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Nearshore sediment dynamics of Kavaratti Island, Lakshadweep archipelago using integrated modelling system

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The Kavaratti Island of Lakshadweep archipelago exhibits high coastal erosion and shoreline changes due to the anthropogenic stresses on the island morphology. This study focuses on the shoreline analysis using Digital Shoreline Analysis System model and nearshore sediment dynamics using an integrated modeling system with high resolution bathymetry of ~15 m. The sediment load and bed level change were estimated using the sediment transport model through the feedback mechanism of flow and wave forces. The model simulations were performed during winter, pre-monsoon, monsoon and post-monsoon seasons for the year 2015 and calibrated using the field observation datasets. Shoreline change studies indicate the coastal erosion of about 83.43 % and accretion of about 16.55 % along the island coast. The study signifies the erosion around the fishing jetty and accretion at the western (Katchery) jetty due to wave induced currents and tidal influx. The scouring effect due to the presence of tetrapods along the island coast is observed between 0.02 and 0.18 m.

[Keywords: Hydrodynamics, Sediment transport, Suspended sediment, Waves, Wave induced currents]

Introduction

The coastal processes are driven by strong interaction of nearshore waves, currents, tides and local wind field such as land and sea breeze. This process majorly leads to accretion and erosion features along the coast by changing the shoreline morphology. However, spatial variation of erosion/accretion rates depends on natural and manmade activities. Hydrodynamic conditions tend to change the nearshore dynamics and morphology of the coast[1-3]. Dynamic variation occurs in the lagoon due to the continuous striking of ocean waves and wave breaking over the reef crest[4]. Wave breaking causes the longshore drift, sedimentation and sediment suspension over the coral reefs[5,6]. The magnitude of suspended sediment concentration is directly proportional to the bed materials, sizes and the resuspension of bed sediment induced by waves and currents[7]. The sediment transport using currents, turbulence and wave orbital motion were measured using the Acoustic Doppler Velocimeter (ADV)[8]. Sedimentation rate in coral reefs is a key factor for controlling the reef development and distribution. The sediment transport and the water circulation within the lagoon predict the shoreline changes. Thus, it is essential to conduct studies on coastal process and nearshore hydrodynamics to prevent shore erosion and protect island coasts. Such studies help to identify suitable soft measures and environmentally eco-engineering approach to protect the eroding regions of island coast.

The present study focuses on nearshore hydrodynamics and sediment movement on the Coast of Kavaratti Island in Lakshadweep archipelago. The study also examines the impact of coastal sediments on reef ecosystem of the lagoon, and evaluates the erosion and accretion rates to identify suitable soft mitigation measures.

Materials and Methods

Study area

The Lakshadweep Islands in the Arabian Sea, also known as coral islands is situated off the west coast of India on a submerged volcanic surface. The geographical extent of Lakshadweep Islands is about 32 km^2 of coastline length 132 km and 4200 km^2 lagoon area. The 36 islands of Lakshadweep comprise of 12 coral atolls, 5 submerged banks and 3 reefs in-between the latitude 8°00′ to 12°30′ N and longitude

71°00′ to 74°00′ E in the north of the Indian ocean[9]. The island elevation above the mean sea level varies from 0.5 to 6.0 m. The islands are narrow and fringed by corals on the western side with beaches consisting of calcareous sand. The majority of Lakshadweep Islands are sheltered by shore protection measures to minimize coastal erosion[10]. These islands are unique and rich in marine biodiversity, productivity and socio-economic values.

Amongst the Lakshadweep Islands, Kavaratti Island (Fig. 1) exhibits rich coral habitat and marine biodiversity which is the principal town of Lakshadweep Island with a total land area of about 3.63 km^2 and total population of about 11210. Its orientation is in north-south direction, lying east of the submarine Lakshadweep-Chagos ridge. Kavaratti Island is in the middle off neighboring islands such as Amini to the north, Suhelii to the south, Andrott to the northeast and Kalpeni to the south east. The northern part of the island is wide and tapers to narrow width towards south of island called “chicken neck area” while the southern part of the island is narrow. The three major jetties: the eastern (318 m length), fishing (119 m length) and Western/Katchery (263 m length) jetties show a major role in the hydrodynamic environment. The bottom slope is steeper on the southern side near the helipad area of the island compared to the northern part near the desalination plant.

Model description

The Digital Shoreline Analysis System (DSAS) is used to identify the shoreline change in terms of erosion and accretion. The Mike 21 Numerical Model was used to simulate the coastal processes in and around the Islands to analyze the dominant physical mechanisms causing coastal erosion/accretion. The overall block schematic representation was given in Figure 2.

1) Digital Shoreline Analysis System (DSAS) Model

The DSAS Model is used for the shoreline analysis using the multi-spectral and multi-temporal satellite images. Ideally, the extraction of shoreline positions for the past and current data from satellite data sources involves distortion removal and geo-referencing. These images were rectified and transformed to Universal Transverse Mercator (UTM) projection in the World Geodetic System Datum of 1984 (WGS 84) prior to shoreline extraction. The shoreline extraction was determined using the

