

Nearshore waves and longshore sediment transport along Rameshwaram Island off the east coast of India

Rajamanickam Gowthaman¹, V. Sanil Kumar¹, Gowdagere Siddaramaish Dwarakish²
P.R. Shanas¹, Basanta Kumar Jena³ and Jai Singh¹

¹*Ocean Engineering Division, CSIR-National Institute of Oceanography, Dona Paula, India*

²*Department of Applied Mechanics & Hydraulics, National Institute of Technology Karnataka, Surathkal, India*

³*National Institute of Ocean Technology, Pallikaranai, India*

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ABSTRACT: *Wave-induced Longshore Sediment Transport (LST) play an important role in the dynamics of the Dhanushkodi sandspit located southeast of Rameshwaram. The LST along the Dhanushkodi coast is studied based on data collected simultaneously in Gulf of Mannar (GoM) and Palk Bay (PB) using directional waverider buoys. The numerical model REF/DIF1 was used to calculate the nearshore waves and the LST rate was estimated using three different formulae. The model validation was done based on the measured nearshore waves using InterOcean S4DW. Numerical model LITPACK was also used for simulating non-cohesive sediment transport and the LITLINE module was used to study the shoreline evolution over 5 years. Low net annual LST along PB ($\sim 0.01 \times 10^6 \text{ m}^3$) compared to the GoM region ($0.3 \times 10^6 \text{ m}^3$) were due to the weak waves. Accretion in the region led to growth of the Dhanushkodi sandspit by 65 m during the period 2010-2015.*

KEY WORDS: Wave characteristics; Longshore sediment transport; Wave transformation; Remote sensing.

INTRODUCTION

A shoreline is defined as the line of contact between the land and a body of water (Dolan et al., 1980). The shoreline is strictly the water edge that migrates back and forth with the tide, but it is difficult to capture since the water level is always changing. The accurate demarcation and monitoring of a shoreline are necessary for understanding coastal processes (Natesan, 2008). Remote sensing technology is commonly used to map the shoreline and offers the potential of updating maps frequently (Frihy and Lofty, 1997). Short-term shoreline changes are also simulated and predicted using the one-dimensional LITPACK model (Mishra et al., 2014).

Knowledge of Longshore Sediment Transport (LST) is necessary for the assessment of natural shoreline changes due to the construction of nearshore structures. Normally, the gross LST is used to determine the dredging requirements or shoreline changes at a particular site based on the data covering one annual cycle. Rameshwaram Island, the geological formation of coral atoll with a huge sand cover between India and Sri Lanka, plays a vital role in the exchange of littoral drift between the east and west coasts of India (Rao, 2003). The Gulf of Mannar (GoM) receives sediment from the east-flowing rivers of the state of

Corresponding author: V. Sanil Kumar, e-mail: sanil@nio.org

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Tamil Nadu. It also receives sediments from the west coast of India via Kanyakumari (southern tip of India) and from Palk Bay (PB) (Chandramohan et al., 2001).

Studies on sediment transport along the east coast of India were initiated by Lafond and Prasada Rao (1954) and subsequently conducted by many investigators. Chandramohan et al. (1990) estimated the LST rate based on ship-reported data at a few locations along the Tamil Nadu coast. The east coast of India has a littoral drift pattern towards the north for eight months (March to October) and towards the south for four months (November to February) with a net drift towards the north (Chandramohan et al., 1990). Natesan and Subramanian (1993) studied the seasonal shoreline oscillation of the Tamil Nadu coast. Ramanujam et al. (1996) studied energy variations in the beach along with the morphological and sediment properties based on the surf-scale parameter along the Tamil Nadu coast. Jena and Chandramohan (1997) studied the LST near the peninsular tip of India, and Kumar et al. (2000) studied the longshore currents and LST along the Kannirajapuram coast, Tamil Nadu. Jena et al. (2001) reported the LST along the north Tamil Nadu coast based on directional waves. Kumar et al. (2003) compared the LST rate estimated using the CERC, Walton and Bruno, and Van Rijn formulae (Van Rijn, 1993) with measured data from along the central west coast of India. Natesan (2008) studied the shoreline dynamics of Dhanushkodi, Rameshwaram using the Geographical Information System. In view of the proposed Sethusamudram channel connecting the GoM and PB through the Dhanushkodi sandspit, there is an interest in knowing the nearshore wave characteristics, LST rate, and shoreline change along the coast facing the GoM and PB. Hence, a study on nearshore waves and LST was carried out based on the measured time series data on waves covering a one-year period.

STUDY AREA

Rameshwaram Island, Tamil Nadu, India is situated between PB in the north, the GoM in the south, and Sri Lanka in the east. The study area is located between the latitude of $9^{\circ} 25'$ to $9^{\circ} 31'$ N and the longitude of $79^{\circ} 05'$ to $79^{\circ} 31'$ E (Fig. 1). The length of the island is about 28 km in the east-west direction and it has a maximum width of 8 km in the north-south direction. The eastern end of Dhanushkodi, called the “Arichamunai Tip”, acts as a mixing point of the two water bodies (PB and the GoM) with different hydrodynamic conditions (Natesan et al., 2015). Dhanushkodi is on the eastern side of Rameshwaram Island, and this narrow strip of land is a few meters wide and is surrounded on all other sides by seas (the GoM in the south and PB in the north; Gowthaman et al., 2013). High intensity storms and cyclones attacked this area in 1964 and led to vast material and human losses. The beach berm is highly elevated (~ 2 m) along the sandspit bordering the GoM, but it is very low (< 1 m) and flat along the side bordering PB. There is a marked depression in the sandspit level between PB and the GoM between Dhanushkodi and Arichamunai. Most of the time, the water is stagnant and remains along the trough of the spit.

