NbS-PATS
NbS Pacific Atolls

Nature-based Solutions (NbS) for Resilient Societies to Climate Change in Pacific Atoll Nations

-Project concept paper (DRAFT)-

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“NbS-PATS” Research Team

(https://nbs-pats.org/)

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Executive Summary

Pacific atoll nations face a distinctive climate-adaptation challenge because their low-lying islands are created and maintained by coral reef ecosystems that dissipate wave energy and supply carbonate sediments. Climate change, reef degradation, and inappropriate coastal development therefore threaten both coastal safety and the natural processes that sustain atoll land. Long-term adaptation must protect and restore these processes while reducing risks to communities and infrastructure.

The Republic of the Marshall Islands (RMI) is highly vulnerable to sea-level rise, wave-driven flooding, and coastal erosion. In Majuro, coral reef degradation has reduced wave dissipation and sediment production, while vertical seawalls can increase wave reflection and inhibit beach formation. Together, these changes have weakened the resilience of densely populated coastal areas.

This project proposes an integrated Nature-based Solutions (NbS) approach combining ecosystem-compatible coastal engineering, sediment management, and coral reef conservation and restoration (Fig. 1). Core measures include wave-dissipating structures, wave-breaking mounds, sand traps, beach nourishment, Beachrock technology, and coral reef restoration, complemented by other adaptation measures identified in the National Adaptation Plan (NAP).

These measures are combined according to coastal hazards and local environmental and socio-economic conditions. Different strategies are proposed for urban, semi-urban, and rural areas and for ocean- and lagoon-side coasts. By addressing chronic erosion, episodic flooding, and long-term inundation together, the project provides a continuous adaptation pathway from community-level protection to the long-term resilience of Majuro and RMI.

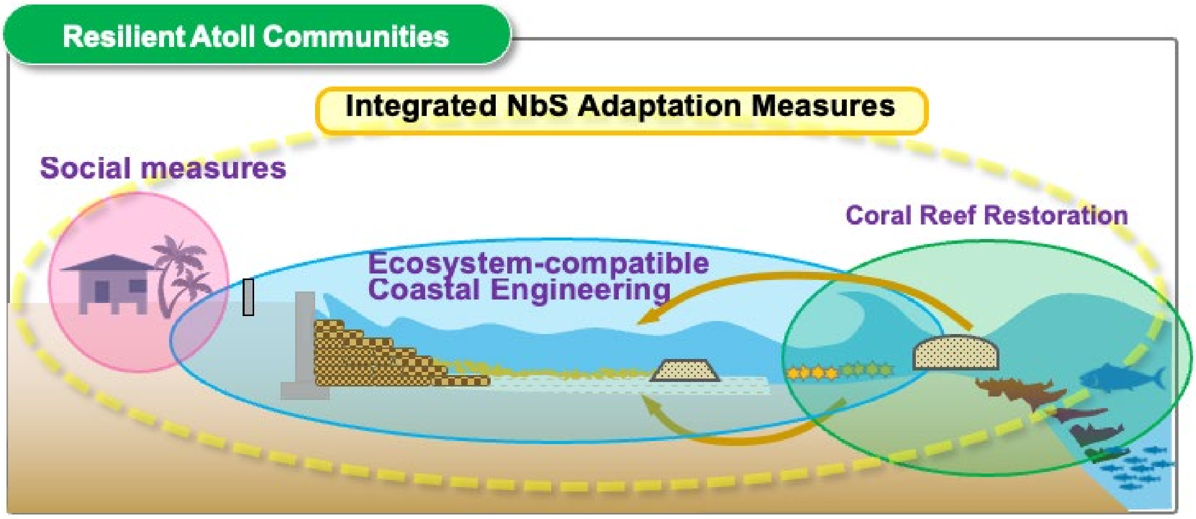


Fig. 1. Conceptual framework of the proposed integrated NbS approach, combining ecosystem-compatible coastal engineering, coral reef restoration, sediment management, and complementary social measures to enhance the resilience of atoll communities.

The long-term vision of the project is to restore resilient sandy beaches that protect coastal communities while maintaining the natural processes through which coral reef ecosystems create and sustain atoll islands (Fig. 2). The objective is not simply to defend shorelines with conventional hard infrastructure, but to recover coastal systems in which healthy coral reefs dissipate waves and produce sediments, reef flats and beaches retain those sediments, and ecosystem-compatible engineering measures reinforce these natural functions. Through this integrated approach, degraded urban shorelines can gradually be transformed into resilient coasts where ecosystem restoration and coastal protection function together.

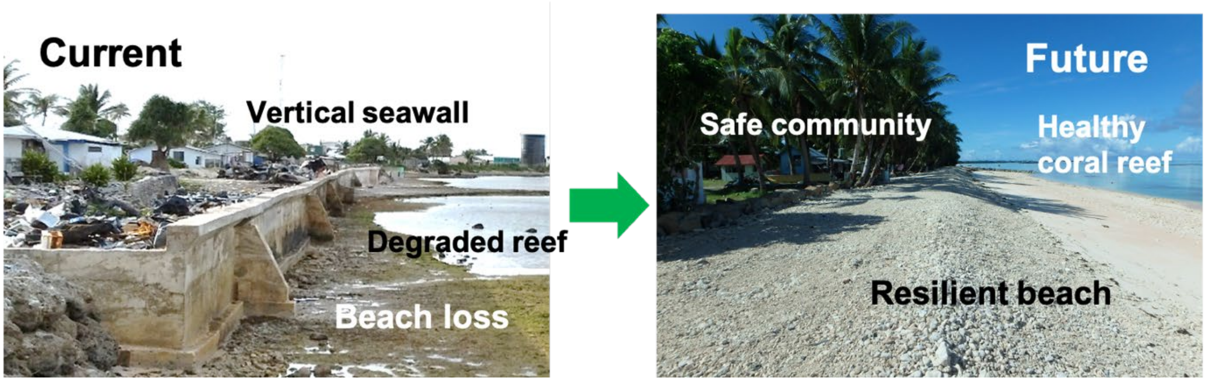


Fig. 2. Long-term vision of the proposed NbS project.
From degraded urban shorelines protected by conventional vertical seawalls (left) to resilient sandy beaches created and sustained through integrated Nature-based Solutions (right).

Initial implementation is proposed for high-priority coastal sections of Majuro, including approximately 1 km of the D-U-D urban coast and selected lagoon-side sections of Long Island–Ajeltake. The current indicative package covers approximately 2.8 km of coastline, with an estimated project cost of US$45.5 million, including coastal protection and coral reef restoration. The final locations, designs, and costs will be refined through ecological assessment, engineering investigations, economic evaluation, and consultation and co-design with the Government of RMI, landowners, and local communities.

The project is fully consistent with the RMI National Adaptation Plan and is intended to complement ongoing national and international adaptation initiatives. Although the initial implementation focuses on Majuro Atoll, the technologies, planning framework, and implementation experience developed through the project are intended to provide a practical model for wider application within RMI and ultimately to other Pacific atoll nations, including Kiribati and Tuvalu. By restoring coral reef ecosystems together with the natural sedimentary and coastal processes they support, the project provides a pathway toward safer communities, resilient coastal ecosystems, and the long-term maintenance of atoll land under future sea-level rise.

1. Development Challenges of Pacific Small Island and Atoll Nations

1.1 Small Island Developing States (SIDS) in the Pacific

Approximately 680 million people live in low-lying coastal areas worldwide, including about 65 million in Small Island Developing States (SIDS) (IPCC, 2019). The Pacific Island Countries (PICs), scattered across the world's largest ocean, include many of the world's smallest and most geographically isolated nations. Nearly 2,000 islands are distributed across the Pacific, including 14 Small Island Developing States.

With the exception of relatively large countries such as Papua New Guinea, Solomon Islands, and Fiji, many Pacific SIDS have very small land areas, limited natural resources and domestic markets, and are geographically remote from major international markets. Their economies therefore depend strongly on external assistance and overseas employment. In many countries, government employment supported partly by external aid provides an important source of stable domestic income, while remittances from migrants working abroad also play a major role. This economic structure has been described as the MIRAB model, referring to Migration, Remittances, Aid, and Bureaucracy.

1.2 Climate Change and Coastal Hazards

Pacific Island Countries (PICs) are among the countries most vulnerable to climate change and climate-related hazards, including coastal flooding, droughts, and tropical cyclones. These hazards have caused substantial human and economic losses and continue to constrain long-term sustainable development.

Sea-level rise poses a particularly serious threat to low-lying Pacific islands. Global mean sea level rose by approximately 0.20 m between 1901 and 2018, and human influence has very likely been the main driver of the observed rise since at least 1971. By 2100, global mean sea level is projected to rise by 0.28–0.55 m under a very low greenhouse-gas emission scenario (SSP1-1.9), 0.44–0.76 m under an intermediate scenario (SSP2-4.5), and 0.63–1.01 m under a very high emission scenario (SSP5-8.5), relative to 1995–2014 (IPCC, 2021, 2022). As sea level rises, extreme sea-level events that occurred approximately once per century in the recent past are projected to occur at least annually at more than half of tide-gauge locations by 2100, increasing coastal flooding and erosion.

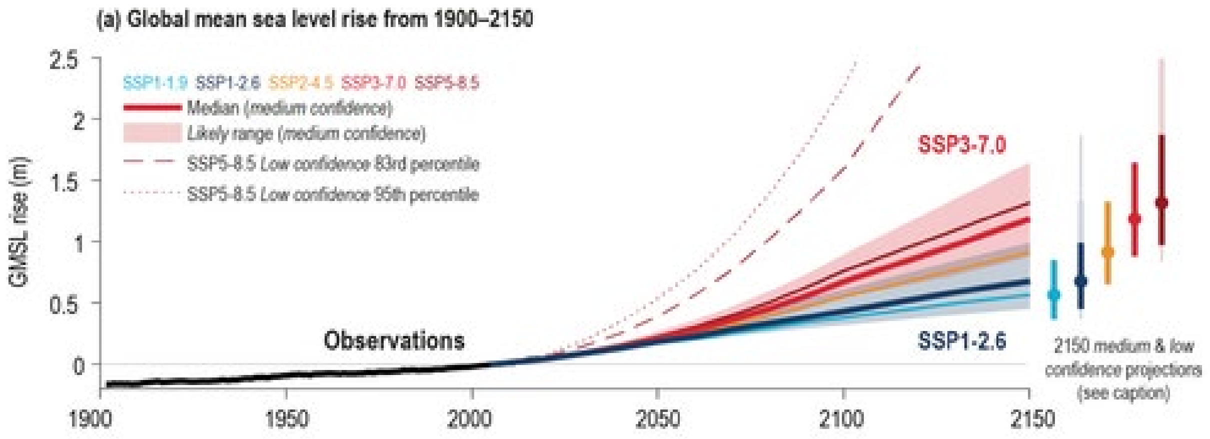


Fig. 3. Global mean sea level change from 1900 to 2150, observed (1900–2018) and projected under the SSP scenarios (2000–2150), relative to a 1995–2014 baseline. Solid lines show median projections. Shaded regions show *likely* ranges for SSP1-2.6 and SSP3-7.0. Dotted and dashed lines show respectively the 83rd and 95th percentile *low confidence* projections for SSP5-8.5 (IPCC 2021).

Among small islands, atoll islands are particularly vulnerable to sea-level rise. Atolls are ring-shaped coral reef systems, often enclosing a lagoon, on which low-lying islands have formed through the accumulation of coral gravel, foraminiferal sand, and other reef-derived sediments. These islands are typically only about 1–4 m above sea level. Approximately 500 atolls occur worldwide, about 400 of them in the Pacific. The Republic of the Marshall Islands, Kiribati, and Tuvalu are composed almost entirely of atolls, while numerous atolls also occur in the Federated States of Micronesia, French Polynesia, and the Cook Islands.

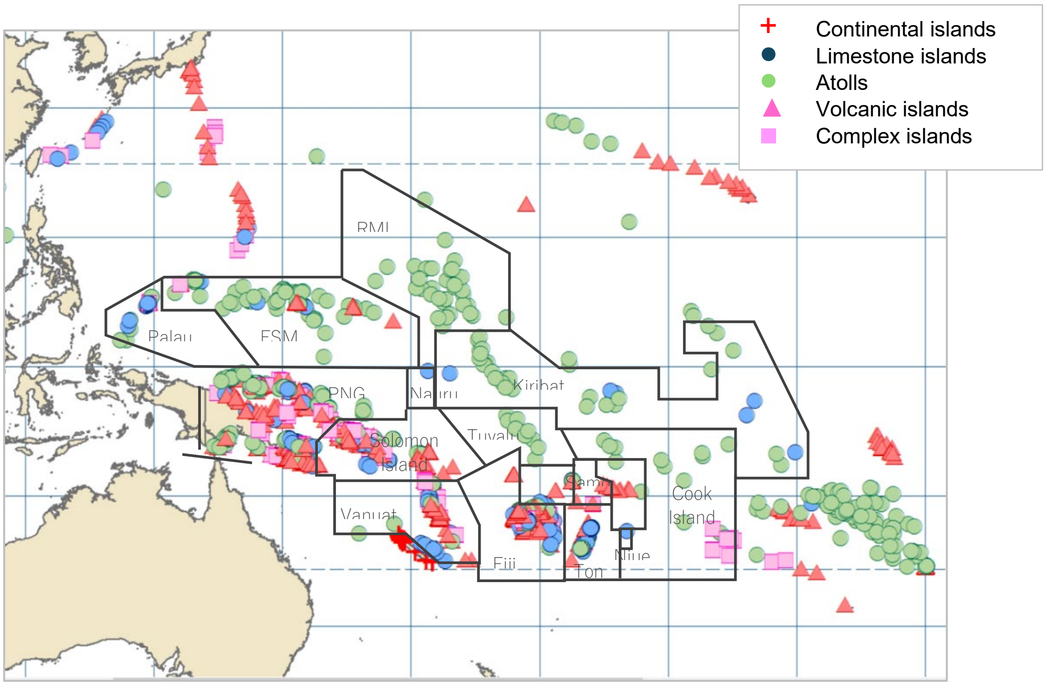


Fig. 4. Distribution and geological types of islands in the Pacific, showing the widespread occurrence of atolls.

1.3 Atoll Formation and Coral Reef Ecosystems as Natural Infrastructure

Atoll islands are created and sustained through natural processes operating within coral reef ecosystems. Reef-building corals produce carbonate skeletons that are broken down into gravel and sand, while larger benthic foraminifera living on reef flats continuously produce carbonate sand. These reef-derived sediments are transported by waves and currents and deposited on reef flats and shorelines, thereby building and maintaining atoll islands.

Coral reefs therefore function as natural infrastructure in two complementary ways: they produce the sediments required to maintain atoll land, and they act as natural breakwaters that dissipate ocean-wave energy before it reaches the shoreline. Healthy reef-building coral communities can produce approximately 10–20 kg $CaCO_3$ m^{-2} yr^{-1} of carbonate material (van Woesik & Cacciapaglia, 2018)**,** equivalent to approximately 75–150 m^3 ha^{-1} yr^{-1}. In addition, healthy reef crests exhibit upward growth rates of approximately 0.2–0.5 cm yr^{-1} as sea level rises (Kayanne, 1992), helping to maintain their wave-dissipation function. Maintaining these biological and geomorphological processes is therefore fundamental to the long-term resilience of atoll islands.

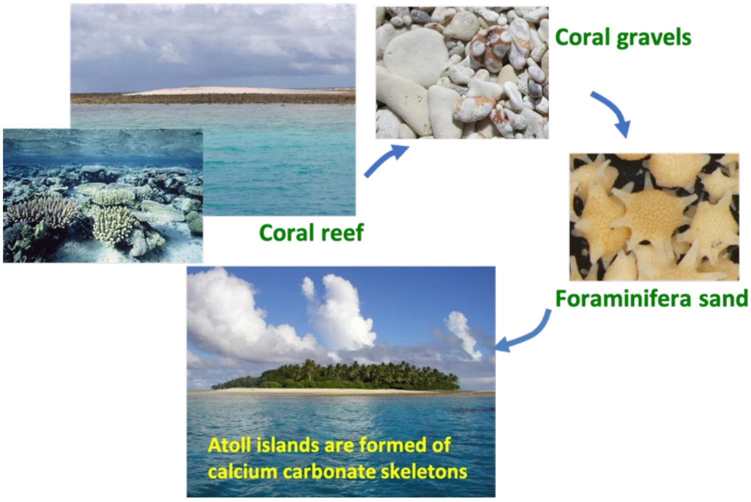


Fig. 5. Schematic sequence of atoll-island formation, from coral reef development to the accumulation of coral gravel and foraminiferal sand, which form and maintain low-lying atoll land.

1.4 Needs for Nature-based Solutions (NbS)

The vulnerability of atoll islands is determined not only by sea-level rise but also by local human impacts that disrupt the natural processes of island formation and maintenance. Coral reef degradation reduces the production of reef-derived sediments, while coastal development, including causeways, piers, dredging, and other structures, can alter sediment transport and prevent the natural accumulation of sand and gravel along shorelines. These impacts have weakened the capacity of many atoll islands to adjust naturally to changing sea levels.

Long-term adaptation therefore requires not only protection from rising sea levels, but also the restoration and enhancement of the natural processes that create and sustain atoll land. Nature-based Solutions (NbS) provide an approach for integrating coral reef conservation and restoration, sediment management, and ecosystem-compatible coastal protection to strengthen the resilience of atoll islands.

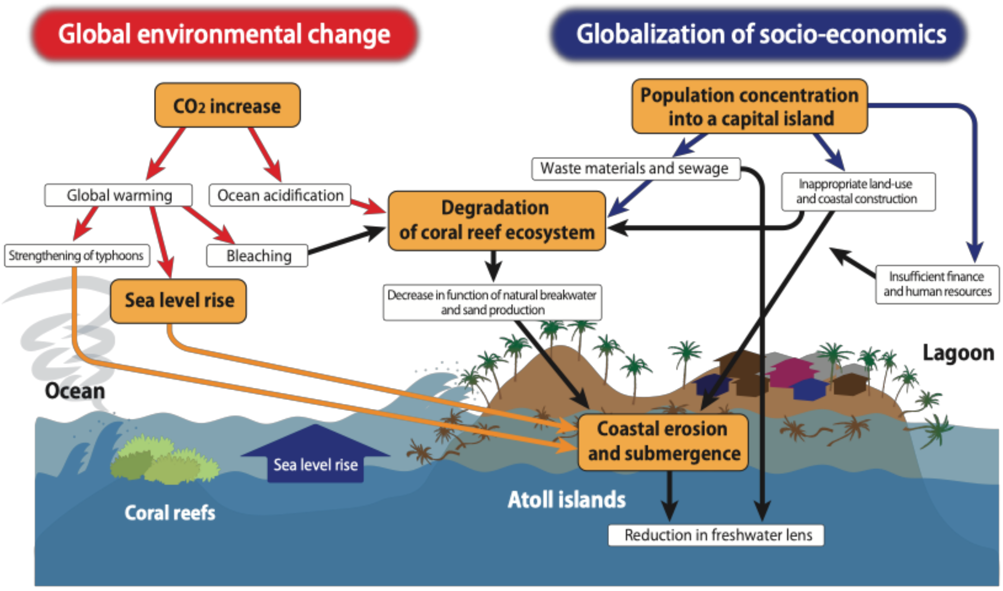
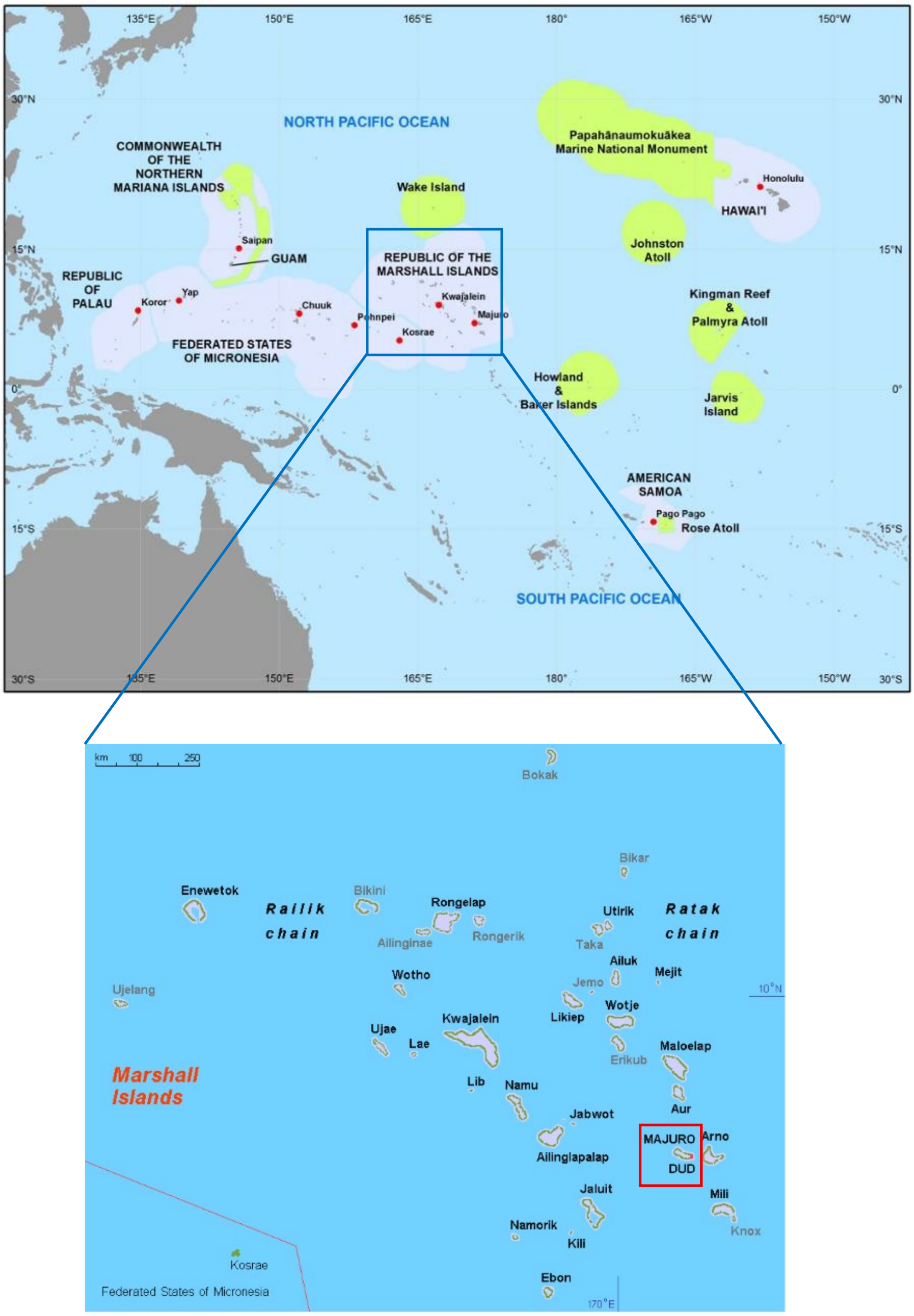


Fig. 6. Global and local drivers that increase the vulnerability of atoll islands. Climate change and socioeconomic pressures degrade coral reef ecosystems and disrupt natural island-building processes, increasing coastal erosion, submergence, and freshwater stress.

