MODELLING OF SHORELINE CHANGES OF CORAL REEF ISLANDS USING SATELLITE OBSERVATIONS AND CLOUD COMPUTING

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ABSTRACT: Coral reef islands are highly vulnerable to impacts of climate change and sea level rise. Information on long-term shoreline changes in coral reef islands is critical for effective coastal management and response to climate change and sea-level rise. However, such information is either unavailable or difficult to obtain, in particular for atoll islands. There has been a growing awareness that remote sensing has the potential to provide more detailed information for shoreline change modelling and assessment. This study presented ways to model the shoreline changes of coral reef islands in the Maldivian Archipelago using satellite observation and cloud computing. Eight coral reef islands from different atolls in the Maldives were selected for this study. Results show that the coral islands have undergone significant shoreline changes. The long-term changes were attributed to erosion and land reclamation. The seasonal shifts were caused by monsoon changes. The outcomes from this study contribute to knowledge for low-lying coral reef islands management in response of climate change and sea level rise.

1. INTRODUCTION

Low lying coral reef islands are highly vulnerable to impacts of climate change and sea level rise (Jaleel, 2013; Ford and Kench, 2015; Kench *et al.*, 2018; Brown *et al.*, 2023; Mortreux *et al.*, 2023). Information on long-term shoreline changes in coral reef islands is a prerequisite for effective coastal management and response to climate change and sea-level rise (Ford and Kench, 2015; Kench *et al.*, 2018; Magnan and Duvat, 2020; Holdaway *et al.*, 2021; Sengupta *et al.*, 2021; Burke and Spalding, 2022; Liang *et al.*, 2022; Techera, 2023). However, such information is either unavailable or difficult to obtain, in particular for atoll islands (Vos *et al.*, 2019b; Sengupta *et al.*, 2021). There has been a growing awareness that remote sensing has the potential to provide more detailed information for shoreline change modelling and assessment (Hedley *et al.*, 2018; Dong *et al.*, 2019; Vos *et al.*, 2019a; Vos *et al.*, 2019b).

Remotely sensed data including satellite and aerial imagery have been used for shoreline extraction and change analysis over coral reef islands (Ford and Kench, 2015; Mann and Westphal, 2016; Purkis *et al.*, 2016; Aslam and Kench, 2017; Duvat *et al.*, 2017; Dong *et al.*, 2019; Vos *et al.*, 2019a; Holdaway *et al.*, 2021). However, the existing research has focused more on islands in a single atoll coral reef (Mann and Westphal, 2016; Purkis *et al.*, 2016; Aslam and Kench, 2017). Some research work used aerial photos only to extract the shorelines (Aslam and Kench, 2017; Duvat *et al.*, 2017; Sengupta *et al.*, 2021). In most cases, the acquisitions of the aerial photos were for the applications of specific projects and were not quite suitable for long-term shoreline extraction. Open-source satellite observations on the other hand offer a great opportunity to model long-term shoreline changes. It is a big challenge for processing massive volumes of Landsat data if using commercial imaging processing software on workstation or a PC computer (Teluguntla *et al.*, 2018). An alternative powerful computing platform, e.g., high perform computing (HPC) or cloud computing environment, e.g., Google Earth Engine (GEE) (Gorelick *et al.*, 2017) must be used to implement the image processing (Vos *et al.*, 2019b; Zhang *et al.*, 2022).

This study aims to model the shoreline changes of coral reef islands in the Maldivian Archipelago using satellite observation and cloud computing. Specific objectives include a) monitoring of spatiotemporal shoreline changes using Landsat and Sentinel-2 imagery on GEE platform; b) analysis of shoreline change rates; and c) discussion of drivers of the shoreline changes in the Maldives.

2. MATERIALS AND METHODS

2.1 Study Area

The Maldivian Archipelago consists of a double chain of 22 atolls stretching over 800 km in the Indian Ocean (Rovere *et al.*, 2018). Eight coral reef islands from different atolls, (northern, central and southern) in the Maldivian Archipelago as shown in Figure 1 were selected for this study. Four islands (Kela, Hanimaadhoo, Kaashidhoo and Fuvahmulah) are naturally formed coral reef islands while two islands (Hulhumale’ and Gulhifalhu) are fully reclaimed islands in the central region of the Maldives. The selection of these islands also considered the shapes and locations of the islands where climate conditions are different.