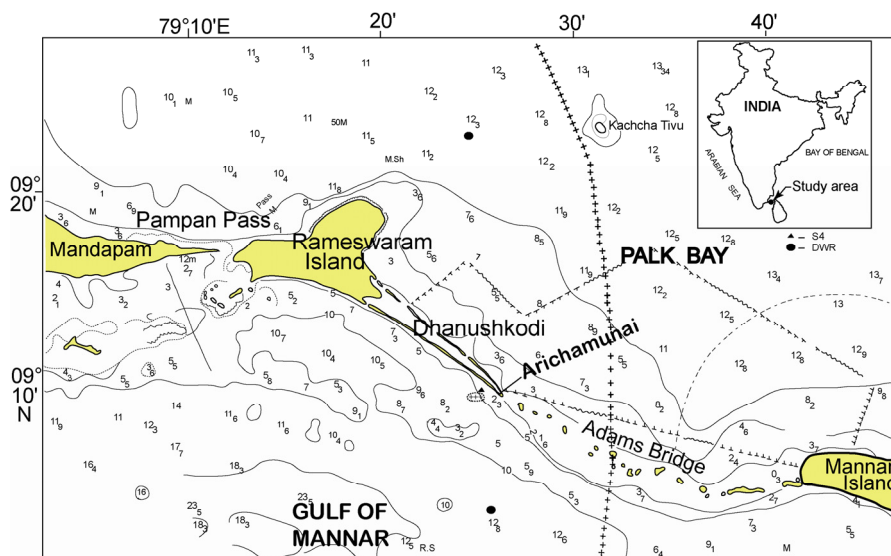


Fig. 1 Map showing the study area along with the waverider buoy locations (solid circle) in Palk Bay and Gulf of Mannar and the S4 current meter location (triangle) in Gulf of Mannar.

The tides in this region are semi-diurnal with a spring tidal range of 0.6 *m* and a neap tidal range of 0.16 *m* (Anonymous, 2011). Loveson et al. (1990) have indicated that large amounts of sediments are removed constantly by rainfall, carried by minor rivers, and dumped into PB. Natesan et al. (1993) observed the accretion pattern in PB at Ammapattinam, Mandapam, and Rameshwaram.

METHODS

This section describes the data used in the study and the methodology used for estimating the longshore sediment transport and shoreline changes.

Nearshore waves

The directional wave data used in the study was collected using Datawell directional waverider buoys placed in the GoM and PB at the locations 9° 06.75' N; 79° 24.42' E (GoM) and 9° 19.16' N; 79° 26.02' E (PB). The depth of the water at both measurement locations is 12 *m*. The wave parameters were collected at half-hour intervals for a period of one year from February 2010 to February 2011. The details of the data analysis and the characteristics of the measured wave data at a 12 *m* water depth are presented by Gowthaman et al. (2013). The model REF/DIF1 (Kirby and Dalrymple, 1983) is used in the present study to simulate the nearshore wave patterns from the measured wave data at a water depth of 12 *m*. Bathymetry of the GoM and PB region is digitized from the Naval Hydrographic Chart No. 358 and is used in the study. The measured wave characteristics are given as the input at the model boundary (12 *m* water depth). The model output gives the wave height and the wave propagation angle at each grid point. For the GoM and PB regions, the breaker heights at 1.5 *m* are extracted from the model output.

Wave data for validation of the nearshore wave transformation model is measured using the InterOcean S4DW wave gauge. The S4DW is moored at 0.5 *m* above the seabed at a water depth of 1.5 *m*. The gauge records pressure that is converted into depth data and the data records are transformed from the time domain to the frequency domain using the Fast Fourier Transform. The data are sampled at a rate of 2 *Hz* every three hours. The wave height and wave period are obtained from the wave spectrum.

Longshore currents

The longshore current is estimated using two commonly used equations: (i) Longuet-Higgins (1970) (Eq. (1)) and (ii) Galvin (1987) (Eq. (2)).

$$V = 20.7m(gH_b)^{1/2} \sin(2\alpha_b) \quad (1)$$

$$V = KgmT \sin(2\alpha_b) \quad (2)$$

where *V* is the longshore current velocity (*m/s*), *g* is acceleration due to gravity (*m/s²*), *m* is the slope of the sea bottom in the surf zone (*m*), *T* is the wave period(*s*), *H_b* is the breaking wave height (*m*), *α_b* is the angle between the breaking wave crest line and the local shoreline (*deg*), and *K* is the dimensionless coefficient depending on the geometry of the breaking wave. *K*=1 is used in the present study.

Longshore sediment transport

The Longshore Sediment Transport Rate (LSTR) is estimated using three different formulae: the CERC formula, the Walton and Bruno formula, and the Kamphuis formula.

