

Modelling of sediment plume associated with the capital dredging for sustainable mangrove ecosystem in the Old Mangalore Port, Karnataka, India

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Abstract

Old Mangalore Port is located at the Confluence of River Gурpur and Netravathi in the Mangalore District, Karnataka. The Ministry of Shipping has promoted the modernisation of ports, including the Old Mangalore port, under the Sagarmala Project. The Old Mangalore port's navigational channel is approximately 3.2 km long and 80 m wide. It is proposed to deepen the existing approach channel to 7 m to allow medium-capacity vessels access to the port. The expected quantity of dredging is estimated to be 1160000 m³. We investigated the sediment spill plume movement of the dredging/dumping operations at Old Mangalore port using FVCOM (Finite Volume Community Ocean Model). Analysis showed that the spill plume was moved towards the offshore direction during the wet season and is primarily dictated by the prevailing currents and freshwater influx from the rivers. During the dry season (minimal discharge), the plume spreads approximately 8 km to the upstream regions and is mainly controlled by tidal currents. The study also revealed that the dumping point at a distance of 18-20 km offshore (depth > 20 m) is ideal for the optimum settling of the sediments for both seasons. The capital dredging of a navigational channel and construction of a new coastal berth is a one-time operation. Any siltation of the river mouth during the dry season will likely be flushed out in the subsequent wet season. We identified 12 types of mangrove species in the vicinity of the dredging area, and mangroves near the Old Mangalore port may be more exposed to the dredging activities impacts. Spillage during the dredging produces the sediment plume, and its transport to the mangrove region may choke the root system, thereby reducing oxygen availability. Hence, the study recommends that dredging operations can be carried out at any season but restricted to the ebb tide, thereby preventing the movement of sediment plumes to the mangrove region and thus conserving the mangrove ecosystem.

Keywords: FVCOM, Sediment transport modelling, Capital dredging, Dumping zone, Sediment plume, Old Mangalore Port.

1. Introduction

India's coastline extends to 7516.6 km, including 12 major ports (6 each on the east and west coast of India) and 205 minor and intermediate ports. According to the Ministry of shipping, about 95% of India's trading by volume and 70% by value is done through the maritime transport of goods and services. Ports are the locations on the coast containing one or more harbours selected to optimise access to land and navigable water for commercial demand and shelter from wind and waves (Dwarakish and Salim, 2015). In 2015, the Ministry of shipping promoted a port-led development Sagarmala project to enhance ports' major activities and modernisation. Due to the continuous activities irrespective of the season, ports and harbours should be maintained for the ship's harmless passage through navigational channels. A harbour can be of two types; natural and artificial (Yuvaraja, 2013). Harbour protected by storms and waves by natural landforms is called a natural harbour. Initially, no artificial changes are required in the natural harbour, but it is maintained to improve harbour operations. In the artificial harbour case, a breakwater is constructed for protection from winds and waves, and the depth is adequately maintained to estimate the grounding danger of ships by remediating environmental risks. During the past 20 years, dredging activities have increased rapidly around the world along densely populated coasts and estuaries. The primary purpose of dredging is to increase/maintain the depth of navigational channels for better transportation of goods and services through large ships. This would facilitate the enhancement of existing ports and the coastal areas as it plays a vital role in the nation's economy.

Capital dredging removes bottom materials such as sediments and debris from the lakes, rivers, harbours, and other water bodies and relocates them elsewhere, enhancing navigational channels (Nichols and Howard-Strobel, 1991). During the dredging operation, the four significant considerations (four R's) are the resuspension of dredged materials, its relocation, the residual sediment plume transport, and the risk and consequences (Bridges et al., 2010, 2008). The resuspended material can be tracked by measuring turbidity, an optical property of water that identifies the maximum extension of resuspended sediments. Depending on the plume dynamics, resuspension of sediment and its transport can cause a variety of water quality and ecological problems in terms of pollution, and it will also affect the health of mangrove ecosystems, marine organisms, and the behaviour of fish (Manap and Voulvoulis, 2014; PIANC, 2006; Shao et al., 2015; Suedel et al., 2015; Wilber and Clarke, 2001). The dredging operation should consider the unique ecosystem of nearby mangroves as the environment requires mangroves for erosion control, coastal protection from high waves, indicators of climate change, ecosystem protection, water quality, carbon sequestration, etc. Different mangrove species adapt to the change in salinity, flow rate, and muddy conditions. Dredging activities may

change the flow rate of water from the river to the sea or vice versa and the tidal prism, resulting in standing water covering the aerial roots of mangroves and reducing oxygen consumption. Mangroves are tolerated to live in saline habitats with a distinct zonation pattern with respect to regular tidal inundation (flooding and ebbing) (Foti et al., 2012; Krauss et al., 2008; Lovelock et al., 2016; Reef and Lovelock, 2015). Dredge-induced hydrological modifications may affect the water balance in coastal wetlands by altering salinity, which in turn affects mangrove growth and health. Mangrove habitats with naturally high turbid zones are well adapted to the high sedimentation rate caused by river flux, tide, waves, etc., which are of little concern with continuous dredging activity. At the same time, the sensitive mangrove area requires awareness of the impact due to dredging operations when too much sediment enters the shallow waters. Management of dredging methods is essential; the timing of work and control of turbid plumes from the equipment and the correct disposal of dredged materials are crucial. The transport of sediment plumes varies with respect to the hydrodynamics (tide, currents, waves, river flux, etc.) during different seasons. The spatial dimension of the sediment plume comprises three phases; 1) dredging zone 2) near-field plume 3) far-field plume (Palermo et al., 2008) (Fig. 1). The Spatio-temporal variation and vertical extension of the sediment plume strongly depend on the geometry of the dredging zone, which further transports through the adjacent regions before settling. Coarser particles will settle in the nearby areas, while finer particles will settle in the far-field region driven by environmental conditions and oceanographic factors.