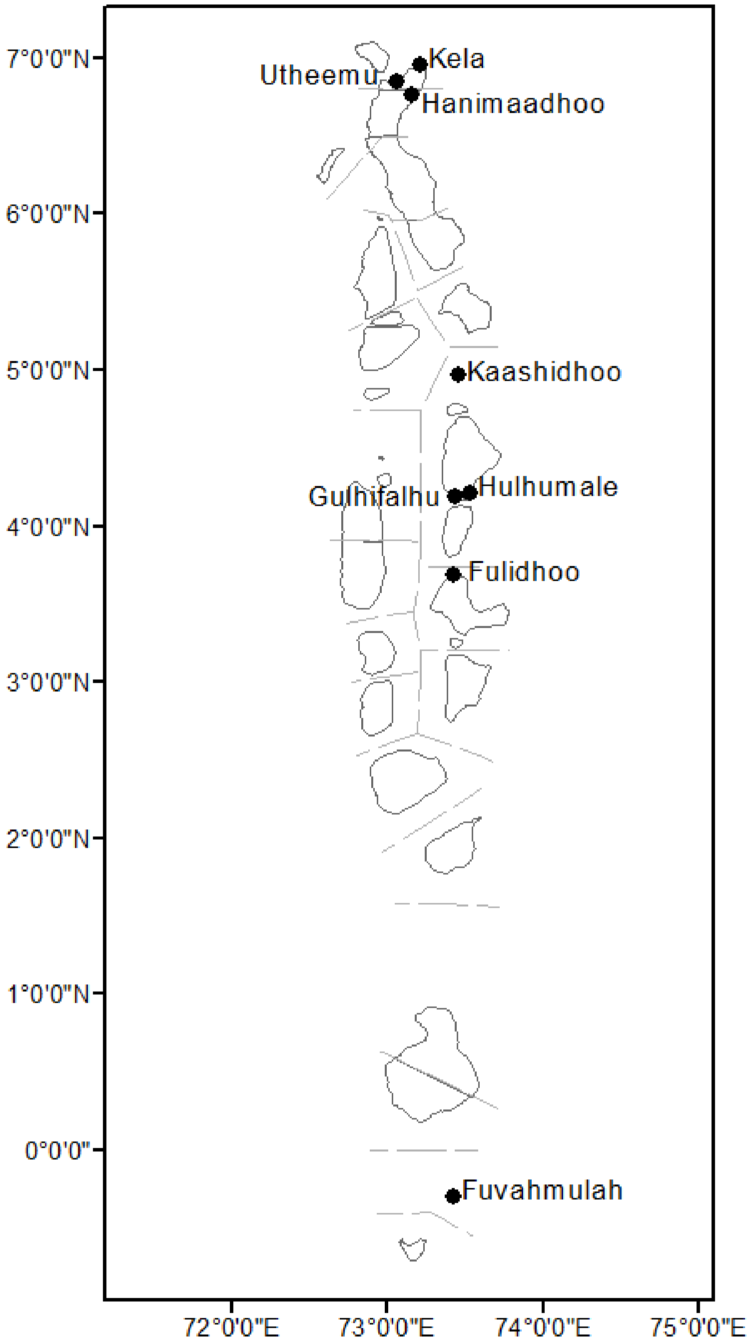

Figure 1. Study area showing 8 coral reef islands in the Maldivian Archipelago.

2.2 Methods

The available Landsat and Sentinel-2 images for the study area were collected from GEE. The Top-of-Atmosphere (TOA) images of Landsat 5, 7, 8 and Sentinel-2 imagery were used for shoreline extraction and change analysis. The images were first pre-processed, including geometric and radiometric correction, and georeferencing and cloud masking. Images with high cloud covers and shadows, and Landsat 7 scan line corrector-off gaps were identified and isolated and discarded. Pan sharpening and down-sampling methods using principal component analysis (PCA) and bilinear interpolation were used to increase the spatial resolution of the satellite images. High resolution images including from Digital Globe (WorldView-3) and Google Earth, ground survey data, aerial and drone images from Housing Development

Corporation, Land Survey Authority and other government organisations of the Maldives were also collected for validation and accuracy assessment.

Modified normalised difference water index (MNDWI) (Xu, 2006) was calculated using TOA values of relevant bands by the following formula:

$$MNDWI = \frac{\rho_{Green} - \rho_{SWIR1}}{\rho_{Green} + \rho_{SWIR1}} \quad (1)$$

Where ρ_{Green} and ρ_{SWIR1} are the AOT values of bands green and shortwave infrared 1.

Otsu's algorithm (Otsu, 1979) was used to automatically determine a threshold value to separate water and non-water pixels from the NNDWI values. Once a threshold has been applied and the land and water pixel has been separated, edge detection methods and contouring algorithm were used to detect and extract a vector shoreline from the MNDWI images. Two methods were used to extract vector shorelines from the GEE cloud computing platform: one is Canny Edge detection (Canny, 1986); and the other is CoastSat (A GEE-enabled Python toolkit for shoreline extraction) developed by Vos *et al.*, (2019b).