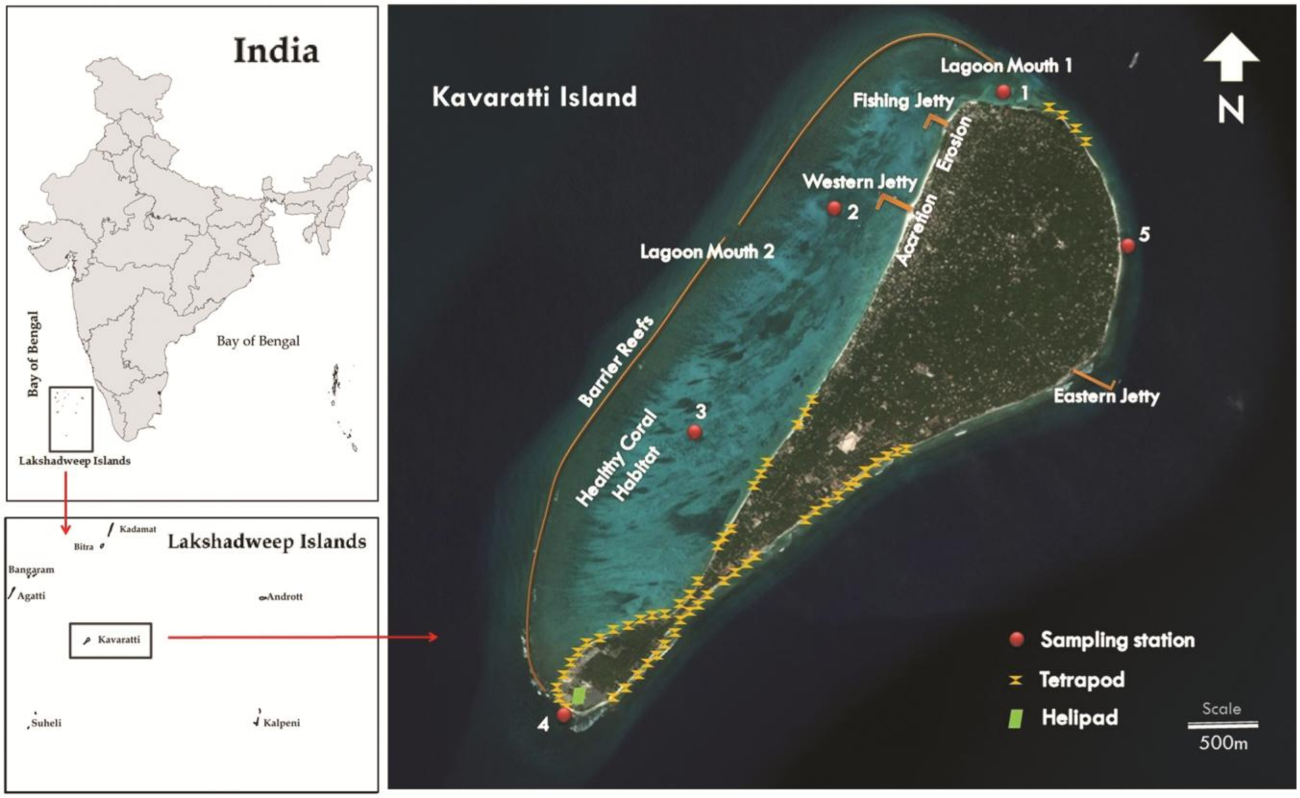

Fig. 1 — Map of the study region: Lakshadweep Islands, Kavaratti Lagoon with the sampling sites

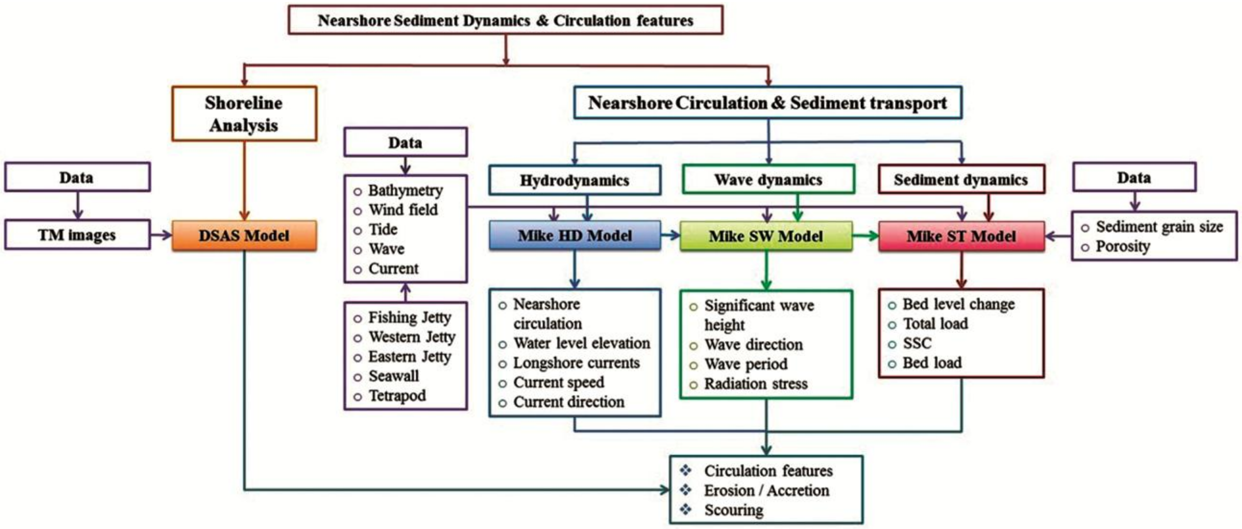

Fig. 2 — Flow chart of the integrated numerical modeling system for prediction of nearshore sediment dynamics along the coastal regions of Kavaratti island

technique digital image processing. Using Digital Shoreline Analysis System (DSAS) model to calculate shoreline change rates developed by United States Geological Survey (USGS), multiple shorelines were extracted from satellite images for an ArcGIS environment. In order to find the rate of shore change, statistical baselines were constructed on the landward side of ~50 m neighboring to shoreline positions. The DSAS model computes shoreline change rates using several statistical methods such as i) linear regression rate, ii) end point rate, iii) average of rate, iv) jackknife, v) shoreline change envelope and vi) net shoreline movement within the ArcGIS environment. The minimum of three shorelines at each DSAS transect is essential for the change computation. In this study, Linear Regression Rate (LRR) was used for stating the rate of shore change.

2) Mike 21 Numerical Model

Three numerical models were used in the study (Fig. 2) (i) hydrodynamic, (ii) spectral wave and (iii) sediment transport models to compute the water level variations, flow environment, wave conditions and sediment dynamics within the lagoon and around the island[11].

Hydrodynamic model

The hydrodynamic model a part of the MIKE21 Flow module was used in this study to comprehend the flow and circulation features in the vicinity of Kavaratti Island. This is a comprehensive 2–dimensional modeling system for difficult uses within the estuarine, coastal and oceanographic environment with the support of flexible mesh. It simulates flows and water level changes in response to a diversity of forcing in the study region. The Flexible Mesh tool used to prepare an optimal degree unstructured grid of flexibility on representation of difficult geometries and allows smooth boundaries. It also generates finer elements in the nearshore areas and coarse elements in the offshore regions for better understanding of coastal processes. The model uses spatial discretization of the governing incompressible equations Reynolds-Averaged Navier-Stokes to integrate momentum, continuity, density, and temperature equations. It also performs the Boussinesq and hydrostatic pressure approximations using a finite volume cell-centered method[12,13]. The primitive equations of the model consist of momentum, continuity, density, and temperature equations and are represented below as:

The continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S$$

Conservation of horizontal momentum eqn. for X, Y components

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z} = fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_\circ}\frac{\partial p_a}{\partial x} -\frac{g}{\rho_\circ}\int_z^\eta \frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial Z}\left(v_t\frac{\partial u}{\partial z}\right)+u_s S$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z} = fu - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho_\circ}\frac{\partial p_a}{\partial y} - \frac{g}{\rho_\circ}\int_z^\eta \frac{\partial \rho}{\partial y}dz + F_v + \frac{\partial}{\partial Z}\left(v_t\frac{\partial v}{\partial z}\right) + v_s S$$

Conservation of transport diffusion equations

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}+\frac{\partial wT}{\partial z} = F_r + \frac{\partial}{\partial z}\left(D_v\frac{\partial T}{\partial z}\right) + \widehat{H} + T_s S$$

$$\frac{\partial s}{\partial t}+\frac{\partial us}{\partial x}+\frac{\partial vs}{\partial y}+\frac{\partial ws}{\partial z} = F_s + \frac{\partial}{\partial z}\left(D_v\frac{\partial s}{\partial z}\right) + s_s S$$

The horizontal diffusion equation

$$(F_T, F_s) = \left[\frac{\partial}{\partial x}\left(D_h\frac{\partial}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_h\frac{\partial}{\partial y}\right)\right](T, s)$$

Spectral wave model

The spectral wave model is a third-generation spectral wave model to simulate the growth, transformation, and decay of wind-generated swells and waves in coastal and offshore areas. It is formulated with directional decoupled and fully spectral parametric formulations. The full spectral formulation is depends on wave action conservation equation[14,15] and the directional decoupled formulation is depends on a parameterization of wave action conservation equation. The discretization of the equation in spectral and geographical space is performed using finite volume cell-centered method. The integration is achieved using a fractional step method that is applied to propagation of wave action. It uses numerous applications such as assessment of wave climates in coastal and offshore areas in forecast and hindcast mode, the design of offshore, wave prediction on regional and local scales.

The conservation eqn. for wave action is as follows:

$$\frac{\partial N}{\partial t} + \nabla.(\bar{\vartheta}N) = \frac{S}{\sigma}$$

where, $\bar{\vartheta}$ is propagation velocity of the wave group, N is action density, S is the source term for energy balance equation, and σ is relative angular frequency.

The source function term, S, on the right side of the conservation equation for wave action is given by

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{surf}$$

where, S_{in} denotes the momentum transfer of wind energy to the wave generation, S_{nl} is the transfer of energy due to non-linear wave interaction, S_{ds} is the dissipation of wave potential due to white-capping, S_{bot} is the dissipation in terms of bottom friction and S_{surf} is the wave energy dissipation based on induced breaking depth.

Sediment transport model

The sediment transport model is the grid model that resolves processes not taken by hydrodynamic model. The model simulates sediment transport and movement rates in a flexible grid mesh to cover the area in terms of hydrodynamic parameters that are attained from the hydrodynamic model and the parameters such as wave direction, significant wave height, and radiation stresses from the spectral wave model, together with data on the features of bed material. It quantifies sand or sediment transport capacity in all regions where waves and current are triggering non-cohesive sediment and sand movements. It could be used for all scales from regional (10 km) to local nearby areas about structures where resolutions are down to meters. The equilibrium sediment transport are considered on the basis of manning number, mean horizontal velocity component, local water level depth, and properties of bed material.

Data collection and methodology

Shoreline change of Kavaratti Island was studied with spatial resolution of 30 m using Landsat ETM+ image for 1999, 2007 and Landsat TM 8 for the year 2015. The study using Digital Shoreline Analysis System (DSAS) model on shoreline change was carried out and the rate of change was evaluated using the orthogonal transects.

The model bathymetry for the study area was extracted from sources GEBCO 30”, Mike C-Map and EOMAP data. The GEBCO (General Bathymetry Chart of Oceans) data has a horizontal resolution of about 900 m whereas, EOMAP and Mike C-Map have a horizontal resolution of 15 m and 90 m respectively. EOMAP data are satellite derived bathymetry (SDB) data, using optical algorithm with high resolution in nearshore regions compared to other data sets. Bathymetry of the domain was prepared accurately from the three sets of data using optimum interpolated methods (Fig. 3).

Ocean Surface Current Analysis (OSCAR) data was obtained from DAAR (Physical Oceanography Distributed Active Archive Center) of Jet Propulsion Laboratory (JPL). This data has a horizontal resolution of one third of the degree (~35 km). The

