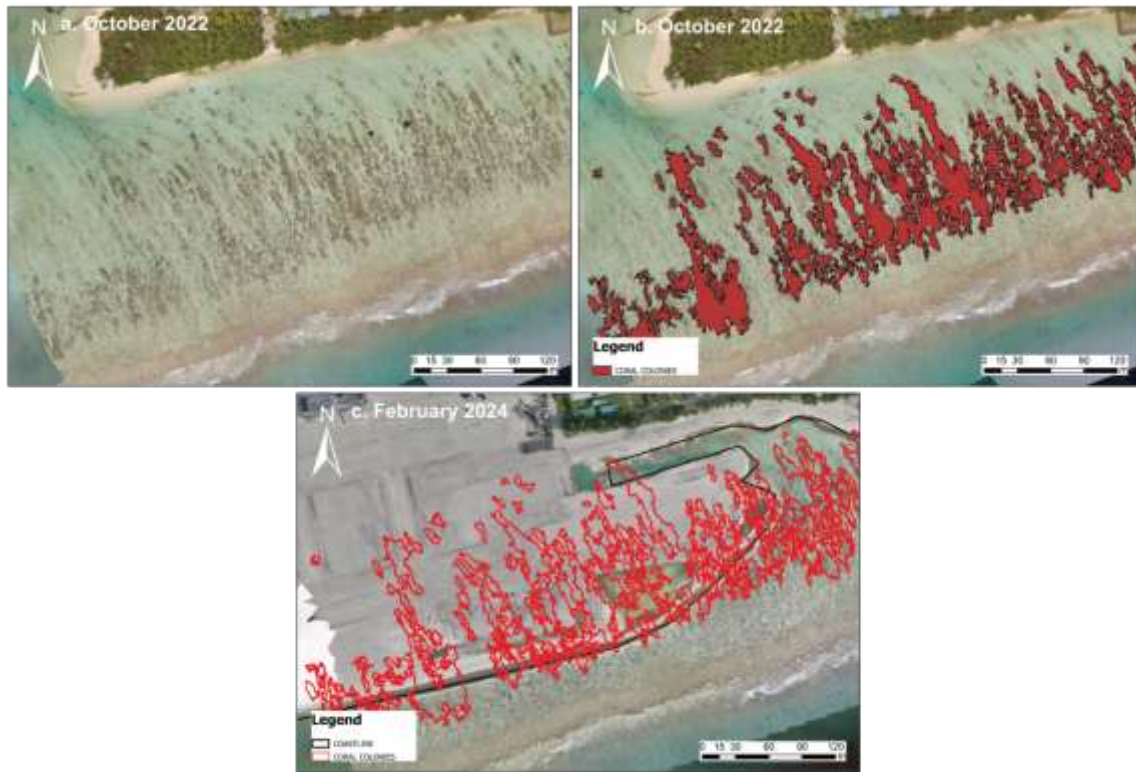


Figure 9. (a) The southern part of the reef flat before the reclamation with (b) the coral colonies classified and mapped through OBIA analysis. (c) Overlap of the coral colonies map, outlined in red, on the same area recorded with a UAV after the reclamation in February 2024. Source: elaborated by Fallati.

The single drone orthomosaic derived from a flight in March 2022 (Fig. 10) shows that this area, selected for the airport runway, consists mainly of sand, including submerged sandbanks, and coarse sediment, with only a few coral colonies.



Figure 10. High-resolution orthomosaic obtained from UAV images (February 2022) of the western part of the reef flat, overlaid on a satellite basemap with a resolution of 3 m/pixel. The orthomosaic includes the shapefile of the reclaimed area of the airport runway as it appeared in February 2024 (depicted by a red polygon). Source: Image © 2022 Planet Labs PBC, elaborated by Fallati.

