

What drives nearshore sediment transport controls on the depletion of beach placers at Manavalakurichi, southwest coast of India?

P. K. Dinesh Kumar^{1*}, R. Mani Murali,² M. T. Babu², K. Sudheesh², P.Vethamony² and K.R. Naveen Kumar¹

¹*CSIR-National Institute of Oceanography, Regional Centre, Kochi, 682018, India;* ²*CSIR-National Institute of Oceanography, Dona Paula, Goa, India.*

Abstract

An in-depth analysis has been made to simulate hydrodynamic scenarios for understanding the nearshore sediment transport controls of placer mineral depletion at Manavalakurichi, India. From the analyses of topographic configuration (extracted from Hydrographic Nautical Chart No.2048 and data generated during year 2010), we inferred that the 5-m isobaths had broadened and exhibited shallowness. Distances between the coastline and the isobaths were found to have increased significantly over the past five decades. Along with this, the 10-m and 20-m contours were found to have shifted about 35 m–100 m horizontally landward. These changes led to severe sediment deposition in these regions due to the changed wave energy levels and refraction patterns. Numerical simulations linking bathymetry, hydrodynamics, sediment load, and significant wave heights revealed that changes in bathymetry would amplify the wave heights and convergence of wave energy. Associated removal of sand from the high-energy zones will eventually lead to sediment starvation situations and depletion of placers in the adjacent beaches. As the observed trends of depletion generate great concern, detailed oceanographic investigations should be taken up immediately in the region. Fine-resolution hydrodynamic data sets should prove useful for further evaluating the physical responses of the system to the signatures resulted from the altered geometry and for exploring remedial measures for restoring the heavy mineral content of the beach sand.

Keywords: Beach placers; coastal processes; sediment transport; numerical models; depletion; India

*Corresponding author e mail: dineshku@nio.org

Introduction

Placers occur worldwide at all elevations and most latitudes. Beach placers supply almost all the world's heavy minerals. Formation, transportation, accumulation and concentration of placer deposits in the beaches are identified as a result of complex coastal processes (Rittenhouse, 1943). The fertile province of hinterland rocks are deeply weathered during which process the minerals are liberated, the stable and resistant minerals become enriched, and well connected drainage systems in the vicinity transport the sediments to the coastal zone. Dynamic actions within the coastal zone further facilitate concentration and enrichment of minerals in the adjacent beaches. Waves sort out heavy minerals and transport them onshore based on size and specific gravity. The direction and strength of the coastal currents invariably determine the final location of the deposits.

Placer concentration along the beach is considered to be due to cumulative factors, and drastic depletion of mineral content in beach placers is a well-discussed topic worldwide (Peter, 2008). However, the processes of sediment transport controls for this phenomenon are less explained and less understood. Numerical modelling of coastal processes, validated with field studies has great potential to assist with the understanding of formation and depletion of placers in the coastal marine environment. In turn, a study of existing deposits enhances our understanding of changes affecting present-day coastlines and of factors leading to placer depletion.

With a vast coastline of over 7000 km, large deposits of beach sand minerals have been reported at selected locations in the coastal stretches of peninsular India (Ali, Krishnan, & Banerjee, 2001; AMD, 2000; Ashwathanarayana, 1964; GSI, 1976; Gujar, 1996; Hashimi, Kidwai, & Nair, 1984; Jacob, 1956; Siddiquie & Rajamanickam, 1979; Tipper, 1914). Rich deposits of heavy sands occur at Manavalakurichi, on the southwest coast of India, which is considered to be one of the largest deposits in the world. Over the past several decades, this deposit has been extensively exploited commercially for important minerals, such as ilmenite, rutile, garnet, and monazite (Ali, Krishnan, & Banerjee, 2001; Vivekandan, 2005).

Over the decades, it has been observed that the quantity of heavy minerals in the sand mined through beach washing in the mining belts of Manavalakurichi has diminished considerably (Anonymous, 2011). The present study is an attempt to identify the processes controlling near shore sediment transport, with a consideration of the scale of associated components of coastal hydrodynamics. An in-depth analysis has been made by integrating coastal ocean current-meter deployments and topographic signatures, to simulate scenarios of transport, and coastal circulation characteristics, for

understanding the near shore sediment transport controls, to identify the specific factors that play prominent roles in sediment transport controls and concentration of the beach placers.

Physical setting

The study area is located along the southwest coast of India, bordered on the east by the Western Ghats and the Arabian Sea on the west. Manavalakurichi (Figure 1) is situated at about 35 km from Kanyakumari, the southernmost tip of India. The coast forms a promontory in the center with adjacent creeks, dunes and open sandy beaches enriched with heavy minerals. The placer deposit zone falls between Lat $8^{\circ} 08' 5''$ and $8^{\circ} 10' 05''$ N and Long $77^{\circ} 15' 50''$ and $77^{\circ} 18' 15''$ E. Sorting effects of waves and coastal currents play important roles in the formation and deposition of placers. Rajamanickam, Vethamony, & Gujar(1986) attributed the segregation level of heavy minerals to the effect of zones of convergence and divergence of waves along the coast. Nayak (1997) described a distribution pattern of high-density minerals near the river mouth and low-density minerals far offshore. The genesis of the southwest placers might have been heavily influenced by changes in the shoreline of the west coast in the Quaternary, associated with tectonic and sea-level changes (Suresh Babu & Thirvikramaji, 1993). It is argued that the development of estuaries along the coastal fringe, the submerged beaches, and paleo-placers offshore form the main source of enrichment of the present-day placer deposits aided by waves and currents (Dhanunjaya Rao, KrishnanaianSetty, & Raminaidu, 1989; Kurian, Prakash, & Jose, 1997; Nair, Damodaran, & Suresh Babu, 2002; Prakash, Kurian, & Jose, 1997; Thirvikramaji & Anirudhan, 1991). In spite of these studies, the genesis and processes involved in the evolution have not been understood clearly.

Methodology

Field data and analysis

Field investigations of physical oceanographic characteristics off Manavalakurichi were carried out during the year 2010 to generate baseline data for assessing the prevailing characteristics of the hydrodynamics of the coastal marine environment. Detailed bathymetric survey was also carried out during this period to generate scenarios of bathymetric change analysis (Anonymous, 2011). Tides and currents were measured in the study domain by deploying self-recording current meters and tide gauges. To achieve an understanding of the coastal hydrodynamics and circulation patterns in the region, it is essential to carry out multiple deployments of recording current meters. Periods of intensive sampling are required to cover tidal cycles of neap and spring periods for arriving at the most comprehensive understanding of coastal currents using moored current meters. Current velocities will vary spatially throughout, and measurements should therefore extend to cover the

likely range of nearshore circulation zones for the pre-monsoon and post-monsoon seasons. Ultimately, the data generated are utilized to calibrate the hydrodynamic transport model developed for the region. Measurements were made during April and October 2010 by deploying recording current meters in the sea. The current meters were deployed at 1 m below the surface and at 1 m above the bottom to measure surface and near bottom currents at Lat $8^{\circ}11' 30''$, Long $77^{\circ} 10' 45''$ during the periods 13–25 April 2010 and 15–30 October 2010.