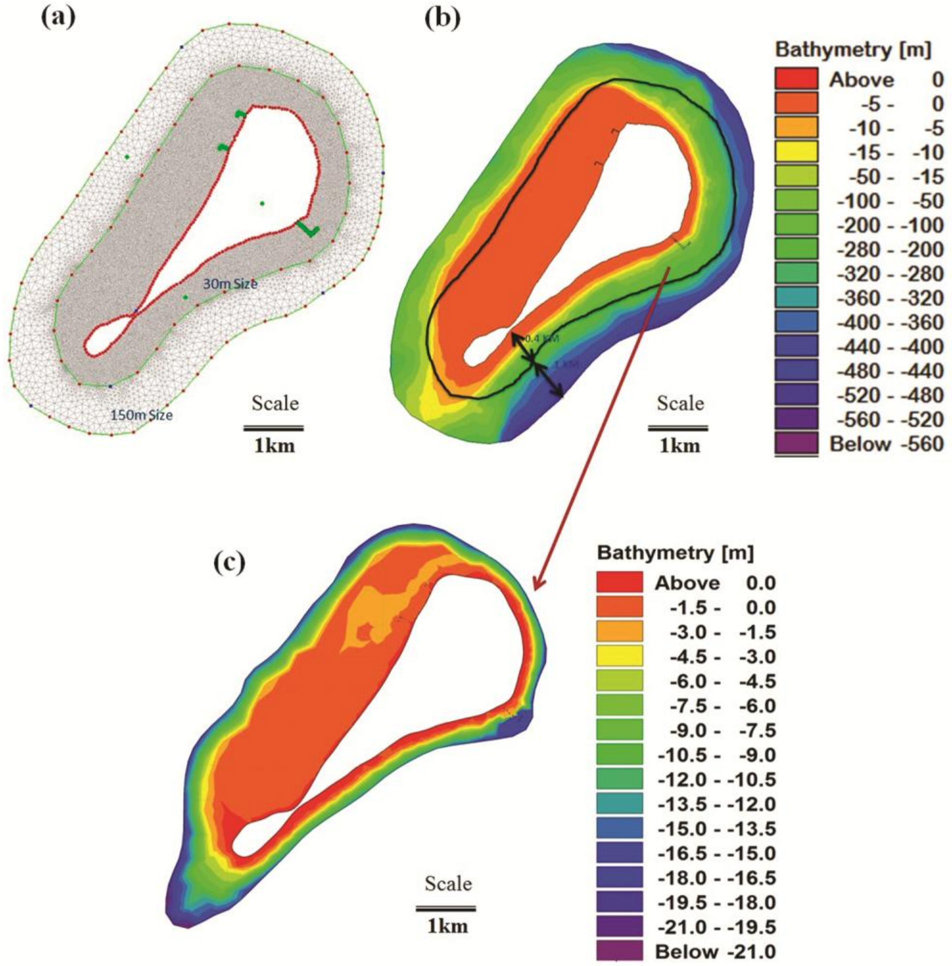

Fig. 3 — (a) Mesh grid of numerical model with nested domains (b) C-MAP bathymetry (m) and (c) EOMAP bathymetry (m).

near-surface current velocity is directly derived from ocean sea surface height, wind stress, and sea surface temperature (SST). OSCAR currents are the sum of geostrophic, Ekman-Stommel shear dynamics and thermal wind currents.

Further, five sediment samples were collected in the lagoon during 2015 and were analyzed by using the high accurate and laser technology Microtrac particle size analyzer. The particle size was determined by the blue/red, multi-detector, tri-laser, multi-angle optical system.

The integrated coupled modeling system (hydrodynamic, spectral wave and sediment transport models) were configured and simulated for Winter (January 2015), Pre-monsoon (April 2015), Monsoon (August 2015) & Post-monsoon (December 2015) with a nested domain having finer horizontal resolution in the lagoon area and coarse resolution outside the lagoon. The horizontal resolution of the triangular mesh varied from 5 to 10 m close to the coast and then increased to 500 m in the offshore region. The initial condition and lateral boundary conditions for the numerical model were provided from field observed datasets. The details of input parameters and their description are given in Table 1. The tidal data of Kavaratti Island was extracted from Mike C-Map. The tidal elevations for different seasons were given in Figure S1. The principal tidal constituent was analyzed and the amplitude of the constituent M2, S2, K1 and O1 were shown in Figure S2 (Table S1). Grain size of sediments obtained from the field samples was further used for the preparation of initial conditions to simulate the sediment transport. The validation of model was extensively performed out using observational data, and a few existing literatures.

Field survey was conducted to collect sediment samples and met-oceanic parameters at Kavaratti Islands during the year 2015. ADV (a SonTek 5-MHz versatile) was used to calculate 3D velocity

Table 1 — Details of the model input parameters & Boundary conditions

Model inputs	Input Details
Bathymetry	GEBCO-30 arc sec (900 m) CMAP (90 m) EOMAP (15 m)
Module	Hydrodynamic, Sediment transport & Spectral wave
Surface wind fields	Interim – ECMWF winds (12.5 km)
Tides	Global tidal data
Sediment	Field collected samples Global sediment tables
Lateral boundary conditions	In-situ wave data (Wave Rider Buoy), In-situ current data (RCM data)
Simulation period	January 2015, April 2015, August 2015 & December 2015
Time Step	Every 60 Seconds
Critical CFL (Courant–Friedrichs–Lewy) number	0.8
Boundary formulation	Water level
Time Integration & Space discretization	Low order, Fast Algorithm
Eddy Type	Smagorinsky formulation (constant 0.28)
Resistance Type	Manning Number (constant 32)
Bed load & Suspended Load formulation	Engelun Hansen
Porosity	0.4
Grain diameter (d_{50})	0.06

fields at single point in the marine environment. It was deployed to measure the water flow velocity in a 3-dimensional view by using the volume sampling method with an approximate distance of 5–18 cm at four locations in the lagoon. Turbidity and suspended sediment concentrations were measured using the Optical Back Scatter Sensor with infrared wavelength of 850 nm ± 5 nm with maximum suspended sediment concentration up to 4,000 NTU. The turbidity and sediment samples were collected at an interval of one minute and averaged to 6 hour interval to evaluate the effect of tides on the sediment characteristics.

Met-oceanic parameters were collected from various observations such as Automatic Weather Station (AWS), wave rider buoy in the vicinity of island for the year 2015. Wind speed and direction were obtained at an interval of 2 minutes from AWS of NCSCM which is installed over the Science and Technology building of Kavaratti Island and averaged to every one-hour interval using the moving average method (Figure S3). Wave parameters such as wave period, significant wave height and wave direction were obtained from the wave rider buoy at 6 hours interval deployed by the INCOIS (Indian National Centre for Ocean Information System), near Kavaratti Island. The observed and collected datasets for the year 2015 is shown in Figure S4 and corresponding details were given in Table S2. Recording Current Meter (RCM) was deployed to measure water currents in the lagoon during 2015 and cross-examined with the ADV measured currents to estimate the absolute error in the instruments, and then used for validation of the model results.

Results

Model validation

The performance of the numerical model was analyzed and validated using parameters such as water level elevation, wave period, wave height, and wave direction (Figure S5). The numerical model inputs and its boundary conditions were described in Table 1. The maximum wave height during August 2015 was 3.4 m and the significant wave height is of about 2.5 m at the southern tip of the island. Best fit analysis has been carried out between predicted and observed values of water elevational level and significant wave height. The water elevation and wave height shows the R^2 values about 0.77 and 0.85, respectively (Figs. S5e, f). Statistical analysis of various parameters such as wave height, water level elevation, wave direction, and wave period are presented in Table 2. The Correlation coefficient output and Root Mean Square error (RMSE) values of significant wave height and the water level elevation showed 0.92, 0.88, 0.10 and 0.12, respectively.

Shoreline change

The shoreline changes were analysed using DSAS model along Kavaratti Island. These shoreline changes were categorized into eight classes for Lakshadweep Islands as erosion class (high, medium and low erosion) and accretion class (high, medium and low accretion), stable and artificial coast as shown in Table S3. The erosion (landward drifting of the shoreline) are represented as negative and accretion (seaward drifting of the shoreline) are represented as positive. The average shoreline movement rate for Kavaratti Island is 0.64 m/yr, an accretional trend. The Island is prevailed by artificial structures along the coast, Moreover, the artificially protected coast at lagoon side of the island is erosional with net rate of -10.7 m/yr. The east coast of the island shows a positive shoreline change rate of 0.28 m/yr due to artificially protected structures. Moreover, the shoreline is protected by hard structures of about 9.67 km along the coast of island (Table S4).