The CERC formula

One of the simplest and most commonly used methods for calculating the LSTR is the Coastal Engineering Research Center (CERC) formula (SPM, 1984). Here, the LSTR is calculated from the empirical equation relating longshore energy flux in the breaker zone:

$$Q = \frac{KA\rho g H_b^2 T \sin(2\alpha_b)}{64\pi} \quad (3)$$

where Q is the LSTR (m^3/yr), K is the dimensionless empirical proportionality constant (taken as 0.39), $A = \frac{1}{(\rho_s - \rho)g(1-p)}$, and ρ_s is the sediment density (kg/m^3), ρ is density of seawater (kg/m^3), g is acceleration due to gravity (m/s^2), p is porosity factor (0.4), T is wave period (s), θ_b is wave breaking angle (deg).

The Walton and Bruno formula

Another equation used to calculate the LSTR was put forward by Walton and Bruno (1989). Using the breaker height and longshore velocity, the LSTR is calculated by the Walton and Bruno formula as:

$$Q = \frac{KA\rho g H_b W C_f}{0.78 \left(5\pi/2\right) \left(\frac{V}{V_0}\right)_{LH}} \quad (4)$$

where V is mean longshore velocity (m/s), W is surf zone width (m), C_f is friction coefficient, $(V/V_0)_{LH}$ is the theoretical dimensionless longshore current velocity with the mixing parameters as 0.4 (Longuet-Higgins, 1970).

The Kamphuis formula

Kamphuis (2002) developed an empirical formula that includes the nearshore slope, the wave period (T_p), and the sediment grain size (d_{50}) based on their laboratory experiments and existing field data:

$$Q = \left(\frac{2.27 H_b^2 T_p^{1.5} m^{0.75} d_{50}^{-0.25} \sin(\alpha_b)}{(\rho_s - \rho)g(1-p)} \right) \quad (5)$$

Shoreline changes

LITtoral Processes and Coastline Kinetics (LITPACK) numerical model in MIKE-21 software package developed by the Danish Hydraulic Institute (DHI) is used for estimating the sediment transport of non-cohesive sediments and shoreline changes (DHI, Version 2008). The main modules of the LITPACK are; Long-shore current and littoral drift (LITDRIFT), Coastline evolution (LITLINE), Cross-shore profile evolution (LITPROF). The LITDRIFT module was used to estimate the LST rates. The module includes important sediment transport mechanisms, such as nonlinear wave motion, the turbulent bottom boundary layer, wave breaking, and sediment grading (DHI, 2008). It is an essential combination of a One-Dimensional (1D) wave model, a 1D hydrodynamic model and an intra wave sediment transport model (STP). The suspended sediment transport is calculated as the product of sediment concentration and the mean circulation current average over the wave period. The input data for the LITDRIFT module are the wave climate as a time series data, the initial coastline, and the sediment characteristics. The LITDRIFT profiles are created using bathymetry, roughness, mean grain size, fall velocity, and geometrical spreading. The profiles considered in the study are shown in Fig. 2. The roughness used in the study is 0.004 and the geometrical spreading is 1.5.

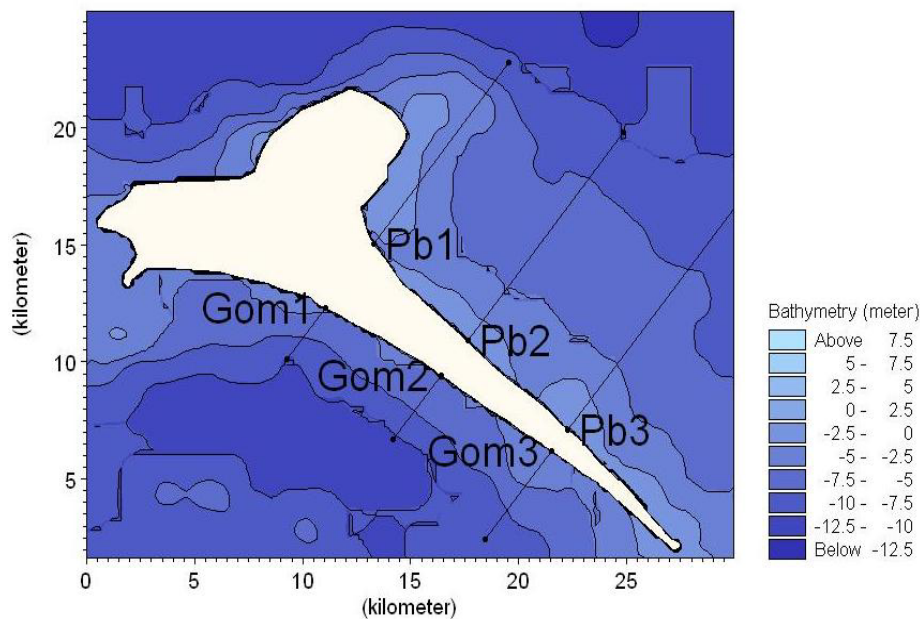


Fig. 2 Bathymetry and cross section profile used in LITDRFIT model.