2. Development Context and Challenges in RMI and Majuro

2.1 Geographic Setting and Climate-related Coastal Hazards

The Republic of the Marshall Islands (RMI) is one of the world's smallest, most geographically isolated, and most climate-vulnerable countries. It consists of 29 coral atolls and five isolated islands, with a total land area of only 181 km², compared with an Exclusive Economic Zone (EEZ) exceeding 1.9 million km². The population is approximately 37,500 (World Bank, 2024) and has declined in recent years. About 75% of the population is concentrated in the two principal urban centers, Majuro and Ebeye.



Source: Wikimedia Commons

Fig. 7. Map of Republic of Marshall Islands and Capital, Majuro.

Most of the population lives on low-lying atolls with an average elevation of approximately 2 m above mean sea level. One hundred percent of the population lives along the country's 370-km coastline, making settlements and infrastructure highly exposed to extreme sea levels, ocean waves, coastal flooding, and erosion. Although tropical cyclones affect RMI only occasionally, remotely generated ocean swells and unusually high sea levels can cause severe coastal impacts even in otherwise calm weather.

Coastal Flooding and Erosion

Among the impacts of climate change in RMI, sea-level rise, wave-driven flooding, saltwater intrusion, and coastal erosion pose particularly serious threats to livelihoods, infrastructure, freshwater resources, and ecosystems. Because land area is extremely limited, coastal erosion can directly result in the loss of land available for settlements and infrastructure and therefore has major social, cultural, and economic consequences.

Sea-level rise is already increasing the frequency of extreme high-water events. Combined with ocean-wave forcing and the reduced wave-dissipation capacity of degraded coral reefs, even relatively modest increases in sea level can substantially increase coastal flooding and wave overtopping. The RMI National Adaptation Plan therefore identifies wave-driven flooding and permanent inundation as major threats to the long-term survival of the nation.

Tidal Levels and Wave Climate

Majuro experiences a relatively large tidal range of approximately 1.8–2.1 m. High astronomical tides, elevated regional sea levels associated with climatic variability such as La Niña, and wave setup generated by ocean swells can combine to produce exceptionally high coastal water levels.

A major driver of extreme wave conditions around Majuro is long-period ocean swell generated in the North Pacific and Southern Ocean. When these swells reach the atoll, wave setup and overtopping across the reef flat can substantially raise coastal water levels and cause flooding. Such remotely generated swells may arrive under otherwise calm local weather conditions, producing the “sunny-day flooding” experienced in parts of Majuro.

The largest swells generally approach from the northeast. Numerical analyses indicate that the 50-year return significant wave height (Hs) exceeds 5 m along the northeastern ocean side of Majuro, whereas waves reaching the southern coast are estimated to be approximately 3 m (Deltares, *CVA Draft*, p. vi). Majuro is partially sheltered from easterly ocean waves by Arno Atoll, located approximately 20 km to the east. Although the lagoon is generally sheltered from direct ocean swell, large northeasterly swells can enter through the northern passages and affect the southern lagoon shoreline.

Sea-Level Rise

Tide-gauge observations at Majuro indicate that mean sea level rose by 128 mm between 1993 and 2018, compared with a global average rise of 81 mm over the same period. The observed rate of sea-level rise increased from an average of 35 mm per decade over 1968–2018 to 49.2 mm per decade over 1993–2018 (NOAA, 2019).

Future sea-level rise is projected to substantially increase coastal hazards in RMI. Based on available projections, the National Adaptation Plan (2023) adopts planning scenarios of approximately 0.5 m of sea-level rise by 2070–2100 and 2.0 m by 2150 (NAP, p. 24).

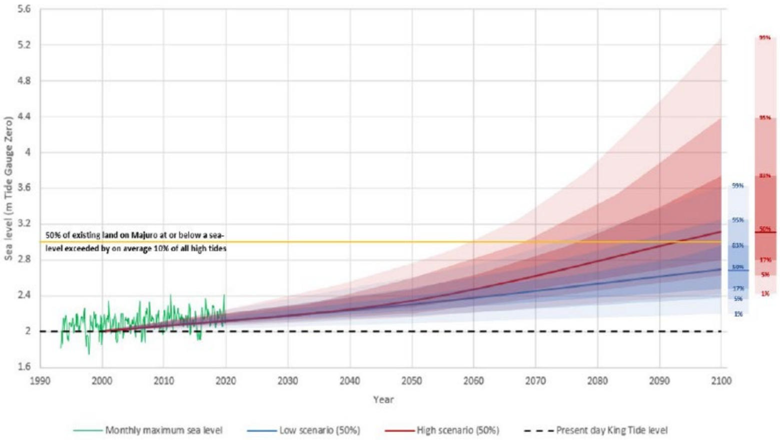


Fig. 8. Sea level observations and projections for Majuro (Barber et al., 2019). *(National Adaptation Plan, RMI Government,2023, p87)*

Urban Coastal Challenges

Coastal hazards are particularly serious in the densely populated urban areas of Majuro and Ebeye, where flooding and erosion directly threaten housing, roads, public infrastructure, and essential services. Saltwater intrusion into the freshwater lens also threatens already limited freshwater resources.

DUD district (*Raycrew, Hiro*)

Majuro, 1979 (*Digital Micronesia*)

Fig. 9. Wave overtopping and flood in Majuro.

In Ebeye, a climate-resilient coastal protection system is being implemented under the Pacific Resilience Program II (PREP II), with support from the Green Climate Fund (GCF) and the World Bank. In Majuro, by contrast, coastal protection consists largely of fragmented sections of vertical concrete seawalls. These structures can reflect incoming wave energy and inhibit the accumulation and maintenance of sandy beaches, thereby disrupting the natural processes through which reef-derived sediments help create and sustain atoll land. Many existing seawalls are also of varying design standards and are frequently overtopped during high-water events. Where seawalls are absent, houses, roads, and other infrastructure remain directly exposed to coastal flooding and erosion.

2.2 Coral Reef Condition and Ecosystem Degradation in Majuro

Coral reefs in Majuro are affected by both global climate pressures, including rising sea-surface temperatures and ocean acidification, and local human impacts. In densely populated areas, domestic waste and other land-based pollutants further degrade reef environments and reduce their ecological functions.

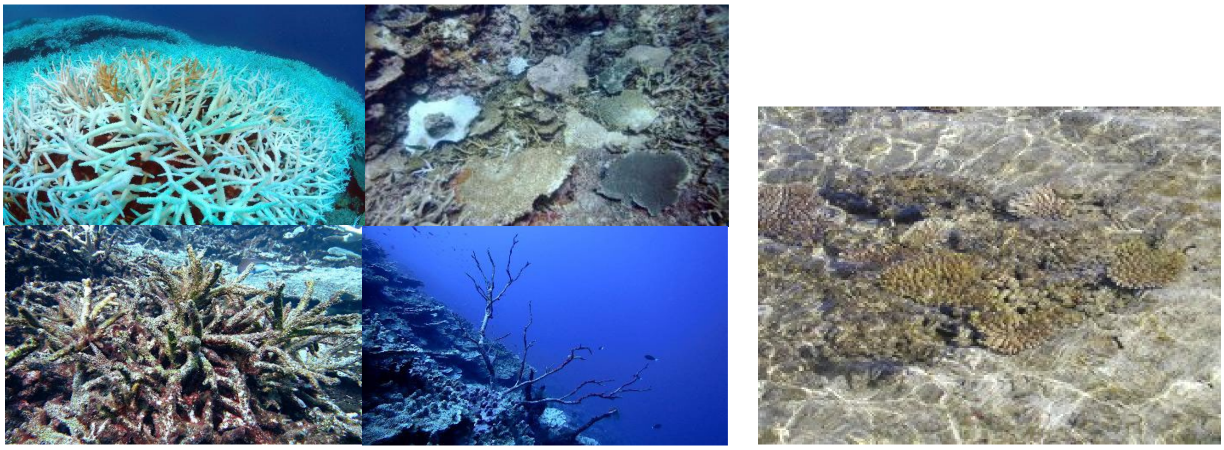


Fig. 10. Contrasting coral reef conditions in Majuro Atoll, showing relatively healthy reefs and degraded reefs adjacent to densely populated urban areas.

Available reef-monitoring data also indicate marked spatial variation in coral cover and benthic community composition within Majuro Atoll (Fig. 11). Coral cover is generally lower on reefs adjacent to densely populated islands, whereas healthier coral communities remain in less disturbed areas. These spatial differences provide an important basis for identifying areas where coral reef conservation should be prioritized and degraded areas where active restoration may be required.

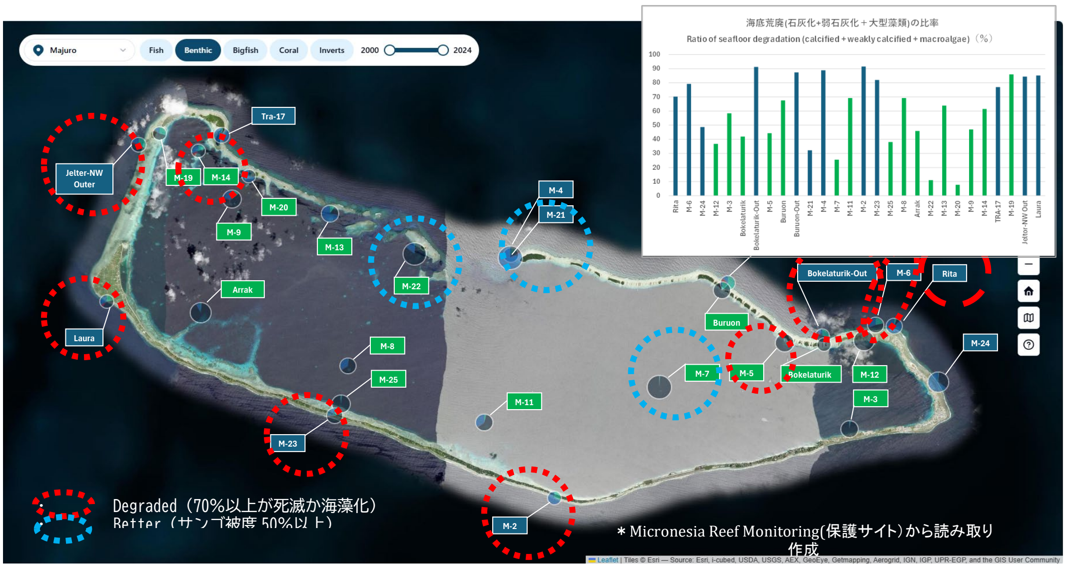


Fig. 11. Spatial variation in coral reef condition in Majuro Atoll, compiled from Micronesia Reef Monitoring data (University of Guam).

2.3 Reef-derived Sediment Production and Atoll-land Maintenance

The spatial differences in reef condition described above are reflected in the capacity of coral reef ecosystems to produce the carbonate sediments that create and sustain atoll land. Field surveys conducted between 2002 and 2006 showed that outer reef flats around the northern islands of Majuro supported 5–9 × 10^5 individuals m^{-2} of larger benthic foraminifera, producing 1–10 kg $CaCO_3$ m^{-2} yr^{-1} of carbonate sediment (Fujita *et al.*, 2009), equivalent to approximately 20–200 m^3 ha^{-1} yr^{-1} of sand. In contrast, estimated foraminiferal sediment production on degraded reef flats in the D-U-D district was only about 0.2 m^3 ha^{-1} yr^{-1}.

Although direct measurements of coral-derived sand and gravel production in Majuro remain limited, healthy reef-building coral communities have been reported to produce approximately 10–20 kg $CaCO_3$ m^{-2} yr^{-1} of carbonate material (van Woesik & Cacciapaglia, 2018), equivalent to approximately 75–150 m^3 ha^{-1} yr^{-1}.

As a first-order estimate, assuming equal areal contributions from coral-derived material and foraminiferal sand production, a healthy reef could generate approximately 50–175 m^3 ha^{-1} yr^{-1} of reef-derived sediment (Fig. 12). Assuming a 100-m-wide sediment-production zone along 1 km of shoreline, this corresponds to approximately 500–1,750 m^3 yr^{-1} per kilometer of shoreline. If this sediment were retained within a 50-m-wide coastal zone, it would be equivalent to vertical accumulation of approximately 1–3.5 cm yr^{-1}. This potential rate is greater than the present rate of sea-level rise of approximately 0.5 cm yr^{-1}, illustrating the capacity of healthy coral reef ecosystems to contribute to the formation and maintenance of atoll land.

Not all reef-derived sediment is retained on the island, however, because part is transported offshore or into the lagoon. Maintaining atoll land therefore requires not only continued sediment production by healthy reef ecosystems but also coastal conditions that allow sediments to be transported toward and retained along the shoreline. Healthy reef crests can also grow upward at approximately 0.2–0.5 cm yr^{-1}, helping to maintain their wave-dissipation function as sea level rises.

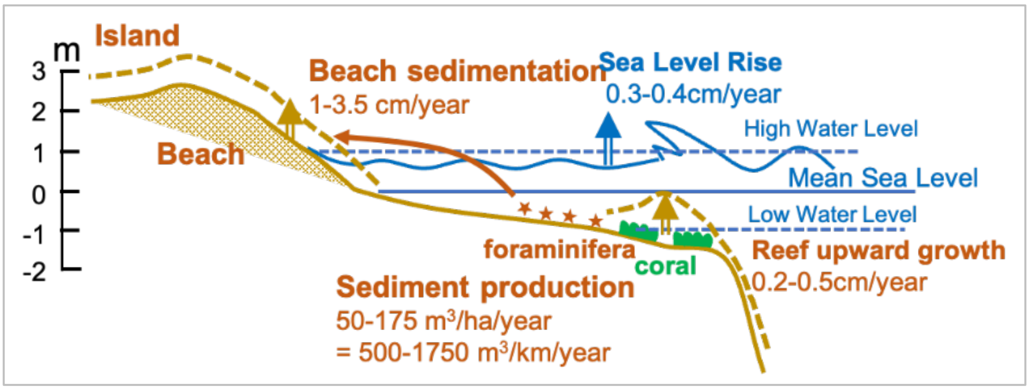


Fig. 12. Healthy coral reef ecosystems produce carbonate sediments and maintain reef elevation, providing natural processes that can create and sustain atoll land under sea-level rise.

These processes constitute the natural infrastructure on which the long-term resilience of atoll islands depends. The NbS approach proposed in this project therefore seeks to conserve and restore coral reef ecosystems while using ecosystem-compatible coastal measures to enhance the transport and retention of reef-derived sediments.

In degraded urban reef areas such as the D-U-D district, sediment production is far too low to sustain these natural island-building processes (Fig. 13). Vertical seawalls can increase wave reflection and inhibit the accumulation of beach sediments, while land reclamation directly removes reef habitats and the biological processes that generate reef-derived carbonate material. Together with coral reef degradation, these interventions can lead to the progressive loss of sandy beaches and increase the vulnerability of urban shorelines.

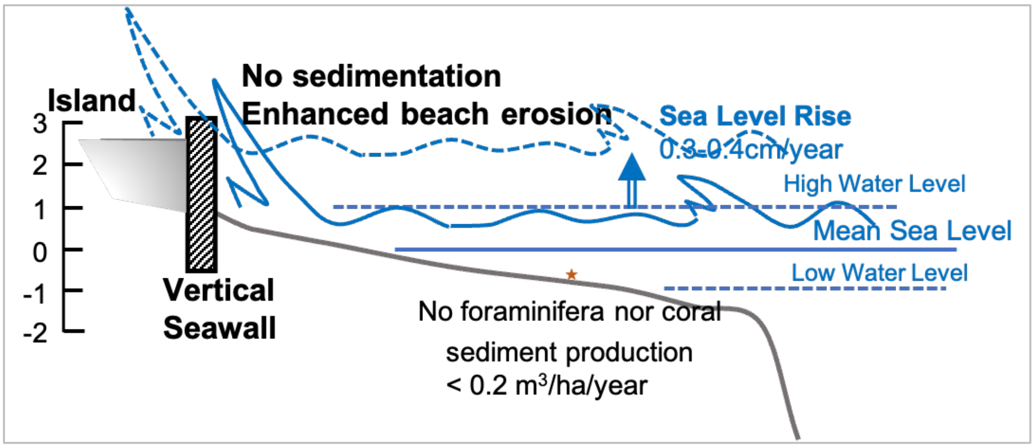


Fig. 13. Loss of natural island-building processes associated with coral reef degradation, vertical seawalls, and coastal development.

2.4 Society and Economy

The population and economic activities of RMI are highly concentrated in a small number of urban centers, particularly Majuro and Ebeye. This concentration places housing, public infrastructure, utilities, and economic activities within narrow and highly exposed coastal areas, increasing their vulnerability to flooding, erosion, and sea-level rise.

The economy of RMI is small and depends on a limited number of sectors, together with substantial external financial support. Many essential economic activities and public services are closely linked to the coastal environment, including fisheries, transportation, water supply, and tourism. Damage to coastal infrastructure and ecosystems can therefore have impacts extending well beyond the directly affected shoreline.

Climate-related disasters impose significant economic costs through damage to infrastructure and property, disruption of public services and economic activities, and longer-term impacts on livelihoods. At the same time, the small domestic economy and limited financial resources constrain the capacity of RMI to finance large-scale adaptation measures independently.

Out-migration also has important implications for the long-term social and economic sustainability of RMI. While migration and remittances can provide important sources of household income and opportunities for adaptation, continued population loss may also reduce the human and institutional capacity needed to maintain communities, infrastructure, and adaptation measures over the long term.

2.5 Communities and Social Context

Adaptation measures in RMI must be planned within the social, cultural, and institutional context of local communities. Land and reef resources are closely connected to community livelihoods, identity, and traditional practices, while land tenure and local decision-making arrangements strongly influence where and how coastal adaptation measures can be implemented. Understanding these relationships is therefore essential for project planning and long-term management.

Climate and coastal hazards do not affect all members of society equally. Low-income households and other vulnerable groups may have fewer financial resources and alternative options for recovery after disasters. Following Tropical Storm Nangka in July 2015, for example, low-income households experienced greater hardship because of limited access to insurance, financial assets, and alternative sources of income. Although sex-disaggregated information remains limited, women are also considered particularly vulnerable to climate- and disaster-related risks because of inequalities in access to health care, education, social protection, economic opportunities, and decision-making processes (FP66, Sections 11–21).

Community concerns extend beyond direct damage to houses and infrastructure. Consultations conducted under the National Adaptation Plan and related studies indicate concerns about coastal erosion and flooding, debris deposited during inundation, degradation of freshwater resources and agricultural land, health risks, and sudden flooding occurring even under otherwise calm weather conditions (NAP Communication Engagement Summary Report, Majuro Atoll (Delap), IOM, 2023). Such concerns need to be reflected in the selection, design, and evaluation of adaptation measures.