Circulation features

The mesoscale circulation features were studied using the OSCAR data over the Lakshadweep Islands during the winter, pre-monsoon season, monsoon season and post-monsoon seasons. Only during the monsoon season and post monsoon seasons, the hydrodynamic flow conditions of the Island shows diverse pattern. The flow field and magnitude of current were observed in between the range of 0.1 and 0.22 m/s during the monsoon seasons (Fig. 4). However, this data is insufficient to understand the effect of the flow field patterns between the groups of islands. Therefore, the integrated model approach is used to simulate the local scale features of the islands by providing the boundary conditions of the mesoscale circulation features. This improves the prediction of circulation features inside the lagoon and at the reef edges to understand the effect of coastal processes on shoreline changes, sediment accumulation and sediment movement along the coral reef of the lagoon.

The local scale flow conditions, wave characteristics and sediment transport were predicted during different seasons (winter seasons, pre-monsoon seasons, monsoon seasons and post-monsoon seasons) for the year 2015. The prediction of circulation features during monsoon (Southwest - August 2015) and post-monsoon (Northeast - December 2015) seasons around Kavaratti Island is shown in Figures 5 (a, b). The magnitude of the current varied from 0.2 to 0.4 m/s in the southwest monsoon season and between 0.1 to 0.15 m/s in northwest monsoon season. This flow environment is induced by tides and breaking waves on the west and east sides of the lagoon. Strong currents were observed on the south and north mouth area of the western lagoon. Therefore, in both seasons a high flow environment is observed in the southwestern and northwestern (Channel mouth) side of the lagoon. It also observed that high current was observed on the southern tip (near to helipad area) of the island. The current direction at the channel mouth varied between 210° and 250° during southwest monsoon whereas it

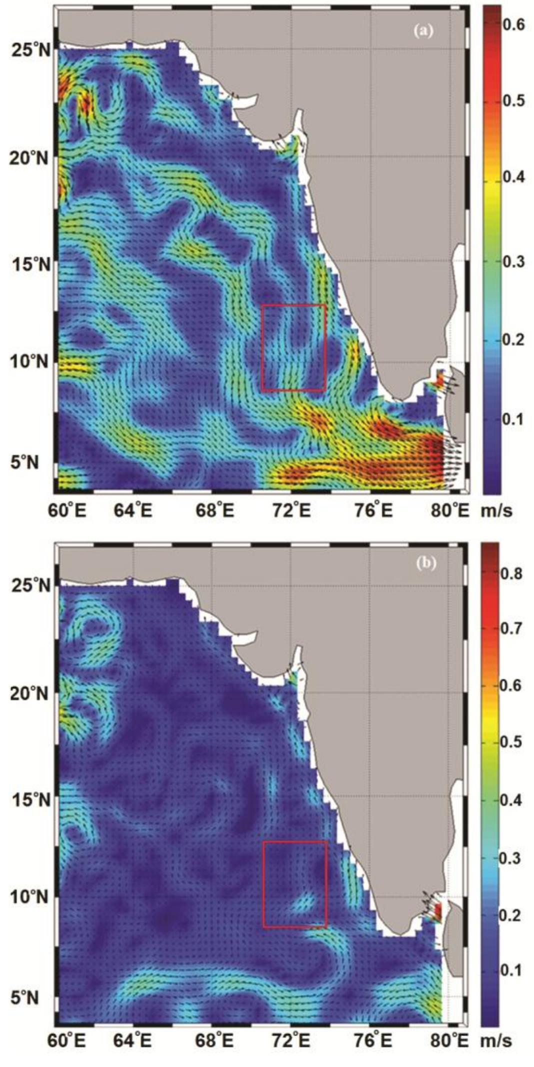

Fig. 4 — Mesoscale circulation features in the Arabian Sea and the Lakshadweep Islands (Box marked with red colour), India: (a) Southwest monsoon season, and (b) Northeast monsoon season.

Table 2 — Statistical analysis in between the observed and predicted data sets in the vicinity of Kavaratti island

Parameters	Mean Absolute Error	Correlation Coefficient	R Square	ABS-BIAS	RMSE
Wave height	0.11	0.92	0.85	0.06	0.10
Wave Direction	9.56	0.89	0.79	8.17	10.00
Wave period	0.64	0.88	0.78	0.51	0.68
Water level elevation	0.15	0.88	0.77	0.09	0.12