Numerous studies were undertaken in different regions on the dredge-induced bedload transport, bottom sediment thickness changes, and settling of sediment plume after dredging and dumping operations, which explains the impact of dredging operations and changes in the hydrodynamics (Haimann et al., 2018; LaSalle et al., 1991; Pennekamp and Quaak, 1990; Purnama et al., 2016; Schubel et al., 1978; van Rijn, 2018). Open water disposal of the dredged material is a common practice adopted by major ports in India (Shukla et al., 2015, 2014). Finding a suitable dumping point is always a major concern because of the larger quantity, sediment characteristics, settling, and its return to the adjacent coastal areas, navigational channels, and ports under prevailing hydrodynamic conditions. Proper monitoring and mitigation measures can help to prevent antagonistic environmental impacts. Therefore, it is important to understand the trajectory of sediment plume transport mechanisms under different hydrodynamic conditions by integrating *in-situ* data of mangroves and sediment into a numerical model. In recent years, advanced numerical models like COCIRM-SED, MIKE-21, DELFT-3D, FVCOM, etc., have emerged to study the advection and dispersion phenomena of sediment and pollutants with suitable on-field measurements (Sun et al., 2016).

The FVCOM (finite-volume community ocean model) was simulated for the dredged sediment plume transport and its dumping to various locations at Old Mangalore port. The study combined the information of *in-situ* collected mangroves and sediment data from Old Mangalore port and integrated it into FVCOM. The present study focuses on the capital dredging activities in the Old Mangalore port with the objectives a) status of mangroves and sediment texture, b) hydrodynamic variations before and after dredging, c) simulation of dredged sediment plume transport and its impact on the mangrove ecosystem and d) identification of suitable dumping locations.

2. Study Area

The Old Mangalore port is a riverine lighterage fair weather port on India's west coast, located at the confluence of the Gurpur and Netravathi rivers (Fig. 2). The port is functional only from September to May due to the high wind, wave activity, precipitation, and river discharge during the southwest monsoon season. The region experiences four types of seasons: monsoon (June to September), post-monsoon (October to December), winter (January to February), and summer (March to May), with an average rainfall of 1,248 mm (more than 90% during monsoon). Mangalore city (MC) is situated at an average elevation of 22 m above the mean sea level from coastal flatlands in the west to the valleys and hilly areas towards the Western Ghats in the eastern region. According to the 2011 census, MC has a population of 499000 within an area of 132.45 km², and the region is famous for its fishing activity (> 2000 mechanised fishing boats). Most of the population depends on the existing facilities in the fishing harbour near the Old Mangalore port. The Old Mangalore port provides a 350 m length of berth in the south wharf portion and 76 m in the central wharf portion. Still, a shallow commercial navigation channel (4 m) needs to deepen (7 m) to properly navigate higher capacity cargo vessels to the port. This port handles coastal cargo like Soda ash, cement, steel, aggregates, other construction materials, rice, other food grains, etc., mainly to Lakshadweep islands and other provinces. Dredging operations will enhance the transportation of goods and services, access of large vessels to the port, maritime shipping, and increase the city's economy. Without proper remedial measurements, it may negatively affect the environmental ecosystems such as mangroves. According to the Forest Survey of India (FSI), mangroves in Karnataka state are approximately 10 km² in an area which shows the increasing trend of mangroves in the last couple of years (FSI, 2019) (Fig. 3). According to the Coastal Regulation Zone (CRZ) notification, mangrove regions in the country have been categorised under CRZ-I, and therefore mangrove maps could be used for delineating CRZ-I areas. The identified site for the proposed project for dredging and constructing a coastal berth at Mangalore is within the existing premises of Old Mangalore port. For better management in terms of the sustainability of the environment and mangrove ecosystems during dredging and dumping operations, validated numerical

models are useful as a preliminary step for understanding sediment plume dispersion, transport, and settling.

3. Methodology

3.1 *In-Situ* Observations

Time-series observations of water levels and currents were conducted in the Mangalore region from 8th December to 16th December 2018 to validate the model. Water levels were recorded at 10-minute intervals in stations S1 and S2 using SBE-26 plus water level recorder (Fig. 2). A single point current meter (Aanderaa RCM-9) deployed 1 m below the surface was used to record water speed and direction at 10-minute intervals in station S1. The river discharge data was sourced from the daily measurements at Gurpur and Netravathi rivers gauge stations by the Central water commission (CWC), Government of India. A field survey of mangroves was conducted around 17 locations in Mangalore from 3rd to 4th March 2020 (Fig. 4). A GPS was used to locate mangrove patches, linear formations, etc., and delineated them on the maps to calculate the area. A digital camera was used to take photographs for the identification of mangrove species. To understand sediment texture, sediment samples were collected using the Van Veen Grab sampler from 23 locations (Fig. 4). Sediment texture analysis was performed to separate clay and silt (< 63 μm) and sand (> 63 μm) fractions using a standard sieve and pipette analysis (Krumbein et al., 1938).

3.2 Modelling Hydrodynamics

The prime objective of the study is to understand the dispersion and transport of the dredged sediment plume and its impact on the mangrove ecosystem during wet and dry seasons associated with the prevailing environmental conditions at Old Mangalore port. In this context, an unstructured grid, primitive equation, Finite Volume Community Ocean Model (FVCOM), has been utilised for simulating the coastal currents, water level variations, dredged plume dispersion, and sediment transport dynamics from global to estuarine scales (Chen et al., 2006). The FVCOM model's unstructured grid capability simulates sediment transport with higher horizontal and vertical resolutions near dredging/dumping zones, which is especially useful in regions with irregular complex coastlines, islands, inlets, creeks, and inter-tidal zones. The estuarine and inshore bathymetry was prepared from the Old Mangalore port bathymetry charts, while offshore bathymetry from the GEBCO 30 arc dataset (Fig. 2). The domain extends up to 100 km towards the sea and 200 km (100 km each towards the north and south) along the coast, forming a rectangular geometry. The river influx was included in the model by keeping it as a riverine boundary. Flexible triangular grids of acceptable resolution ranging from 10-30 m near the islands, coast, and 100 m to 2 km towards the offshore region

were generated using GMSH software within the model domain using the bathymetry data (Geuzaine and Remacle, 2009). Two specific modules used in the study are 1) FVCOM hydrodynamics and 2) FVCOM sediment transport (FVCOM-SED). Input data required to simulate the hydrodynamic model was taken from global models such as HYCOM (Hybrid Coordinate Ocean Model, <http://tds.hycom.org/thredds/catalog.html>), NCEP (National Centers for Environmental Prediction, <https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html>), ECMWF (European Centre for Medium-range Weather Forecasts, <https://www.ecmwf.int/>), etc., which includes the parameters like wind speed, wind direction, pressure, water level, air-sea heat flux, waves, currents, temperature and salinity at model boundaries. Similarly, the tide data taken from FES2014 is allowed to propagate tide from the open boundary in the west. The CWC provided river discharge data for the Netravathi and Gurpur rivers from 2000 to 2018. The daily climatology river flux computed based on these data was used to provide river discharge at the riverine boundary (Fig. 5). The simulations were carried out for one year (2018). From these results, surface elevation and velocity components were generated for the validation of the model.