The LITLINE simulates the coastline using the wave climate and five beach variables (i.e., beach position, sand dunes position, height of dunes, profile number, and water depth). The wave climate is prepared from the observed wave data. The simulation is carried out for the evolution of 6 km of coastline on both sides of the GoM and PB to predict the scenario of the coastline for 3 years (2010-2013) and 5 years (2010-2015).

RESULTS

This section describes the characteristics of waves measured at water depths of 12 m and 1.5 m along with the estimated breaker parameters and longshore sediment transport.

Nearshore waves

In the GoM, waves are high during May-October. The monthly average significant wave height (H_s) is above 1 m and the maximum H_s is 2.7 m. During November-March, the monthly average H_s is 0.5-0.6 m. In December, a H_s up to 2.4 m is recorded due to tropical depressions/storms. During the one-year period examined in this study, 47% of the recorded waves had a H_s between 0.5 m and 1 m and 26% of the recorded waves had a H_s between 1 and 1.5 m (Fig. 3). The mean wave period varied from 2-11 sec with high values occurring during February-April owing to the dominance of swells. During the rest of the year, wind-seas are dominant. The dominance of the swells is at its maximum (98%) during March and the dominance of the wind-seas is at its maximum (93%) during October. Waves are predominantly from the south-southwest direction (Fig. 3).

Since PB is a semi-enclosed basin with a shallow connection to the Bay of Bengal and the GoM, the waves in PB are dominated by the wind-seas. The monthly average H_s is less than 0.6 m, except during the period December-February. The maximum H_s recorded is 1.8 m during November. Forty-six percent of the waves recorded had a H_s between 0.5 m and 1 m. The mean wave period varied from 2-5 sec. Waves were predominantly from the north-northeast during the period November-February and from the south-southeast during the period April-October (Fig. 4). The relatively small values of wave heights measured at 12 m depth, particularly in the PB are due to the attenuation after propagating for a long distance over the shoals connecting to the Bay of Bengal and due to the natural shelter i.e. the North end of Sri Lanka.

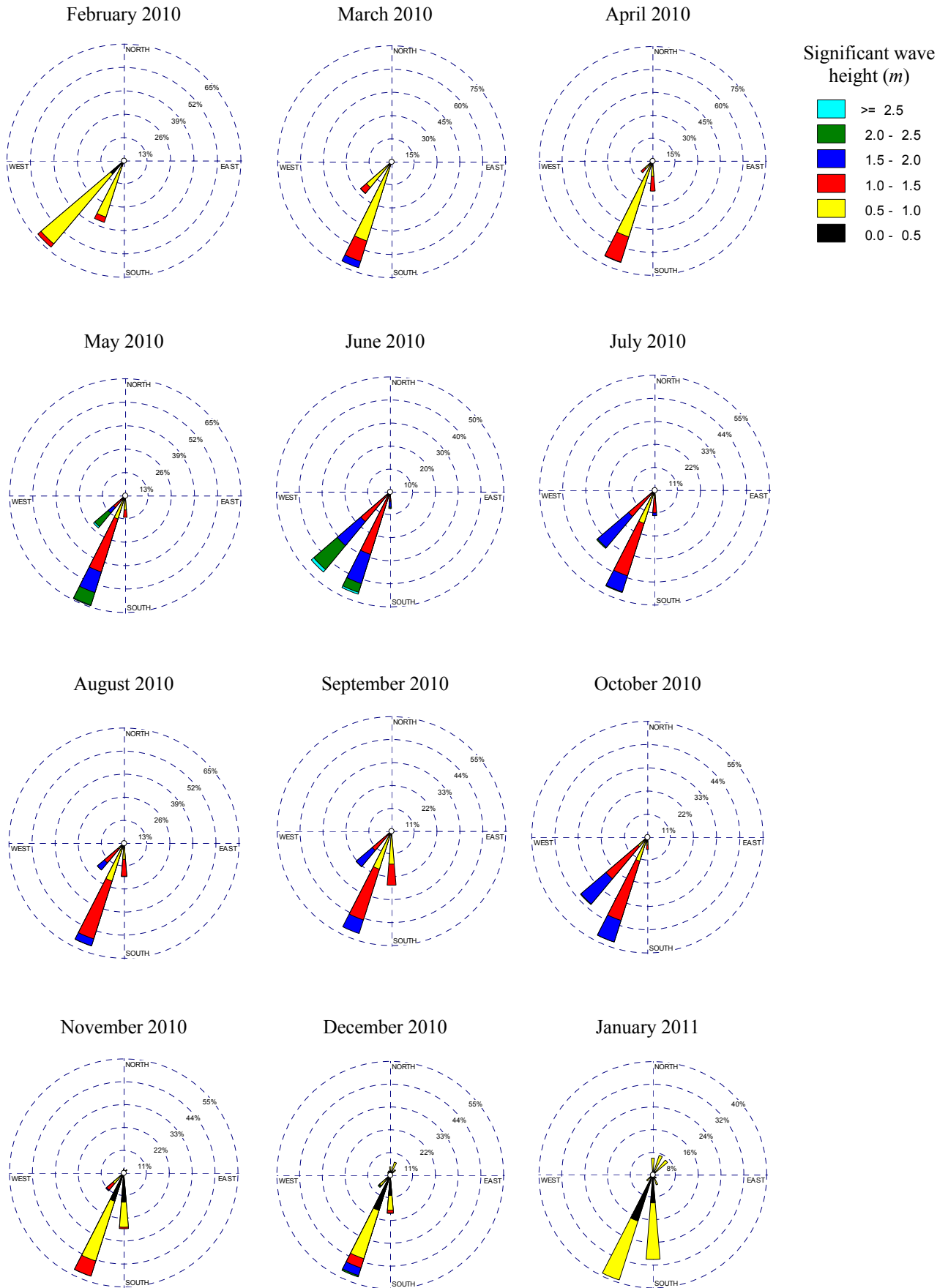


Fig. 3 Monthly wave rose diagram based on data collected in Gulf of Mannar.