*ABS BIAS – Absolute Bias
RMSE - Root Mean Square Error

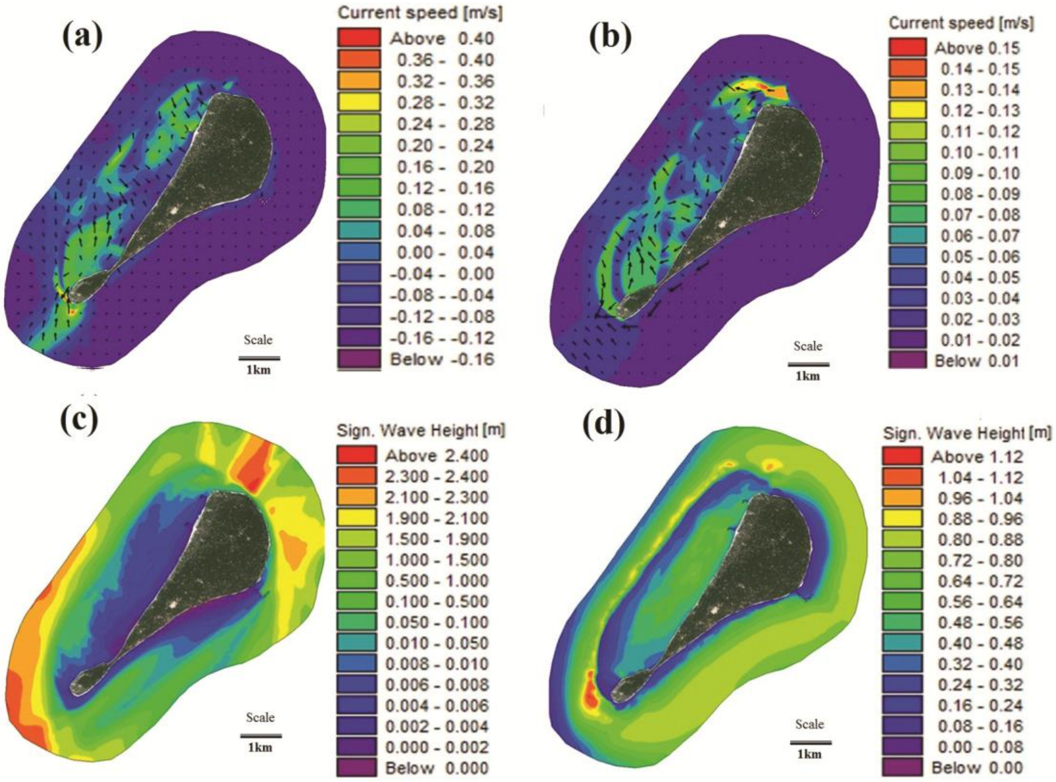

Fig. 5 — Prediction of integrated modeling system: (a & b) circulation features and (c & d) significant wave height in the vicinity of Kavaratti island during the southwest and northeast monsoon season of 2015.

was about 45° in northeast monsoon. The significant wave elevation was high during the southwest monsoon season compared to other different seasons (Figs. 5c, d). It varied from 1.5 to 2.4 m during southwest monsoon and about 1.5 m during the northeast monsoon season. Wave height significantly increased due to wind speed and the steep slope of the reef crest in the offshore region. The mean wind speed varied from about 3.5 m/s to 5.6 m/s in the southeast direction during post-monsoon season and monsoon seasons. The predominant wave direction varied in between 200° – 250° on the offshore region of the island. The current speed varied between 0.35 and 0.5 m/s in the southwest and northeast directions, respectively. The magnitude and direction of currents clearly indicated that there exists strong flow in the south and north parts of the island. The longshore currents along the west and east coast of island varied in between 0.23 and 0.54 m/s during monsoon season. The average longshore current along the eastern coast induced major erosion on the east coast of the island. The longshore current enters into the lagoon through the channel mouth, which might have dragged the sediment from the fishing jetty and accumulated over the western jetty during monsoon season. The longshore current on the east coast moves the sediments around the chicken neck region. Therefore, the longshore drift highly trapped the sediments in the fringing reefs of Kavaratti island.

Sediment characteristics

Sediment characteristics are studied using collected sediment samples in the Kavaratti Island and were analyzed using a Microtrac particle size analyzer. It was observed that the sediment particles were mostly calcareous sediments and composed of medium and fine sand. The details of sediments size distribution are shown in Figure 6. Sediments exhibited typically sand characteristics except at KV-1 & KV-5 sites. The percentage of sediments corresponding to their grain size is presented in Table 3. Sediment size varied between 0.3 - 0.6 mm at five locations. The percentage of medium sand on the five sampling sites were 52.4 %, 46.5 %, 65.7 %, 63.4 % and 55.6 %, respectively and it is shown in Table 3. The size of the sediment (D_{50}) was calculated using folk and wards method (ø) and varied between 1.024 and 1.821.

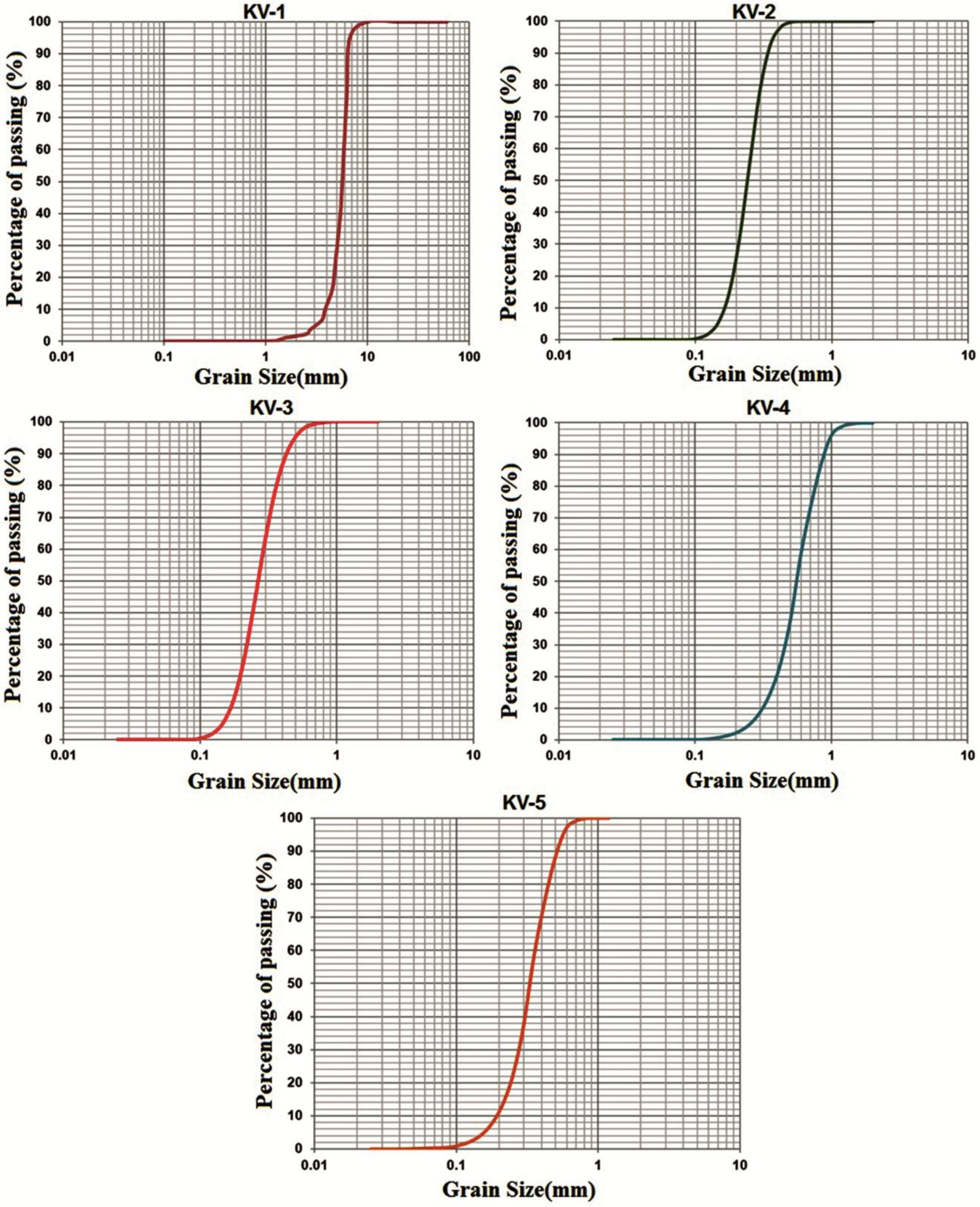

Fig. 6 — Distribution of sediment particle size at different sites of the Kavaratti Island