3.3 FVCOM Sediment transport and dredge plume modelling

The study region features heavy river discharge during the wet season to moderate river efflux in the dry season. This river discharge carries a heavy load of sediments and varies with the seasonal river efflux. The sediments get distributed in the inlet region and along the coast. The FVCOM model was used to track the trajectories of the dredged sediment plume. The sediment transport model in FVCOM (called FVCOM-SED) is based on the Community Sediment Transport Model (CSTM) (Chen et al., 2006), which includes suspended sediment transport, flux limited solution of sediment setting, number of sediment classes (sand, silt, and clay), and cohesive/non-cohesive sediment erosion/deposition algorithms. The model has been tested in various coastal environment studies for the calculation of tides and current induce transport of sediment (Lettmann et al., 2010; Wu et al., 2011). Sediment transport is calculated by solving the advection-diffusion equation with vertical settling and exchange with the bed as the source and sink terms (Chen et al., 2011). The general form of the source and sink terms can be written as (Chen et al., 2011),

$$C_{\text{source}} = -\frac{\partial W_{s,m} C_m}{\partial s} + E_{s,m} \quad (1)$$

where $W_{s,m}$ is the vertical-settling velocity (positive upwards), C_m the quantity of suspended sediment, $E_{s,m}$ the erosion source, and m the number of sediment classes. The quantity of suspended sediment spill rate (C_m in Kg/sec) was calculated as (modified equation from van Rijn, 2018),

$$C_m = \frac{H \times \epsilon \times CH \times D}{\text{Duration of Dredging}} \quad (2)$$

Where H is the hopper capacity, ϵ is the dredge spill, CH is the sedimentation factor, and D is the wet density of soil. FVCOM-SED can incorporate different types of sediments with varying densities, grain sizes, and setting parameters (Table 1) (Eisenstadt and Sims, 2005; Flemming, 2016; Kotter, 2017; Long et al., 2016; Shukla et al., 2014; van Rijn, 2018). By considering the peculiarities of the study region, model simulations were carried out for the year 2018, including the wet (July) and dry (January) seasons for all cases. The model study was carried out in the domain of five simulation cases (three dredging and two dumping cases) (Fig. 2). Case1: sediment spill near the Old Mangalore port (location C1) and coastal berth construction area (location C1), Case 2: sediment spill inside the estuary (location C2), Case 3: sediment spill outside the estuary (location C3), Case 4: dumping area at 10 m depth (location C4) and Case 5: dumping greater than 20 m depth (location C5) are other two locations.

4. Results

4.1 Status of Mangroves in the Old Mangalore port premises

The present study identified a total of 12 species near the channels and coast; *Acanthus ilicifolius*, *Avicennia officinalis*, *Avicennia alba*, *Avicennia marina*, *Excoecaria agallocha*, *Kandelia candel*, *Porteresia coarctata*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Sonneratia alba*, *Pemphis acidula*, and *Derris trifoliata* (Table 2). The total area of mangrove species found in the study region was 9.89 ha. Most of the mangroves in the region were patchy mangrove types and dominated by the mangrove species *Avicennia officinalis* (approximately 4.34 ha). The study region was divided into three zones; Zone 1: Near Old Mangalore Port, which is close to the proposed dredging and coastal berth construction area; Zone 2: Northern region of Old Mangalore Port; and Zone 3: Netravathi river entrance (Fig. 4). The total mangrove area in Zone 1, Zone 2 and Zone 3 is 2.4 ha, 0.61 ha, and 6.88 ha respectively. Mangrove diversity in zone 1 (7 types) is typically an association of *Rhizophora mucronata* and *Rhizophora apiculata* species with the dominancy *Avicennia officinalis*. Station S2 in Zone 1 shows the distinctive mangrove of *Pemphis acidula* is a mangrove flowering plant, a typical sprawling mangrove species, and can grow as a densely branched evergreen shrub or small tree. There are nine types of mangroves in Zone 2, but the area is relatively less compared to other zones. Station 8 in Zone 2 has three different types of mangroves with an area of 0.33 ha. *Acanthus ilicifolius* and *Porteresia coarctata* were identified in Zone 2 as patchy mangrove types. Station S16 in Zone 3, close to the estuarine mouth near the entrance of the Nethravathi river, has no diversity and richness but showed the highest evenness as only *Avicennia officinalis* distributed. Station S15 and S17 in Zone 3

showed five types of mangrove species with an area of 6 ha and three types of mangrove species with 0.86 ha, respectively.

4.2 Model validation of tides and currents

The model results were compared and validated with the observed tide and current data during December 2018 (Fig. 6 and Table 3). Tides were validated for locations S1 (inside estuary) and S2 (outside estuary), while currents for location S1. Model results are in good agreement with measured tides (correlation coefficient > 0.9 , standard deviation and root mean square error were < 0.15 and 0.04 m, respectively) and currents (correlation coefficient > 0.82 , standard deviation, and a root mean square error < 0.17 and 0.04 m respectively). The analysis showed that the maximum measured and simulated current speed inside the estuary is 0.9 m/s and 1.04 m/s, respectively. The current direction is mostly towards east and west, indicating the flood and ebb tidal phases.