Advances in the knowledge of coastal processes combined with improvements in the availability of advance computing facility has permitted increased mathematical simulations of sediment transportation in the coastal zones. These mathematical simulations/models, coupled with oceanographic data are useful tools for use by scientists and coastal zone managers for estimating the transport and fate of coastal sediments. The MIKE21 numerical modelling system, having different modules to analyze varied coastal processes, was used to simulate hydrodynamics and waves of the study region (DHI, 2009). Simulation results were validated with available measurements. The modelling software has been used in the present study to simulate water level, currents, and waves. Specific modules used in the present study were Flow Model FM (Flexible Mesh) for hydrodynamics (HD) and Spectral waves FM (SW). The hydrodynamic simulation has been done for the different scenarios of bathymetry of the study region. Simulation results were validated with the field data generated therein. Hydrodynamic simulation was carried out for the following scenarios: Case (i) with Naval Hydrographic Office chart bathymetry (Anonymous, 2000) and Case (ii) with the latest bathymetry (updated NHO with the near shore bathymetry generated during 2010). Model runs for these cases were carried out to simulate the variation in surface elevation and currents, and the results were validated with observed data sets. The data generated were used to calibrate the hydrodynamic transport model developed for the region. A comparison between model-simulated tides extracted at the current meter mooring location and tides obtained from measurements was attempted to test the validity of the results obtained.

Results and discussion

Tides

Tides prevalent in the region are mixed and predominantly semi-diurnal in nature (Anonymous, 2010). During any particular day, the dominant forcing is semi-diurnal and the diurnal signal may be seen during some phases of the moon. The mean spring tide ranges are 62 cm and 56 cm at Manavalakurichi and the nearest major port, Vizhinjam, whereas the mean neap tide ranges are 13 cm and 20 cm, respectively. Further, it can be observed that that the spring-to-neap variability is

higher at Manavalakurichi than at Vizhinjam. As the tidal range is below 2.0 m, both locations are classified as micro-tidal. The range at Manavalakurichi is less than 1.0 m, which is slightly higher than the range at Vizhinjam.

Currents

Currents play a significant role in governing the various physical processes in the coastal marine environment. The coastal ocean is an extremely dynamic environment due to the combined actions and interactions between different components of forces acting there. Tidal velocity oscillations provide the important mechanisms of energy supply in the coastal waters. Reasonable understanding of coastal hydrodynamics could be achieved by generating and analyzing site-specific physical oceanographic parameters, such as tides and currents. Measurements of tides and currents were carried out during October 2010 and used for the analysis and to calibrate the hydrodynamic transport model developed for the region.

Variation of current speed and direction observed during 15 October 2010, 1200 hrs, to 30 October 2010, 0500 hrs, is presented in Figure 2. The alongshore component of current (U-component) showed a mean of 6.3 cm/s, with a standard deviation of 9.0 cm/s; the minimum and maximum components were 15.2 cm/s and 44.6 cm/s. The cross-shore component of current (V-component) showed a mean of 7.6 cm/s, with a standard deviation of 5.9 cm/s; the minimum and maximum components were 25.7 cm/s and 11.0 cm/s. The current speed showed a mean of 12.9 cm/s, with a standard deviation of 6.7 cm/s; the minimum and maximum speeds were 1.9 cm/s and 51.1 cm/s. Currents observed were found to be moderate. Further, the U and V components of currents also clearly showed negative and positive values, reflecting bi-directionality and suggesting onshore-offshore movement as well as along-shore flow. The progressive vector diagram of the currents is presented in Figure 3. The overall movement of the current during the period of observation was found to be in the south-eastward direction, the maximum east-west movement being 84.5 km, and the maximum north-south movement 97.7 km. The mean flow direction was generally directed towards 145°, showing the physiographic reflectance of the geomorphology of the adjacent coast.

Bathymetric signatures

Recent sedimentation processes on the sea bed can be attributed to functions of bathymetry, as changes in bathymetry can result in differences in the depositional environment, with corresponding changes in bed form. Historical bathymetric data sets, along with the updates, are a primary source of information for documenting the long-term changes that have taken place. The bathymetry of the past is available in the form of the Hydrographic Nautical Chart No. 2048, published in the year 2000. The chart depicts the bathymetric data compiled from Indian Navy surveys in the years 1962,

1969, and 1992, and corrections in 2000. To compare the bathymetric data, the latest surveyed data were gridded and superimposed on Hydrographic Nautical Chart No. 2048, using a common geodetic coordinate system. Further, to study the topographic variation of the seabed, depth profiles were extracted perpendicular to the depth contours. Past and present bathymetric signatures in the study region are depicted in Figure 4.

Comparative analysis of bathymetry data for different time periods, spanning over five decades, revealed that 5-m isobaths have broadened and exhibited shallowness in the nearshore region of the study domain. The distance between the coastline and 5-m isobath significantly increased. The 10-m and 20-m isobaths, too, have shifted about 35 m to 100 m horizontally. These changes imply severe deposition in this region, which resulted from the wave energy levels and refraction patterns. The shallow depths observed all along the nearshore regions may lead to the deposition of placer minerals at offshore zones instead of deposition along the beaches. A small valley-like feature was found developed off of Manavalakurichi and can be seen in the NHO charts. A similar type of deepening can be observed near Mandakkad, and the offshore zones of Kadiapattinam and north of Kolachel were also shallow. The contour of 20 m depth, which was showing a curve in 1992 data at north of $2^{\circ} 8'08''$, $77^{\circ} 16'$, was not seen in the 1969 chart. Broadening of the 0-m to 5-m depth zones had resulted in the changed steep to gentle slopes. Overall observation of bathymetry over the decades leads us to conclude that the nearshore regions have become shallow, with gentle slopes. Thesea bed gradient is found to be moderate along the SE regions, but to increase towards the NW direction. The seabed in the survey region, too, was steeper near the coast, with a gradient of 1:200, whereas it is undulating in deeper zones, with a gradient of 1:300. The comparison reveals that the 30-m contour retains its horizontal position in the latest bathymetry data, as well. Further, there exists a slight horizontal shift of about 35–55 m in the 20–m depth contour towards the shore. The 10-m depth contour also follows a similar shift of about 70–100 m landward. These marked changes in the bathymetry may play a significant role in changing the transport and distribution pattern of placer deposits in the adjacent beaches.

Model simulations

The model domain of 52 km x 33 km, with the measurement location of currents (M), is shown in Figure 5. Bathymetric survey data generated during the year 2010 in the region are integrated with depth data digitized from the Hydrographic chart (Chart No. 2048). Digital bathymetry files were prepared in UTM coordinates. Southern, northern, and western boundaries were kept open and, accordingly, the boundary conditions were applied. Fine-resolution flexible triangular grids were

generated within the model domain using the bathymetry data. The maximum water depth encountered in the model domain was 70 m.

Open boundary tides and winds are the basic model input parameters used for the hydrodynamic simulations. The model domain was set up with the southern boundary kept at Muttam and the northern boundary at Vizhinjam so that the tide data available at these stations could be used as input parameters. Surface elevations at Muttam ($77^{\circ} 23' E$, $8^{\circ} 6' N$) in the south and Vizhinjam ($76^{\circ}59' E$, $8^{\circ}22' N$) in the north were predicted using the harmonic constituents available for the tide gauge stations and the tides along the open boundary were generated.