Community participation and consensus building are therefore fundamental components of coastal adaptation in RMI. Existing community-based management approaches, including the Reimaanlok process, provide an institutional basis for involving communities in the planning and management of coastal and marine resources. Building on these existing mechanisms can help ensure that adaptation measures are socially acceptable, locally appropriate, and sustainable over the long term.

2.6 National Adaptation Policies and Project Rationale

In response to these challenges, the Government of the Republic of the Marshall Islands (RMI) adopted its National Adaptation Plan (NAP) in 2023. The NAP presents a comprehensive strategy for adapting to sea-level rise, wave-driven flooding, and coastal erosion through a combination of Nature-based Solutions (NbS), engineered (grey) coastal protection, land raising, community resilience, expansion of protected areas, and managed retreat (NAP, p. 8). Described by the Government as the nation's "survival plan" (NAP, p. 9), it identifies wave-driven flooding and permanent inundation as major threats and gives high priority to protecting urban centers such as Majuro.

In parallel, the Government of RMI, in collaboration with the World Bank, is implementing the Pacific Resilience Program II (PREP II). The program supports coastal protection standards and land-use policies based on future sea-level-rise scenarios, coastal hazard assessment and zoning, early warning systems, disaster-risk management, and coastal protection in Majuro and Kwajalein Atolls. In Ebeye, substantial coastal protection structures have already been constructed to reduce flooding associated with wave action and sea-level rise. The World Bank is also undertaking feasibility studies and design of nature-based coastal protection for Arno and Mili Atolls under PREP II.

RMI has also established community-based approaches to marine and coastal resource management. Through the Micronesia Challenge, the Reimaanlok process was developed as a national framework for community-based conservation and ecosystem management and continues to support the designation and management of conservation areas.

RMI therefore already has a comprehensive policy framework for climate adaptation. However, Majuro still lacks an integrated approach that combines coral reef conservation and restoration, reef-derived sediment production and management, and ecosystem-compatible coastal protection while maintaining the natural processes that create and sustain atoll land. Addressing this implementation gap provides the central rationale for the project proposed in this Concept Paper.

3. Project Objectives

The fundamental concept of this project is that coral reef ecosystem processes constitute the natural infrastructure that creates, maintains, and protects atoll islands (Fig. 14). Rather than replacing these natural processes with conventional hard infrastructure, this project proposes engineering interventions that work with, protect, and enhance ecosystem processes to strengthen the long-term resilience of atoll nations. Ultimately, the project aims to restore resilient sandy beaches that protect coastal communities while maintaining these natural land-building processes.

To achieve the sustainable maintenance of national territory under rising sea levels, this project proposes an integrated NbS approach that combines ecosystem-compatible coastal protection with coral reef restoration. The proposed measures are designed to maintain and enhance the natural production of reef-derived sediments and the wave-dissipation capacity of coral reefs without disrupting sediment transport or other essential ecosystem processes. Together, these measures provide an integrated strategy for coastal management and the long-term maintenance of atoll land.

Although this proposal focuses on Majuro Atoll, the approach is intended to provide a model that can be applied throughout the Republic of the Marshall Islands and, ultimately, to other atoll nations such as Kiribati and Tuvalu.

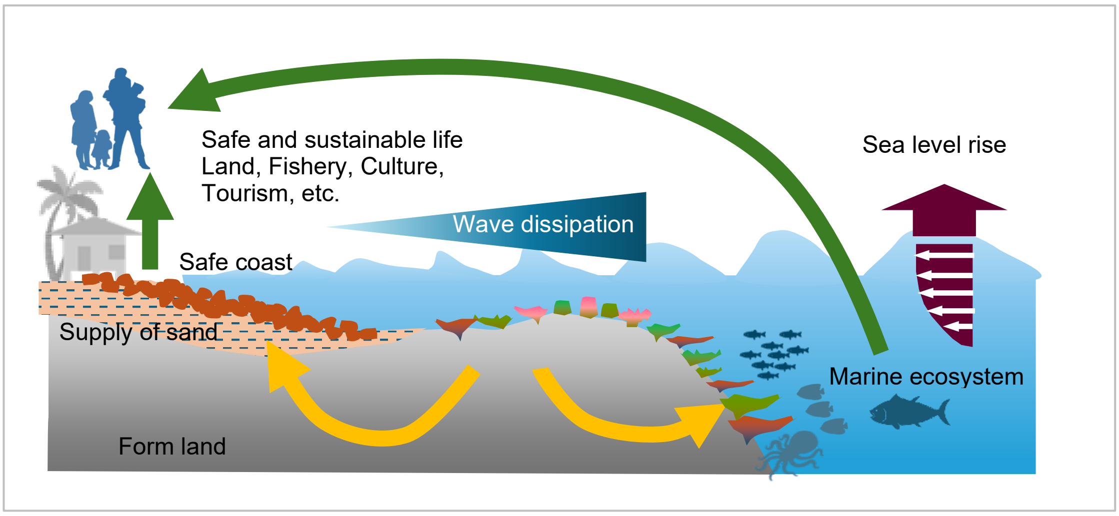


Fig. 14. Conceptual vision of ecosystem functions

4. Project Area and Adaptation Strategy

4.1 Project Area

This project focuses on Majuro Atoll, the capital of the Republic of the Marshall Islands (RMI). Located at approximately 7°N, 171°E, Majuro extends about 40 km from east to west and up to 9.7 km from north to south. The total land area is approximately 9.7 km², surrounding a lagoon of approximately 324 km² with a maximum depth exceeding 60 m (Responsible Sourcing of Aggregates in the Pacific, PRIF, 2025).

Majuro is the political, economic, and administrative center of RMI and has the country's largest population and highest population density. Approximately 28,000 people live on the atoll, of whom about 20,000 are concentrated in the Dalap–Uliga–Djarrit (D-U-D) urban district on the eastern end of the atoll.

Although Majuro is often regarded as a single atoll, its coastal environments and exposure to climate hazards vary considerably from place to place. Population density, island width, elevation, and exposure to prevailing winds and waves create distinct spatial patterns of coastal flooding and erosion. These differences require adaptation measures that are tailored to local environmental and socio-economic conditions rather than applying a single solution throughout the atoll.

Following the concept adopted in the National Adaptation Plan (NAP), this project classifies Majuro into three planning zones—Urban, Semi-urban, and Rural—based primarily on population density and settlement characteristics (Fig. 15). These zones also broadly correspond to differences in wave exposure and coastal vulnerability (Fig. 16), providing the spatial framework for selecting appropriate Nature-based Solutions (NbS) and engineering interventions in each area.

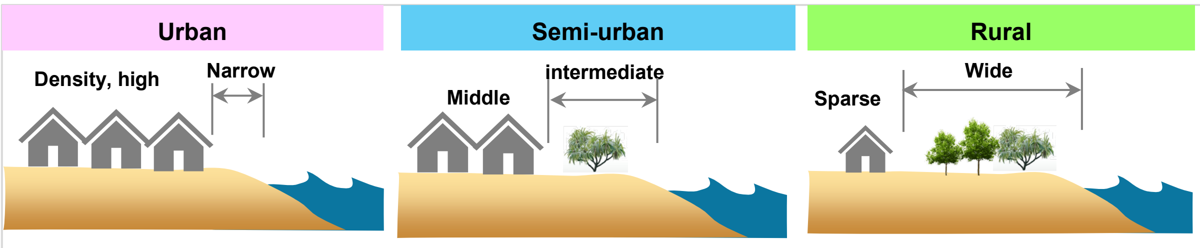


Fig. 15. Three community types defined in the National Adaptation Plan (NAP)

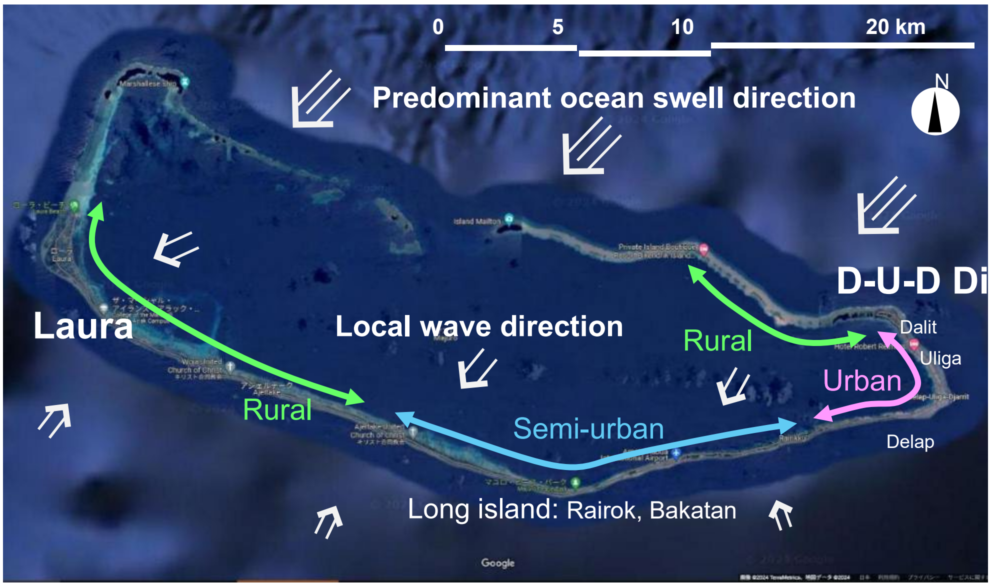


Fig. 16. Spatial features of Majuro Atoll, showing community types and predominant wave conditions.

4.2 Adaptation Strategy for Different Hazard Levels

Table 1 classifies the major coastal hazards affecting atoll nations into three categories: (1) chronic coastal erosion, (2) episodic coastal flooding, and (3) permanent or recurrent inundation associated with long-term sea-level rise. As sea level rises and shorelines erode, damaging coastal impacts are expected to occur more frequently. The proposed NbS measures aim to limit this increase and maintain present-day levels of coastal resilience as far as practicable.

Table 1. Major climate-related coastal hazards in Majuro Atoll.

Type of hazard (Image of time course)	Image photo	Descriptions
(1) Coastal erosion  Present >>Future	 *3 March 2026, airport lagoon side*	**Cause:** Decrease of sediment supply. A vertical seawall enhances sediment loss on the reef. **Frequency:** Chronically progressing **Impacts:** Loss of coastal land. Weaken wave dissipation function and enhance inundation hazard.
(2) Flooding  Present >>Future	 *ANZIEEG (copyright image 216440)*	**Cause:** High wind wave / swell significantly overflows the seawall under high tide, likely combined with amplified infra-gravity waves. **Frequency:** Return period of a few years to several decades. Likely increases with SLR and coastal erosion. **Impacts:** Damage of houses and infrastructure, and threats of human life, disease outbreaks, disruption of community activities, and salinization of freshwater resources.
(3) Permanent inundation  Present Future	 *March 14, 2024_RMI Journal*	**Cause:** Significant SLR and high tide combined with coastal erosion. **Frequency:** Permanent inundation / tide-associated cyclic inundation under significant SLR. **Impacts:** Loss of land, relocation of communities and infrastructure, and major social and economic impacts.

Conventional adaptation planning often addresses these hazards separately: engineering measures focus primarily on short- to medium-term coastal protection, while land raising, relocation, and other social measures address longer-term risks. In contrast, this project combines ecosystem-compatible coastal engineering, sediment management, and coral reef restoration across these timescales.

The proposed engineering measures, including wave-dissipating structures, breaking-wave mounds, sand traps, beach nourishment, and Beachrock technology, are primarily intended to reduce the impacts of frequent wave overtopping, coastal erosion, and partial inundation. At the same time, coral reef restoration enhances the natural capacity of reefs to dissipate wave energy and produce reef-derived sediments, thereby strengthening the long-term natural processes that create and maintain atoll islands.

When combined with complementary social measures such as land raising, resilient infrastructure, early warning systems, and disaster preparedness, these integrated measures contribute not only to reducing relatively frequent coastal impacts but also to improving resilience to larger-scale flooding and long-term sea-level rise.

4.3 From Community Resilience to National Resilience

The expected outcomes of the proposed NbS project extend beyond reducing coastal hazards at individual sites. As illustrated in Fig. 17, improvements achieved at the community level—including safer settlements, more resilient livelihoods, and enhanced ecosystem services—collectively strengthen national resilience. Healthy coral reef ecosystems function as natural infrastructure that protects coastal communities while sustaining sediment production, biodiversity, and the natural processes that create and maintain atoll islands. These community-level benefits contribute directly to national security, resilient infrastructure, economic stability, social cohesion, and the international leadership of the Republic of the Marshall Islands in climate-change adaptation. Thus, the proposed NbS approach provides benefits across multiple spatial and temporal scales, from individual communities to the nation as a whole.

1. National-level Outcomes

1.1 Strengthened national resilience and long-term security

By reducing the risks of coastal flooding, erosion, and permanent inundation, the project will strengthen national resilience, improve long-term security, and enhance confidence in the country's future.

1.2 More resilient infrastructure and a stable economy

Improved protection of water supply, electricity, sanitation, health care, transportation, and other critical infrastructure will increase the resilience of communities while supporting sustainable fisheries, tourism, and other key economic sectors.

1.3 Stronger communities and preservation of cultural identity

Reduced climate-related risks will help reduce involuntary displacement and climate-driven migration pressures, maintain community cohesion, and preserve the cultural identity and traditional way of life of atoll communities.

1.4 Regional and International leadership in climate adaptation

The knowledge, technologies, and implementation framework developed through this project will provide a practical model for other atoll nations, strengthening the international contribution of RMI to climate-change adaptation.

2. Community-level Outcomes

2.1 Safer and more sustainable communities

Reduced coastal flooding, erosion, and saltwater intrusion will protect land, housing, public facilities, infrastructure, and freshwater resources, improving the safety and sustainability of coastal communities.

2.2 More resilient livelihoods

Healthier coastal ecosystems will support fisheries, reduce salt damage to agricultural land, protect tourism resources, and improve long-term livelihood security.

2.3 Enhanced ecosystem services

Healthy coral reefs together with ecosystem-compatible coastal engineering will function as **natural infrastructure**, providing coastal protection, sustaining sediment production, conserving biodiversity, and supporting long-term island resilience.

Fig. 17. Community-level outcomes achieved through integrated NbS measures collectively contribute to national resilience and long-term climate adaptation.

5. Project Concept and Framework

5.1 Guiding Principles

The overall objective of this project is to enhance the resilience and sustainability of coastal communities on Majuro Atoll against climate-change impacts, including wave overtopping, coastal flooding, and erosion. To achieve this, adaptation measures are selected and combined according to their effectiveness, cost-efficiency, environmental and social impacts, and suitability for different locations and stages of sea-level rise.

The proposed approach recognizes that healthy coral reef ecosystems constitute the natural infrastructure that both protects atoll shorelines from wave energy and supplies the carbonate sediments required to create and maintain atoll islands. Accordingly, restoring and conserving coral reef ecosystems forms a central component of the project. At the same time, the project also recognizes the protective functions of natural coastal landforms and coastal vegetation, and seeks to restore and utilize these natural processes wherever possible.

The proposed NbS strategy therefore integrates ecosystem restoration with ecosystem-compatible coastal engineering, creating a Green–Grey approach that works with, rather than against, natural coastal processes.

The guiding principles are as follows:

- Maximize the use of Nature-based Solutions (NbS) by utilizing the wave-attenuation functions of healthy coastal landforms, beach vegetation, and coral reefs, together with the sediment-production processes that naturally maintain atoll islands.
- Combine ecosystem-based measures with engineering solutions, including Green–Grey coastal protection, land raising, resilient buildings, and early warning systems, to provide adaptive, cost-effective, and sustainable coastal protection that can be implemented widely throughout the Republic of the Marshall Islands.

5.2 Design Conditions

To ensure consistency throughout the project, the following design conditions are adopted for all proposed NbS measures.

(1) Design Time Horizon

This proposal is designed for the period **2070–2100**, assuming a projected **sea-level rise of 0.5 m**, consistent with the National Adaptation Plan (NAP). Adaptation measures required beyond 2100, including those associated with the **2.0 m sea-level rise scenario** for 2150 adopted in the NAP, are considered to be part of subsequent adaptation stages.

(2) Design Hazards

The proposed measures are designed for **0.5 m of sea-level rise** and wave conditions with **return periods of up to 30–50 years**. Hazards exceeding these design conditions are assumed to be addressed primarily through complementary measures such as disaster preparedness, emergency response, and other non-structural adaptation strategies.

(3) Design Water Levels and Wave Conditions

The design water levels and wave conditions adopted in this proposal are summarized in Tables 2 and 3. The design water level consists of the mean sea level (MSL), high water level (HWL), storm surge, projected sea-level rise, and wave setup. The design wave conditions are based on offshore and nearshore wave analyses corresponding to the selected design return period.

Table 2. Design Water Levels

Sea level	Δh Difference (m)	h Sea level (MSL+ m)
HWL	1.25	1.334
HHWL (Storm surge)	0.42	1.754
Sea level rise by CC	0.23→0.5	2.254
Wave setup	0.76	3.014

Table 3. Design Wave Conditions

Items	H(wave height) (m)	Planned Return period
Hs_0 : Deep sea significant wave height	4.600	50 year
H: After analyzing the shallow sea (on the reef flat)	2.300	
Hs: significant wave height (shore front)	2.130	

Source: JICA (2020), Water Storage Improvement Project Report

5.3 Project Structure

The proposed project adopts an integrated Nature-based Solutions (NbS) approach that combines social measures, ecosystem-compatible coastal engineering, and ecosystem restoration to enhance the long-term resilience of atoll communities (Fig. 18).

Social measures—including land-use planning, institutional arrangements, waste management, and disaster preparedness—provide the foundation for reducing climate-related risks.

Engineering measures focus on protecting coastal communities while maintaining natural coastal processes. Green–Grey coastal protection, land raising, and sediment-retaining structures are designed to work with ecosystem processes rather than replacing them.

Ecosystem measures focus on restoring and conserving healthy coral reef ecosystems through complementary restoration techniques adapted to both ocean-reef and lagoon environments. These measures enhance reef growth, carbonate sediment production, and the natural wave-attenuation capacity of coral reefs, thereby supporting the long-term maintenance of atoll islands.

Together, these integrated measures establish a continuous adaptation pathway that links short-term coastal protection with long-term resilience against sea-level rise.

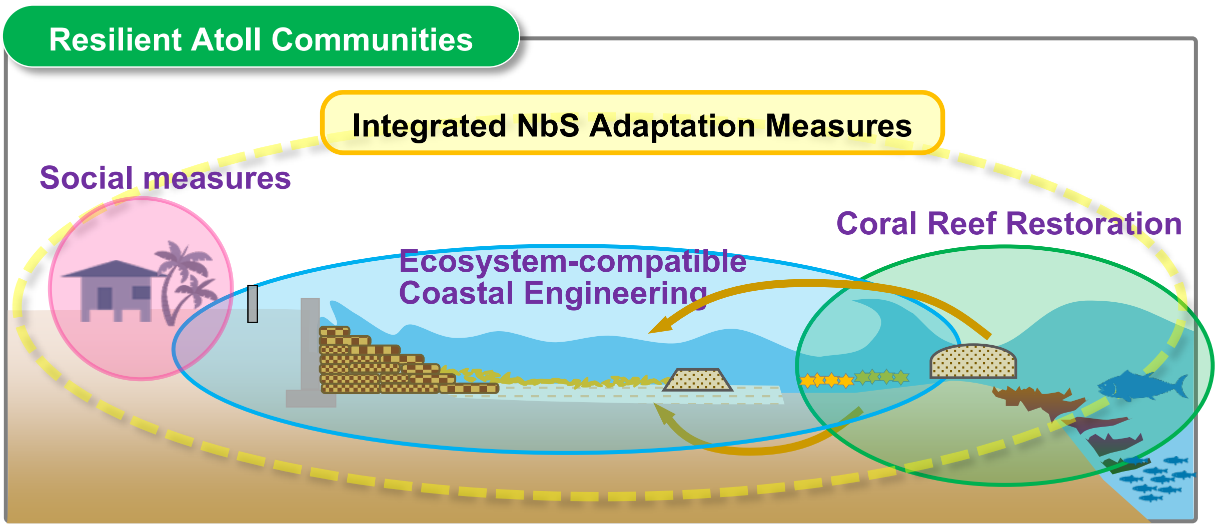


Fig. 18. Project Structure Concepts

The ultimate objective of the proposed NbS approach is not simply to reduce coastal hazards, but to restore resilient sandy beaches that protect coastal communities while maintaining the natural land-building processes of coral reef ecosystems. Figure 19 illustrates the long-term vision of the proposed project, showing the transformation from degraded urban shorelines dominated by vertical seawalls to resilient coasts sustained by integrated Nature-based Solutions. The effectiveness of this integrated NbS approach in achieving this long-term vision is conceptually illustrated by the damage-frequency relationships shown in Fig. 20.