4.3 Variation of hydrodynamics before and after dredging

The study captured the extreme variations of physical parameters, revealing that the estuarine and coastal waters of Old Mangalore port have a strong horizontal variation in the salinity (0 to 36 psu) and flow velocity (0 to 1 m/s). Supplementary figures 1 to 4 showed the variation of salinity and water speed before and after dredging during the flood and ebb tide time of the wet and dry seasons. During the wet season, heavy rainfall with high river discharge from the Netravathi and Gurpur rivers (4 times less than the Netravathi river) creates a fresher estuarine region that further protrudes out of the estuary and transports as a buoyant plume towards the southward direction following the coastal currents. The cumulative freshwater efflux from both the rivers modifies the salinity to less than 5 psu up to 2 km offshore from the inlet, and the entire estuarine region was filled with fresh water with a salinity of less than 2 psu, including mangrove regions. The subsequent flood tide alters the salinity to a maximum of 34 psu at the inlet against the outflow of river discharge. The high salinity is concentrated only at the inlet, and the freshwater discharge restricts the intrusion of high salinity towards the mangroves. During ebb tide, the area of maximum velocity increases (1 m/s), and the following flood tide limits the area of maximum water velocity only in the inlet region. The mangrove regions experience an average water velocity of 0.3 m/s and 0.4 m/s during flood and ebb tide, respectively. The dry season restricts the offshore extension of the buoyant plume owing to the absence of river discharge. The salinity ranges from 28 to 36 psu from the upstream regions of Netravathi and Gurpur towards the coastal and offshore regions. The flow velocity pattern showed the northward transport of coastal currents with a maximum of 1 m/s at the inlet regions. During the dry season, an average salinity of

33 psu was observed near the mangroves with an average flow velocity of 0.2 m/s during both flood and ebb tides.

The average difference (before dredging is subtracted from after dredging and averaged for both wet and dry seasons) in the variation of salinity and water speed during ebb/flood tide time is shown in Fig. 7. Positive values indicate that the parameter increased after dredging, and a negative value indicates the parameter decreased after dredging. Overall, the flow velocity in the inlet regions increases slightly after dredging (a positive increase of 0.3 m/s during flood tide and 0.15 m/s during ebb tide) as the channel depth increases, which is conducive to the smooth flow of water. During the flood phase, saltwater intrusion into the estuarine area is slightly greater than (~ 1 psu) pre-dredging. At the ebb phase, the distance of the salinity plume that protrudes out of the estuary is increased slightly after dredging, but salinity variation before and after dredging was similar. During the dry season, the flow velocity increased to 0.2 m/s and 0.1 m/s, respectively, as the channel depth increased during the flood and ebb stages. At the same time, the average salinity before and after dredging in this period was 34 psu. The mangrove regions in the Gurpur estuary showed a decrease in the flow velocity of 0.1 m/s during flood tide and an increase of 0.15 m/s during ebb tide in both wet and dry seasons with a maximum of 1 psu variation in salinity. This variation indicates that the difference in hydrodynamic factors before and after dredging was insignificant.

4.4 Dredge plume modelling for the wet and dry season

The result of the grain size analysis and the respective nomenclature of the sediment was presented in Fig. 8. Sediment texture, in terms of sand, silt, and clay, varied from 35 to 74 %, 16 to 45 %, and 5 to 26 %, respectively. The graphical analysis of sediment indicates the dominance of sand-sized particles. The estuarine stations were dominated by silt and sand particles. Adjacent to the shoreline, the bottom consists of a longitudinal sandy strip with an average width of about 1km. In the northernmost part, and immediately south of the Netravathi-Gurupur river mouth, this sandy strip has a minimum width of about 100 m, while near the river mouth, the sandy belt has a maximum width of about 2.5 km and shows seaward convexity. In this study, the calculated quantity of suspended sediment spill rate (C_m) using equation 2 is varied from 4.83 to 5.83 kg/sec by considering a grain size from less than 0.002 to 2 mm (Table 1). The study revealed that sand particle fraction was dominant in the stations (7 to 23) near the dredging locations (Figs. 2 and 8). According to the capacity of the dredge hopper (500 m³), the maximum quantity of spill for sand is 5.83 kg/sec by considering a maximum grain size of 2 mm with 5 % of dredge spill. The FVCOM-SED model was initialised according to the sediment parameter classification shown in table 1 with a 5.83 kg/sec spill rate at dredging locations. The model result includes the concentration of sediments at each grid point and the direction of propagation of sediments

on the coast. Dredge plume modelling for the wet and dry seasons was carried out and the results were plotted at an interval of 3 hours. The wet season was distinguished by heavy rainfall and southward-flowing monsoon winds (Supplementary figs. 5 and 6). These monsoonal winds (Supplementary fig. 6) enhance the southward coastal currents (Beal et al., 2013; Carugati et al., 2018; Gurupadappa and Animal, 2015; Hareesh Kumar and Anand, 2016; Jayaraj, 1997; Rao et al., 2015; Schott and Jr, 2001; Seena et al., 2019; Shetye et al., 1991). The river discharges increase to a great extent of 1800 m³/s on average; hence the sediment flow. Detailed spill movement for various cases concerning dredging locations and dumping areas during the wet and dry seasons are shown in Figs. 9 to 13.

4.4.1 Case 1 (Fig. 9): Sediment spill near the Old Mangalore Port and coastal berth construction area

During the wet period (July in Fig. 9), the average concentration of dredged plumes was confined to the Old Mangalore Port and coastal berth area itself after 3 hours of dredging. The concentration of the sediment gradually decreases towards the coast. After 6 hours of dredging, increased sediment concentration was noticed in the inlets. The sediment plume reaches the coastal region after 9 hours and spreads along the shelf following the coastal currents. The trajectory of the sediment plume towards the south was due to the prevalence of intense southwest monsoonal winds and currents. After dredging, the dredge-generated sediment plume concentration gradually dilutes due to coastal dynamics within 12 hours and is almost settled by 21 hours.