The MIKE21 toolbox utilities were used for predicting the surface elevations from the major tidal constituents, such as M2 (principal lunar semi diurnal), S2 (principal solar semidiurnal), K1 (lunar diurnal), O1 (lunar diurnal), N2 (larger lunar elliptic semidiurnal), K2 (lunisolar semidiurnal), P1 (solar diurnal), Q1 (larger lunar elliptic diurnal), M4 (shallow water over tides of principal lunar), MS4 (shallow water quarter diurnal) and N4 (shallow water over tides of principal solar) at these coastal tidal stations. The predicted water levels at Muttam and Vizhinjam are given in Figure 6 and the maximum and minimum predicted water levels in Table 1. The tide elevations along the open model boundaries were prescribed based on interpolated tides. Model simulations were carried out for the months of measurements where surface elevation and currents

were generated. A comparison between model simulated tides, extracted at the mooring location M and tidal patterns obtained from measurements is presented in Figure 7.

Model validation

Preliminary runs of the model were carried out with a meso-scale model, wind, current, and tides simulated off Manavalakurichi. The model results obtained have been validated using the measured tide and current data generated during October 2010. A comparison between model simulated tides extracted at the mooring location M and that obtained from measurements is presented in Figure 7. The results showed that the model results are in good agreement with the measurements.

Currents were resolved into U and V components to quantify their directional predominance, with U positive as eastward flow, U negative as westward flow, V positive as northward flow, and V negative as southward flow. Measured currents at the mooring location have been used for model validation. Maximum measured and simulated current speeds at M were 0.51 m/s and 0.25m/s, respectively. Current direction was mostly from NNE (north-northeast) and SSW (south-southwest). A comparison between measured and model-simulated current velocity components and current

speed at location M is given in Figure 8. It shows that model-predicted values agree very well with the measured values, except for the maximum observed currents.

The hydrodynamic model results have been further used for hydrodynamic, sediment transport, and wave modelling for the Case (i) and Case (ii) bathymetry situations, where, the NHO digitized depth data as bathymetry were used for Case (i) and the NHO bathymetry updated with the latest bathymetry survey data of the year 2010 was used for Case (ii). A comparison between Case (i) and Case (ii) scenarios is made to find out the impact of bathymetry changes on the sediment transport. This is achieved by comparing the currents simulated by the model at location M for Case (i) and Case (ii) bathymetries and the variation of V-component, U-component and the total current speed obtained for both cases as shown in Figure 9. Similar comparisons have been made at all the four locations A, B, C and D, are shown in Figure 10. The U-components obtained for these locations are shown in Figure 11 and the V-components in Figure 12. Results obtained thus suggest that there was no significant change in the currents observed at these locations when the new bathymetry was incorporated.

Wave and sediment transport modeling

MIKE21-SW (Spectral Wave) module has been used for wave modeling. Comparison between the significant wave heights obtained for Case (i) and Case (ii) are shown in Figure 13.

These results are substantiated by the model results obtained from sediment transport simulation, as shown in Figures 14–17, for locations A, B, C and D. Increased sediment transport is noticeable at the near shore locations A, B, and C. The latest bathymetric survey data of year 2010 indicate marginal deepening at these points. Nearshore currents and waves are most important in determining the heavy mineral distribution and concentration. Longshore current flows parallel to the shore in the surface zones. Waves initiate sediment movement and drive the current system. The breaker height is significant in determining the quantity of sands in motion, and the breaker direction is important in determining the direction and rate of longshore movement. Thus, major parameters influencing the onshore-offshore movement are breaker character, period, height, angle of incidence, longshore drift, and beach slope. Studies showed that the distribution of wave energy and concentration of black sand showed good correlation, except in areas where there is a change in the configuration of the coast (Prakash, Kurian, & Jose, et al., 1997). Wave-convergent bathymetry focuses and confines material extracted from a larger than usual source area. Refraction also results in a far greater range and zonation of wave energy, thereby concentrating a greater range of sediments in specific hydrodynamic zones. A gentle, sloping shore (sloping bathymetry) makes a far greater area susceptible to erosional range of force, hence a greater source area is susceptible to extraction.

Refraction, diffraction, reaction, caustic interference, resonance, and the interaction with longshore and rip currents are all potential mechanisms which favor the concentration of heavy minerals. They also result in a far greater range and zonation of wave energy, concentrating a greater range of sediments in specific hydrodynamic zones. The model results suggest that changes in bathymetry would amplify the wave height, leading to convergence in wave energy (Figure 17c). These could eventually result in increased sediment transport and removal of sand from the high-energy zones, leading to starvation of sediments and associated depletion of placer deposits in the adjacent beaches.

Conclusion

Breaking waves, consequent onshore-offshore transport, and associated processes determine beach sand transport. These processes act in an environment of tidal and wave interactions on beach systems that are at some stage of physiography between dissipative and reflective situations. Based on this study at Manavalakurichi, we conclude that nearshore regions have become shallower and the slope has become gentler. Changes in bathymetry would amplify the wave heights in the region, leading to convergence of wave energy, associated with increased sediment transport and removal of sand from the high-energy zones. These situations eventually lead to sediment starvation, resulting in the depletion of placer deposits in the adjacent beaches. Short and Hesp (1982) described the importance of the shelf slope in controlling the wave energy applied to the coastline. In general, wide and shallow nearshore zones expend more wave energy. Changes in energy levels and the relative physical characteristics of the sediments determine the nature of placers thus formed.

Beach placers result from an increase of energy that winnows out the hydraulically lighter particles near the surface. Accumulation is formed by selective settling of hydraulically heavier particles due to a reduction in energy. Minerals are preferentially concentrated and depleted at various scales by external physical conditions that create localized energy changes (Garnett & Bassett, 2005). In this area, contour shifts resulted in marked shifts in the wave-breaking regimes, with a tendency for offshore sediment drifts. The shallow bathymetry, along with the shifting of contours, might have resulted in overall changes in the hydrodynamic regime and sediment transport pattern, causing consistent depletion of the placers.

The Indian Ocean Tsunami of 26th December 2004 caused major havoc and inundated coastal communities of the region in and around Manavalakurichi (Chandrasekar, 2007). Henry, Chandrasekar, Saravanan, and DajkumarSahayam(2010) analyzed the influence of geomorphology and bathymetry on the effects, based on the estimate that the tsunami wave front, which originated from Sumatra, was diffracted by the island of Sri Lanka, which diverted some of the wave to the southern part of the west coast of India. The combined refraction-diffraction process as the wave

front propagated in the shelf water of the west coast could have caused convergence and divergence zones, leading to considerable variations in wave intensity along the coast. As most of the evidence disappeared quite quickly, the signatures found in the latest bathymetric map, generated during the present investigation, may also include the lasting imprints left over by the tsunami waves. To further understand the role of a larger source area and processes associated there in, it is necessary to carry out a detailed mapping of coastal topography and near shore bathymetry (including inlet configuration) and to develop the scenarios of transport pathways for predicting the vulnerability due to inundations. These investigations may further bring out elements and factors for resolving the unresolved complexities of processes, such as boundary layer flow, shear stresses in the swash zones, and sediment transport dynamics of bore propagation in the water-table outcrops in the adjacent coastal zones.