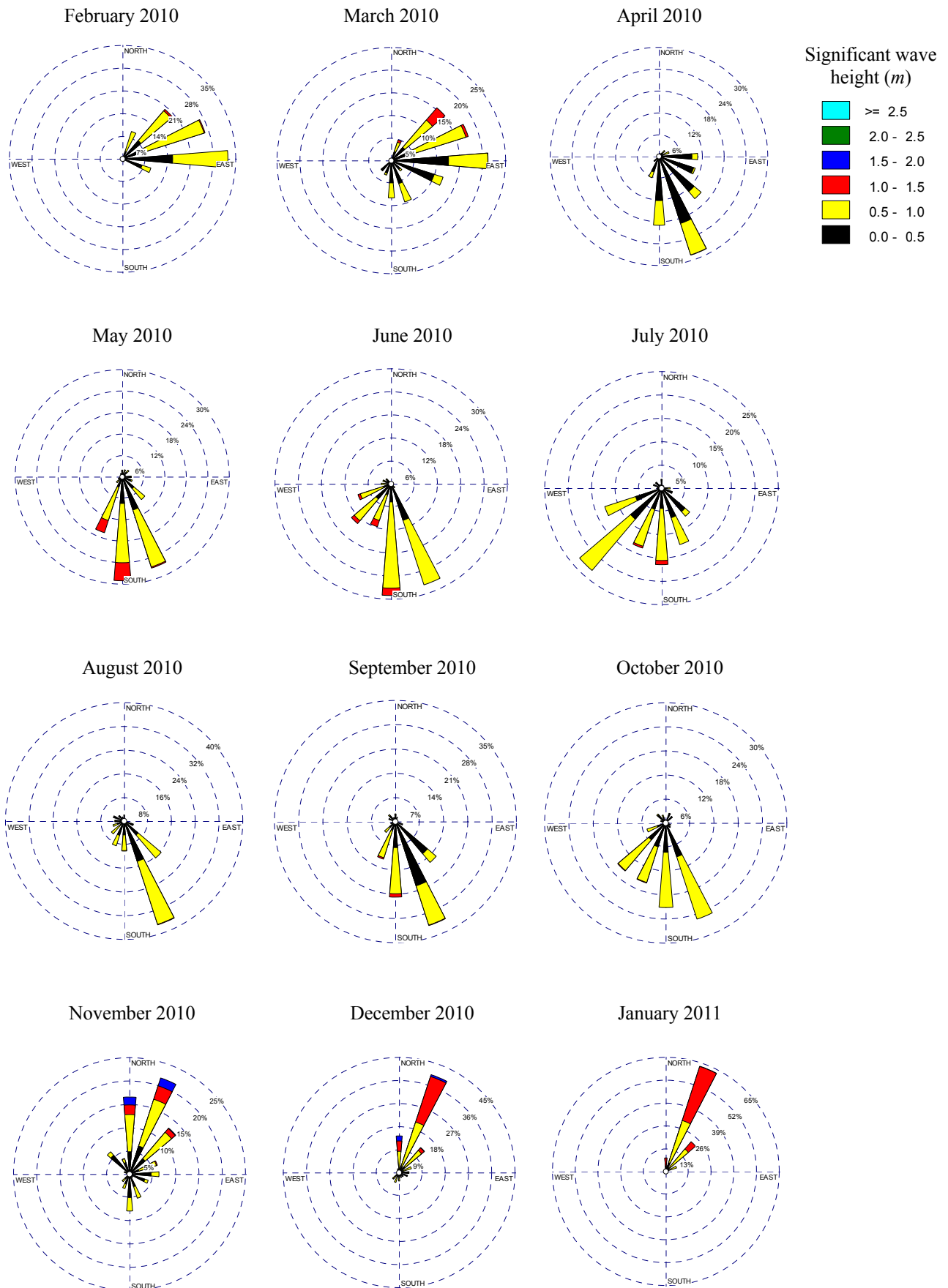


Fig. 4 Monthly wave rose diagram based on data collected in Palk Bay.

Breaking wave characteristics

The results of the model output are compared with measured wave data at a 1.5 m depth for a period of 40 days during the months of November to December along the GoM (Fig. 5). The correlation coefficient between the model estimated value and the measured value is 0.62. During 6-9 December 2010, there is a large difference between the model and measured wave height and the model estimated value is almost double of the measured value. The large difference is due to the depression "BOB06" formed over the Bay of Bengal during 6-9 December 2010, which generated high waves at 12 m water depth, but the measurements at 2 m water depth shows that its influence is less at 2 m water depth may be due to the frictional dissipation and breaking. Fig. 5 indicates that the numerical model will not give good results during tropical storm/depression. During the study period, the breaking wave height varied between 0.1 m and 1.7 m in the GoM with the maximum value occurring during the southwest monsoon season (June to September).