During the dry period (January in Fig. 9), the studies were repeated and found that the sediments tended to move offshore than along the coast. The offshore bulge of the sediment plume was more compared with that in the wet season. The least amount of river discharge greatly improves the transport of sediment plumes, and tides play an essential role in the settling process. The settlement of the dredge plume takes place at a slow rate. The plume spreads approximately 8 km to the upstream regions during flood tide and is mainly controlled by tidal currents (Fig. 9 and Supplementary Figs. 7 and 8).

4.4.2 Case 2 (Fig. 10): Sediment spill inside the estuary

During the wet season (July in Fig. 10), the sediment concentration was confined in the dredging location inside the estuary and gradually decreased towards the inlet, where these sediment plumes settled in the coastal region within 6 hours. Thus, the sediment plume's spreading takes place faster so that the increased concentration of sediments was noticed on the southern coast after dredging. As in the previous case study, settling sediments on the shelf occurred within 21 hours after dredging. The dry season featured less riverine discharge, so the sediment plume is more affected by tidal dynamics and transported between upstream of the estuary and offshore than along the coast with more settling time (January in Fig. 10).

4.4.3 Case 3 (Fig. 11): Sediment spill outside the estuary

The model studies well depicted the enhanced sediment concentration due to dredging. As the present location lies outside the main channel, the sediment plume enters the coastal region within a limited time (3 hours). The bulging of the sediment plume uniformly protrudes out of the dredged location. In addition to previous cases, during the wet season, the bulging of the sediment plume was extended offshore, and the monsoon winds and currents gradually transported it further south. (July in Fig. 11). The sediments formed by dredging outside the estuarine area settled more offshore than along the coast. Studies in the dry season revealed that offshore bulging of the dredge-generated sediment plume in the wet period coincided with the early stages of dredging. (within 6 hours) (January in Fig. 11). Tides and coastal currents play an essential role in the settling processes; ultimately, the sediments settled offshore.

4.4.4 Case 4 (Fig. 12): Sediment spill at the dumping region (10 m contour)

The primary dumping area was offshore, where the depth is about 10 m and located at a distance of 10 km from the coast. The dumping takes place for about 12 hours, and the sediment concentration concerning dumping was well depicted in the studies. During the wet period (July in Fig. 12), the concentration of dumping materials gradually increases with respect to time. The noticeable feature is that within 6 hours after dumping, the sediments tend to move towards the coast. It was mainly due to the influence of wind-driven currents and coastal processes. With time, the sediment drags towards the coast due to currents and settles along the coast within 24 hours of dumping. We noticed that the sediments tend to shift towards the south during the wet period and settle along the coastal area. During the dry period (January in Fig. 12), the sediment plume behaves in a stagnant state (slightly shifting from dumping area), and the sediments settle nearer to the dumped area within 24 hours after dumping.

4.4.5 Case 5 (Fig. 13): Sediment spill at the dumping region (≥ 20 m contour)

The second dumping area is in the offshore region, where the depth is > 20 m and is about 18-20 km away from the coast. In wet and dry seasons, the sediment concentration gradually increases within 12 hours of dumping, and thereafter the concentration decreases due to the settling process. During the wet season (July in Fig. 13), the sediment tends to drag towards the south due to monsoonal winds and currents, but finally, it settles within 21 hours nearer to the dumping area. During the dry season (January in Fig. 13), the concentration of sediments gradually increases with respect to dumping. The noticeable feature is the stagnant nature of the sediments in the dumping area itself. The settlement of the sediments in January takes place at a slower rate when compared with that in July.

5. Discussion

5.1 The effect of hydrodynamic variation on mangroves

Dredging in the navigation channel remarkably deepens the bathymetry, which is anticipated to alter the exchange/flow rate between estuarine and coastal waters. Since the proposed project targets to deepen the existing channel from 4 m to 7 m, there may be a change in flow parameters and salinity expected. This is one of the important aspects of the sustainable habitat of mangrove species. The salinity plays a vital role in the zonation and growth of mangrove species (Chen and Twilley, 1998). Azeez et al., (2022) revealed that *Avicennia marina* species can survive high salinity and pollution conditions and further concluded that the mangroves can absorb 80 % of the tidal currents, thereby stabilizing the coast. The higher the salinity, the more energy mangroves use to maintain water balance and concentration of ions (Clough, 1984). Species like *Rhizophora mucronata* and *Rhizophora apiculata* can survive in salinity up to 30 psu and 15 psu, respectively (Kathiresan et al., 1996, 1990). Various studies showed that the mangroves can survive in low saline to high saline conditions (Ball and Pidsley, 1995; Clough, 1984; Kathiresan et al., 1997, 1996, 1990; Khan et al., 2000, 1999; Naidoo, 1987; Sivasankaramoorthy, 2012). The dominance of *Avicennia officinalis* in the Old Mangalore port demonstrated their high range of adaptability under the drastic fluctuations of physicochemical properties as the soil is inundated daily two times (semidiurnal tides) by near-surface seawater. The diversity and richness of mangrove species in Zone 3 are lower than in Zone 1 and Zone 2, which may be due to the fast-flowing rate of the Netravathi River (Murugan et al., 2013). Zone 1 and Zone 2 showed a high level of richness and diversity of mangrove species due to the strong tidal interaction as the saline water intrusion into the mangrove regions with a slower river discharge rate from the Gurpur River. The mangroves in the Old Mangalore port experienced a drastic variation in the salinity from less than 2 psu in the wet season to greater than 33 psu during the dry season. The modelling analysis showed that dredging operations can smoothen the flow of water with a marginal increase in the flow velocity (~ 0.15 near mangroves), but the variation in the salinity before and after dredging was comparable and only a maximum of 1 psu difference is evident from the study region. Hence the changes in hydrodynamic factors (flow velocity and salinity) are likely insignificant to the mangroves.