An inter comparison of the changes in the water depth of the sea bed during the past years showed that the total area covered by the shallow sea is reduced. On the other hand, the area covered by deeper sea has increased significantly due to the changes in topography. This had brought in an increase in the slope angle of the sea bed, especially along the coastal portion of the inner shelf. The slope maps of the sea bed prepared for different scenarios clearly showed changes in the slope of the sea bed, which are pronounced in the nearshore regions.

The creation of new sea-bed topography, characterized with high slope values along the nearshore regions, has a colossal effect on the transportation of sediments to the coastal regions. The sediments, particularly the heavier sediments, are transported as bed load by the waves towards the nearshore regions and such transported sediments are prevented from the southward movement by the erstwhile extension of the Muttam headland in the nearshore region. Upon the above changes are brought in, the waves might be unable to carry the sediments towards the nearshore regions, since that would necessitate an upslope movement of sediment. Even if the waves are partly successful in transporting sediments towards the nearshore regions, sediment would further drift along with the prominent southward currents, owing to the lack of an effective physiographic feature to inhibit the southward movement of sediment.

From the results obtained, it appears that numerical modeling of coastal processes has great potential to assist with the understanding of formation and depletion of placers in the coastal marine environment. To address concern regarding observed trends of placer depletion, detailed studies should evaluate the physical variability and hydrodynamic response of the system to alterations of geometry. Closely gridded bathymetric data will be required to assess the changes in depths at different segments and the resultant reduction in volume. All these would provide a clearer picture

on which to base strategies and options for long-term management of placer deposits for the foreseeable part of the next decades.

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Table 1: Maximum and minimum values of predicted water level variations

Station	Water level (m) SW monsoon		Tidal Range (m)	MSL ^a (m)
	Min	Max		
Muttam	0.087	0.945	0.858	0.488
Vizhinjam	0.055	1.067	1.012	0.549

^aMean Sea Level

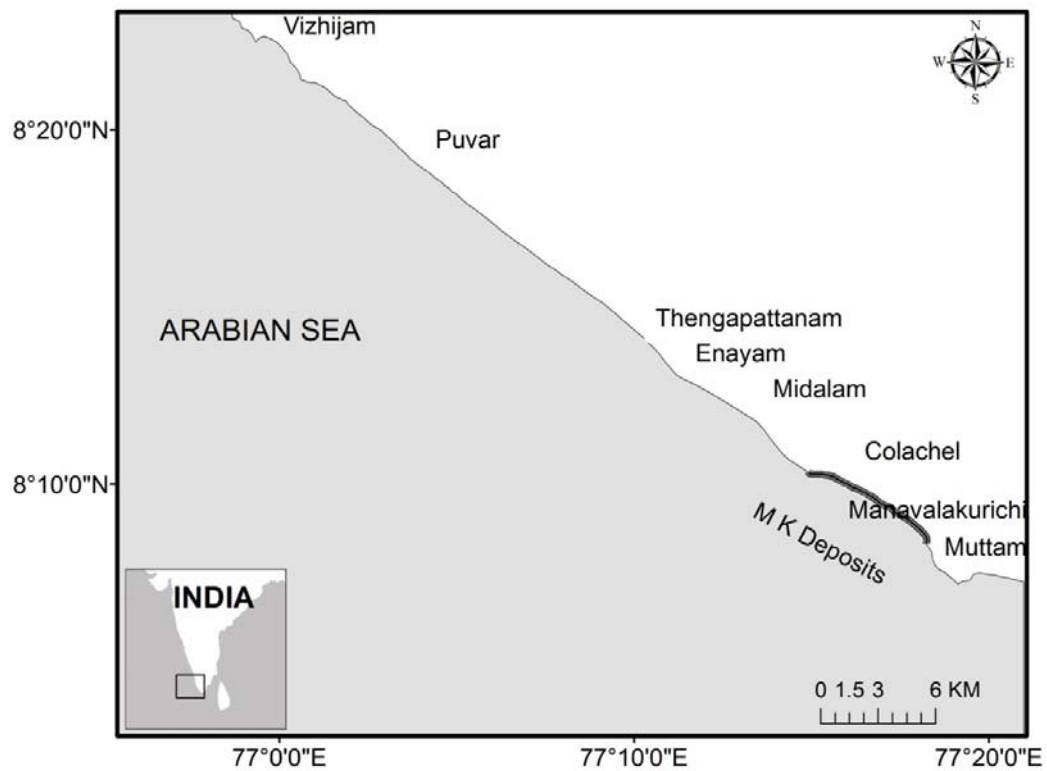


Figure 1. Location of the study area on the southwest coast of India

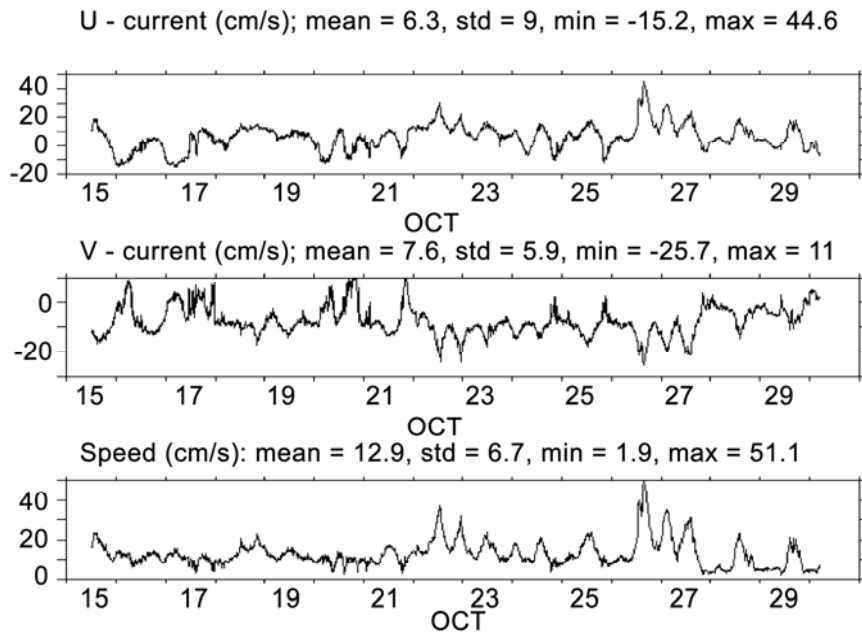


Figure 2: Time series of observed currents (U is east-west component, V is north-south component) off Manavalakurichi in the Indian Ocean study area.

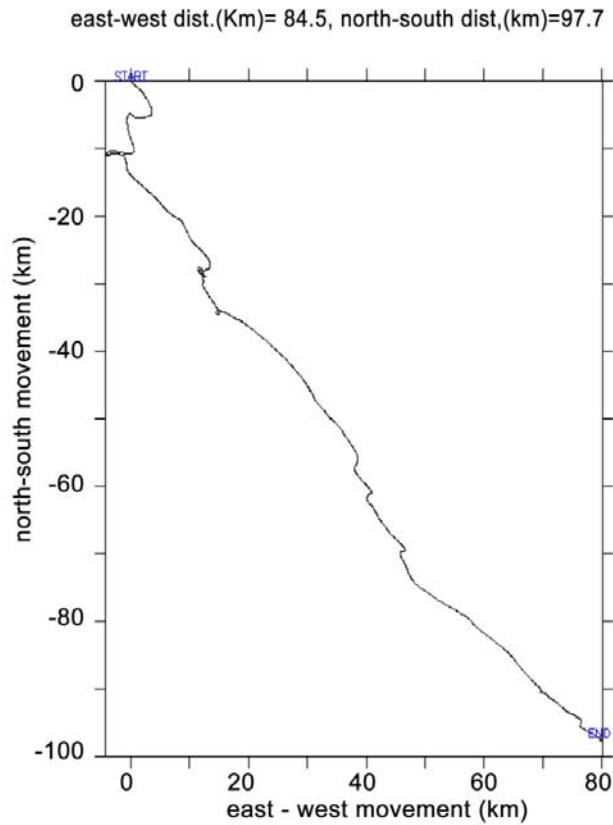


Figure 3. Progressive vector diagram (plot of the observed ocean current vector in sequence) showing the orientations of water particle movement.