Fig. 19. Long-term vision of the proposed NbS project. The proposed integrated NbS approach aims to transform degraded urban shorelines into resilient beaches that support healthy coral reef ecosystems and safe coastal communities.

As introduced in Table 1, coastal hazards range from relatively frequent partial inundation, to rare events associated with large-scale flooding. Future sea-level-rise will also likely to cause permanent inundation. Under climate change and sea-level rise, however, the frequency of hazards of a given magnitude will likely increase. Figure 20 conceptually illustrates how different adaptation measures modify damage-frequency relationship under present and future climate conditions.

A f damage-frequency relationship represents the probability that a coastal system exceeds its resistance capacity and experiences damage under a given hazard frequency (return period). Climate change and sea-level rise shift the damage-frequency relationship leftward, meaning that the same level of damage is expected under more frequent hazard events.

Conventional seawalls reduce disaster risk by shifting the damage-frequency relationship toward **rarer hazard events (longer return periods)**. However, their protective function rapidly diminishes once hazards exceed their design conditions, resulting in a steep increase in damage probability.

Nature-based Solutions (NbS), including sediment trapping, beachrock formation, and coral reef restoration, reduce disaster risk in three complementary ways. First, they increase the resistance of the coastal system, thereby shifting the damage-frequency relationship toward rarer hazard events (longer return periods). Second, they flatten the damage-frequency relationship, reflecting the gradual and adaptive protection provided by natural coastal processes rather than a fixed engineering threshold. Third, by restoring the wave-dissipation and sediment-producing functions of coral reef ecosystems, NbS reduce the increase in the frequency of damaging coastal impacts associated with sea-level rise, thereby enhancing long-term coastal resilience.

Complementary land-based adaptation measures, such as land raising, resilient infrastructure, evacuation systems, and land-use planning, provide further reductions in disaster risk, particularly for less frequent but more severe hazards, by shifting the damage-frequency relationship even further toward rarer hazard events (longer return periods).

The integrated implementation of NbS and complementary adaptation measures therefore establishes a continuous adaptation pathway from frequent coastal hazards to rare extreme events, consistent with the hazard classification presented in Table 1. By limiting the increase in the frequency of damaging coastal impacts associated with sea-level rise, this integrated approach provides the highest level of coastal resilience under future climate conditions.

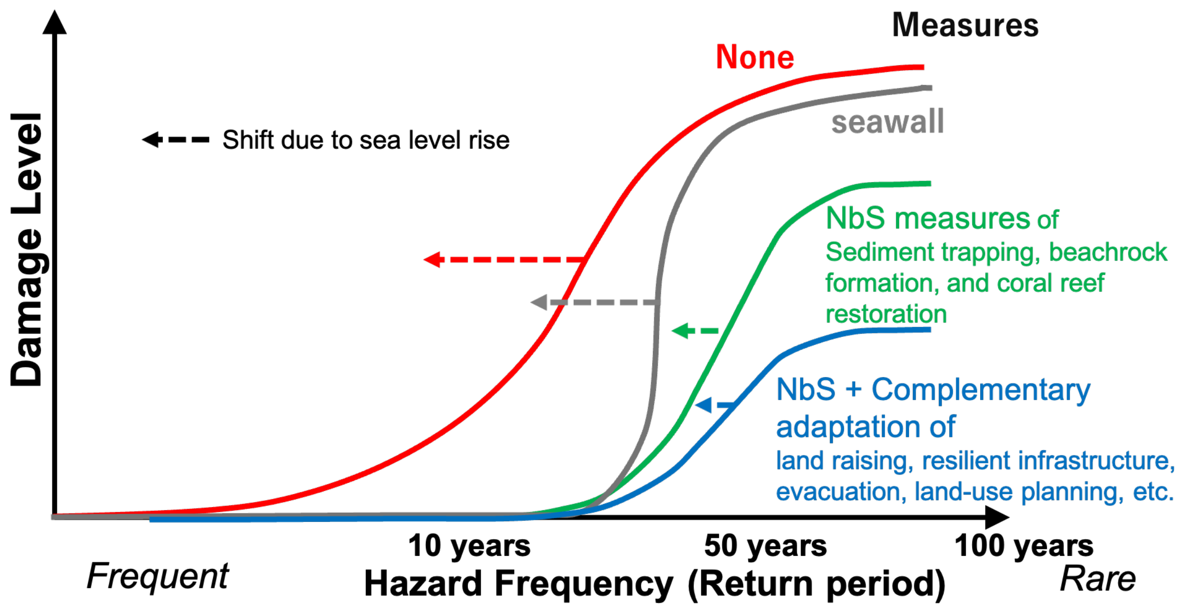


Fig. 20. Conceptual damage-frequency curve/damage-response relationship.

6. Key NbS Measures

This chapter presents the principal Nature-based Solutions (NbS) proposed in this project. These NbS measures provide the basis for the integrated adaptation strategies described in Chapter 7, where they are combined according to the environmental and social conditions of different areas in Majuro Atoll.

6.1 Wave Attenuation and Coastal Protection

6.1.1 Wave-dissipating Structures

Wave-dissipating structures are proposed to reduce wave reflection and wave overtopping while promoting the accumulation of reef-derived sediments along the shoreline. Unlike conventional vertical seawalls, these structures are designed to work with natural coastal processes and to enhance both coastal protection and sediment retention.

Various structural options can be adopted according to local environmental conditions and engineering requirements. In addition to natural rock and conventional concrete armour units such as Seabee blocks and tetrapods, these options include biodegradable sandbags incorporating the proposed Beachrock technology, which promotes the natural cementation of carbonate sediments. It should be highlighted that wave attenuation can be realized through the combination of coastal protection works in front of the seawall, elevated reef bed between sand trap and the seawall, and the breaking mound near the reef edge (Figure 21). Appropriate selection of slope geometry and structural layout can improve wave attenuation while minimizing construction costs. Use of small sand bags and sand tubes may enhance relatively easy and sustainable maintenance by local contractors.

To establish the initial structure and beach profile, a limited volume of carbonate sediment may be obtained from environmentally suitable borrow areas following appropriate environmental assessment. As natural sediment accumulation progresses, excess sediments may subsequently be reused for beach nourishment or land raising in other locations.

Fig. 21. Conceptual wave-dissipating stepped structure. The step is filled by coral gravel or small sand bags with the outer edge surrounded by sand tubes. Beachrock technology may be applied for both fill and sand tubes to enhance the stability. The permeable structure reduces wave reflection and run-up while promoting sediment accumulation and the formation of a gently sloping shoreline.

6.1.2 Breaking-wave Mounds (Artificial Reef)

Breaking-wave mounds (artificial reefs) are proposed near the reef edge to induce wave breaking before ocean swells propagate across the reef flat. By reducing wave energy at the outer margin of the reef, these structures decrease wave heights reaching the shoreline and thereby mitigate wave overtopping and coastal flooding.

Unlike conventional offshore breakwaters, the proposed mounds are designed to function in harmony with the natural reef topography. They are expected not only to enhance wave attenuation but also to provide suitable substrates for coral recruitment and other reef organisms, thereby contributing to the long-term recovery of coral reef ecosystems.

Where appropriate, the mounds may be constructed using carbonate sediments retained by sand traps and subsequently stabilized through the proposed Beachrock technology. This approach utilizes locally available reef-derived materials and has the potential to create semi-natural reef structures that combine coastal protection with ecosystem restoration.

The dimensions, crest elevation, and spacing of the mounds should be optimized according to local bathymetry, wave conditions, sediment transport, and ecological considerations. When combined with sediment traps and Beachrock technology, long-term monitoring, maintenance, and staged additions of material could allow the mound crest to be progressively raised as sea level rises.

Fig. 22. Example of a breaking-wave mound at Oogimi, Okinawa.

6.1.3 Coastal Embankments, Secondary Seawalls, Land Raising, and Coastal Vegetation

Coastal embankments, secondary seawalls, land raising, and coastal vegetation are proposed as complementary measures to enhance the effectiveness of Nature-based Solutions (NbS). These measures provide additional protection against wave overtopping and coastal flooding while maintaining the multiple ecosystem functions of coral reefs and natural beaches.

Unlike conventional vertical seawalls that directly face the sea, landward embankments and secondary seawalls can reduce flood damage while allowing natural coastal processes, including wave dissipation and sediment transport, to continue along the shoreline. Where space is available, gentle embankments combined with coastal vegetation further improve coastal resilience by stabilizing sediments, reducing surface erosion, and providing ecological and landscape benefits.

Land raising may also be implemented in priority areas where long-term protection of important infrastructure and residential areas is required. Such measures should be integrated with ecosystem-based coastal protection and sediment management to provide a flexible and adaptive response to future sea-level rise.

The appropriate combination of these measures should be determined according to local topography, land use, hazard level, and future adaptation requirements.

Fig. 23. Coastal vegetation and a natural berm at Kayo Beach, Okinawa, Japan. *Similar vegetated berms can be incorporated into the proposed complementary adaptation measures for semi-urban and rural atoll coasts.*

6.2 Sediment Management and Reef-flat Enhancement

6.2.1 Sediment Deposition Zones Formed by Sand Traps

Healthy coral reefs continuously produce carbonate sand and gravel that contribute to the natural formation and maintenance of atoll islands. However, a significant proportion of these sediments is transported offshore or into the lagoon before reaching the shoreline. To enhance sediment retention and utilize this natural sediment supply, the project proposes the creation of sediment deposition zones on the reef flat using sand traps.

The proposed sand traps consist of low-profile barriers installed on the reef flat to reduce offshore sediment transport by return flow while allowing waves and water to pass with minimal obstruction. By gradually trapping reef-derived carbonate sediments, these structures promote the formation of shallow sediment deposition zones several tens of meters wide.

As sediment accumulates, water depth over the reef flat decreases, resulting in lower wave heights during storm events and improved wave attenuation before waves reach the shoreline. Unlike conventional engineering structures, this approach enhances natural geomorphological processes and allows the reef flat to adjust progressively to future sea-level rise.

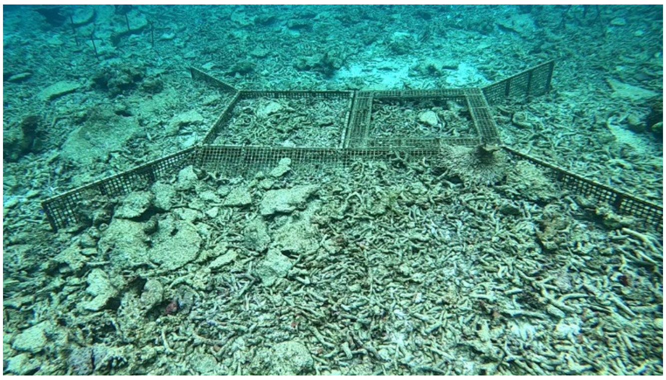


Fig. 24. Sand tube (left, Geotube Marine) and permeable sand trap deployed on Barasu Island, Iriomote-jima.

Where appropriate, the accumulated sediments may subsequently be stabilized by the proposed Beachrock technology or utilized for the construction of breaking-wave mounds and other ecosystem-compatible coastal protection measures. In this way, sand traps provide the foundation for long-term sediment management and reef-flat enhancement.

6.2.2 Beach Nourishment

Beach nourishment is proposed to restore and maintain beaches in areas where the natural supply of reef-derived sediments is insufficient to compensate for coastal erosion. As a complementary measure to sediment management and ecosystem restoration, beach nourishment can enhance coastal protection while maintaining the natural functions of reef-flat and beach environments.

Potential sediment sources include suitable carbonate sediments from the lagoon floor and sand apron deposits in the northern part of the atoll, subject to detailed environmental assessment and sustainable resource management. Carbonate sediments on the deep lagoon floor remain a possible borrow source, although their utilization would require dredging from water depths of approximately 50 m.

An alternative and potentially more sustainable sediment source is provided by the sand aprons developed around the uninhabited northern islets. These deposits are formed by the continuous accumulation of reef-derived carbonate sediments, particularly foraminiferal sands, which are transported from the ocean-side reefs through channels between the islets into the lagoon. Because these sediments would otherwise continue to migrate into the deeper lagoon basin, they may provide a renewable source of nourishment material if carefully managed. Conservation of the sediment-producing reef habitats surrounding the northern islets is therefore an essential prerequisite for their sustainable utilization.

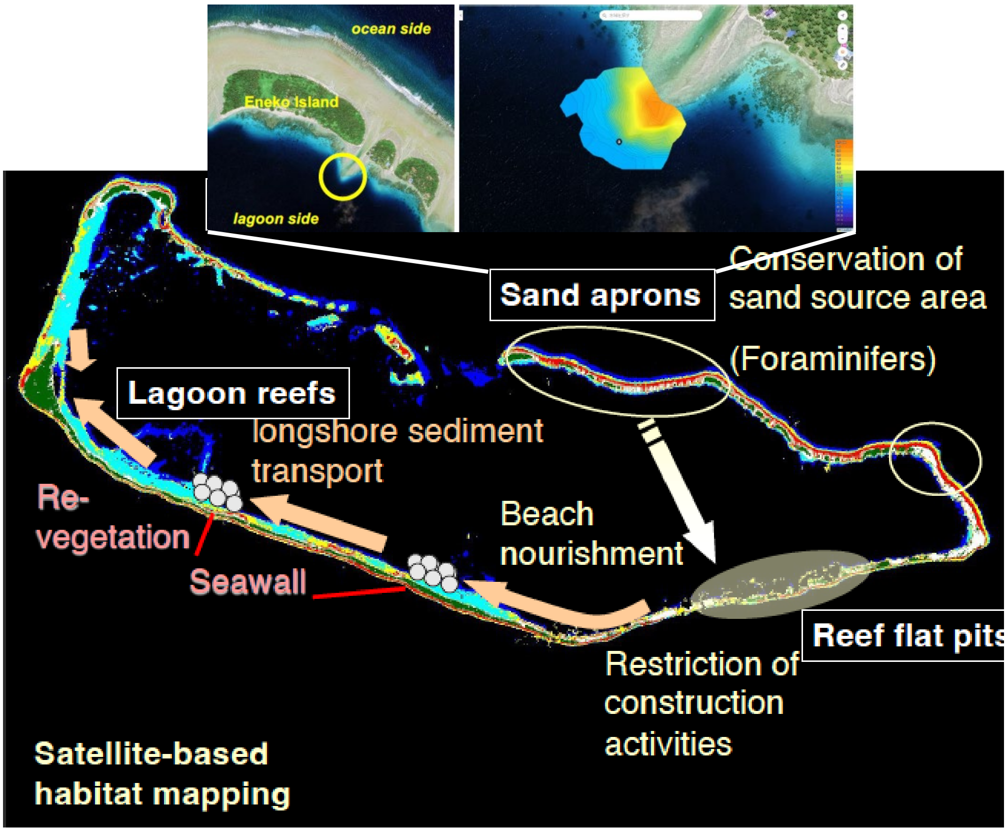


Fig. 25. Concept of beach nourishment using lagoon-floor sediments and sand aprons formed around the northern islets.

The selection of borrow areas should minimize ecological impacts while ensuring the long-term availability of sediment resources.

Beach nourishment is expected to be most effective when implemented together with sediment-retention measures, such as sand traps, and ecosystem restoration measures that promote the continuous natural production of reef-derived sediments. This integrated approach reduces the need for repeated nourishment and contributes to the long-term sustainability of atoll shorelines.

6.2.3 Beachrock Technology

Beachrock technology is proposed as an innovative method for stabilizing reef-derived carbonate sediments while maintaining the natural characteristics of reef-flat and beach environments. The proposed approach accelerates the natural lithification process of carbonate sediments, forming semi-natural hardgrounds that are expected to improve the long-term stability of deposited sediments.

Unlike conventional concrete structures, Beachrock technology utilizes locally available carbonate sediments and is intended to work in harmony with natural coastal processes. The stabilized sediments can reduce erosion, increase the durability of sediment-retention measures, and provide a stable foundation for ecosystem-compatible coastal protection.

The technology can be applied in combination with other NbS measures proposed in this project. For example, sediments accumulated by sand traps may subsequently be stabilized to form durable sediment deposits, while beachrock formation may also contribute to the development and maintenance of breaking-wave mounds and other nature-based coastal protection structures.

Further laboratory and field verification will be conducted to optimize the engineering properties, environmental compatibility, and long-term performance of the proposed technology.

Fig. 26. Coral sand/gravel that solidified within two weeks (left) and artificial beachrock on a shore (right).

6.3 Ecosystem Restoration

6.3.1 Coral Reef Restoration

Coral reef restoration is a key component of the proposed NbS approach because healthy coral reefs function as natural infrastructure that dissipates wave energy, produces reef-derived carbonate sediments, and supports the natural processes that create and maintain atoll islands. Restoring these ecosystem functions therefore contributes not only to biodiversity conservation but also to long-term coastal protection and climate-change adaptation.

The proposed restoration program combines both sexual reproduction using coral larvae and asexual propagation using coral fragments. Sexual reproduction enhances genetic diversity and the long-term resilience of coral populations, whereas asexual propagation enables rapid recovery of coral cover in degraded reef areas. Appropriate restoration techniques will be selected according to local environmental conditions and project objectives.

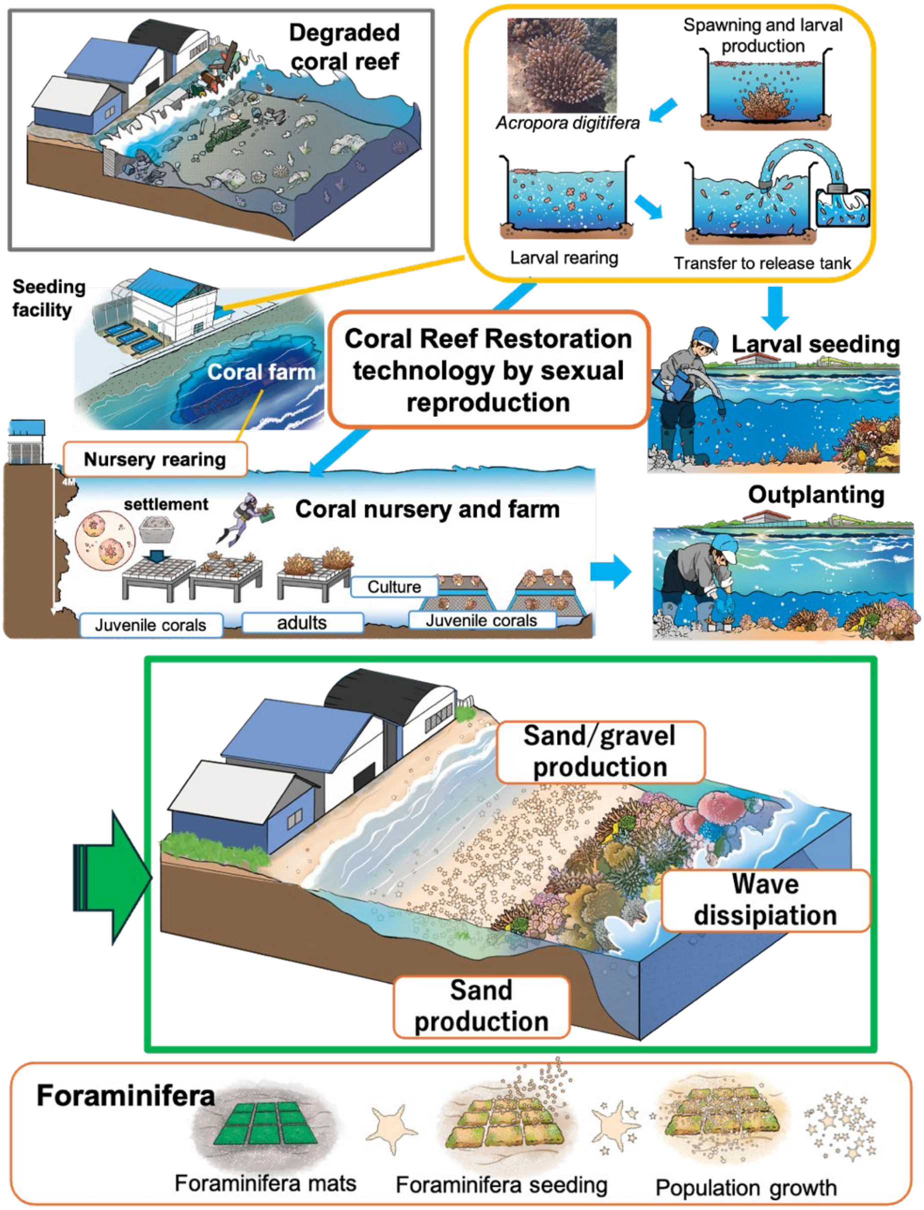


Fig. 27. Proposed process of coral reef restoration based on sexual reproduction for sustainable sediment production and long-term coastal resilience.

To improve restoration efficiency, a variety of coral settlement substrates and nursery techniques developed in Japan may be incorporated into the restoration program. These technologies provide suitable habitats for coral recruitment and juvenile coral growth while facilitating large-scale restoration and long-term monitoring. Representative restoration methods and settlement substrates are summarized in Appendix 1.