5.2 Impact of dredging on the mangrove ecosystem

The effect of the sediment on the mangroves is still a question when the dredging process continues for a long-term operation. Hence, the measurement of mangrove areas should be included in considering sustainable ecosystem management. The sediment transport capacity of the river is responsible for the morphological changes induced by erosion and deposition. If the discharge is

higher, it produces greater velocities and carries a considerable amount of sediment, thereby increasing the sediment transport capacities of the river. The sediments are deposited in regions where the velocity is low. As a result, the bed level of the channel rises. The ebb and flood channels form where there is plenty of loose sediment (mainly sand) within the estuary and where the tidal streams are almost rectilinear. Where the tidal currents are rectilinear, the flood-tidal current tends to use one channel for a longer period than the ebb-tidal current, which uses a neighbouring parallel one for a smaller period. The modelling analysis showed that the ebb/flood channels in the study area are prominent. The model well captured the seasonal shifting of the buoyant plumes with the coastal currents and the wind pattern according to the previous study by Seena et al., (2019). The sediments found in estuaries and coastal areas are usually a mixture of mud and sand, the settling rates of the mud/sand suspension increase with increasing sand content (Torfs et al., 1996). The analyses of the sediment size distribution from field survey data at all locations indicate the channel is predominantly sand-sized particles with 53 % on average, while the average percentage of silt and clay particles was 31 % and 16 % respectively. According to the available *in-situ* data on sediment texture, the FVCOM-SED model was used for the present study to calculate sediment transport and the thickness of accumulated sediments.

Sediment plume transport under prevailing hydrodynamic conditions is elucidated in five cases, showing the sediments' transport following the tidal and coastal currents. During dredging operations, more than half of the total dredged sediment and its spill consists of sand particles and silty sand. Previous studies around Netravathi and Gurpur estuary showed the deposition of sand on the Bengre side of the estuary are mainly due to the sediment brought by the Netravathi and Gurpur rivers (Dattatri et al., 1997; Dwarakish et al., 1997; Dwarakish and Natesan, 2005). The estuary receives net gain sediment of 74.2 m³ sand per linear metre per year across the beaches, and the net sediment transport towards the south is 0.225 Mm³/year (Dwarakish et al., 2010; Jayappa and Subrahmanya, 1989). The Netravathi and Gurpur rivers deliver 14×10^5 and 1×10^5 tons of sediment annually to the Arabian Sea through this estuary (Shankar and Manjunatha, 1997; Subramanian et al., 1987). In Old Mangalore port premises, deepening of the navigational channel from 4 m to 7 m involves a total sediment quantity of 1160000 m³. A comparison of previous studies (Dwarakish et al., 2010; Jayappa and Subrahmanya, 1989; Manjunatha and Shankar, 1992; Shankar and Manjunatha, 1997; Subramanian et al., 1987) on sediment rates with current dredging operations showed that sediment transport rates could be significantly increased by dredging. Table 4 shows the sediment accumulation thickness around dredging locations and the mangrove region after dredging (24-hour simulation). The accumulated sediment thickness around dredging locations varies from 3.2×10^{-3} m (wet) to 5.4×10^{-3} m (dry) per square meter per day. In mangrove regions, the accumulated sediment thickness varies from 0.4×10^{-3}

3 m (wet) to 1.4×10^{-3} m (dry) per square meter per day. Various studies have been conducted on sedimentation due to human-induced disturbances in mangroves. Hutchings et al., (1987) explained the discharge of dredge spoil over the roots of mangroves leads to the decaying phase of mangroves. Deposition of 10 to 15 cm of the marine dredge to the *Avicennia germinans* and *Laguncularia racemosa* cause mortality (Ramcharan, 1997). Gordon, (1988) studied that the harbour dredge spoil smothered pneumatophores and destroyed the fringing of *Avicennia marina*. The analysis from the present study showed sediment plume transport after dredging always concentrates towards Zone 1, which includes dense mangroves, and the impact of dredging is directly affecting this area (Figs 9 to 13). Zone 2 is the moderately impacted region which is almost a 7 km distance from the dredging region. The proposed dredging is in the Gurpur River estuary, where water exchange is greater; thus, sediment transport may be primarily affecting Zones 1 and 2. Zone 3 is the least impacted region because of the influence of the Netravathi River with a higher flow rate. The dredged plume will transport following the flood/ebb tide during the dredging operations (Supplementary fig. 8). If the dredging operation starts during the flood tide, the dredged plume will reach the mangrove regions and be filled with turbid water. The following high slack tide will deposit a huge quantity of sediment near the mangrove regions and affect the root system of mangroves. If dredging begins during ebb tide, strong currents may cause the dredged plume to transport out of the estuary and offshore, where it will be transported by coastal currents and wave action and eventually deposited in coastal regions. The following flood tide will carry some of the sediment towards the estuary because of the strong currents, but it has a minor impact on mangroves. Therefore, the recommended study for the Old Mangalore port is to carry out dredging activities during ebb tide so as not to damage the mangrove ecosystem. The dredged material can be transported to the dumping area located in the deep sea at an average distance of 20 km by hopper barges. The dumping of dredge spoil may lead to changes in sediment quality. However, these changes would not have much impact as the disturbed sediment will resettle within a short time. On the other way, this dredged material can be used to fill the new coastal berth or other activities like beach nourishment after quality checking and environmental clearance. This will avoid the transportation of sand to the deeper dumping location, thereby reducing cost and time.

5.3 Applications and limitations of the study

Several studies reported the impact of dredge spoil on different types of mangrove species (Ellison, 1999; Gordon, 1988; Hutchings et al., 1987; Kwanairara, 1992; Lee et al., 1996; Ramcharan, 1997). The present study is a suitable case for a sediment dredge model dominated by sand particles. The methodology and analysis adopted for the present model study will help stakeholders and decision-makers, including port authorities, to assess the transport of dredged sediment and its impact on the

mangrove ecosystem, identification of suitable dumping location, time of dredging and economic feasibility of beneficial uses of dredged sediments. The present study is concentrated on two seasons (wet/monsoon and dry/pre-monsoon) to capture the hydrodynamics of extreme scenarios. Previous studies substantiate the influence of high river discharge during the monsoon season (June to September) (Gowda et al., 2015; Shankar and Manjunatha, 1997; Subramanian et al., 1987), which minimise the effect of tidal intrusion into the estuary (ebb dominated). The currents in the inlet were driven by freshwater discharge during the monsoon and by tides during the lean discharge period (Reddy et al., 1979). Thus during the monsoon, the dredged plume will quickly transported to the open sea by the outplay of high river discharge. While during pre-monsoon, when the influence of river discharge is minimal, the dredged plume will transport according to the tidal currents. Considering these facts and the general hydrodynamic patterns of the Old Mangalore port, the study recommended dredging operations during ebb tide to reduce its impact on the mangrove regions.