Table 3 — Sediment characteristics of the Kavaratti lagoon, Lakshadweep Island using Folk and ward method

Sediment sample stations / Classifications	KV - 1	KV-2	KV -3	KV -4	KV -5
MEAN SIZE	1.122	1.025	1.822	1.654	1.228
SKEWNESS	-0.080	0.007	0.037	-0.015	-0.200
D_{50}	1.220	1.024	1.816	1.660	1.300
% Verycoarse sand	8.3%	1.4%	0.0%	0.1%	7.3%
% Coarse sand	24.3%	46.5%	1.8%	10.9%	26.3%
% Medium sand	52.4%	49.8%	65.7%	63.4%	55.6%
% Fine sand	14.1%	2.3%	31.9%	25.0%	10.3%

Sediment transport

Predicted sediment load and bed level changes are given in Figure S6. Sediment load varied from -16 (10^{-4} $m^3/s/m$) to 40 (10^{-4} $m^3/s/m$) in the southwest monsoon season whereas between -8 (10^{-4} $m^3/s/m$) and 16 (10^{-4} $m^3/s/m$) in the northeast monsoon season during 2015. High load of sediment between 12 (10^{-4} $m^3/s/m$) and 40 (10^{-4} $m^3/s/m$) was observed in the southwest and northwest of the lagoon (Figs. S6a, b). The predicted bed level changes varied from -5.6 cm to 5.6 cm in the southwest monsoon (Fig. S6c) whereas minor changes predicted in the northeast monsoon season (Fig. S6d). Sediment load was high in the southern tip (near to helipad area) of the island and the rate of bed level change was around ~0.23 m/day in the southwest monsoon season. It clearly indicates that the movement of sediment and its associated distribution within the lagoon are primarily controlled by longshore drift and wave activity. Suspended sediment concentration varied between 153 and 279 mg/L at the western jetty region. Field photographs of turbidity in the Kavaratti lagoon, and deployment of ADV with OBS (Optical backscatter) sensor for orbital velocity and sediment load are shown in Figures S7 (a, b). The suspended concentration and turbidity of the sediments observed were very high at sampling site 2 (Figs. S7c, d). The high turbidity of about 60 NTU and suspended sediment concentration of 279 mg/L were observed near to the fishing jetty of the lagoon.

The magnitude of accretion and erosion rates evaluated based on the sediment load, bed level change and sediment movement along the coast of Island using integrated modeling system. An intensive erosion process has been observed at the southern tip (near the helipad area), fishing jetty, and in the navigational channel of the lagoon. Major part of the coast is covered by hard structures such as conventional concrete blocks and tetrapod which act as a defense system to reduce the wave forces and barrier for littoral drift (Figs. 7a, b). Particularly, the interlocked tetrapod dissipates the energy of incoming waves by passing through them. On the other hand, these hard structures show negative effects on the coast by inducing scouring at the major portions of west and east coast of island. The impact of tetrapod on the shore has been analyzed using scouring analysis around the tetrapod. The scouring depth ranged between 0.084 and 0.187 m/yr at the west coast of island, and varied between 0.022 - 0.117 m/yr near the south tip and east coast of island. The beach sediments were lost by scouring effect due to the existing hard structures on east coast of the island. The results of the model prediction showed high erosion at the northwestern (channel mouth) and around the fishing jetty of the lagoon, whereas accretion is observed at the western jetty of the Island.

Discussion

Kavaratti Island has micro-tidal regime and experiences semi-diurnal and mixed tides. The spring and neap tides are in the range of 0.3 m and 1.2 m, respectively[16]. The water level differs from -0.4 to 0.6 m in the monsoon season. Similarly, the significant wave height differs from 1 to 2.5 m mostly during monsoon. The wave characteristics clearly indicate that the wave height is high during the month June to September and are comparatively low during October to February of the annual year. The predominant wave direction varied between 200° and 250° during the southwest monsoon season and 190° to 210° during the northeast monsoon season. Wave period (Tz) varied from 5.25 s to 11.25 s and the peak wave period (Tz) was about 17 s. The wave height was approximately 2.5 m at the reef barrier and dissipated its energy on the shore of the Kavaratti island during the monsoon season. The direction of approach of these waves varied from southwest to westward in the wave period range of 8 to 9 sec in the lagoon[17].