5. Discussion and Key Learnings

Despite being increasingly framed as instruments of climate resilience and adaptation, land reclamation projects often entail design and implementation challenges that paradoxically increase

hazard exposure for small islands (Ministry of Housing and Environment, UNDP 2011; van der Pol et al. 2023). Building on recent scholarship (Duvat 2020; Brown et al. 2023; Chase-Lubitz 2024), our research underscores the contradictions embedded in the land reclamation narrative by empirically documenting the significant environmental degradation caused by a large-scale reclamation initiative in the Maldives. Rather than enhancing adaptive capacity, the intervention in Magoodhoo illustrates how such projects can compromise the very ecosystems that provide natural resilience. One of the key contributions of this study lies in its methodological approach. The use of UAV-based remote sensing allowed for a fine-grained, longitudinal analysis of ecosystem transformation - something rarely integrated into conventional EIA frameworks. This surveillance should be extended beyond the EIA phase and after project completion, encompassing the entire project lifecycle. Unlike satellite imagery, UAVs increase the resolution of the derived map, enabling a more accurate depiction of the actual impact of land reclamation on the nearshore coral reef environments (Joyce et al. 2022). They offer the operator flexibility - the operator can directly control the image acquisition, making UAVs suitable for ongoing environmental monitoring over time - finer spatial resolution, and fewer limitations related to weather and atmospheric conditions (Fallati et al. 2020). Our comparison between RapidEye satellite images (3 m/pixel resolution) from November 2014 and May 2024 shows a stark transformation of Magoodhoo's landscape across a decade (Fig. 11). While minor interventions such as harbour development on the northern part of the island occurred in the interim (2015-2016) (Fig. 11b), the largest ecological disruption corresponded with the two phases of the land reclamation project. Critically, the resulting habitat maps accurately revealed substantial loss of nearshore coral and seagrass ecosystems - natural infrastructures essential for buffering climate shocks. Approximately 7.7 hectares of seagrass meadows and 2.33 hectares of coral colonies were lost, significantly reducing the island's natural capacity for wave attenuation and carbon sequestration (Beck et al. 2018; Amone-Mabuto et al. 2023). These systems are not only protective but also outperform artificial coastal defences when ecosystem services are holistically evaluated (Rahman, Yaakub 2020). Seagrasses, often termed *blue carbon systems*, store carbon - up to 18% of the global oceanic carbon - more efficiently than tropical rainforests (Fourqurean et al. 2012; Floyd et al. 2024) and mitigate coastal erosion by trapping sediments and reducing wave energy (Duarte et al. 2013; Spalding et al. 2014; Potouroglou et al. 2017). Similarly, healthy corals can reduce wave energy by up to 97%, playing a critical role in safeguarding island coasts (Ferrario et al. 2014). By undermining these ecosystems, reclamation projects may deliver short-term economic gains at the expense of long-term ecological security and adaptive resilience.