Obviously, all numerical models have computational/numerical limitations, and their results should always be interpreted with great care with respect to real time scenario (Rahbani, 2011). Although there are seasonal variations in the physical properties such as mixing, stratification, flow pattern, channel morphologies etc., the sediment distribution in the Old Mangalore port region is predominantly sand and silty sand fraction during most of the year. If *in-situ* data is collected only during one season, it may affect the accuracy and reliability of the model related to seasonal conditions. The lack of *in-situ* data is the major constraint of this study, which limits the data to a single season (hydrology and sediment during December and March, respectively). Changes in the sediment pattern due to different seasons may directly affect the sediment accumulation rate in the mangroves (sometimes channels expect more mud content). Despite the lack of data, previous studies at Netravati and Gurpur confirm the dominance of sand and silty sand particles, which serves as secondary data to support the present model capability to understand hydrodynamics and sediment behaviour (Dwarakish et al., 2010; Jayappa and Subrahmanya, 1989; Manjunatha and Shankar, 1992; Shankar and Manjunatha, 1997; Subramanian et al., 1987). Once developed, the models are most useful when validated between *in-situ* and modelled data for studying hydrodynamics, wave transformation studies and assessing the impacts of domain perturbations such as port dredging (Couriel et al., 2018). Still, some limitations persist in the present model in terms of re-entrainment of sediment and flocculation. If the dredging activity continues for longer, some of the deposited sediments may be transported in and out of the estuary/mangroves. The re-entrainment of deposited material through transient current will be significant for a longer period. The model only quantifies the sediment distribution during dredging and dumping for 24 hours. Flocculation changes sediment particle size, morphology, and

settling velocity (Shi et al., 2019). The experimental study by Manning et al., (2013) showed that as mud content decreased, the particle cohesion efficiency reduced, limiting the growth potential of the macro flocs fraction. Hence, flocculation is not considered in this model due to the dominancy of sand particles as well as the limited availability of high-resolution *in-situ* long-term sediment data. Even though there are limitations, the present study will provide the port authorities with a set of preliminary data (status of mangroves, sediment distribution, dynamics of sediment plume and its impact on mangroves) that may offer actionable recommendations for the sustainable mangrove ecosystem.

6. Conclusion

The Old Mangalore port proposed to expand berth capacity and deepening of approach channels to 7 m for accessing medium-capacity vessels to the port. On account of this, it is expected that a quantity of 1160000 m³ of sediment will be dredged from an area of 30 hectares from the channel and dumped at a suitable location. We investigated the sediment spill plume movement of the dredging/dumping operations at Old Mangalore Port using FVCOM. Five cases have been simulated depending upon various changes used for dredging and dumping operations during the wet and dry seasons. During the wet season, the spill plume moved offshore, primarily due to prevailing coastal currents and freshwater influx from rivers. During the dry period, the plume movement is mostly controlled by the tidal currents with a maximum dispersion of 8 km towards the upstream of the river Netravathi and Gurupur. The dumping area is in the offshore region, 10 km (at a depth of 10 m) from the coast, demonstrating that the dumped sediment is transported back to the coastal region during the wet season. Thus, the study revealed that the dumping location identified at 18-20 km offshore at depth > 20 m will be ideal for both seasons. The dredging of the channel is a one-time operation and siltation of the river mouth during the dry season is likely to be flushed out in the subsequent wet season. As such the impact of dredging during the dry season will have very little effect on the inlet region. There may be some minor accretion alongside the islands and shoals close to the dredging region due to the movement of the plume during the dry period. But the expectation of any erosion or a higher rate of sediment movement from the coastal side to the channel region or shoreline due to dredging activities is negligible. The impact of dredging on the proposed study area further affects the mangrove ecosystem. Dredging of a huge quantity of sediment produces a sediment plume that will transport to the mangroves and suffocate them, thereby reducing oxygen availability to the root systems. The study region contains the dense mangroves in Zone 1 is a hotspot in our context, which needs to be protected during the dredging operations. For the sustainability of the mangroves, the study recommended that dredging operations could be carried out at the Old Mangalore port during ebb tide to avoid damage to the mangrove ecosystem.

ABBREVIATIONS

COCIRM-SED: Coastal circulation and sediment transport model

CRZ: Coastal regulation zone

CWC: Central water commission

ECMWF: European Centre for Medium-Range Weather Forecasts

FES: Finite element solution

FSI: Forest Survey of India

FVCOM: Finite volume community ocean model

GEBCO: General Bathymetric Chart of the Oceans

GPS: Global Positioning System

HYCOM: Hybrid coordinate ocean model

MC: Mangalore city

NCEP: National Centers for Environmental Prediction

UTM: Universal Transverse Mercator

Competing Interests

The authors declare that they have no competing interests.

Consent For Publication

Not applicable

Ethics Approval And Consent For Participate

Not applicable

Funding

The study was funded by Old Mangalore Port and CSIR-National institute of oceanography

Data Availability Statement

Some or all data, models, or codes used during the study were provided by a third party. Direct request for the FVCOM source code may be made to the provider as indicated in the Acknowledgments.

Authors Contributions

Abdul Azeez, S., (AAS), Muraleedharan, K.R., (MKR.), C Revichandran., (CR), Sebin John, (SJ), Seena, G., (SG), Ravikumar C Nair (RCN), Arya K S (AKS), K Sudheesh (KS) and Prabhakaran M P (PMP); AAS managed the field survey, data analysis and writing of the manuscript. MKR identified the problem, field survey, analysis, and interpretation of the data. CR administered the project, involved in the discussion and draft preparation. MKR, AAS, SG, SJ, and KS were involved in the modelling studies. AKS is involved in the sediment data analyses. AAS, SJ, and RCN prepared the figures and model validation diagrams. PMP is involved in the mangrove species identification.