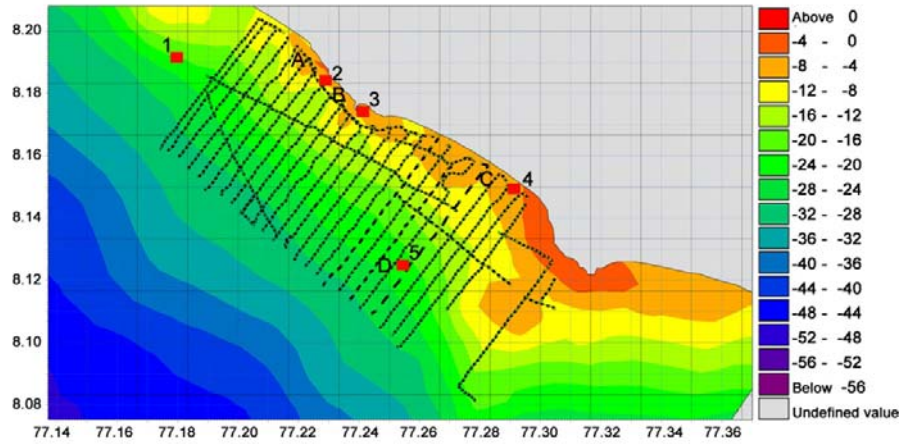


Figure 4. Study area with bathymetry survey points (colored shaded contours represent bathymetry signatures; black lines represent paths of new bathymetry generated; 1-5 represents survey points; A-D represents locations selected for simulations).

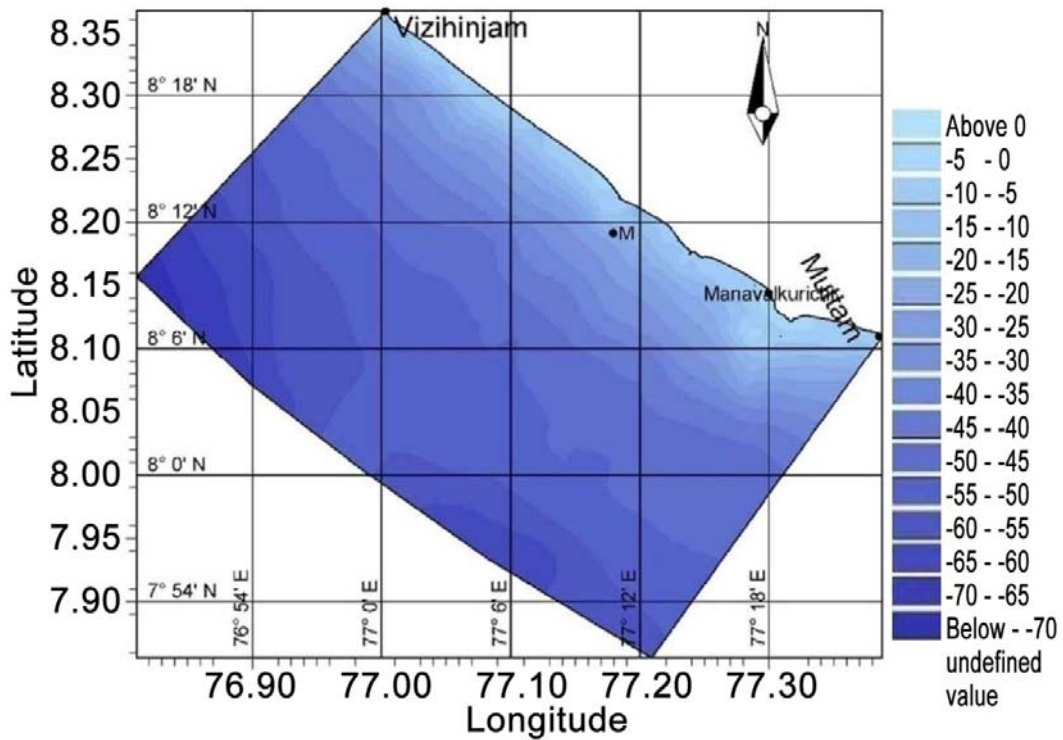


Figure 5. Model domain showing current measurement location (M).

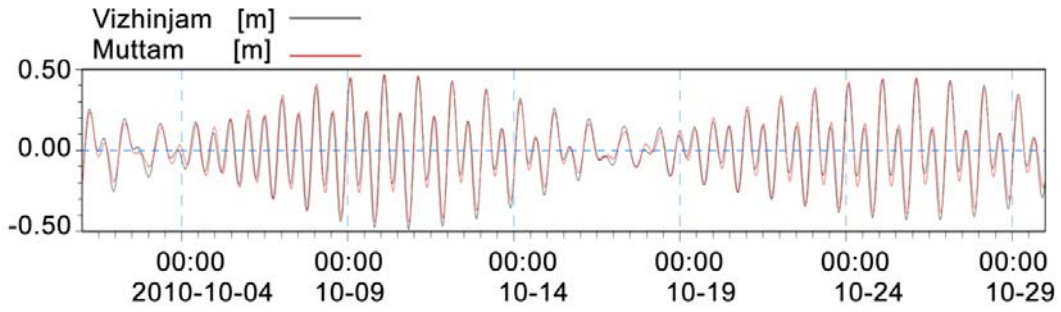


Figure 6: Predicted tidal elevation

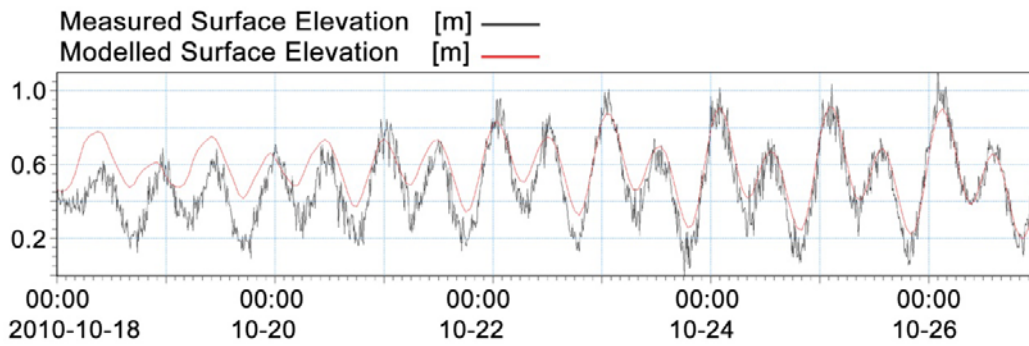


Figure 7: Comparison between measured and model-simulated water surface elevations at mooring location M.