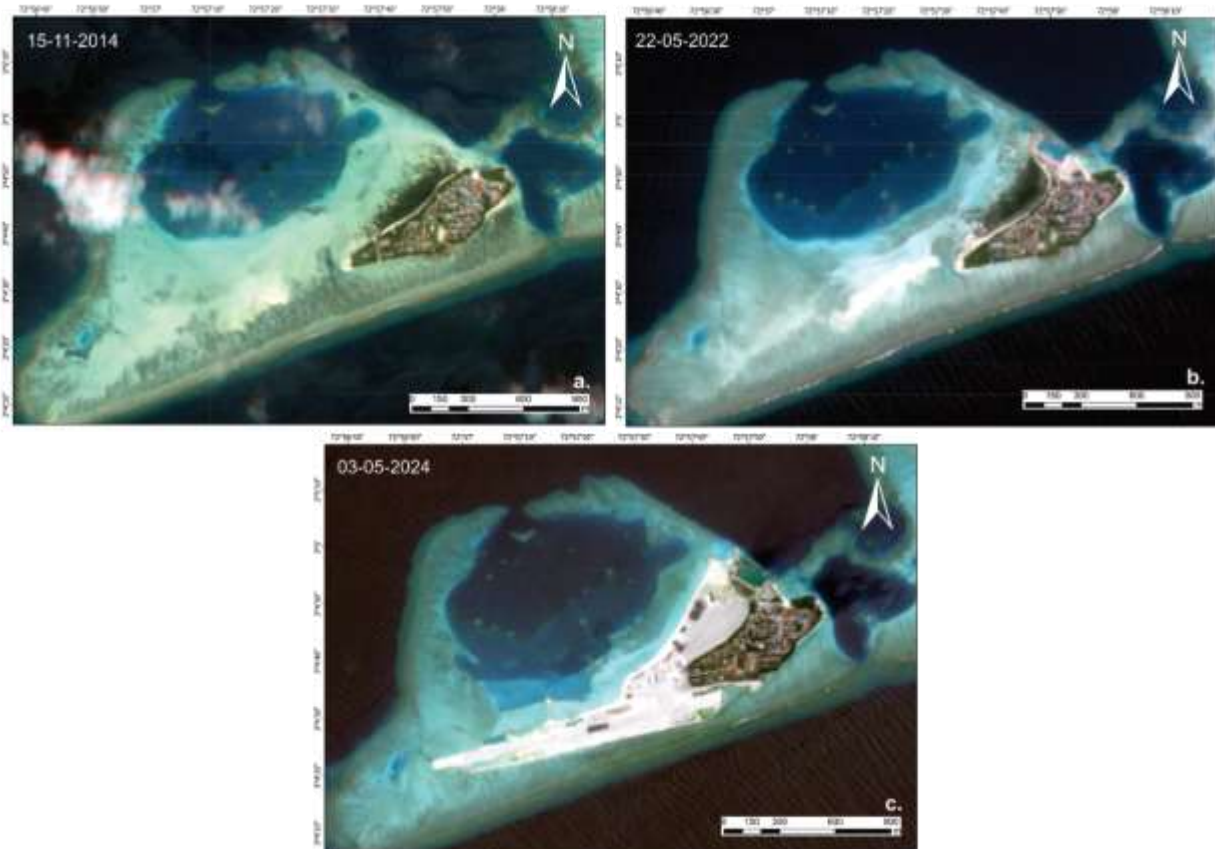


Figure 11. RapidEye satellite imagery with a resolution of 3 m/pixel provides a comprehensive view of Magoodhoo Island and the entire surrounding reef system over time. Panel (a) displays Magoodhoo in November 2014 with no land reclamation activities. Panel (b) shows the island in May 2022, revealing the newly reclaimed land for the harbour. Panel (c) outlines the island's appearance in May 2024 after the last two reclamation phases. Source: Image © 2014, 2022, 2024 Planet Labs PBC, elaborated by Fallati.

The northern shoreline of Magoodhoo Island had long demonstrated notable resistance to erosion, partially attributed to the presence of seagrass meadows that have historically maintained sedimentary equilibrium in the area. Through a combined analysis of satellite imagery and *in-situ*, we determined the optimal health and expansion patterns of these meadows, which reached their peak spatial coverage of 7.7 hectares just before the 2022 reclamation began²² (Fig. 11b). By early 2022, the meadows were thriving, serving as vital nurseries for reef-associated fauna and functioning as blue carbon sinks. Based on sequestration estimates of $9.9 \pm 2.22 \text{ mol C m}^{-2} \text{ yr}^{-1}$ (Duarte et al. 2010), the calculated standing carbon stock is equivalent to approximately 39.5 tonnes of CO₂. However, the onset of the 2022 reclamation marked a turning point. Unlike previous interventions, the scale and method of land transformation during Phase I led to the complete eradication of the seagrass meadows, with no potential for recovery or recolonisation. The loss of these meadows represents not merely a local ecological disturbance, but a significant setback in climate adaptation - substituting resilient natural infrastructure with a vulnerable artificial one. Phase II of the reclamation project significantly altered the south-southwestern reef flat, characterised by mobile sediments and coral colonies, primarily massive corals. This area was selected for constructing the airport runway and associated infrastructure (Fig. 11c). Maps derived from UAV images made it possible to quantify the coral loss estimated at 2.33 hectares. Although direct damage to key habitat-forming coral species was comparatively limited in this phase, the bulk of the reclamation targeted the central reef flat, a zone of subaerial and shallow submerged terrain dominated by fine mobile sediments and coral rubble

²² The 2016 reclamation project for harbour construction had a minimal impact on the seagrass, which subsequently recovered and expanded (Fig. 11b).