Digital Shoreline Analysis System (DSAS) developed by U.S. Geological Survey (Himmelstoss *et al.*, 2021) was employed to analyse the position changes in shoreline and determine the change rages of the shoreline. DSAS algorithm used a baseline and transacts with an interval of 1 m here to detect the intersection of these transacts with the baseline to generate the change rates of the shoreline. End Point Rate (EPR) is calculated by dividing the net shoreline change distance from the start point to end point, by the time elapsed between the two points (Mann and Westphal, 2016; Himmelstoss *et al.*, 2021; Holdaway *et al.*, 2021). Once the EPRs are generated the rate of accretion and erosion can be visualised.

3. RESULTS AND DISCUSSION

Shoreline changes including maximum erosion, maximum accretion, and area changes of 8 islands from 2015 to 2021 are shown in Figure 2. All the islands except for Gulhifalhu have undergone more overall accretion than erosion. Kaashidhoo and Fuvahmulah islands show the highest accretion rates while Hulhumale and Kela islands have the lowest accretion rates. The areas of both Gulhifalhu and Hanimaadhoo islands reduced by more than 5 ha, but all the other islands show increases in areas (Figure 2).

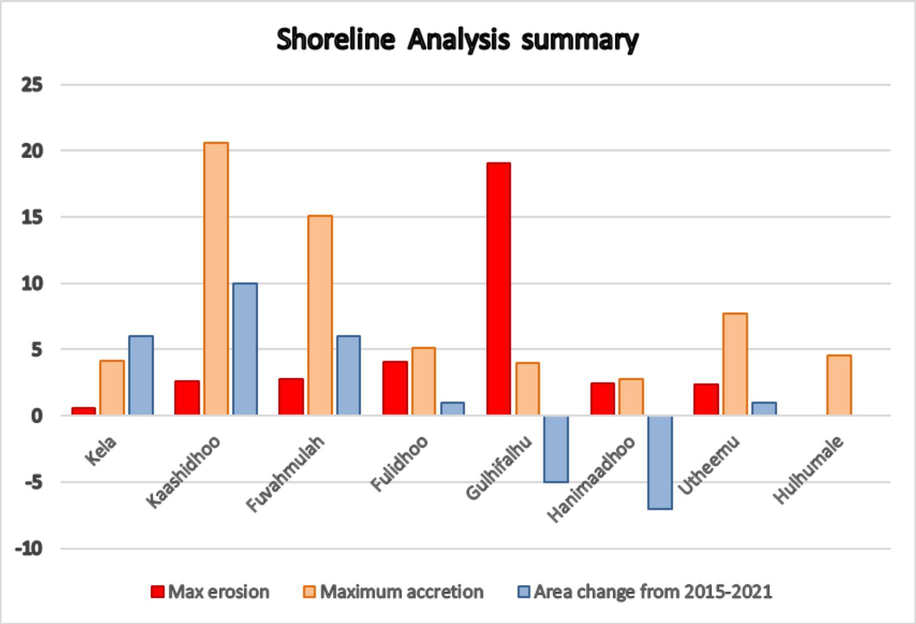

Figure 2. Shoreline change analysis (area in hectare)

The EPR shoreline changes showing the erosion and accretion rates for the islands are presented in Figure 3. Generally, the islands have shown a shift towards the north or northeast direction, especially the smaller islands, Fulidhoo, Gulhifalhu and Utheemu. The islands also show more aggressive shoreline change on the side of the island which faces the inner atoll and lagoon. For example, Fulidhoo and Hanimaadhoo, has seen more changes on this side as they are centrally located inside the atoll. However, Kaashidhoo and Kela shows some contradicting results, and more erosion is observed in the side which faces the outer atoll and towards the main ocean. The inner lagoon side is observed to be experiencing accretion rather than erosion, such as in the case of Utheemu and Fulidhoo.