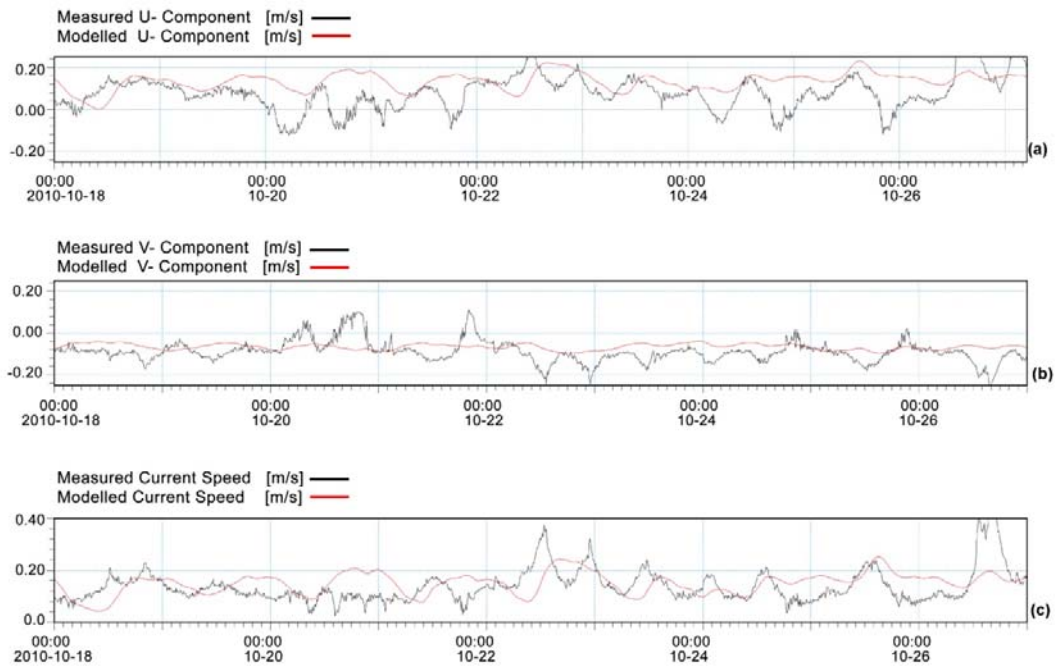


Figure 8. Comparison between measured and model-simulated current components: (a) east-west (U) component, (b) north-south (V) component, and (c) current speed.

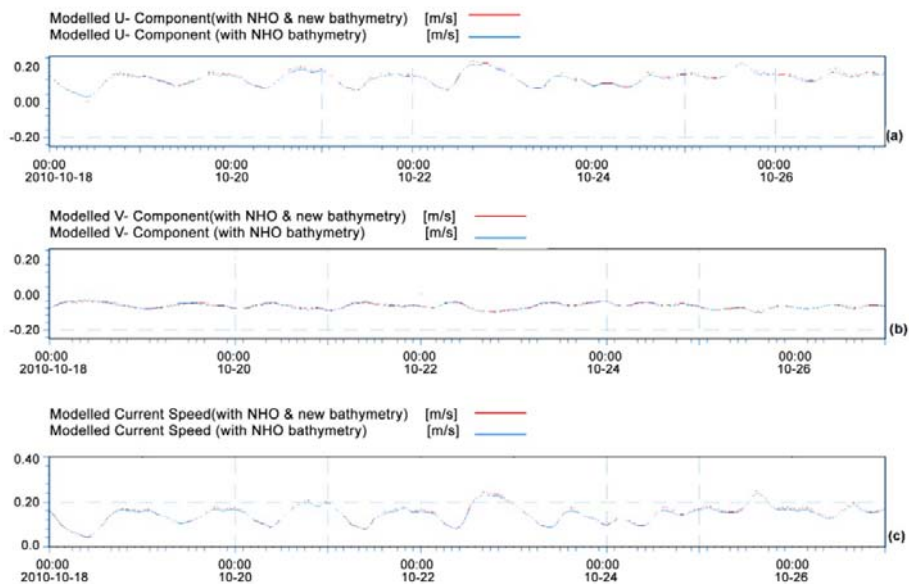


Figure 9. Comparison between Case (i) (NHO bathymetry) and Case (ii) (updated bathymetry) simulations at location M: (a) V-component, (b) U-component, and (c) current speed.

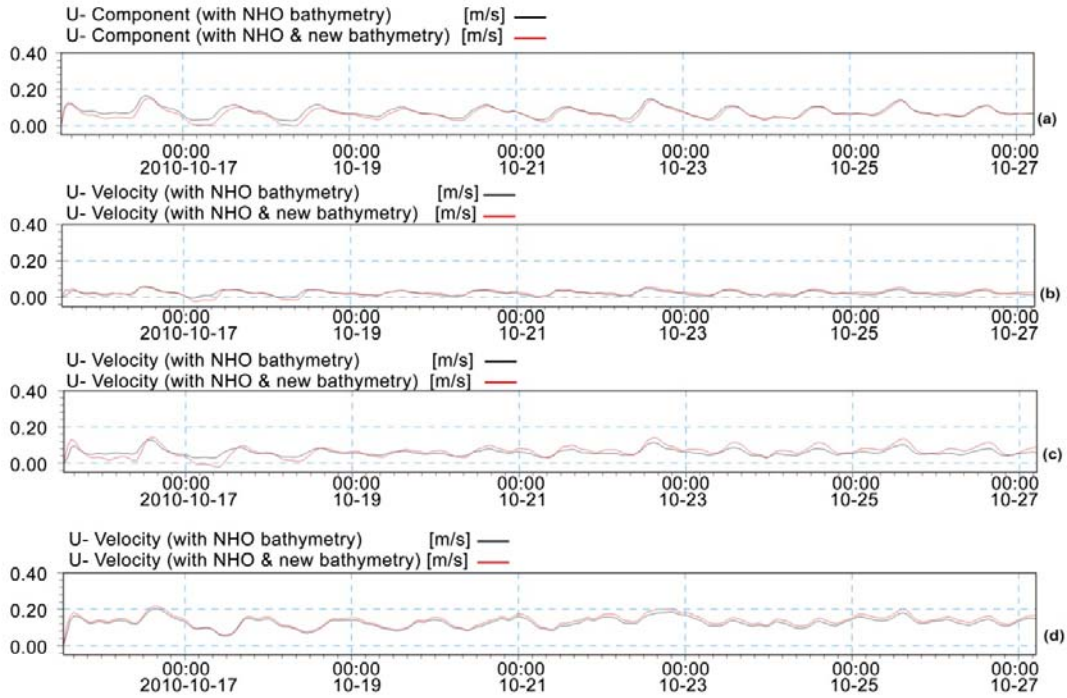


Figure 10. Comparison between Case (i) (NHO bathymetry) and Case (ii) (updated bathymetry): U-component (east-west) at different locations A to D (locations A to D are shown in Figure 4).