(Fig. 10). This area is characterised by low biodiversity and limited ecological functions due to the absence of the three-dimensional structure typical of healthy coral reefs. However, indirect impacts of land reclamation associated with dredging and pumping sand from the lagoon are insidious. These operations unleash sediment plumes that can travel far beyond the immediate construction zone, carried by prevailing currents across the lagoon (Fig. 12a). The plumes act like underwater dust storms, reducing light penetration and blanketing coral habitats with fine particles. Sediment deposition can cause severe damage, including smothering and choking, to coral colonies. In this case, the coral restoration site located at a considerable distance from the dredging area displayed alarming signs of stress and sediment accumulation (Fig. 12b).



Figure 12. The satellite image (a) shows the extent of the sediment plume created by the dredging and pumping activities (yellow polygon). Panel (b) represents an underwater picture of a coral restoration area located far from the reclaiming zone, where the metallic frames are almost completely buried by the sediments moved during the works. Source: Image © 2022 Planet Labs PBC, elaborated by Fallati.

This demonstrates that the ecological impact of the land reclamation project in Magoodhoo Island extends well beyond its narrow reclamation perimeter across interconnected marine habitats, compromising the resilience of its coastal ecosystems, accelerating habitat degradation, and undermining long-term adaptive capacities across the atoll. To avoid maladaptive outcomes, the need for a paradigm shift, from short-sighted, techno-centric adaptation solutions towards integrated, ecosystem-based approaches that recognise the multifunctionality of natural coastal systems, is pivotal. This calls for reforming existing environmental governance mechanisms, particularly the EIA process, to mandate continuous, post-project environmental monitoring.

6. Conclusion

This study contributes to the growing body of literature on land reclamation as a climate adaptation strategy in Small Island States (SIS), with a particular focus on the Maldives. It critically examines the contradictions inherent in using land reclamation simultaneously as a tool for development and adaptation, while highlighting its profound and often irreversible ecological impacts. Drawing on the case of Magoodhoo, we demonstrated how large-scale reclamation projects compromise the integrity of critical coastal ecosystems, thereby weakening the adaptive capacity of island systems to climate-induced hazards and intensifying existing vulnerabilities. While the findings are contextually grounded, they resonate more broadly with ongoing tensions between national climate resilience goals and current reclamation practices. Our analysis shows that these practices directly undermine the objectives of the National Biodiversity Strategy and Action Plan (NBSAP), particularly the target of near-zero natural habitat loss by 2025. By revealing how reclamation projects are frequently designed and executed without adequate environmental safeguards, this paper contributes to the literature on structural maladaptation and maldevelopment in SIS (David et al. 2021; Arnall 2023). These projects often reflect top-down, hard-engineering approaches that marginalise ecosystem-

based and community-led solutions. Through our case study, we identify key lessons for climate-resilient development and adaptation policy planning, offering recommendations for practitioners and policymakers. First, we illustrate the value of UAVs in monitoring and assessing environmental degradation. UAVs provide high-resolution spatial data essential for detecting, monitoring and quantifying anthropogenic disturbances on marine ecosystems. Therefore, we advocate for the systematic integration of UAVs as monitoring tools into all stages of reclamation planning, execution and post-project monitoring, to support data-driven conservation, mitigation, and restoration efforts. Second, we emphasise the need to embed risk reduction mechanisms - such as land elevation and stormwater drainage systems - within reclamation design to enhance long-term climate adaptation potential. Third, we argue for the institutionalisation of compensation measures, including the creation of green areas on reclaimed land and targeted marine biodiversity restoration, which are often recommended in EIAs but rarely implemented due to institutional and financial constraints. To address these challenges, we call for the development of a robust Strategic Environmental Assessment (SEA) framework that incorporates ecosystem service valuation, and for fundamental reforms to the EIA system to improve transparency, accountability, and stakeholder inclusion. Recognising infrastructure as a socio-technical construct shaped by power dynamics, we underline the importance of participatory environmental governance to mitigate maladaptive outcomes and foster more equitable and sustainable development and adaptation pathways in SIS.

Disclosure statement

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