Imperial College London
Department of Earth Science and Engineering
MSc in Environmental Data Science and Machine Learning

Independent Research Project
Project Plan

Multi-factor Driven Modeling of Island Morphodynamics and Infrastructure Resilience in the Maldives under Future Scenarios

by

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ABSTRACT

Approximately 80% of the islands in the Maldives are situated within one meter of mean sea level, making them particularly vulnerable to climate-related extreme events. This study proposes a predictive framework that integrates multi-source remote sensing data with machine learning to model the morphodynamic evolution of two representative islands, Malé and Hulhumalé. This study assesses the long-term, cyclical, and extreme event-driven morphological changes induced by the combined effects of environmental and physical drivers. Additionally, this study assesses the exposure risk of critical island infrastructure under predicted sea-level rise, seasonal monsoonal patterns, and other environmental drivers through the years 2035 and 2050. The assessment is supported by the integration of multi-source datasets, including satellite imagery and open-access geospatial mapping. The study also assesses the resilience of built infrastructure based on the presence and effectiveness of surrounding protective buffers.

PROBLEM DESCRIPTION

The Republic of Maldives holds the lowest average elevation among all reef nations. Thus, it keeps facing the high risks of land loss from climate-induced sea-level rise (Sakamoto et al., 2022).

Previous modeling studies have suggested that rising sea levels and increased wave activity could lead to more frequent and severe marine inundation. If reef accretion lags, soil and freshwater salinization could threaten water and food security and ultimately habitability (Beetham et al., 2017; Gingerich et al., 2017; Shope et al., 2016; Storlazzi et al., 2015; Vitousek et al., 2017; Werner et al., 2017).

Therefore, accurate shoreline and island shape predictions are critical for Infrastructure planning. Based on historical morphological data, island morphodynamics are influenced by three primary elements: (a) ocean-climate drivers such as monsoonal patterns, climate variability (tropical cyclones, distant swells, ENSO phases), and sea-level rise; (b) ecological factors including coral reef health and coastal vegetation; and (c) anthropogenic activities altering island structure and dynamics (Duvat, 2019).

However, current limitations in the existing literature include an overreliance on scenario-based modeling and the use of basic, unoptimized machine learning approaches. Therefore, for the Maldives, there is a notable absence of comprehensive, data-driven, multi-factor modeling frameworks. Additionally, there is a lack of dynamic risk assessments and infrastructure resilience quantification specific to this region.

This study addresses these gaps by developing a machine learning framework for predicting the long-term morphodynamics of Malé and Hulhumalé using multi-source data. Based on SSP2-4.5 and SSP5-8.5 scenarios from the Intergovernmental Panel on Climate Change (IPCC), this study aims to simulate conditions until 2035 and 2050 for both island morphology and infrastructure resilience.

METHODOLOGY

The project will complete the following steps:

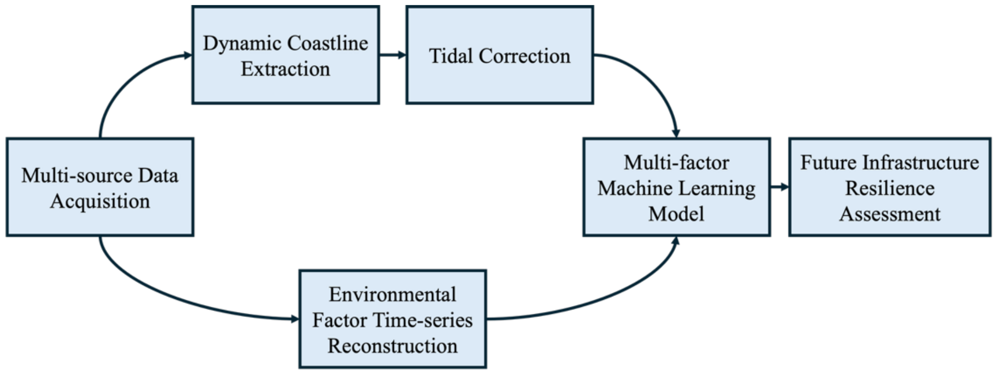

Figure 1. Research steps

1. **Multi-source Data Acquisition**

This study utilizes various datasets including:

- Sentinel-2 L2A (10m/5 days)
- NASADEM (30m/static)
- ECMWF ERA5 (0.25°/hour)
- CMEMS Wave (4km/6 hours)
- OSM (vector)

2. **Dynamic Coastline Extraction**

The shoreline extraction will be performed using CoastSat. CoastSat is an open-source Python package that leverages GEE (Google Earth Engine) to retrieve and process time-series shoreline positions from publicly available Landsat and Sentinel-2 satellite imagery. CoastSat could achieve a spatial accuracy of approximately 10 meters (Vos et al., 2019).