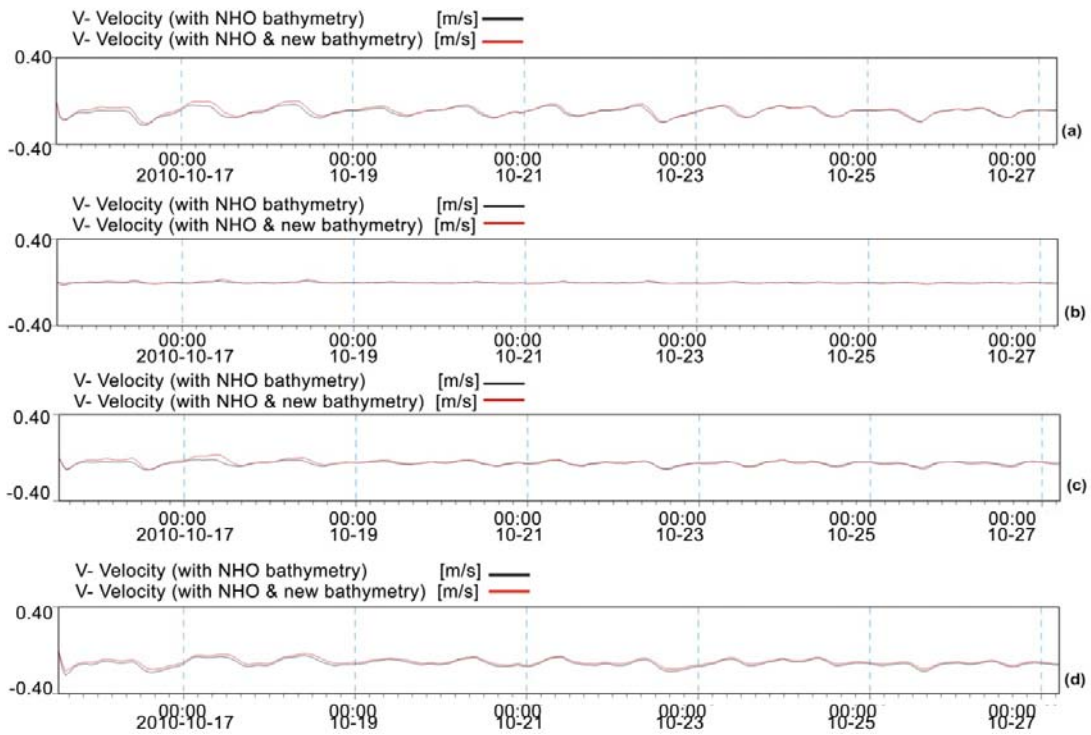


Figure 11. Comparison between Case (i) (NHO bathymetry) and Case (ii) (updated bathymetry): V-component (north-south) at locations A–D.

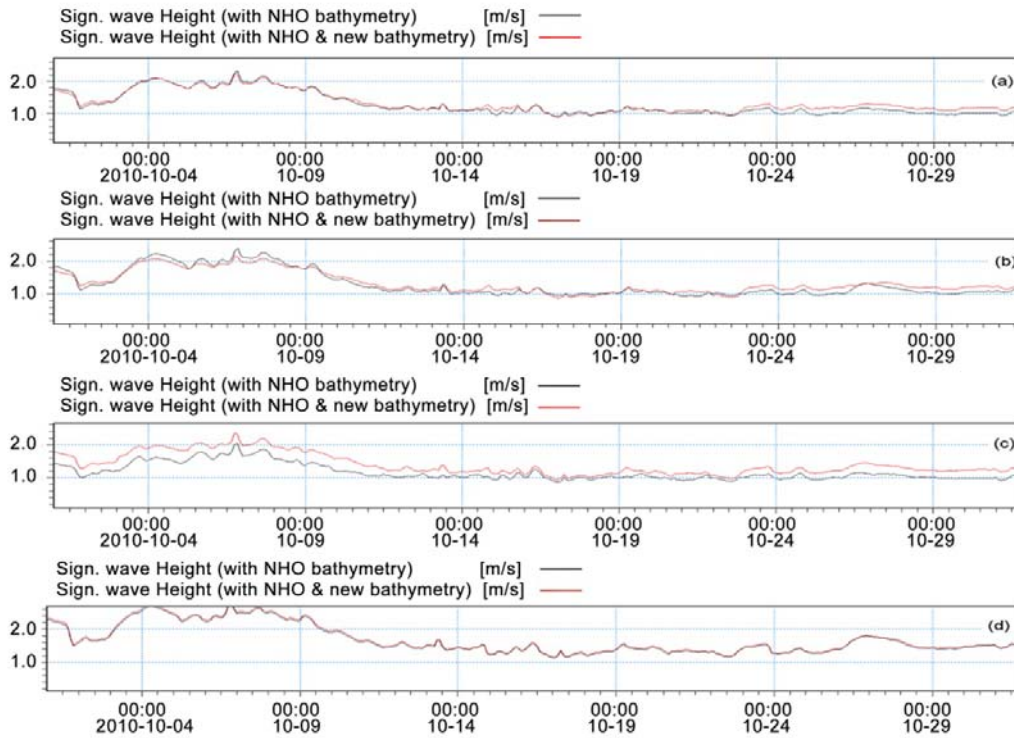


Figure 12: Comparison between Case (i) and Case (ii) Significant wave height at different locations A-D