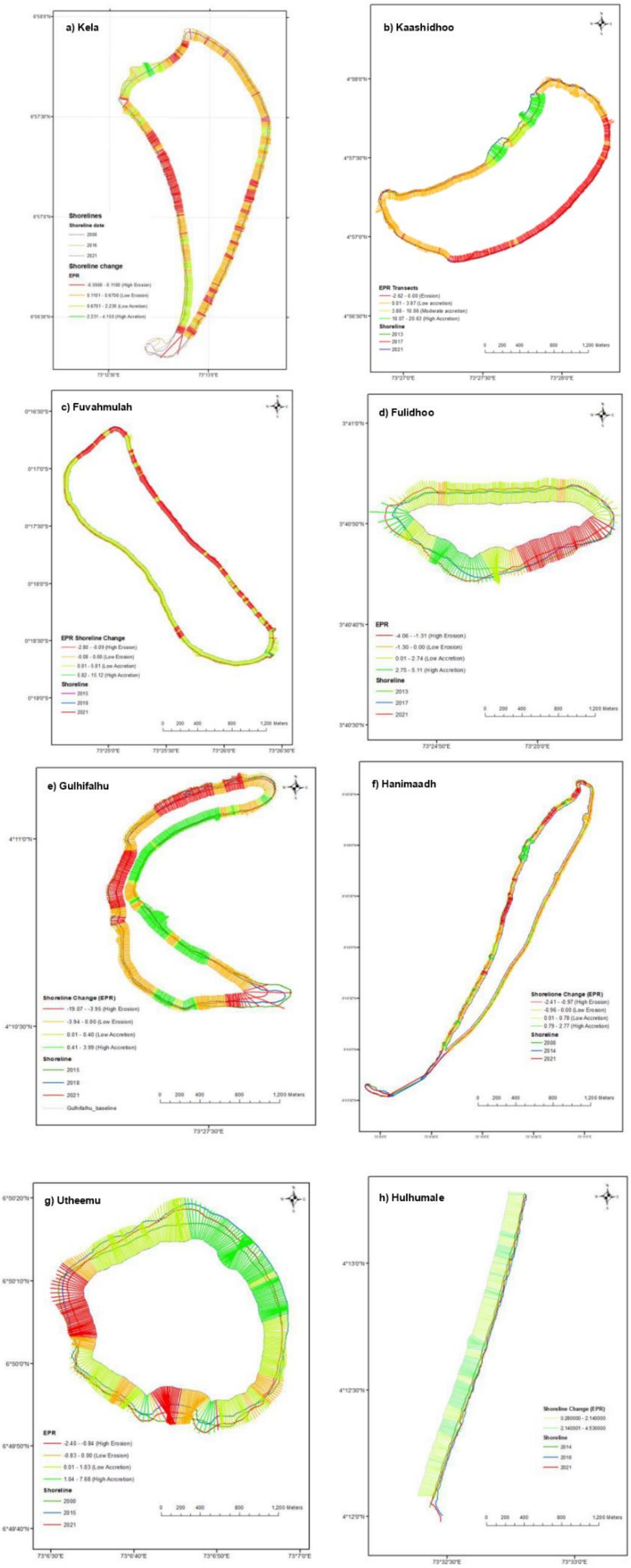

Figure 3. End Point Rate (EPR) shoreline change maps showing the erosion and accretion rates of the islands.

There are two monsoon seasons in the Maldives, Westerly Monsoon (Hulhangu monsoon) and Northeast Monsoon (Iruvai Monsoon), which experience strong reversal of current and wind between seasons (Kench, 2010). The Westerly monsoon is from April to November and has strong winds from southwest to northwest and Northeast monsoon is from December to March and has a reversed wind direction from northeast (Kench, 2010). The strong winds and current causes swells from the wind direction causing movement of sedimentation and reef platform circulation. A distinct movement of shoreline is observed in the analysis where the movement is towards east and east west direction during Westerly monsoon and towards southwest direction during Northeast monsoon as seen in the yearly shoreline diagrams. According to Kench (2010), this change in island shorelines can be explained by the seasonal climate and monsoon periods and wave climate in the Maldives.

Harbour construction, channelling, dredging and reclamation were found to be the major causes that caused the changes in shoreline and alter the natural movement of the shoreline and sedimentation around islands. The designs and construction methodologies should be revised, or other alternative methods may be considered to minimize this impact. the current harbour constructions and designs can be redesigned to minimize the impact on island such as erosion and disruption to sedimentation movement causing other environmental problems. Overall, the islands that were studied show moderate threat to islands in terms of overall area and does not indicate significant loss of land. However, the results indicate a significant sediment and shoreline movement, mostly erosion in different parts of the island in different times that is causing major concern in terms of sustainability.

4. CONCLUSION

Coral reef islands form different atolls in the Maldivian Archipelago were analysed to study the spatiotemporal shoreline dynamics using satellite observation and cloud computing. The long-term and seasonal changes of the shorelines were analysed. The long-term changes were attributed to erosion and land reclamation. The seasonal shifts were caused by monsoon changes. The shoreline of the island moves significantly in a north-easterly direction during the Northeast monsoon during the mid-year causing erosion in parts of the island. The shoreline shifts back to westerly direction during the westerly monsoon season during end/start year. The examination of long-term changes to total island area indicates decrease in area but does not indicate significant decrease. However, a lot of variation was observed. This is due to the fact that the shoreline is rotating and shifting rather than losing area and causing movement of sedimentation around the island.

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