Coral reef restoration will be implemented in coordination with ecosystem-compatible coastal engineering and sediment management. Together, these integrated measures are expected to enhance wave attenuation, increase reef-derived carbonate sediment production, improve ecosystem resilience, and restore the natural functions of coral reefs as coastal protection infrastructure. By strengthening these ecosystem processes, the proposed approach is expected to gradually recover resilient sandy beaches while complementing the coastal protection and sediment management measures proposed in this project.

6.3.2 Priority Coral Reef Conservation Area

Coral reef conservation is an essential complement to restoration. Healthy reefs already functioning as sources of coral larvae, reef-derived sediments, and wave attenuation should be protected as priority conservation areas to maintain their ecological and coastal protection functions.

Priority conservation areas should be designated based on ecological importance, connectivity, and their contribution to coastal resilience. Appropriate management of human activities, together with improvements in wastewater treatment and water quality, will help maintain healthy coral reef ecosystems and maximize the long-term effectiveness of the proposed NbS measures.

6.4 Complementary Social Measures

Although this project focuses primarily on Nature-based Solutions (NbS) and ecosystem-compatible coastal engineering, long-term climate resilience cannot be achieved through coastal measures alone. Complementary social measures are also essential for reducing climate-related risks and enhancing community resilience.

These measures include improvements in wastewater treatment and water quality management to reduce pressures on coral reef ecosystems, climate-resilient housing and public facilities, early warning systems for extreme waves and flooding, disaster preparedness, and evacuation planning. Together, these measures reduce disaster risks while supporting the long-term effectiveness of the proposed NbS measures.

Many of these measures are already included in the National Adaptation Plan (NAP) and other national programmes of the Republic of the Marshall Islands. This project is intended to complement these ongoing initiatives by providing ecosystem-based coastal protection and restoration measures that strengthen their overall effectiveness.

7. NbS Strategies according to Areas

The NbS measures described in Chapter 6 are applied in different combinations according to local environmental and socio-economic conditions. Table 4 summarizes the principal measures proposed for each coastal setting in Majuro Atoll. The following sections describe the recommended adaptation strategies for Urban, Semi-urban, and Rural areas.

Table 4. Recommended Combination of NbS Measures for Different Coastal Settings

Area	Wave attenuation	Sediment management	Ecosystem restoration	Complementary measures
Urban (Ocean)	●	●	○	●
Urban (Lagoon)	○	●	●	●
Semi-urban	○	●	●	○
Rural	△	○	●	△

(● : Primary、 ○ : Secondary、 △ : Optional)

7.1 Urban Areas – Ocean Side

The ocean side of the urban area is the highest-priority target of this project because it is exposed to long-period ocean swells and experiences frequent wave overtopping, coastal flooding, and shoreline erosion. The narrow width of the islands and the high density of residential areas and critical infrastructure leave little space for conventional coastal adaptation measures.

For these reasons, an integrated combination of NbS measures is proposed. Wave-dissipating structures and breaking-wave mounds are recommended to reduce wave energy, while sand traps, beach nourishment, and Beachrock technology are applied to enhance sediment retention and stabilize the shoreline. Coral reef restoration should be implemented simultaneously to recover the natural wave-dissipation and sediment-production functions of healthy reef ecosystems. Where necessary, complementary measures such as secondary seawalls, land raising, and coastal vegetation should be introduced to further reduce residual risks.

Together, these measures are expected to provide effective protection against frequent wave overtopping and coastal erosion while maintaining the natural processes that create and sustain atoll island.

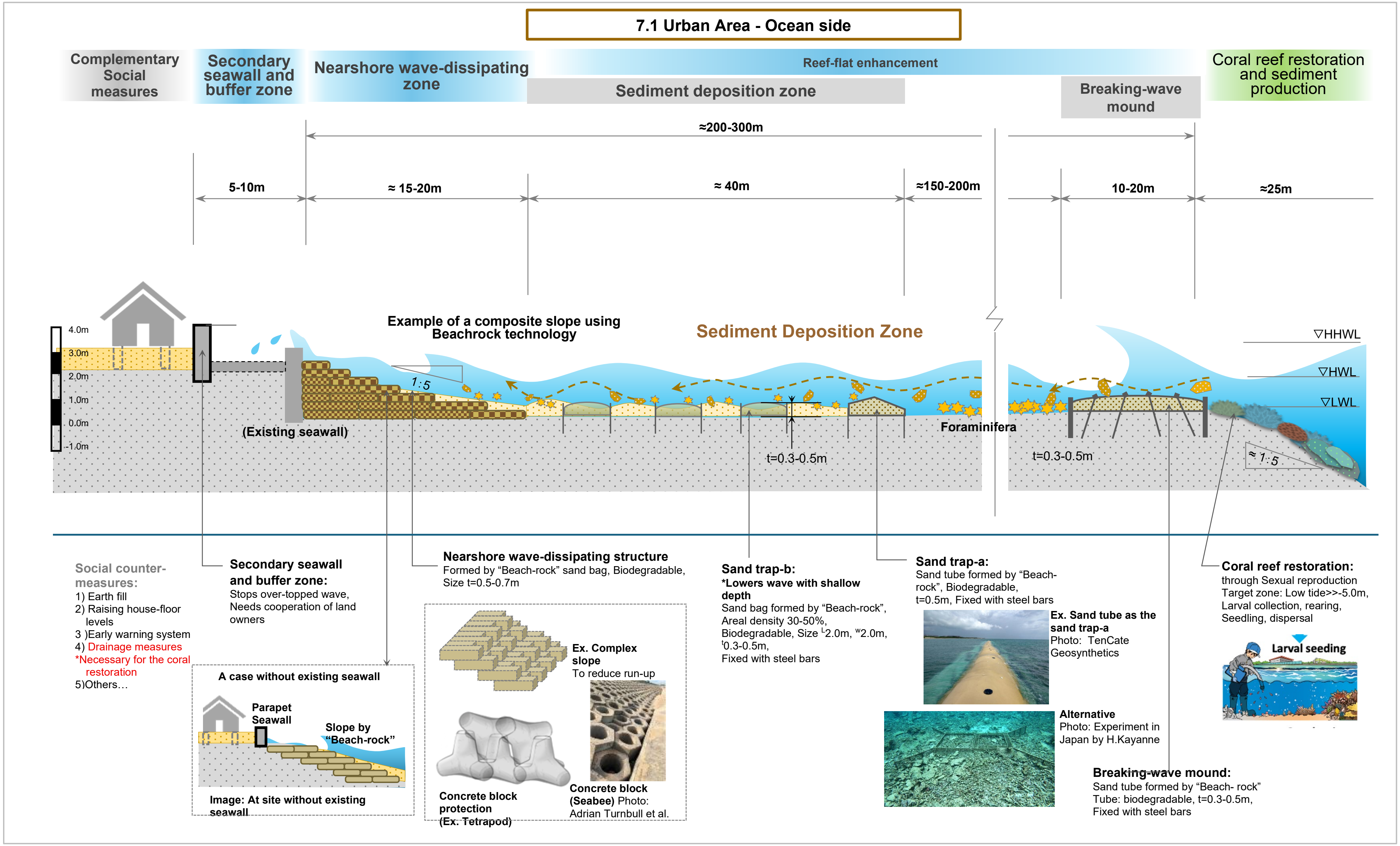


Fig. 28. Conceptual cross-section of Urban Areas – Ocean Side

Fig. 29. Conceptual layout of proposed NbS measures for urban coastal areas.

7.2 Urban Areas – Lagoon Side

The lagoon side of urban areas is generally less exposed to ocean swells than the ocean side but remains vulnerable to locally generated waves, coastal erosion, and flooding associated with elevated lagoon water levels during extreme events. In addition, many shorelines have been modified by reclamation and coastal development, reducing the natural capacity of beaches to retain sediments.

In these areas, priority should be given to sediment management measures, including beach nourishment and sand traps where appropriate, together with low-crested wave-dissipating structures to reduce wave energy and stabilize the shoreline. Coral reef restoration around lagoon patch reefs should also be promoted to enhance ecosystem functions and maintain sediment production. Restoration measures should be planned so as not to interfere with navigation channels, port facilities, and other essential urban functions.

Where necessary, complementary measures such as coastal embankments, secondary seawalls, and coastal vegetation should be incorporated according to local land use and hazard conditions.

Together, these measures are expected to improve shoreline stability and enhance the resilience of urban lagoon coasts while maintaining their ecological functions.

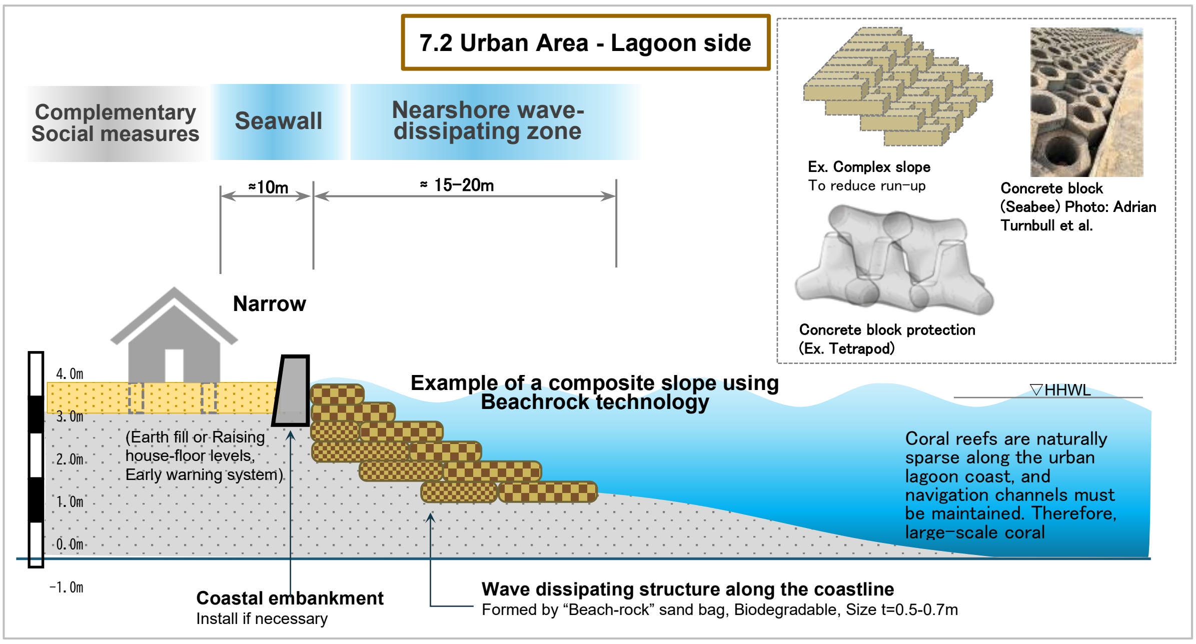


Fig. 30. Conceptual cross-section of Urban Areas – Lagoon Side.

7.3 Semi-urban Areas – Ocean Side

Semi-urban areas provide greater opportunities to utilize natural coastal processes because of their lower population density and wider coastal zones. The objective in these areas is to enhance the natural resilience of the shoreline while minimizing the need for large engineered structures.

The proposed NbS strategy therefore emphasizes sediment management and ecosystem restoration. Where existing reef-flat protrusions or natural topographic features already promote sediment accumulation, these features should be utilized as natural sediment traps before introducing artificial structures. Sand traps, beach nourishment, and Beachrock technology are recommended to promote the accumulation and stabilization of reef-derived sediments, while breaking-wave mounds and wave-dissipating structures may be introduced where wave conditions require additional protection. Coral reef restoration should be implemented to recover natural wave attenuation and sediment production.

Where appropriate, low embankments, coastal vegetation, and other complementary measures should be incorporated to provide additional protection while maintaining the natural landscape and ecosystem functions.

This integrated approach is expected to strengthen coastal resilience while preserving the environmental and scenic values of semi-urban coastlines.

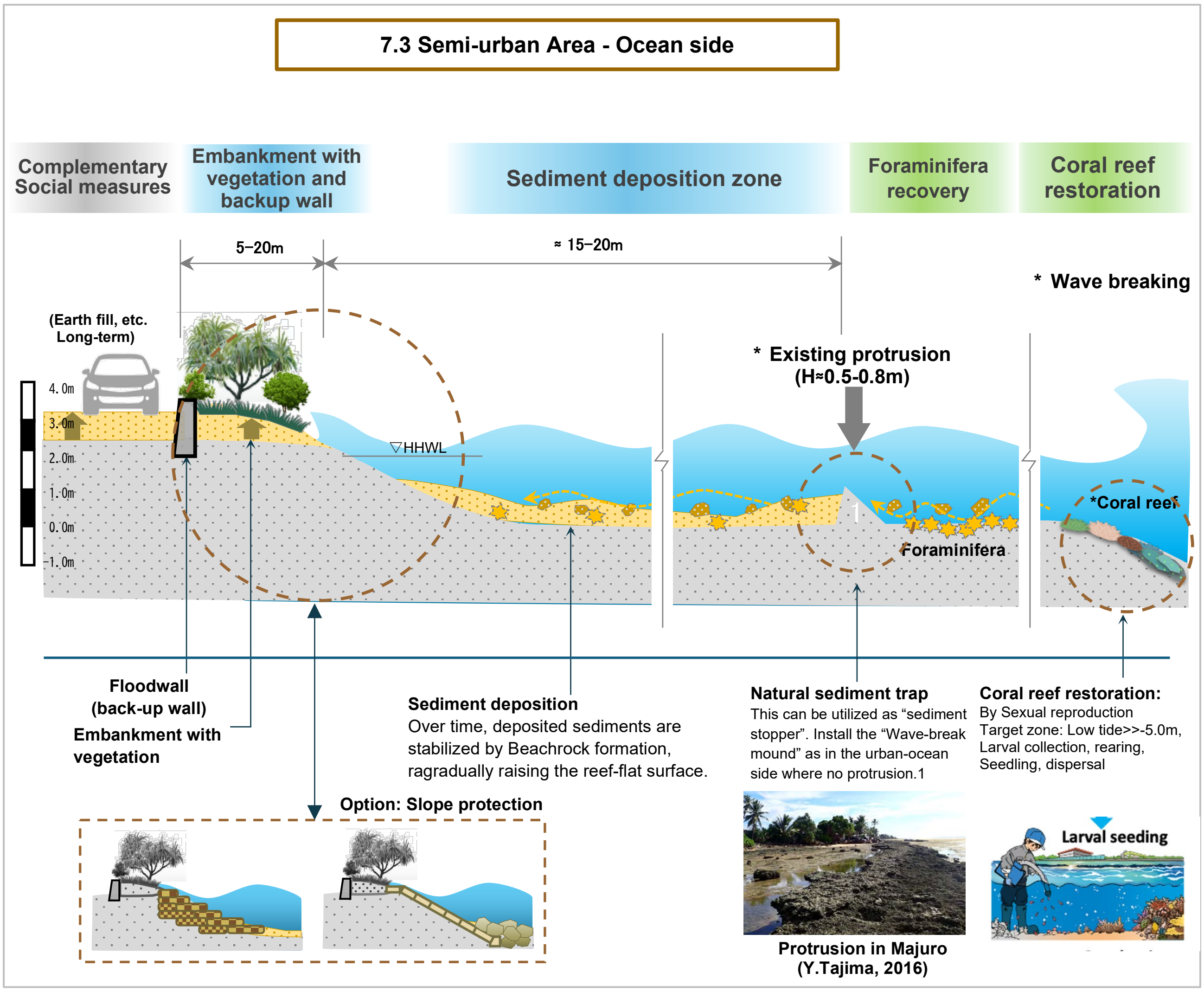


Fig. 31. Conceptual cross-section of Semi-urban Areas – Ocean Side.

7.4 Semi-urban Areas – Lagoon Side

The lagoon side of semi-urban areas provides favourable conditions for Nature-based Solutions because of its relatively sheltered wave environment, lower development intensity, and greater availability of natural coastal landforms. The primary objective is to conserve and enhance these natural functions while improving resilience to coastal erosion and flooding.

Priority should be given to sediment management and ecosystem restoration. Beach nourishment, sand traps where appropriate, and Beachrock technology are recommended to stabilize shorelines and promote the natural accumulation of reef-derived sediments. Coral reef restoration and conservation should be implemented to maintain healthy lagoon reef ecosystems and sustain long-term sediment production.

Fig. 32. Image: Coastal vegetation, Majuro.

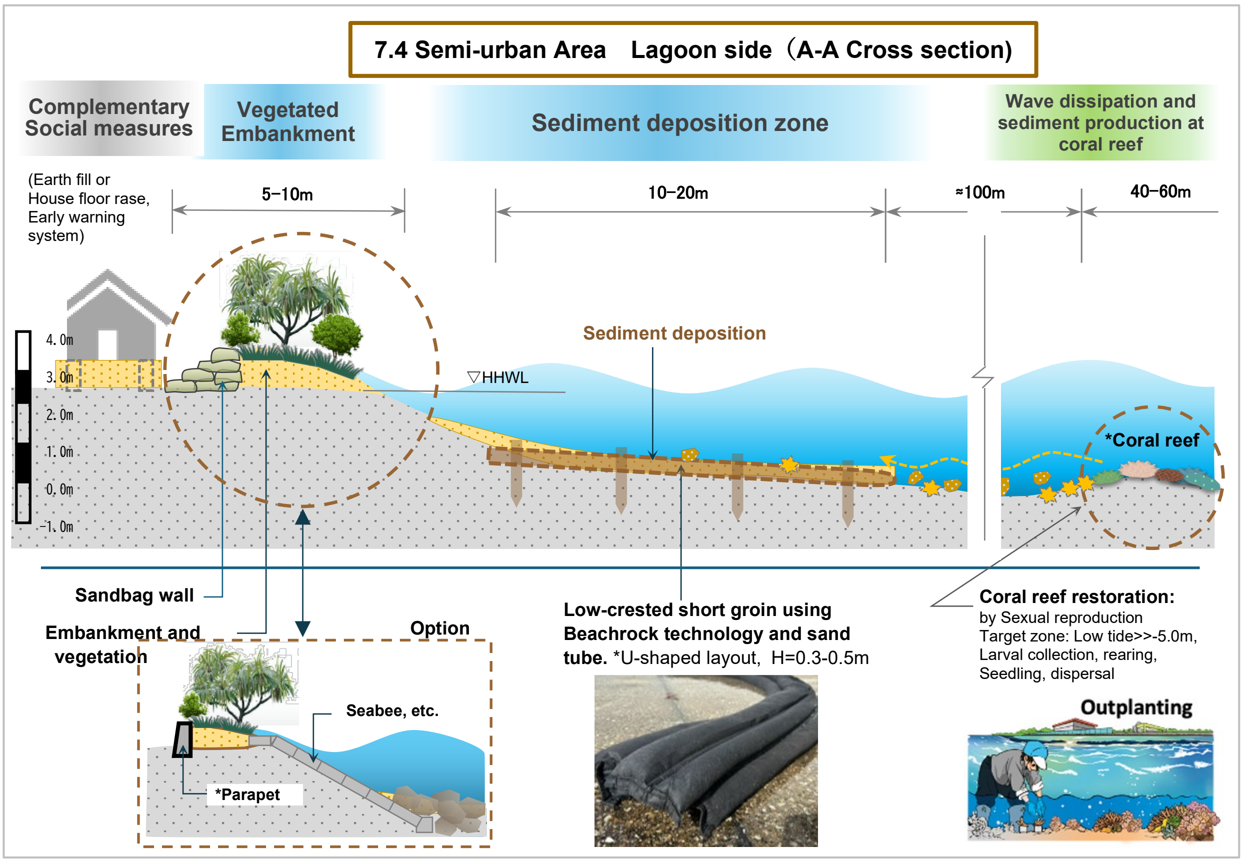


Fig. 33. Conceptual cross-section of Semi-urban Areas – Lagoon Side.

Where necessary, low embankments, coastal vegetation, and other complementary measures may be introduced while preserving the natural landscape and ecological functions of the lagoon coast.

This approach strengthens coastal resilience by working with natural coastal processes and minimizing dependence on large engineered structures.