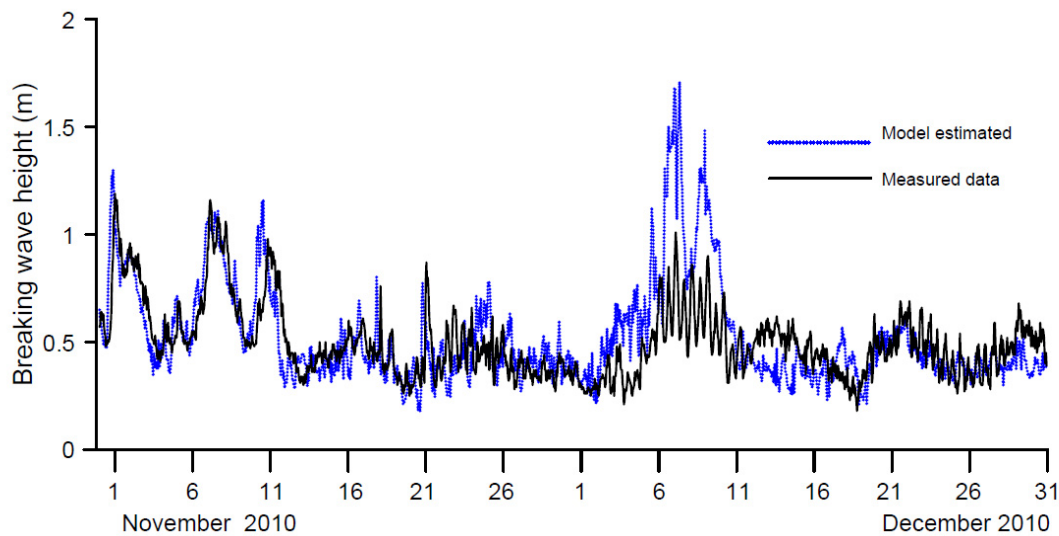


Fig. 5 Time series plot of measured breaker height and that estimated based on numerical model (November-December 2010).

In PB, the breaking wave height varied from 0.05 m to 1 m with maximum values during November to May. The breaker period mostly ranged between 1.9 sec and 10 sec in the GoM and 1.9 sec and 6 sec in PB. The wave breaker angle with respect to the coast ranged from -29 to 29° in the GoM and -12 to 17° in PB. Negative values indicate waves approaching from southwest and positive values indicate waves approaching from southeast in GoM coast. Whereas in the PB coast positive values are for northeast waves and negative values are for northwest waves.

Longshore current

Along the GoM coast, the mean longshore current is predominantly in the south-eastward direction with a speed up to 0.3 m/s (Fig. 6A). Negative values in Fig. 6 indicate longshore current towards east and the positive values indicate current towards west. Along the PB coast, the longshore current speed is less than 0.2 m/s (Figure 6B). Even though the H_s is less (average value 0.7 m) during the pre-monsoon period, the longshore current is high (upto 0.3 m/s) and during the monsoon period, the H_s is high (average value 1 m) and the longshore current is less (upto 0.15 m/s). The correlation of longshore current with breaker angle is high (~ 0.9) compared to breaker height (~ 0.3). The study shows that for the locations considered, the longshore currents are more influenced by the breaker angle than the breaker height and mean wave period. Rao (2003) observed that the longshore currents along the spit remained weak (< 0.1 m/s) during the northeast monsoon, particularly between Dhanushkodi and Arichamunai facing the GoM. Consequently, strong currents (~ 0.2 m/s) are observed between Mukkuperiyar and Dhanushkodi.

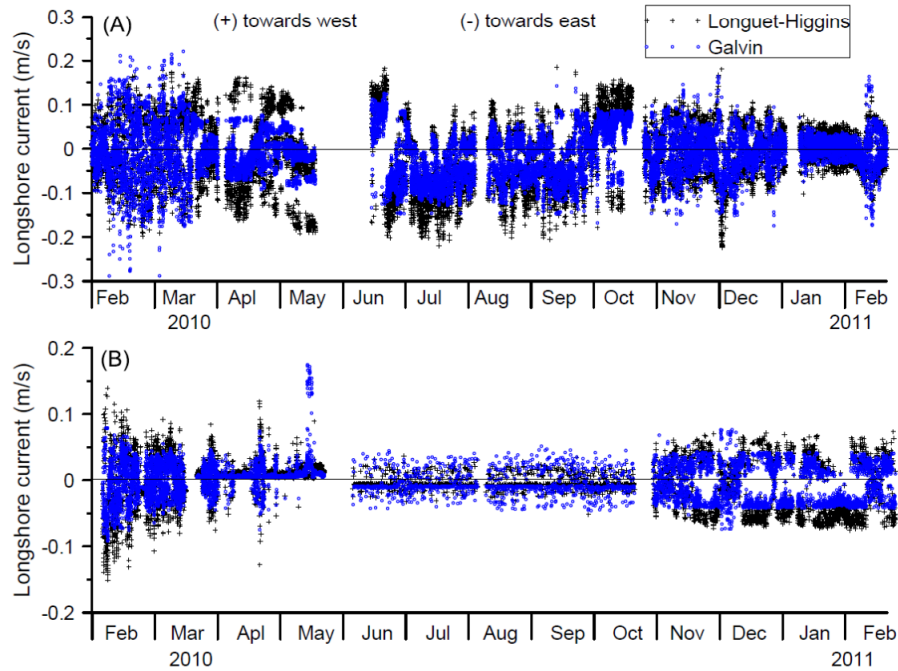


Fig. 6 Time series plot of longshore current off (A) Gulf Mannar and (B) Palk Bay.