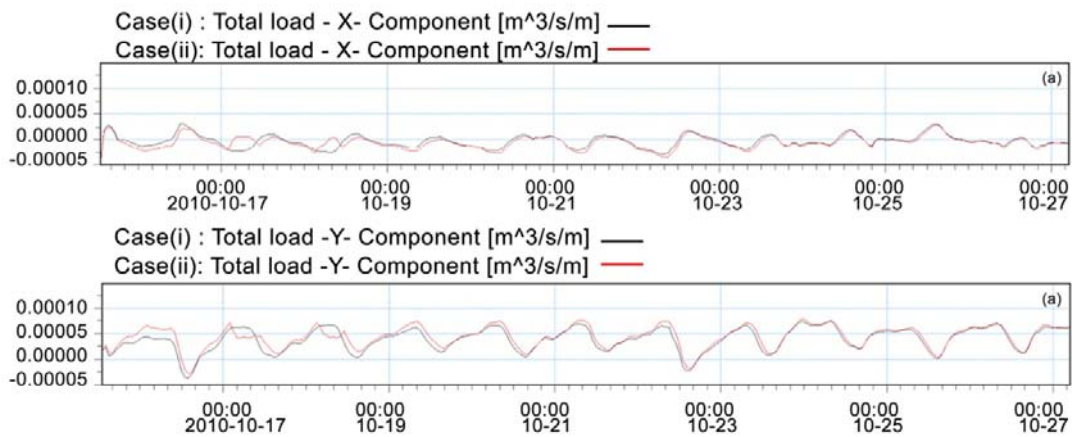


Figure 13. Comparison between Case (i) and Case (ii) of total load at location A

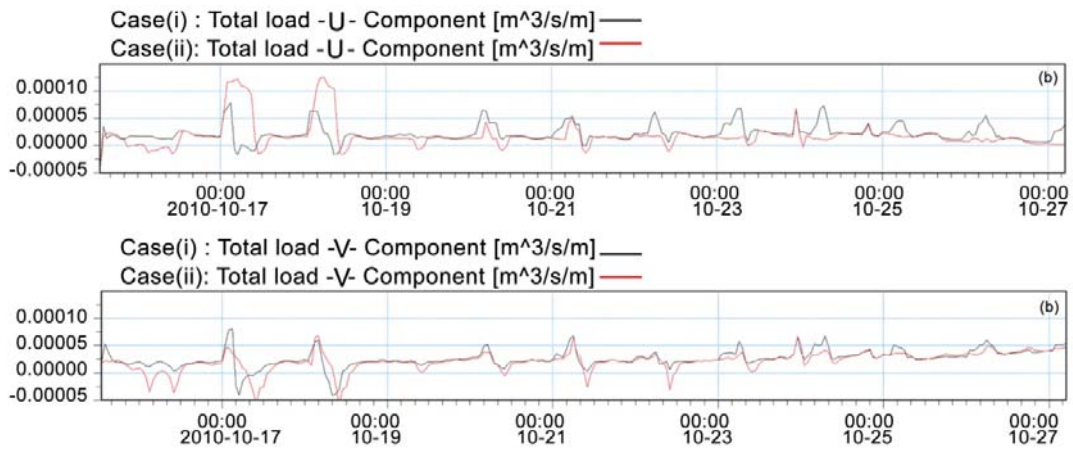


Figure 14. Comparison between Case (i) (NHO bathymetry) and Case (ii) (updated bathymetry): Total sediment load at location B.

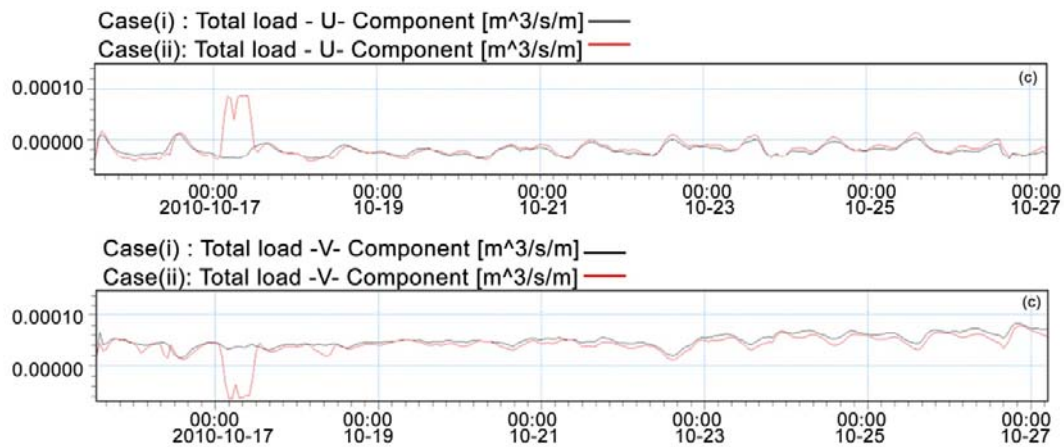


Figure 15. Comparison between Case (i) (NHO bathymetry) and Case (ii) (updated bathymetry): Total sediment load at location C.

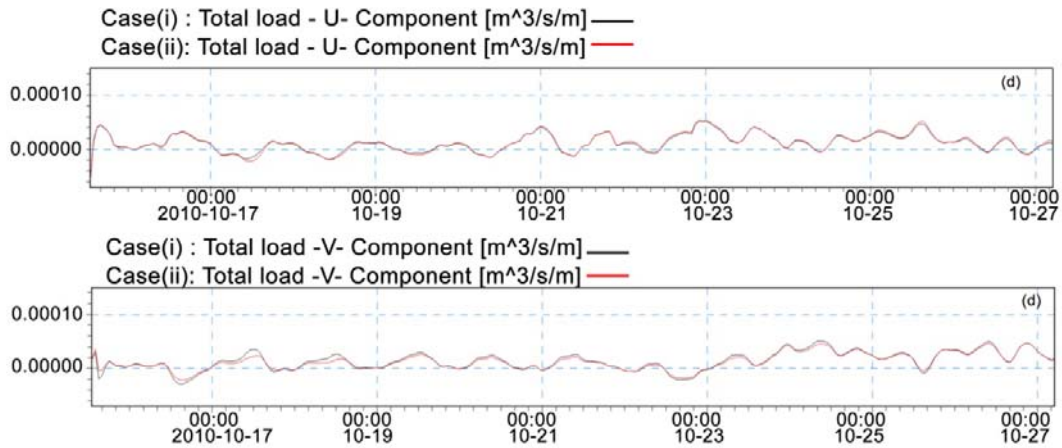


Figure 16. Comparison between Case (i) and Case (ii): Total sediment load at location D.

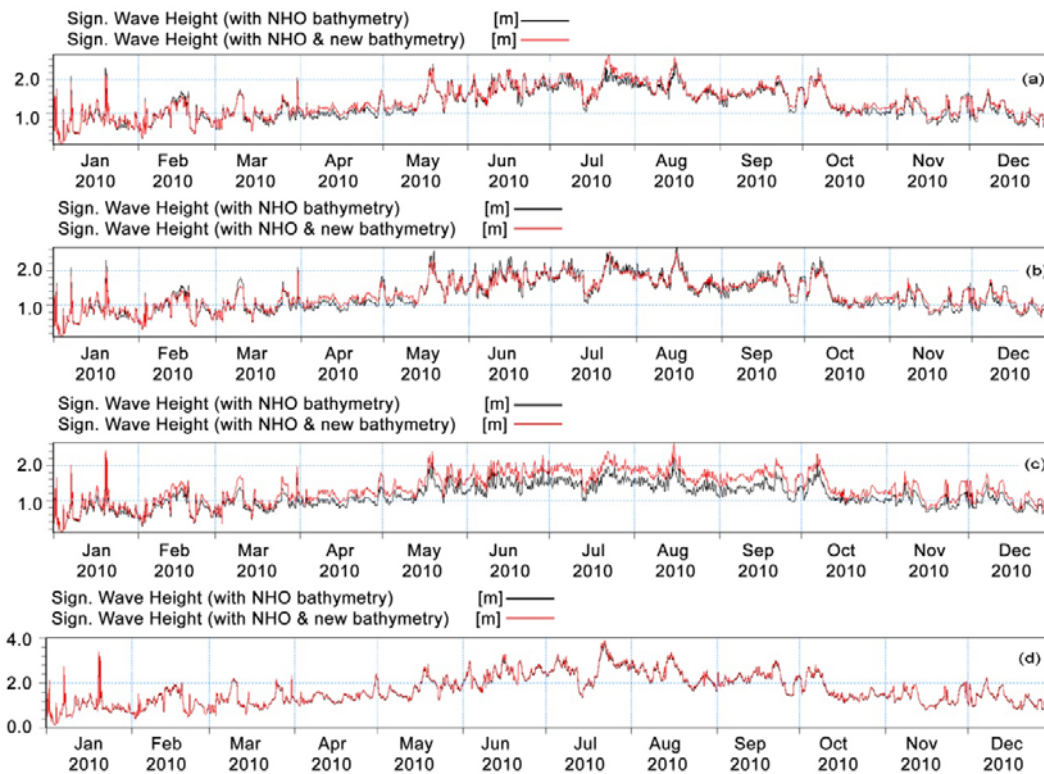


Figure 17. Comparison between Case (i) (NHO bathymetry) and Case (ii) (updated bathymetry): Significant wave heights at locations A to D for different months