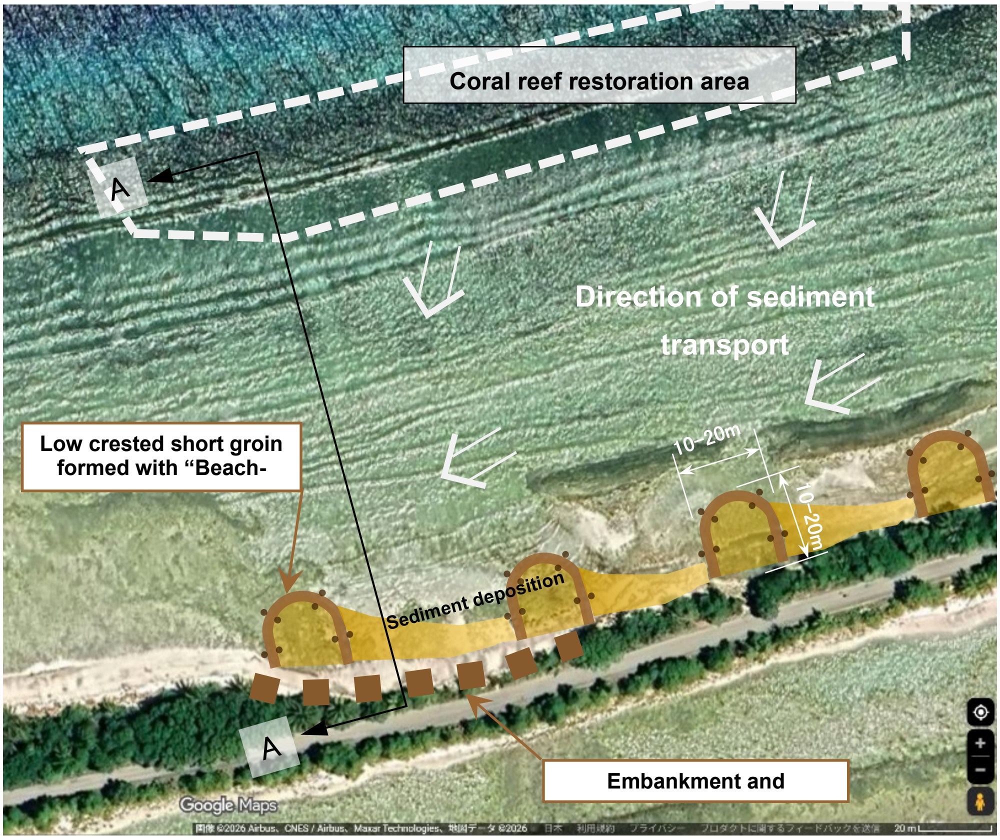


Fig. 34. Plane diagram of semi-urban lagoon coast.

7.5 Rural Areas – Ocean and Lagoon Coasts

Rural areas generally retain healthier coral reef ecosystems, wider reef flats, and more natural shorelines than urban and semi-urban areas. The primary objective in these areas is therefore to conserve and enhance the natural coastal processes that create and sustain atoll islands, while providing appropriate protection against future climate-change impacts.

Priority should be given to coral reef conservation and restoration, together with the protection of natural beaches, coastal vegetation, and sediment transport processes. Engineering interventions should be kept to the minimum necessary and applied only where local erosion or flooding threatens communities or critical infrastructure. Where appropriate, beach nourishment, sand traps, and other ecosystem-compatible measures may be introduced to reinforce natural coastal resilience. Where local conditions require higher levels of protection, the NbS measures proposed for urban or semi-urban areas may be selectively applied.

This approach maintains the ecological integrity and landscape value of rural coasts while preserving their capacity to provide long-term coastal protection and sustain the natural development of atoll islands.

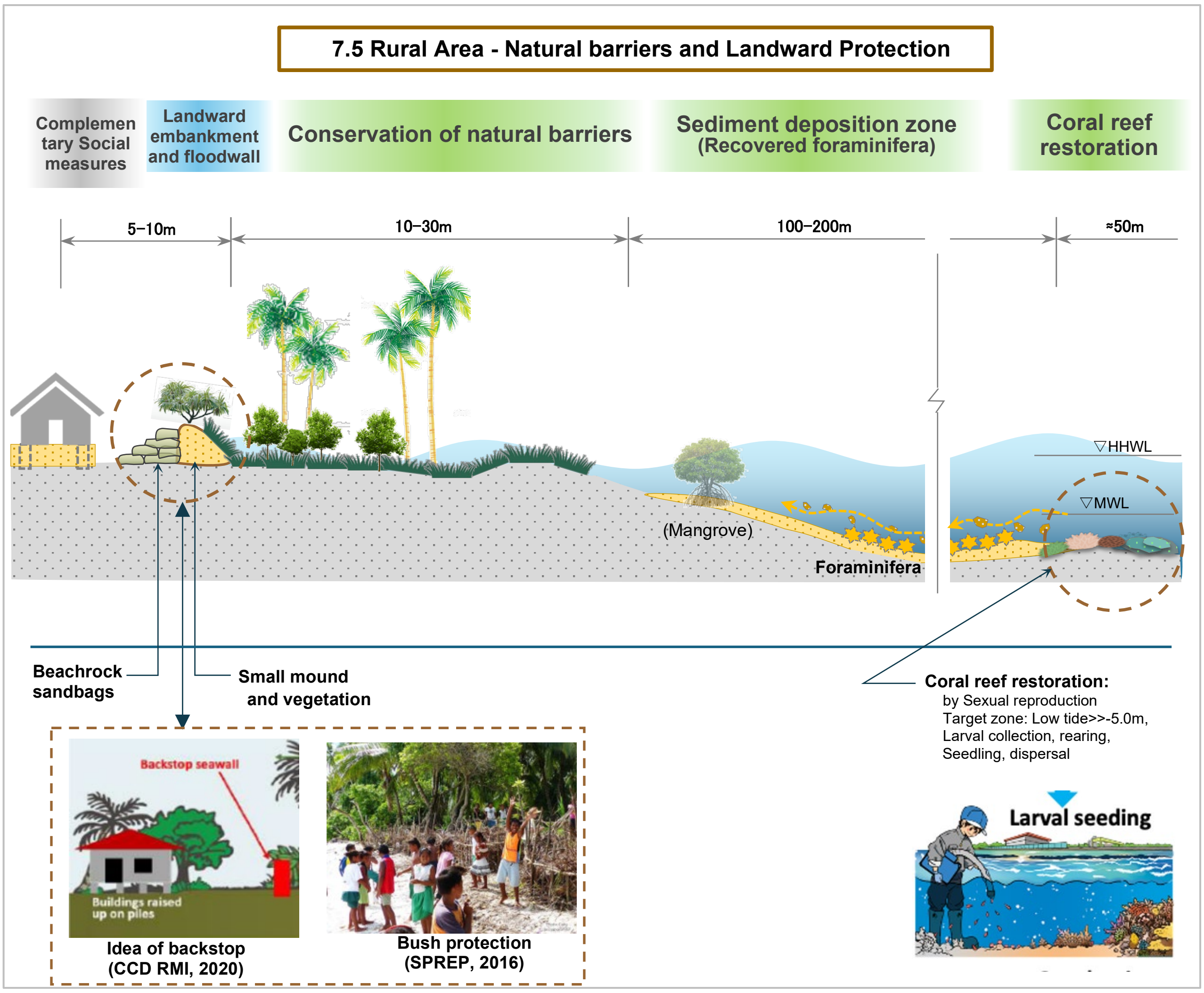


Fig. 35. Conceptual cross-section of Rural Areas – Ocean and Lagoon Sides.

7.6 Priority Areas for Early Implementation

The initial implementation sites proposed in this project are selected based on the urgency of coastal hazards and the expected effectiveness of the proposed NbS measures. Priority is given to urban coastal sections of Majuro where wave overtopping and partial inundation occur frequently, as well as to selected semi-urban areas where coastal erosion threatens the only road connecting the eastern and western parts of the atoll.

The corresponding coral reef restoration areas and Priority Coral Conservation Areas will be identified in conjunction with these coastal priority sites so that ecosystem restoration and coastal protection measures function as an integrated NbS strategy.

The locations presented in Table 5 represent the current priority candidate sites and will be refined through subsequent ecological assessments, engineering investigations, and consultations with the Government of the Republic of the Marshall Islands and local communities.

Table 5. Priority Areas for Early Implementation

Zone	Target area	Description	Approximate coast length
1)D-U-D district	High priority coast in DUD district	Non-protected, vertical seawall	**1,000m** (DUD in total: 6,500m)
2) Long island-Ajeltake (Lagoon side)	Point (a)	500m west from the end of Airport	400m
	Point (b)	East from the peace park	500m
	Point (c)	650m east from the Assembly church	400m
	Point (d)	2.2km east from CMI Arak campus	500m
		Sub Total	**1,800m**

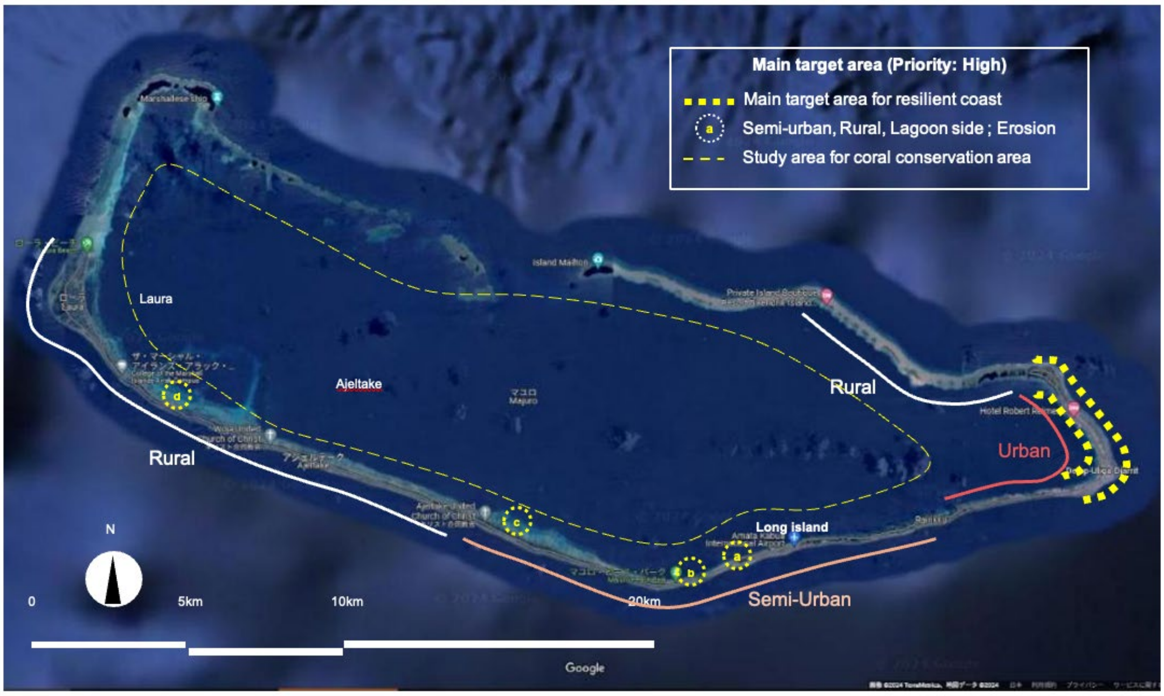


Fig. 36. Areas targeted for this project.

8. Implementation Framework

The implementation framework will be developed in collaboration with the Government of the Republic of the Marshall Islands, local communities, academic institutions, and international partner organizations.

The project is expected to integrate expertise in coastal engineering, coral reef ecology, climate adaptation, and community-based coastal management. Roles and responsibilities of participating organizations, together with the implementation schedule and governance structure, will be finalized during the project preparation phase.

The implementation framework will follow the integrated NbS concept presented in this proposal, combining ecosystem restoration, ecosystem-compatible coastal engineering, and complementary social adaptation measures.

9. Project Cost

The project budget covers the direct costs required for implementation of the proposed NbS measures, including coastal resilience interventions, coral reef restoration, and associated field surveys, monitoring, and project management.

The present cost estimate does not include the implementation costs of broader complementary adaptation measures, including wastewater and solid-waste management to improve coastal water quality, large-scale land raising, housing improvements, and other social adaptation measures identified in the National Adaptation Plan (NAP). However, these measures will be considered within the project as part of the integrated adaptation strategy, including their functions, spatial coordination, and relationships with the proposed NbS measures.

Where implementation of these complementary measures requires substantial additional investment, financing may be provided through relevant national programs, development partners, or other international financing mechanisms. Their consideration within the project will help ensure that the proposed NbS interventions form part of a coherent long-term adaptation pathway for the Republic of the Marshall Islands.

Table 6. Project cost for the urgent target locations.

Zone	Target area	Approximate coastal length (m)	Coastal protection cost (Million $)	Coral reef restoration cost (Million $)	Total (Million $)
1)D-U-D district	High priority area	**1,000**	25.0	2.5	**27.5**
2) Long island-Ajeltake (Lagoon side)	Point (a)	400	3.0	1.0	4.0
	Point (b)	500	3.8	1.3	5.0
	Point (c)	400	3.0	1.0	4.0
	Point (d)	500	3.8	1.3	5.0
	Sub Total	**1,800**	13.5	4.5	**18.0**
Grand total		**2,800**	38.5	**7.0**	**45.5**

Reference：Construction cost per meter

Total of direct construction costs, indirect construction costs, and general administrative costs; Unit: USD per meter of coastal length

Area	Ocean side	Lagoon side
Urban	25,000	12,500
Semi-Urban	10,000	7,500
Rural	5,000	5,000

10. Economic Evaluation

10.1 Purpose of Economic Evaluation

Nature-based Solutions (NbS) provide multiple benefits that extend beyond conventional coastal protection. In addition to reducing coastal flooding and erosion, they restore coral reef ecosystems, enhance fisheries and tourism, maintain the natural production of reef-derived sediments, and contribute to the long-term resilience of atoll communities. Because many of these benefits are closely linked to ecosystem functions, they cannot be adequately evaluated using conventional engineering cost–benefit analysis alone.

To support evidence-based decision-making, this project develops an economic evaluation framework that integrates ecological and socio-economic processes. The framework is designed to quantify not only the direct economic benefits of reduced disaster damage and improved infrastructure, but also the broader ecosystem services generated by healthy coral reef ecosystems. The results will provide a scientific basis for comparing alternative adaptation options, prioritizing investments, and supporting future financing through the Green Climate Fund (GCF) and other international development partners.

10.2 Integrated Economic–Ecosystem Evaluation Framework

The proposed framework integrates an economic model with an ecosystem model to evaluate the multiple benefits generated by Nature-based Solutions (NbS) (Fig. 37). Unlike conventional economic assessments that focus primarily on construction costs and direct damage reduction, this framework explicitly incorporates the interactions among human activities, coastal ecosystems, and the natural processes that create and sustain atoll islands.

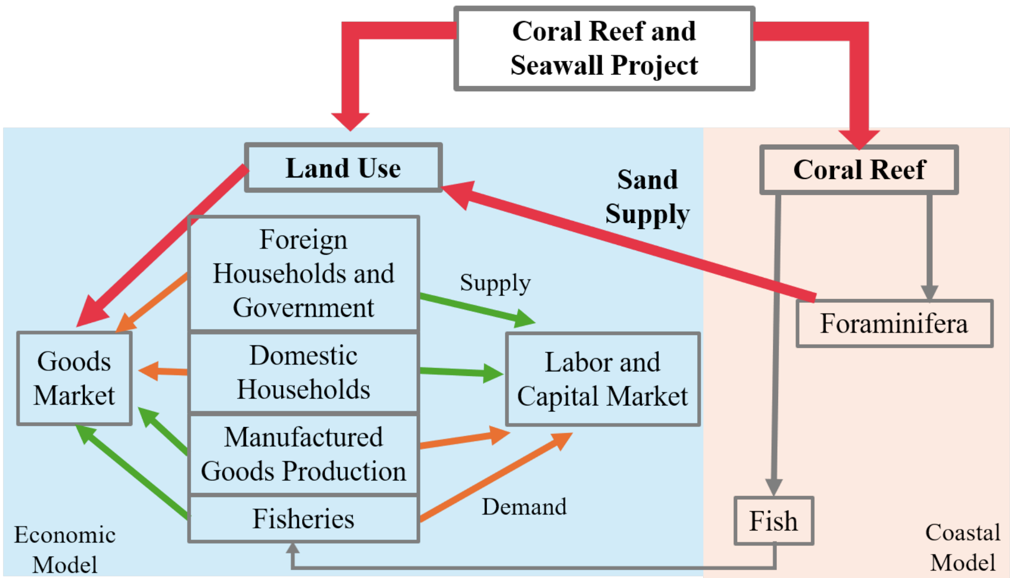


Fig. 37. Integrated Economic Model Incorporating Ecosystem Dynamics.

The economic component represents land use, household activities, fisheries, transportation, and other socio-economic processes within Majuro Atoll. The ecosystem component represents coral reef ecosystems, reef-associated fisheries, and the production of reef-derived carbonate sediments, which are fundamental to the formation and maintenance of atoll land. These two components are linked through ecological processes and ecosystem services, allowing changes in coral reef condition to be translated into both environmental and economic outcomes.

This integrated framework enables quantitative evaluation of how NbS measures—including coral reef restoration, sediment management, beach nourishment, and ecosystem-compatible coastal engineering—contribute to disaster-risk reduction, ecosystem recovery, fisheries, tourism, and the long-term sustainability of atoll communities. It also provides a consistent basis for comparing alternative adaptation strategies under future sea-level-rise scenarios and for identifying investment priorities that maximize long-term social and environmental benefits.

10.3 Land-use Analysis of Majuro Atoll

As the basis for economic evaluation, a GIS-based land-use database has been developed for Majuro Atoll using OpenStreetMap data together with information collected through field surveys (Fig. 38). The database includes residential areas, commercial facilities, schools, public infrastructure, and other major land-use categories distributed throughout the atoll. Particular attention has been given to the densely populated D-U-D district, where coastal flooding and erosion pose the greatest risks to communities and infrastructure.

The land-use database provides the spatial foundation for evaluating the socio-economic impacts of coastal hazards and Nature-based Solutions (NbS). By combining land-use information with hazard maps, transportation networks, and demographic data, the framework enables spatial assessment of potential damage, identification of priority investment areas, and comparison of alternative adaptation strategies. The database also provides the basis for estimating the spatial distribution of households, economic activities, transportation demand, and exposure of assets to coastal hazards, thereby supporting quantitative evaluation of NbS benefits. Figure 38 illustrates the spatial database developed for the central D-U-D district, which provides the basis for subsequent economic evaluation.

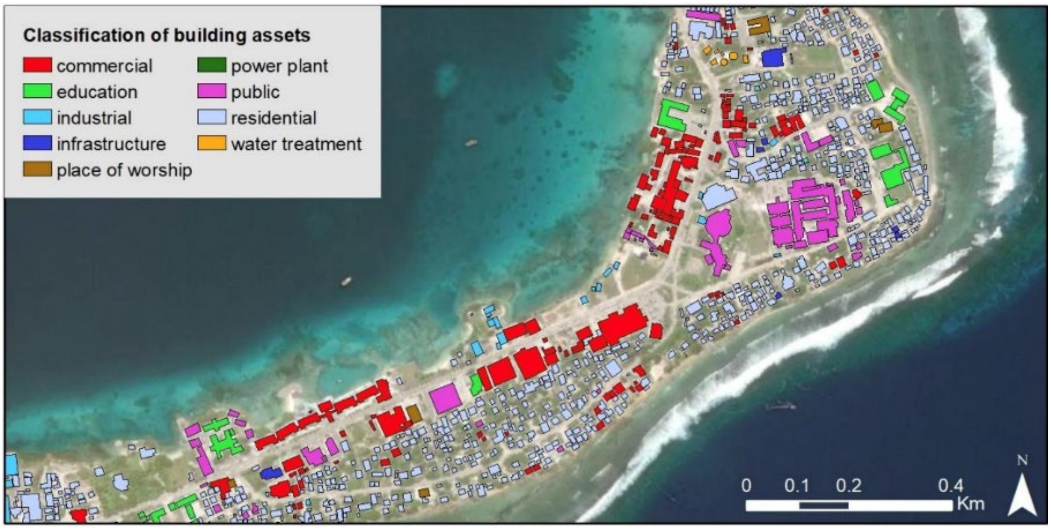


Fig. 38. GIS-based land-use map of the central D-U-D district showing residential, commercial, and public facilities used for spatial economic evaluation.

10.4 Expected Economic Evaluation

The integrated framework enables quantitative evaluation of the multiple benefits generated by Nature-based Solutions. Conventional engineering projects are generally evaluated in terms of construction costs and the reduction of direct physical damage. In contrast, the proposed framework also incorporates the ecological functions of coral reef ecosystems and the ecosystem services they provide, allowing a more comprehensive assessment of long-term adaptation benefits.

The model evaluates reductions in flood and erosion damage to residential areas, public facilities, and infrastructure, together with improvements in fisheries, tourism, and other ecosystem services associated with healthy coral reefs. It also assesses the contribution of coral reef restoration and sediment production to the long-term maintenance of atoll land under future sea-level-rise scenarios.

These analyses provide a scientific basis for comparing alternative adaptation options, identifying priority investment areas, and evaluating the long-term cost-effectiveness of NbS. The results will support future financing by the Green Climate Fund (GCF) and other international development partners while providing practical guidance for adaptation planning in the Republic of the Marshall Islands and other Pacific atoll nations. More broadly, the framework demonstrates how ecosystem restoration and coastal engineering can be evaluated within a common socio-economic framework, providing a transferable methodology for the Republic of the Marshall Islands and other Pacific atoll nations.