3. **Tidal Correction**

Satellites are only able to catch the instantaneous imagery, but shoreline positions are continuously influenced by tidal fluctuations. Therefore, the extracted coastlines need to be corrected to represent the same tidal level. For infrastructure, even a short-term submergence by seawater within the tidal cycle should be considered “dangerous”. Therefore, this study chooses the Mean Higher High Water (MHHW) level, which is the highest observed regular tide level under non-storm conditions, as the correction reference.

4. **Environmental Factor Time-series Reconstruction**

For modeling, the shorelines will be segmented at 5-meter intervals into discrete transects. For these transects, a time-series dataset will be constructed to contain their corresponding environmental and physical features. The features required for model construction will include at least the following components:

- **Monsoon dynamics:** The Maldives experiences two monsoonal seasons: Hulhangu (Southwest Monsoon) and Iruvai (Northeast Monsoon), which are characterized by seasonal reversals in prevailing wind directions (Kench & Brander, 2006).
- **Sea-level rise:** Accelerated sea-level rise alters wave energy dissipation over reef flats, impacting sediment transport processes and shoreline stability (Bramante et al., 2020).
- **Reef health indicators:** Remote sensing-derived proxies such as live coral cover and reef flat width can represent reef condition and wave buffering capacity.
- **Ocean dynamics:** Metrics such as wave power and wind speed are critical. Seasonal gradients in wave energy shift driving shoreline changes (Kench et al., 2009).
- **Island morphodynamics:** Biological sediment production and hydrodynamic forces could facilitate ongoing morphological adjustment through sediment transport along reef shorelines (Kench et al., 2017; Kench et al., 2009).
- **Extreme events:** Events such as tropical cyclones and storm surges can trigger rapid erosion and deposition, leading to abrupt morphological changes (Kench & Brander, 2006).
- **Anthropogenic disturbances:** Land reclamation and coastal structures often disrupt natural sediment flows, reshaping shoreline patterns over time (Webb & Kench, 2010).

5. **Multi-factor Machine Learning Model**

Preliminary investigations indicate that there is currently no dedicated machine learning model tailored specifically for predicting future island area changes in the Maldives. To address this gap, the present study proposes a comprehensive predictive framework that incorporates multiple forcing factors within a unified machine learning architecture.

The modeling strategy will begin with basic models such as XGBoost, Long Short-Term Memory (LSTM) and Convolutional Neural Networks (CNNs), and then choose the best-performing model as the baseline algorithm. In the next step, the study will reasonably adjust and improve the model structure. To capture periodic influences introduced by monsoonal and tide cycles, the model will incorporate seasonal decomposition components (e.g., Prophet) to achieve robust performance enhancement. In addition, the performance of other time-series models will be benchmarked for comparison.

Evaluation metrics will include Pearson correlation coefficient (R^2), root mean square error (RMSE), model bias, and mean absolute error (MAE).

6. **Future Infrastructure Resilience Assessment**

This study will combine infrastructure position from OpenStreetMap (OSM) with features, which will be manually extracted from remote sensing imagery, to establish a vulnerability index assessment framework. Exposure risk will be divided into three different areas:

- **Direct Inundation Zone**: Areas that are visibly submerged under Mean Higher High Water (MHHW) conditions.
- **20-meter Erosion Buffer Zone**: Coastal areas close to the shoreline that are not currently inundated but at risk of potential erosion due to wave activity.
- **50-meter Storm Surge Impact Zone**: Inland areas that remain susceptible to flooding and hydrodynamic impact during extreme weather events such as cyclones or storm surges.

This study also incorporates a protective buffer analysis within a 100-meter radius surrounding each infrastructure. This includes identifying three categories of natural and artificial barriers identified using remote sensing data:

- **Vegetative Barriers**, characterized by high NDVI values;
- **Topographic Barriers**, such as elevated landforms;
- **Engineered Barriers**, such as seawalls constructed to protect against coastal hazards.