Longshore sediment transport

The LST computed for a period of 40 days from November to December along GoM based on the numerical model are compared with the value estimated based on the measured nearshore parameters (Table 1). It is found that the average LST per day computed based on the measured breaker parameters are similar to that based on breaker parameters estimated from the numerical model with a least square error of less than 10%.

Table 1 Longshore sediment transport rate estimated from measured breaker parameters and that based on numerical model along GoM.

Formulae used	Sediment transport rate estimated from measured breaker parameters for 40 days $\times 10^4 (m^3)$	Sediment transport rate computed based on wave parameters obtained from numerical model for 40 days $\times 10^4 (m^3)$	Average sediment transport rate per day	
			Measured $\times 10^3 (m^3)$	Computed $\times 10^3 (m^3)$
CERC	3.1671	2.840	0.791	0.710
Walton and Bruno	3.317	3.016	0.829	0.754
Kamphuis	2.866	2.588	0.716	0.647

The monthly variation of LST is studied based on the value estimated using the CERC, Walton and Bruno, and Kamphuis formulae. The monthly LSTR is high during the southwest monsoon season and the predominant direction of transport is south-eastward. The gross LSTR estimated from February 2010 to January 2011 along the Dhanushkodi sandspit (the GoM region) is found to be $0.6 \times 10^6 m^3$, $0.62 \times 10^6 m^3$, $0.58 \times 10^6 m^3$ for the CERC, Walton and Bruno, and Kamphuis formulae, respectively. The net LST along the Dhanushkodi indicates that the predominant direction of transport is south-eastward. Its value based on the three formulae (CERC, Walton and Bruno, and Kamphuis) is $0.3 \times 10^6 m^3$, $0.28 \times 10^6 m^3$, $0.23 \times 10^6 m^3$, respectively. The sensitivity of the wave direction on the estimation of the LSTR is checked by estimating the LSTR values by increasing and decreasing the value of the wave direction by 5° . The estimated values are 13 to 20% less than the values for a 5° increase in wave direction and they are 30 to 40% more than the values for a 5° decrease. Whereas the LST along PB is negligible as compared to the LST along the GoM, the gross LSTR is only $0.047 \times 10^6 m^3$, $0.045 \times 10^6 m^3$, and $0.042 \times 10^6 m^3$ based on 3 formulae and the net transport is found to be north-westerly (Table 2).

Table 2 Annual net and gross longshore sediment transport rate along GoM and PB.

Sediment transport formula	Longshore sediment transport rate at Dhnaushkodi along GoM in $\times 10^6 m^3/year$		Longshore sediment transport rate at location at Dhanushkodi along PB in $m^3 \times 10^6 m^3/year$	
	Net towards south-east	Gross	Net towards north-west	Gross
CERC	0.30	0.6	0.015	0.047
Walton and Bruno	0.28	0.62	0.010	0.045
Kamphuis	0.23	0.58	0.012	0.042
LITDRIFT	0.45	0.53	0.05	0.06

Simulations are carried out for three different profiles at both the GoM and PB using the LITDRIFT module of the LITPACK numerical modeling software. Based on the simulations, the calculated annual net and gross LST are 0.45 and $0.53 \times 10^6 m^3/year$ along the GoM and 0.05 and $0.06 \times 10^6 m^3/year$ along PB. In contrast, the annual net and gross LSTR from the CERC equation are 0.3 and $0.6 \times 10^6 m^3$ along the GoM and 0.015 and $0.047 \times 10^6 m^3$ along PB. The numerical model over-estimated the net LSTR at both GoM and PB, whereas the difference in gross LSTR values estimated by numerical model and the empirical equations are less. The net LSTR based on empirical equation depends on the direction of the breaking wave and the difference in net LSTR based on empirical equation and numerical model is due to the error in estimation of breaking wave direction.

Simulations are carried out for the evolution of $6 km$ of coastline on both the GoM and PB coasts for 3 (2010-2013) and 5 years (2010-2015). The initial shoreline used in the study is based on the field measurements carried out in 2010 using RTK-GPS. The measured coastline is compared with the coastline extracted from a satellite image and the compared results show that the measured shoreline are very compatible with the extracted coastlines using the remote sensing technique. The coastline change between 2010 and 2015 is presented in Fig. 7. The study shows that the prediction of shoreline variation needs field observation and continuous wave and current data. If the time history of the original shoreline measurement is not available, remote sensing technology helps to monitor the shoreline. Accretion in the region led to growth of the sandspit along Dhanushkodi by $65 m$ during the period 2010-2015. Natesan (2008) observed a growth of small land mass along with elongation of about $0.02 sq.km$ near the tip during the period 1986-1996.