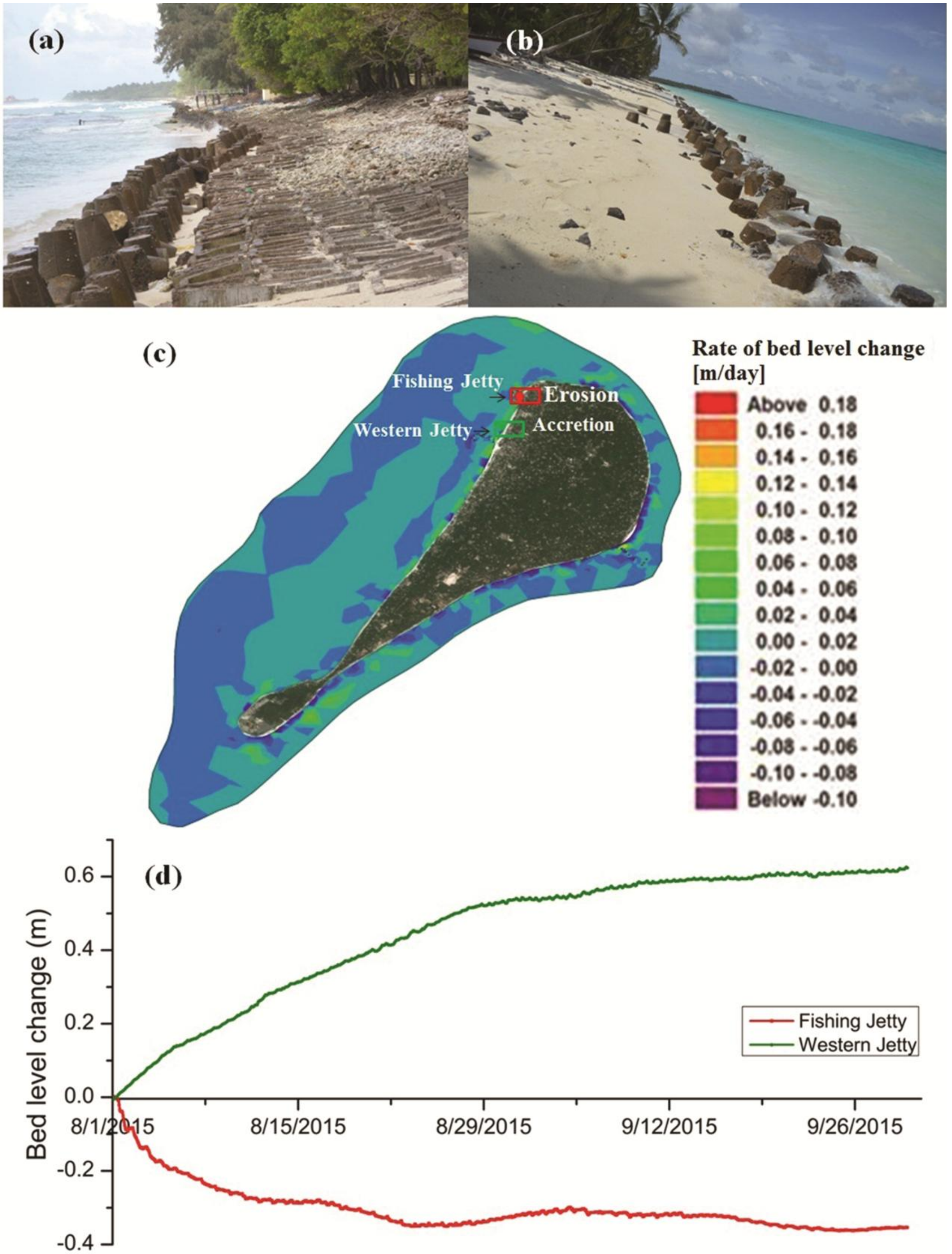

Fig. 7 — Field photographs of: (a) shore protection measures, (b) Erosion over the protection measures, (c) predicted bed level changes, and (d) Time series of bed level changes (m); at fishing jetty and western jetty of Kavaratti Island.

The complex flow field by the monsoonal wind fields, tides, and wave induced currents was observed around the island. Strong monsoonal currents of about 0.46 m/s were observed at the southern tip (near to helipad area) of the island during southwest monsoon, and 0.16 m/s at north and northwest of the island during the northeast monsoon season. Wave heights varied between 0.5 and 1.5 m during October to February, and 1 to 3.7 m during June to September around the island. Waves diffract and dissipate their energy in the lagoon and form the longshore currents around the barrier reef and at the shore of the lagoon. These longshore currents are actively interacting with the existing hard coastal structure and defense system of lagoon, thereby causing more accretion and erosion at the fishing and western jetty locations of the lagoon respectively (Figs.7c, d). Majority of the waves break at the barrier reef during the ebb tide and then tidal currents move in the dredging channels causing strong circulations in the lagoon. Similarly, waves crossing over the reef barrier breaks on the shore during flood tide. The breaking waves induced the average longshore current of about 0.15 m/s in the western side and 0.5 m/s in the eastern part of the Island. This current causes major alteration in the morphology of lagoon and enhanced the erosion/accretion activity along the coast in the monsoon season compared to other seasons.

The sediment grain size distribution significantly showed their effect on the deposition of sediments and is controlled by waves and currents. The beach sediment in the south part (near the helipad area) of the island are transported to north along the west coast in the lagoon and are redistributed after the monsoon season due to littoral current. Sedimentation is high in the southern tip and northern part of the lagoon compared to the central part of the island due to natural and anthropogenic effects. Moreover, the motorized boats, boat anchoring and mooring, dredging in the channel mouth causes the churning and suspension of sediments[18]. The strong currents enter through the channel mouth into the lagoon and move the sediments from the north mouth to south of the lagoon. This directly causes threats to the coral reefs and associated ecosystem health in the north part of the lagoon. The northwest lagoon ecosystem is highly affected by the anthropogenic stresses resulting in declining of reefs and threats to their survival due to the deposition of sediment over the reef system. The reef crest area in south west region of lagoon is healthy and has good live coral cover due to less sedimentation.

The occurrence of erosion is observed mainly due to the dredging of navigational channels and natural phenomenon. Kavaratti is highly affected by erosion, covering 84 % of the coast, by construction of infrastructure development and hard structures along the coast for shore protection. These have an adverse impact on an adjacent coral reef and also cause damage to coral reef[18]. The model predicted that the wave induced currents are responsible for the sediment transport in the west coast of the island. A few regions of the coast are stable because of control measures like boulders, tetrapods (Figs. 7a, b). The installed tetrapods along the coast of the island dissipate the wave energy by allowing the incoming waves, but they also enhanced erosion activities by scouring of the sediment particles through the swash. The model predicted that the most eroding sites are fishing jetty, helipad area, and chicken neck area of the island. This is useful information to the island administration to adopt suitable soft measures to protect the coast and for free movement of trapped sediments in the reef system of lagoon.

Conclusions

An integrated modeling approach is used to understand the nearshore sediment dynamics of the Kavaratti island. The results of model predictions revealed that the magnitude of ebb current is high compared to the flood current in the lagoon. It also predicted that strong monsoonal currents and high wave heights were at the south side and barrier reef off the lagoon region during the monsoon period. Sediment load is more on the south coast compared to the north part of the island. It is observed that more erosion is at the fishing jetty and accretion at the western jetty of the northwest of the island due to the combined effect of coastal processes and infrastructure development activity. Furthermore, the continuous dredging in the channel mouth and decline of outer lagoon reef will show negative response on the shoreline morphology. The real-time monitoring of hydrodynamic parameters and sediment transport using integrated model is highly expedient to the island administration to implement the suitable protection measures to control the sedimentation in the coral reef ecosystem and eroding sites along coast. This study will be also extended to identify the suitable mitigation measures such as geo-tube, geotextiles, beach nourishment etc. to prevent the shore erosion, and their cross-impact on the existing shoreline and sensitive coral ecosystem.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at http://nopr.niscair.res.in/jinfo/ijms/IJMS_49(05)845-857_SupplData.pdf

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Conflict of Interest

The authors declare no conflict of interests.

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