The study will develop protection strategy plans that focus on each risk and resilience scenario. The design of these protection measures will support urban planning authorities in prioritizing and implementing relevant coastal actions to prevent further economic damage.

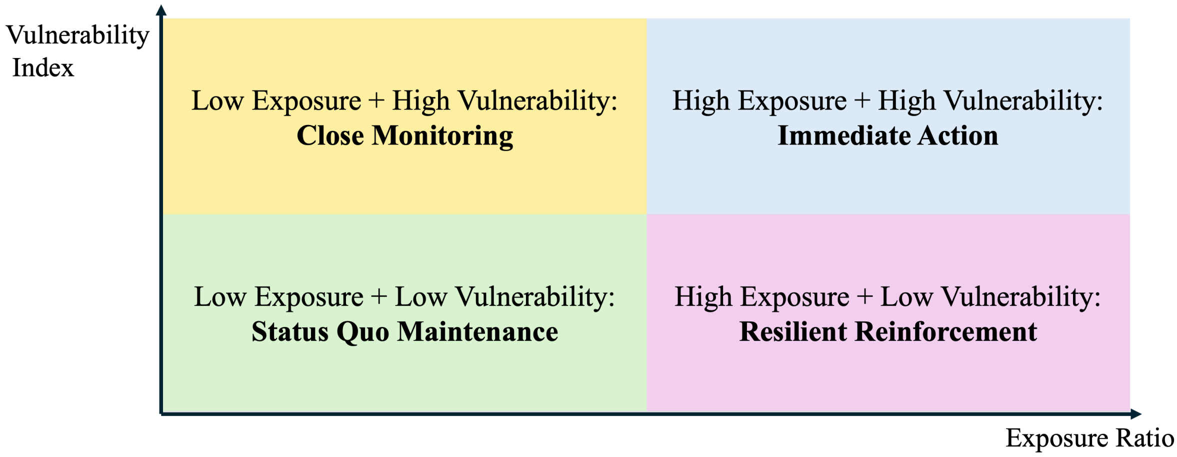

Figure 2. Risk Response Strategy Matrix

DELIVERABLES

The core deliverables of this study include:

1. **Maldives Island Morphology Change Database**: This study will establish a high spatiotemporal resolution database documenting shoreline changes on the islands of Malé and Hulhumalé in the Maldives.
2. **Multi-Factor Dynamic Machine Learning Model**: This study will propose an integrated machine learning framework that incorporates multiple dynamic environmental drivers, which could predict morphological evolution of Malé and Hulhumalé over the next 10 and 25 years.
3. **Infrastructure Exposure Risk and Resilience Mapping**: This component delivers spatial assessments of infrastructure exposure risk across future scenarios, combined with resilience mapping.

FUTURE PLAN

Phase	Timeframe	Core Tasks	Milestone
Project Planning	May 28 – June 13	‣ Conduct an in-depth review of relevant literature on island morphology and environmental modeling ‣ Identify suitable datasets, tools, and methodologies ‣ Define step-by-step workflow logic	Completion of IRP project plan
Data Preparation	June 14 – June 30	‣ Extract MHHW-corrected shorelines for Malé and Hulhumalé	Spatial-temporal shoreline dataset

		‣ Segment shorelines into 5-meter transects ‣ Collect and process features from different data resources ‣ Construct the spatiotemporal feature dataset	(MHHW corrected) for Malé and Hulhumalé
Model Development	July 1 – July 15	‣ Construct and optimize models for shoreline prediction ‣ Conduct experiments against alternative models	Experimental results and model comparison completed
Scenario Simulation	July 16 – July 29	‣ Simulate shoreline and infrastructure exposure under different scenarios for the years 2035 and 2050 ‣ Extract infrastructure layers from OSM	Future scenario-based island prediction results completed
Risk Assessment	July 30 – August 17	‣ Extract remote sensing-based barrier data ‣ Manually annotate barrier zones ‣ Compute exposure and resilience scores for all infrastructures	Completed resilience assessments for all infrastructures
Results Integration	August 18 – August 29	‣ Finalize the technical report ‣ Organize reproducible code and document deliverables	Final report and code repository submitted

Table 1. Project Timeline and Milestones

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AI Acknowledgement Statement

This report made use of DeepSeek, a generative AI tool developed by DeepSeek AI (*https://deepseek.com*). The tool was used exclusively for code debugging support and providing planning suggestions during the preparation process. All the submitted work is my own, despite the assistance received from generative AI tools.