11. Environmental and Social Considerations

11.1 Land Tenure and Coastal Management

In the Republic of the Marshall Islands, most land is held under customary private ownership. Land ownership is generally understood to extend to the adjacent nearshore area, although the offshore extent of these rights is not clearly defined under existing legal and customary arrangements.

As a result, individual landowners have often undertaken shoreline reclamation and seawall construction to protect their own properties from coastal erosion and flooding. While these measures may provide local benefits, they can also result in fragmented shorelines and reduce the overall effectiveness of coastal protection at the community scale.

The proposed NbS strategy therefore emphasizes integrated coastal management based on cooperation among national and local governments, communities, landowners, academic institutions, and other relevant stakeholders. Coastal protection measures should be planned and implemented at the community scale while respecting existing land tenure systems and traditional governance, through an iterative co-design process that brings together scientific, local, and traditional knowledge to support the collaborative design of locally appropriate, socially accepted, and environmentally sustainable coastal adaptation measures.

The project will therefore promote stakeholder consultation and consensus building so that coastal resilience measures can be implemented in a manner that is both socially acceptable and environmentally sustainable.

11.2 Other Environmental and Social Considerations

Additional environmental and social safeguards, including biodiversity conservation, community participation, cultural values, and project governance, will be developed during project preparation in collaboration with relevant stakeholders.

The project recognizes that effective NbS implementation requires coordination beyond individual land ownership because coral reefs and coastal processes function as shared natural infrastructure at the community and national scales. Long-term success therefore depends not only on technical feasibility but also on inclusive governance, stakeholder ownership, trust-building, and continued collaboration throughout implementation and adaptive management.

12. Financing Arrangement

The proposed project is intended to be implemented as an initial Small-Scale Project under the Green Climate Fund (GCF), complemented by co-financing from relevant stakeholders, development partners, and other funding organizations.

The GCF financing is expected to support the core NbS interventions, including coral reef restoration, ecosystem-compatible coastal engineering, and associated monitoring and project management. Co-financing will be sought to complement these activities and to facilitate future scaling-up and replication in other atolls within the Republic of the Marshall Islands and, subsequently, in other Pacific atoll nations.

The proposed project is expected to serve as a demonstration model for climate adaptation in atoll nations, providing a foundation for future investment through larger GCF programs and other international climate finance mechanisms.

13. Project Schedule

An indicative implementation schedule is shown in Table 7, assuming financial support through the Green Climate Fund (GCF). The schedule illustrates the expected sequence of project preparation, Concept Note (CN) development, Project Preparation Facility (PPF) support, funding proposal preparation, approval procedures, and project implementation. The actual schedule will be adjusted in consultation with the GCF Secretariat, the National Designated Authority (NDA), the Accredited Entity, and other project partners.

Table 7. Indicative Implementation Schedule under the GCF Funding Process

	2026	2027	2028	2029	2030-
1.Project Preparation Facility (PPF)	Prepare and submit PPF proposal				
		FS, Designing, Making funding proposal(FP)			
2. Concept Note (CN)	Prepare CN				
	Submit CN				
3. NDA Approval	No-Objection Letter (NOL) for CN	NOL for FP			
4.Funding proposal (FP)		Prepare FP	Submission and review	GCF Approval	
5.Project implementation					

Appendix 1. Coral Reef Restoration

Healthy coral reefs perform two essential functions for atoll islands: they dissipate wave energy from the open ocean and continuously produce the carbonate sediments that maintain island land. In Majuro Atoll, however, coral reefs have been increasingly degraded by coral bleaching associated with rising sea temperatures and by declining water quality.

To restore these essential ecosystem functions, this project proposes large-scale coral reef restoration based primarily on sexual propagation. Compared with conventional coral transplantation, sexual propagation maintains greater genetic diversity and therefore provides a more suitable approach for developing coral populations that are resilient to future climate change, particularly increasing sea temperatures.

Unlike conventional coral transplantation, sexual propagation also enables restoration at the spatial scale required to recover reef ecosystem functions, including wave attenuation and carbonate sediment production that sustain atoll islands.

(1) Restoration Methods

Sexual coral propagation was first developed in Japan in the early 2000s and is now recognized internationally as one of the most promising approaches for large-scale coral reef restoration.

This project considers three complementary restoration methods following fertilization of coral eggs and sperm collected either in the field or under controlled land-based conditions.

1. Larval seeding, in which competent coral larvae are released directly onto the restoration site to settle naturally.
2. Deployment of larval-settled substrates, in which larvae are first settled onto artificial substrates that are subsequently distributed throughout the restoration area.
3. Outplanting of nursery-grown juvenile corals, in which juvenile colonies are reared to several centimeters in size in land-based or in-water nurseries before being transplanted to the restoration site.

To improve long-term resilience, broodstock colonies used for spawning will be selected preferentially from coral populations exhibiting relatively high thermal tolerance, based on field observations and physiological analyses.

Because the ocean side of Majuro is continuously exposed to strong wave action and restoration areas are extensive, direct transplantation by divers is generally impractical. In these areas, larval seeding or the deployment of larval-settled substrates from the reef crest or from boats is considered the most practical restoration approach.

On lagoon reefs, where wave conditions are generally calmer, restoration methods should be selected according to the size of the restoration area. For extensive sites, larval seeding or the deployment of larval-settled substrates from boats is appropriate. For relatively small restoration sites, however, diver-assisted outplanting of nursery-grown juvenile corals is expected to achieve higher establishment success.

Depending on local environmental conditions, various settlement substrates—including steel frames, mesh structures, and mineral accretion substrates—may also be installed to enhance larval settlement and juvenile coral survival.

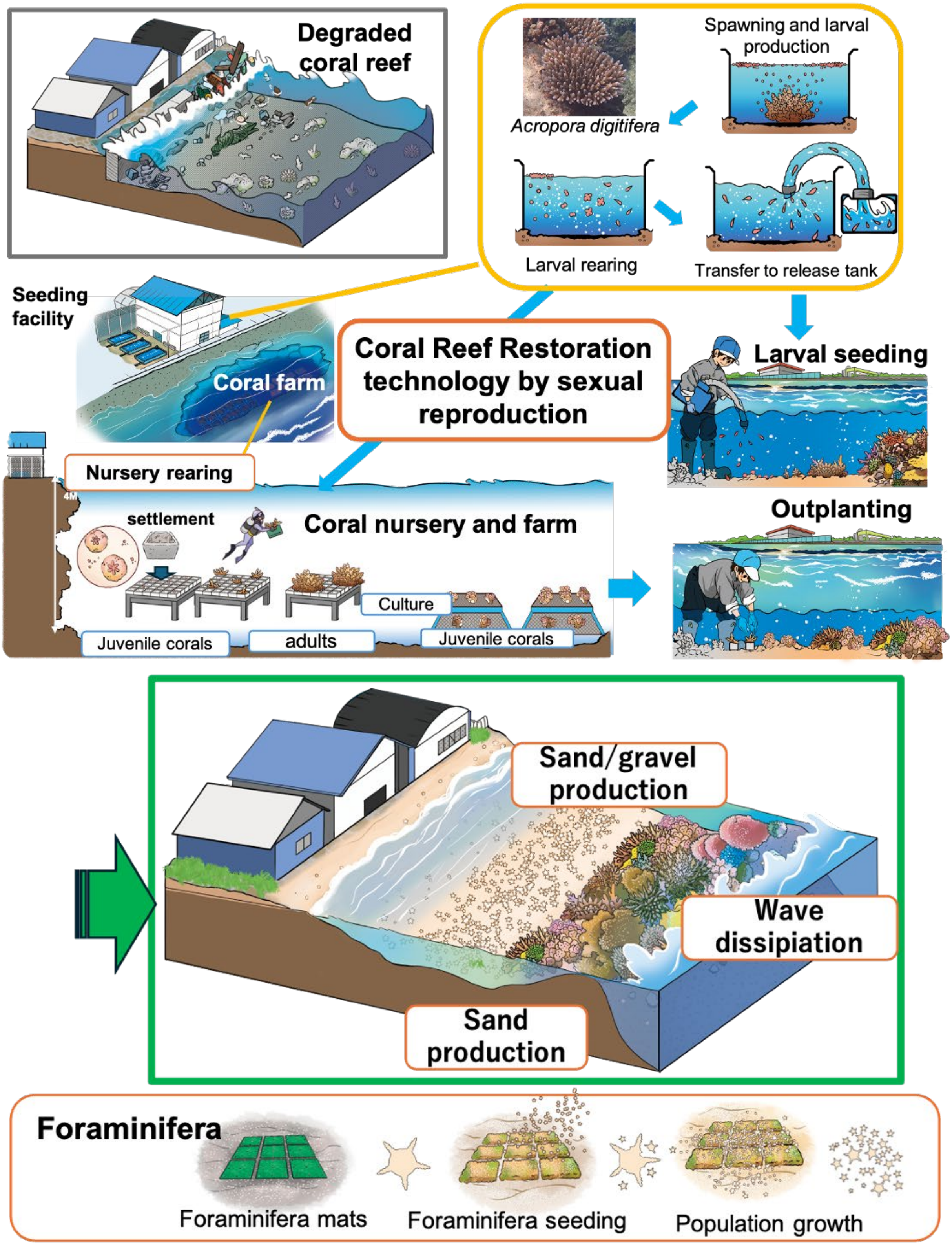


Fig. A1. Proposed Process of Coral Reef Restoration based on Sexual Reproduction for Sustainable Sand Production and Coastal Resilience

Urban coastal areas are characterized by **high population density**, **intensive coastal development**, and **limited space available for adaptation**. Along the ocean shoreline, natural coastal environments have been extensively modified through coral reef degradation, land reclamation, and the construction of vertical concrete seawalls. As a consequence, these areas are highly vulnerable to wave overtopping, coastal flooding, and shoreline erosion.

Using the ocean coast of the **D-U-D district** as a representative example, this project proposes the following integrated NbS measures.

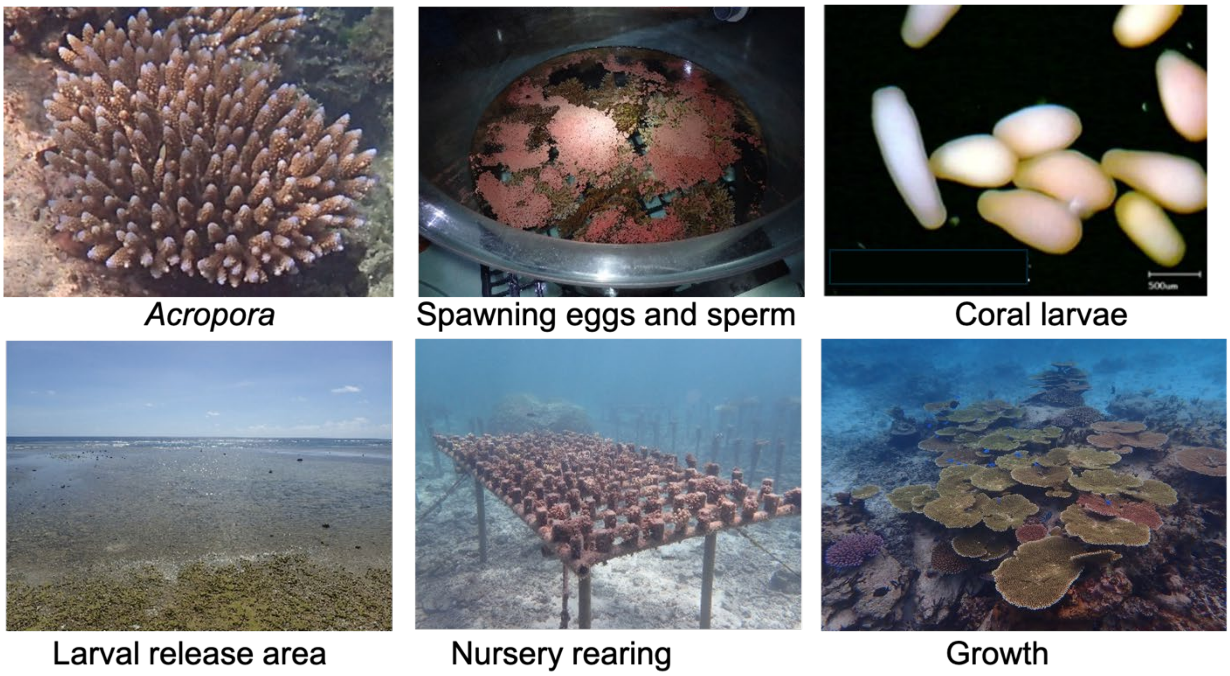


Fig. A2. Image photos of Coral Reef Restoration

Japan has developed a variety of settlement substrates for coral larvae and juvenile corals, and these technologies can be incorporated into the proposed restoration program according to local environmental conditions. Representative examples include Coral Net, galvanized mineral accretion cages (GMC), and steel settlement substrates. These substrates have demonstrated high durability and favorable coral recruitment and growth in field applications, and are expected to enhance the effectiveness and long-term sustainability of coral reef restoration.

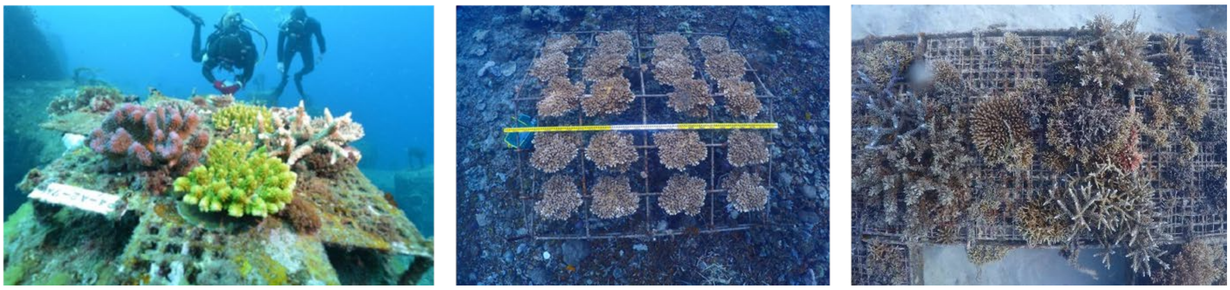


Fig. A3. Representative settlement substrates developed in Japan for coral reef restoration. Left: Coral Net (Kajima Corporation); Center: Galvanized Mineral Accretion Cage (GMC) (MMB Co., Ltd.); Right: Steel settlement substrate (Fisheries Agency of Japan).

(2) Restoration Area

On the ocean side of the atoll, restoration will focus on reef slopes extending to a depth of approximately 5 m, where reef-building corals are most abundant and contribute directly to carbonate sediment production. Corals growing at greater depths are considered to make only a limited contribution to shoreline sediment supply, while natural recruitment from restored shallow reefs is expected to facilitate recovery of deeper reef communities.

Within the lagoon, restoration will target shallow coral reefs located approximately 50–200 m offshore and running parallel to the coastline. As on the ocean side, restoration will focus on reef areas shallower than 5 m, where coral growth contributes most effectively to coastal protection and sediment production.

For deeper lagoon reefs that are not included within the active restoration area, this project proposes designation as coral conservation areas, where appropriate management measures will be implemented to enhance ecosystem resilience under future climate change.

(3) Target Coral Species

Restoration will primarily target Acropora species, which have experienced severe degradation and bleaching, particularly around the reef crest of Majuro Atoll. Additional coral species will be selected according to the ecological characteristics and environmental conditions of individual restoration sites.

(4) Expected Ecosystem Functions Restored by Coral Reef Restoration

1) Wave Attenuation

Healthy coral reefs function as natural breakwaters by inducing wave breaking at the reef crest and dissipating wave energy across the shallow reef flat. Depending on reef morphology and wave conditions, coral reefs can reduce incident wave energy by up to approximately 95% (Guannel et al., 2016).

Healthy reef crests also exhibit vertical growth rates of approximately 0.2–0.5 cm yr^{-1}, enabling them to maintain their wave-attenuation function under present rates of sea-level rise. The combined effectiveness of coral reef restoration and the proposed NbS coastal engineering measures will be evaluated separately as an integrated coastal protection system.

2) Carbonate Sediment Production

A healthy coral reef is estimated to produce approximately 50–175 m^3 ha^{-1} yr^{-1} of carbonate sediments, assuming equal contributions from coral-derived sediments and larger benthic foraminifera. This corresponds to an annual sediment supply of approximately 500–1,750 m^3 km^{-1} yr^{-1} of shoreline.

If all produced sediments were retained within a 50-m-wide cross-shore zone of the island, they would provide a potential vertical accretion of approximately 1–3.5 cm yr^{-1}, exceeding the present rate of sea-level rise (0.5 cm yr^{-1}). These estimates indicate that healthy coral reefs possess the natural capacity to sustain atoll islands through continuous sediment production, provided that effective sediment-retention measures are implemented.

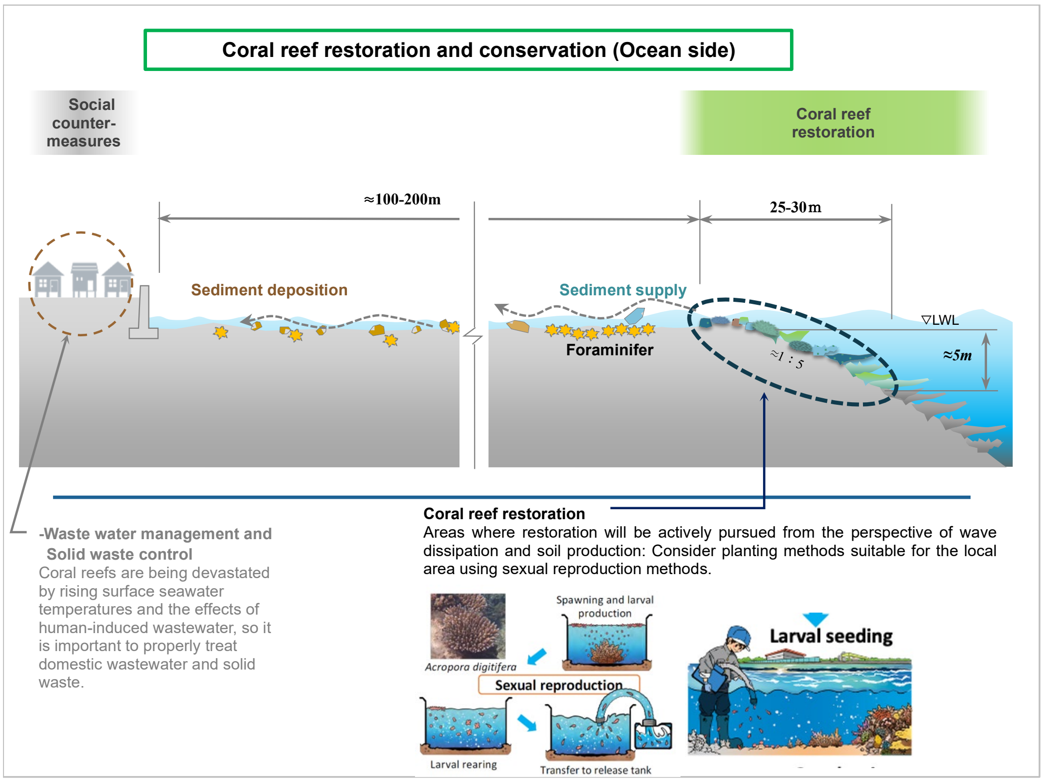


Fig. A4. Concept of coral restoration area (Ocean side)

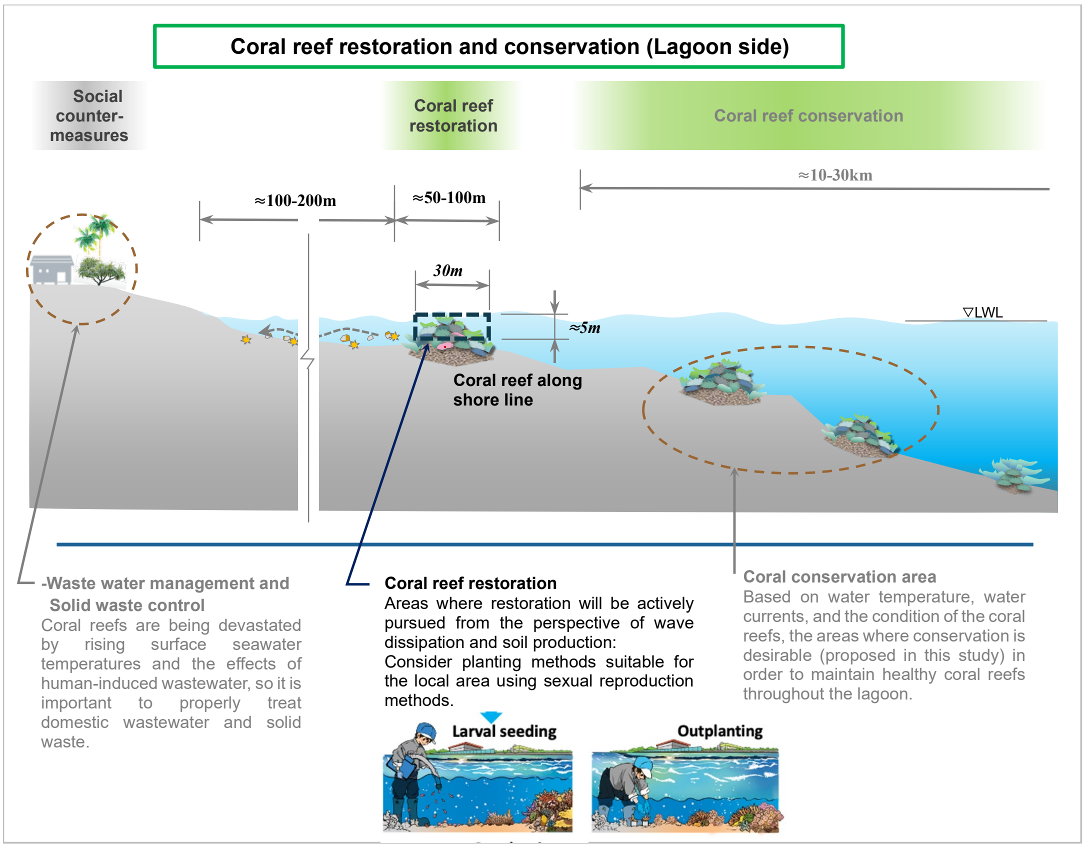


Fig. A5. Concept of coral restoration area (Lagoon side)

Appendix 2. Priority Coral Reef Conservation Areas

Healthy coral reefs provide the foundation for atoll nations and societies by providing multiple ecosystem services. Atoll islands are fully composed of reef- derived materials, including corals and foraminifera. Coral reefs form and maintain the islands by producing carbonate sediments and by dissipating wave energy. Furthermore, coral reefs are home to diverse marine organisms, providing fisheries and tourism resources. Identifying priority conservation areas and implementing conservation and restoration measures are essential to maintain the ecosystem services, as well as to supply coral larvae to other reefs.