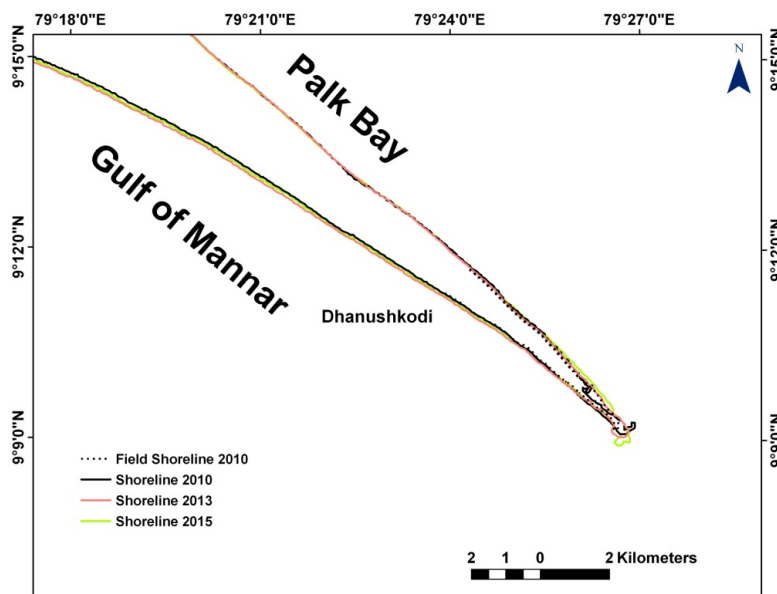


Fig. 7 Shoreline measured during 2010 and that predicted for 2013 and 2015.

DISCUSSION

The GoM is open to predominant swells from the South Indian Ocean. Hence, both wind-seas and swells are observed in the GoM. In contrast, PB is nearly a semi-enclosed region and no swells from the South Indian Ocean enter this region. Local winds play a major role in generating waves in PB. Waves in both the GoM and PB were generally weak during the months of February–April (the pre-monsoon season) because the local and synoptic wind systems are weak during this period. Cyclones and storms are prevalent in the Bay of Bengal during May and in October/November; therefore, large waves are generated during these periods. Also, the summer monsoon winds during the months of June–September had a significant impact on the region. The waves are higher in the GoM than in PB with a maximum H_s of 2.7 m in the GoM and a maximum H_s of 1.9 m in PB. Seasonal variation in the wave height was recorded in both locations. The H_s was higher during the summer monsoon in the GoM and during the northeast monsoon in PB. The waves in PB are relatively high during the northeast monsoon compared to the rest of the year because the local winds are stronger at this time of the year.

During the northeast monsoon period, the littoral currents move towards the south and alter the rate of change of erosion/accretion. This is similar to the observation of Thanikachalem and Ramachandran (2003). Although the longshore current is extremely weak along the sandspit facing PB, it tends to be easterly during the southwest monsoon and the fair weather period. Similarly, at Arichamunai, the direction of the longshore current is southerly during the southwest monsoon and the fair weather period and northerly during the northeast monsoon. This indicates a phenomenon that is opposite to the phenomenon observed along the GoM coast. Such processes indicate the accumulation of littoral drift on either side of Rameshwaram Island during the southwest monsoon and the removal of sand during the northeast monsoon: making this region a sediment storage reservoir.

It is seen that the annual LST is relatively low along the Dhanushkodi coastline as compared to the rest of the east coast where the transport is well over $1 \times 10^6 m^3$ (Chandramohan et al., 1990). Based on the monthly visual Littoral Environmental Observation, Rao (2003) reported a LSTR of $0.8 \times 10^5 m^3$ along the GoM coast and a LSTR of $0.027 \times 10^5 m^3$ along the PB coast. The large difference in the values of the LSTRs observed in the present study compared to Rao (2003) is because the estimates in Rao (2003) are based on a single value in a month, whereas in the present study we have used values at 30 minutes interval. In reality, the wave characteristics and longshore currents vary significantly in a month (in fact, they vary hourly).

CONCLUSIONS

This study examines the longshore sediment transport rate (LSTR) around the Dhanushkodi sandspit. The LSTR computed for the period November to December is compared with the value estimated based on measured nearshore parameters. The LSTR obtained from the numerical model (LITDRIFT) is compared with the LSTR obtained from the CERC formula. The net sediment transport along the GoM coast at Dhanushkodi indicates that the predominant direction of transport is south-eastward and is $0.3 \times 10^6 m^3$, $0.28 \times 10^6 m^3$, $0.23 \times 10^6 m^3$ based on the CERC, Walton and Bruno, and Kamphuis formulae, respectively. The LSTR along the PB coast at Dhanushkodi is negligible as compared to the LSTR along the GoM. The gross LSTR along the PB coast is $0.045 \times 10^6 m^3$ and the net transport is westerly. The numerical model studies based on the LITLINE module of LITPACK shows that, during the last 5 years (2010–2015), the sandspit along Dhanushkodi grew by 65 m due to the net south-eastward LST along the GoM coast.

ACKNOWLEDGMENTS

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