While active coral reef restoration is essential for accelerating the recovery of degraded reefs, long-term resilience also depends on conserving healthy coral communities that continue to function as larval source reefs. Recent studies have demonstrated that healthy coral communities act as important larval sources, supporting the recovery and persistence of surrounding reefs. Future climate change is also expected to alter patterns of larval dispersal and recruitment, increasing the importance of protecting coral populations that are likely to remain resilient under rising sea temperatures. Conserving these source reefs will help maintain genetic diversity, ecological connectivity, and the adaptive capacity of the reef ecosystem as a whole. Accordingly, this project proposes the strategic designation of Priority Coral-Reef Conservation Areas as a complementary component of its integrated NbS strategy.

Priority Coral-Reef Conservation Areas will be identified for the reef flats and the lagoon by integrating ecological, environmental, and societal information, including current coral distribution, carbonate sediment production, wave dissipation function, projected climate impacts, and the social values. High-resolution spatially-explicit sea-surface temperature data and future climate projections will be used to identify potential climate refugia, where bleaching risk is relatively low and coral survival is expected to remain high under future climate conditions. Social values will be examined based on the resource use, including fisheries and tourism, and conservation activities. A successful example that identified the priority coral-reef conservation areas, based on the current coral distribution, future climate projections, and the resource use and the conservation activities by local communities, is presented in Fig. A6 (Abe et al., 2021).

Candidate conservation areas should be investigated further according to their ecological functions. Coral cover, community composition, reproductive capacity, and recovery following previous bleaching events will be assessed to identify reefs that function as effective larval sources. Particular attention will be given not only to shallow reefs but also to deeper coral communities that may serve as thermal refugia and continue to supply larvae following bleaching events.

Because coral reefs function as interconnected ecosystems rather than isolated habitats, conservation areas should be established as an ecological network. Hydrodynamic modelling, larval dispersal simulations, and population genetic analyses will therefore be used to quantify connectivity among reefs, distinguish self-recruiting reefs from larval-source reefs, and identify priority locations for long-term conservation.

Implementation of this approach in the Republic of the Marshall Islands should be in line with the community-based Reimaanlok framework for marine resource management. Scientific information on larval-source reefs, ecological connectivity, and climate refugia will be provided as decision-support information during community-led planning processes. By combining scientific evidence with local values and traditional ecological knowledge, conservation areas can be designed to strengthen climate resilience while maintaining local ownership of management decisions. Continuous monitoring and periodic revision of conservation plans, consistent with the adaptive management framework of Reimaanlok, will further improve the long-term effectiveness of coral reef conservation.

Together with active coral restoration, the designation of Priority Coral-Reef Conservation Areas forms the ecological foundation of the proposed NbS strategy. While restoration accelerates the recovery of degraded reefs, strategically protected source reefs maintain larval supply, genetic diversity, and ecosystem resilience over the long term. Combined with ecosystem-compatible coastal engineering, these NbS measures strengthen the natural infrastructure that builds, maintains, and protects atoll nations under future climate change.

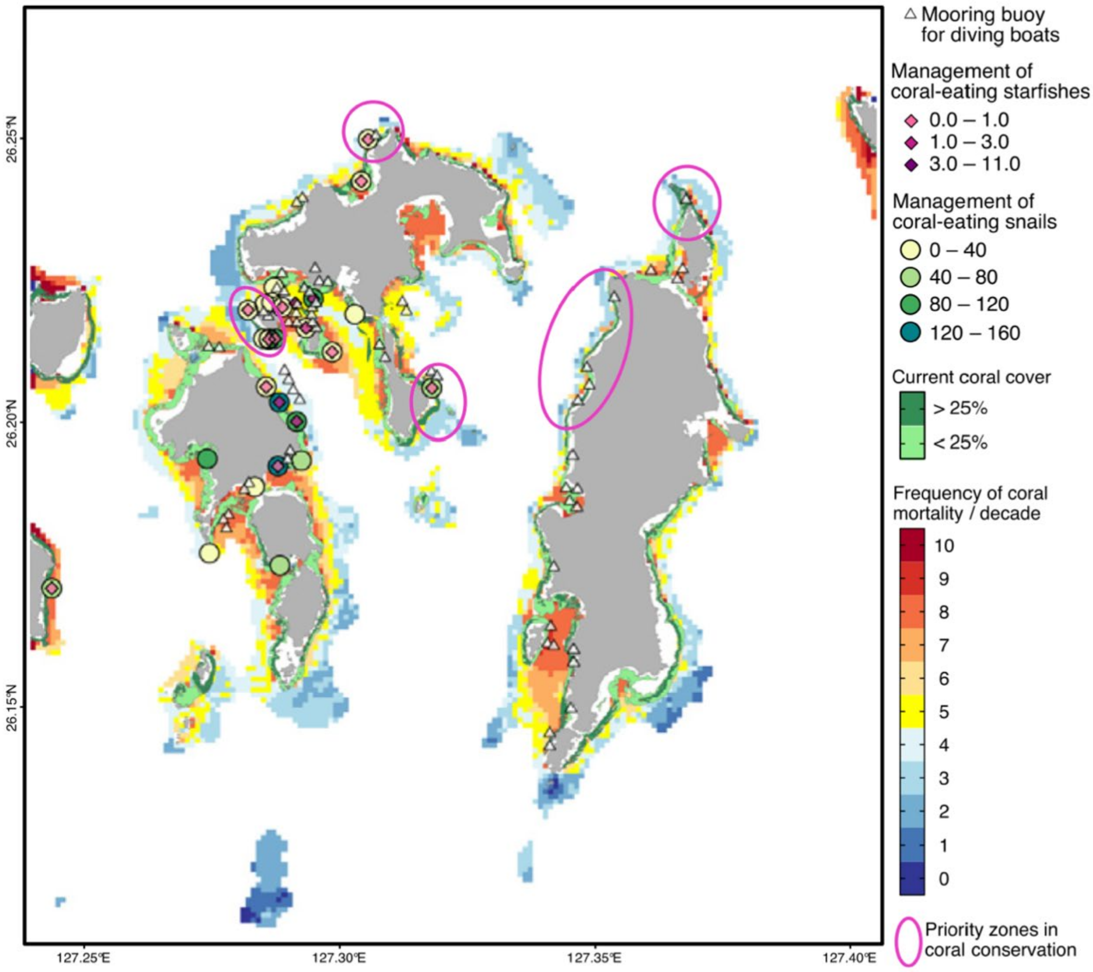


Fig. A6. Example of selecting priority coral-reef conservation area for Kerama Islands, Japan

Appendix 3. Economic Evaluation

The economic evaluation of this project consists of the following three tasks:

1. Developing an integrated framework that combines an economic model with an ecosystem model;
2. Organizing land-use data; and
3. Reviewing the literature on available ecosystem models.

Each of these tasks is described below.

(1) Development of an Integrated Economic–Ecosystem Modeling Framework

To evaluate Nature-based Solutions (NbS) spatial planning, this study develops an integrated framework that combines an economic model incorporating land use on Majuro Atoll with an ecosystem model representing the coastal environment.

The land-use model is constructed using existing land-use data collected for Majuro. Urban travel, including commuting, school trips, and shopping trips, is modeled based on a set of simplifying assumptions within an urban economic framework. Building upon the urban economy–ecosystem model developed by Yoshida and Kono (2020, 2022; Table 2), the ecosystem component is extended to explicitly represent coastal ecosystems. In addition, the model incorporates the supply of sediment derived from coral reef foraminifera, which contributes to both land maintenance and ecosystem dynamics.

Figure A7 illustrates the overall structure of the proposed integrated model, including the inputs and outputs of both the economic and ecological components.

A distinctive feature of the economic model is that it explicitly represents the MIRAB economy by incorporating overseas households and the government sector, while also modeling the fisheries sector separately. The land-use model extends to a conventional urban economic model based on the framework proposed by Yoshida and Kono (2020, 2022).

The ecosystem model explicitly represents coral reefs, foraminifera inhabiting coral reefs, and fish populations as marine resources influenced by coral reef ecosystems. If necessary, trophic interactions among fish species will also be modeled in greater detail.

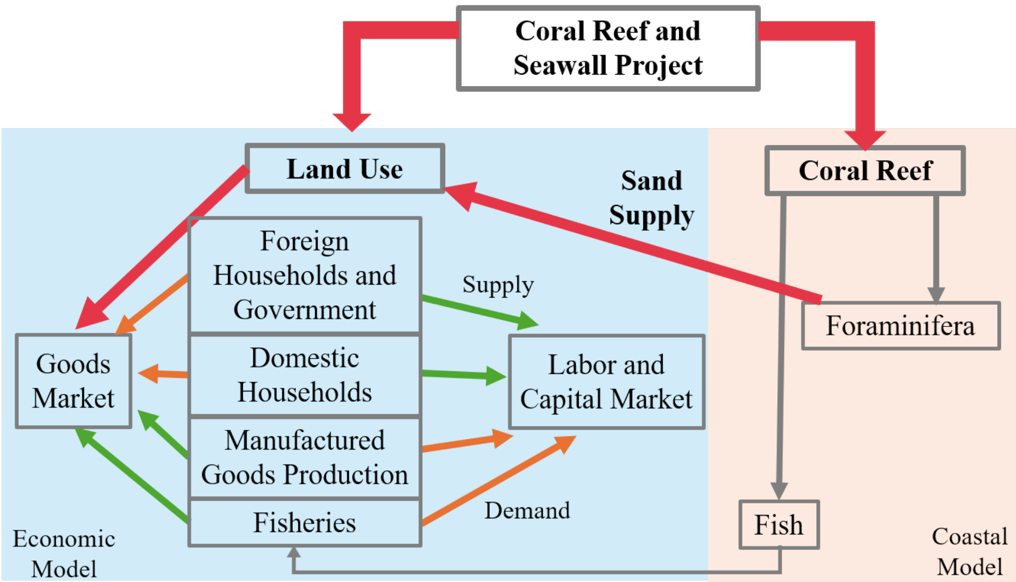


Fig. A7. Integrated Economic Model Incorporating Ecosystem Dynamics

Furthermore, following Yoshida and Kono (2020, 2022), the ecosystem model incorporates, to the greatest extent possible, the ecological process whereby plants and animals relocate to locations that provide more favorable environmental conditions.

The linkage between the economic and ecosystem models is established through two primary mechanisms: (1) interactions between fisheries and fish populations, and (2) land formation through sediment supplied from coral reef-derived foraminifera.

The integrated economic–ecosystem model enables welfare evaluation while accounting for a wide range of ecosystem services. Because the framework explicitly considers resource constraints, it also allows the welfare impacts of different financing schemes for NbS projects to be evaluated.

Residents are assumed to travel by private automobile from every location to the central area of Majuro (around the K&K Supermarket) for shopping and other daily activities. Their utility is derived from housing, travel, composite goods, fishery products (offshore and coastal fishery products), and education. The spatial distribution of households (population density) is treated as exogenous. The costs of coral reef restoration and beach nourishment are financed through a lump-sum tax.

To capture the impacts of storm surges, the probability of storm-surge occurrence is specified for each location. Residents are assumed to experience an income reduction equivalent to the expected monetary damage caused by storm surges (see Kono et al., 2016). When affected facilities include schools or other public infrastructure, direct benefit measurement is difficult; therefore, welfare losses are estimated using proxy values (e.g., three times the daily educational expenditure).

Storm surges may also disrupt road networks, reducing the frequency of trips to the central district and thereby lowering residents' utility. Airport users, including tourists, are likewise assumed to suffer mobility constraints. Land that is inundated once every two years (i.e., an annual probability of 50%) is assumed to lose its usable area entirely. For areas subject to lower inundation probabilities, welfare losses are evaluated using expected damage values.

Sea-level rise further reduces the width of the urban area. Permanent inundation results in household relocation, and the associated welfare loss is represented through changes in population density within each spatial segment (100–200 m intervals). Where schools or other public facilities are affected, reductions in land area are also taken into account.

Because detailed economic data for Majuro are limited and land allocation is not governed by a market mechanism, model parameters are calibrated using reasonable assumptions and sensitivity analyses to ensure robust policy evaluation.

Majuro Atoll consists of a long and narrow strip of land extending approximately 50 km in length. Firms are generally small and spatially dispersed. A single arterial road runs through the atoll, and there are no traffic signals. Transportation relies almost exclusively on private automobiles, resulting in substantial traffic congestion.

Accordingly, the utility functions of residents—composite-goods workers $(j = a)$and fishers $(j = f)$—are specified in quasi-linear form as

$$u^j(x) = z^j + \alpha_1 \ln y_1^j + \alpha_2 \ln y_2^j + \beta \ln \bar{q}\,(x) + \gamma n\left(1 - \int_0^x \phi\,(m)\,dm\right) + \lambda\Theta \qquad (1)$$

The budget constraint of a composite-goods worker is

$$I + G - K - \phi(x^a)D = z^a + p_1 y_1 + p_2 y_2 + r(x^a)\bar{q}(x^a) + p_D n\left(1 - \int_0^x \phi\,(m)\,dm\right) + \Theta \qquad (2)$$

Similarly, the budget constraint of a fisher is

$$p_1Y_1 + p_2Y_2 + G - K - \phi(x^F)D = z^F + r(x^F)\bar{q}(x^F) + p_D n\left(1 - \int_0^x \phi(m)\,dm\right) + \Theta \qquad (3)$$

where

Symbol	Definition
$u^j(x)$	Utility of resident j
z^j	Consumption of the composite good
$y1^j$	Consumption of offshore fishery products
$y2^j$	Consumption of coastal fishery products
$\bar{q}(x)$	Housing area
n	Number of trips to the central district
Θ	Expenditure on education
I	Income from composite-goods production
G	Overseas transfer income
K	Project cost
$\phi(x)D$	Expected storm-surge damage
p_D	Travel cost to the central district
p_1, p_2	Prices of offshore and coastal fishery products
Y_1, Y_2	Fishery products supplied to the market
$r(x)$	Land rent
$\alpha_1, \alpha_2, \beta, \gamma, \lambda$	Model parameters
h_T	Number of trips made by tourists
p_T	Travel cost for tourists
c	Round-trip airfare between the airport and the hotel

The benefits of education (and, where appropriate, other public services) are incorporated into household welfare through the utility function. Although residential land rents are not determined through a market mechanism, this assumption does not affect welfare evaluation because landowners and land users are aggregated in the model.

The utility function and budget constraint of tourists are specified as

$$u^T(x^T) = z + \alpha_1^T \ln y_1^T + \alpha_2^T \ln y_2^T + \kappa\left(1 - \int_{\text{Airport}}^{\text{Hotel}} \phi(m)\,dm\right) + \kappa_T h_T\left(1 - \int_{\text{Hotel}}^{\text{Tourist Spot}} \phi(m)\,dm\right) \qquad (4)$$

$$I^T = z + p_1 y_1^T + p_2 y_2^T + p_T h_T + c. \qquad (5)$$

where h_T denotes the number of trips made by tourists, p_T is the travel cost, and c is the round-trip airfare between the airport and the hotel.

(2) Organization of Land-use Data

Land-use data for Majuro Atoll have been organized using OpenStreetMap data, which are available for research purposes, together with information collected through field surveys. GIS-compatible datasets have been prepared for all building parcels on the island, including their mapped land-use categories (e.g., commercial facilities, schools, and other public facilities).

Figures A8 and A9 present the land-use map for the entire island of Majuro and an enlarged view of the central district, respectively. Although detailed population density data are currently unavailable, it is expected that population density can be estimated reasonably from parcel information. Likewise, travel demand between locations can be estimated based on the spatial distribution of schools and commercial facilities.

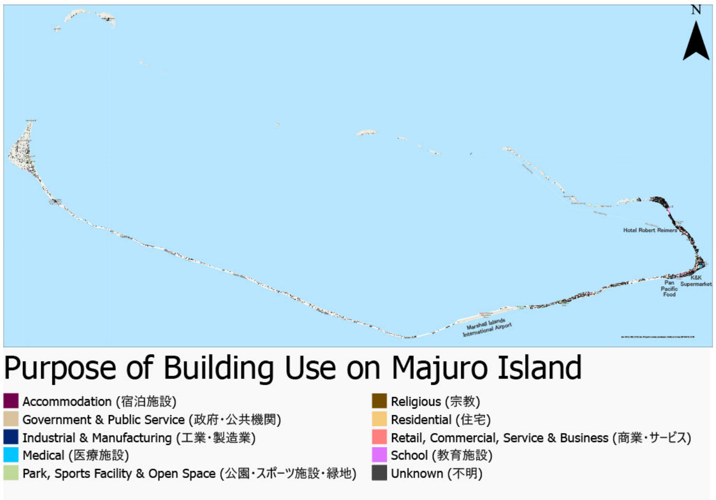


Fig. A8. Land-use Map of Majuro Atoll

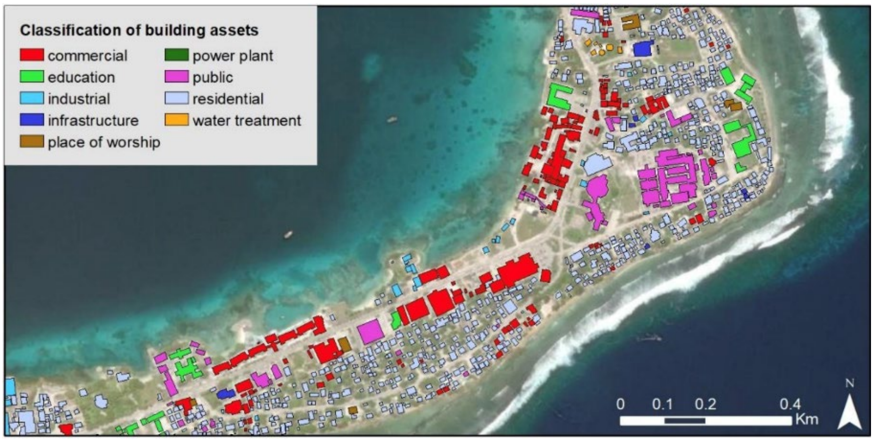


Fig. A9. Land-use Map of Central Majuro

(3) Review of Available Ecosystem Models

A comprehensive review of existing ecosystem models has been conducted, with particular emphasis on coral reef ecosystem models. The findings from this review will provide the ecological basis for developing the integrated economic–ecosystem model proposed in this study.

The following literature on coral reef ecosystem models has been collected. We use this literature to set parameters of the coral reef ecosystem model.

McClanahan, T. R. (1995). A coral reef ecosystem-fisheries model: impacts of fishing intensity and catch selection on reef structure and processes. *Ecological Modelling*, *80*(1), 1-19.

McClanahan, T. R., & Muthiga, N. A. (1989). Patterns of preedation on a sea urchin, Echinometra mathaei (de Blainville), on Kenyan coral reefs. *Journal of Experimental Marine Biology and Ecology*, *126*(1), 77-94.

Robertson, D. R. (1987). Responses of two coral reef toadfishes (Batrachoididae) to the demise of their primary prey, the sea urchin Diadema antillarum. *Copeia*, 637-642.