Acknowledgments

The study was carried out under the projects funded by the Old Mangalore Port, and the authors are grateful to the Old Mangalore Port authority. The authors are thankful to the Director, NIO, Goa, and Scientist in Charge, NIO, Regional Centre, Kochi for providing the facilities throughout the study. The field survey throughout this study was supported by the staff (scientists, technical staffs, and project assistants) of NIO, Kochi, and the authors are thankful for the kind support during the field survey. We are also thankful to the physical oceanography department, NIO, Goa for the instrumentation supports. We are also grateful to the FVCOM development team members in the Marine Ecosystem Dynamics and Modeling Laboratory, School of Marine Science and Technology, UMASSD for providing FVCOM source code and QGIS community for the support of software facilities.

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List of Tables

Table 1. Various sediment parameters used for the present study in the FVCOM-SED model

Dredge Hopper Capacity (m³)	500		
Dredge Spill percentage (%)	5		
Expected Duration of dredging (hr)	1.81		
Sediment	Clay	Silt	Sand
Particle Size (mm)	<0.002	0.002 - 0.05	0.05 - 2
Settling Velocity (cm/s)	0.00025	0.025	2.5
Wet density (Kg/m³)	1800	1850	1900
Sedimentation coefficient	0.7	0.75	0.8
Spill Rate (Kg/s)	4.83	5.32	5.83

Table 2. Area of mangrove species in three zones

Zone	Stations	Mangrove Species	Area in Hectares (ha)
Zone1	S1	<i>Avicennia officinalis</i> <i>Rhizophora mucronata</i> <i>Rhizophora apiculata</i>	0.33
	S2	<i>Pemphis acidula</i>	0.065
	S3	<i>Avicennia officinalis</i> <i>Avicennia marina</i> <i>Excoecaria agallocha</i>	0.6993
	S4	<i>Avicennia officinalis</i> <i>Rhizophora mucronata</i>	0.94
	S5	<i>Avicennia officinalis</i> <i>Rhizophora mucronata</i>	0.239
	S6	<i>Avicennia marina</i> <i>Kandelia candel</i>	0.077
	S7	<i>Avicennia officinalis</i> <i>Kandelia candel</i>	0.0525
Zone2	S8	<i>Avicennia officinalis</i> <i>Rhizophora apiculata</i> <i>Rhizophora mucronata</i>	0.334
	S9	<i>Sonneratia alba</i> <i>Avicennia alba</i>	0.0746
	S10	<i>Porteresia coarctata</i> <i>Kandelia candel</i>	0.0156
	S11	<i>Avicennia officinalis</i> <i>Derris trifoliata</i>	0.0685
	S12	<i>Acanthus ilicifolius</i>	0.043
	S13	<i>Avicennia officinalis</i>	0.0535
	S14	<i>Avicennia officinalis</i> <i>Kandelia candel</i>	0.01911
Zone3	S15	<i>Avicennia officinalis</i> <i>Excoecaria agallocha</i> <i>Kandelia candel</i> <i>Rhizophora apiculata</i> <i>Rhizophora mucronata</i>	6
	S16	<i>Avicennia officinalis</i>	0.022
	S17	<i>Avicennia officinalis</i> <i>Rhizophora mucronata</i> <i>Sonneratia alba</i>	0.86

Table 3. Statistical analysis of Observed and Modelled data

	Inlet Mangalore (S1)			Off Mangalore (S2)		
	Tide	Currents		Tide	Currents	
	Elevation	U	V	Elevation	U	V
Correlation coefficient	0.906	0.829	0.864	0.957	NM	NM
Standard deviation	0.145	0.141	0.161	0.119	NM	NM
Root mean square error	0.033	0.039	0.027	0.015	NM	NM

*NM- No Measurement

Table 4 Sediment accumulation around dredging locations and mangrove region after dredging
(24 hour simulation)

Seasons	Accumulated Sediment Thickness (m) per square meter per day x 10 ⁻³	
	Dry	Wet
Dredging locations	5.4	3.2
Mangrove region	1.4	0.4

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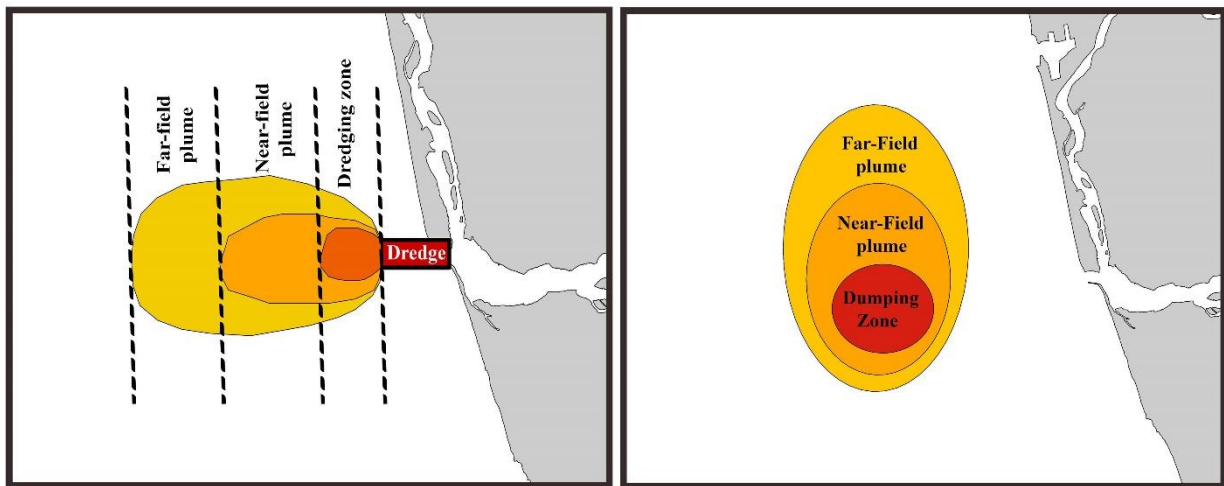


Fig. 1. Schematic representation of sediment plume at dredging zone (left) and dumping zone (right)

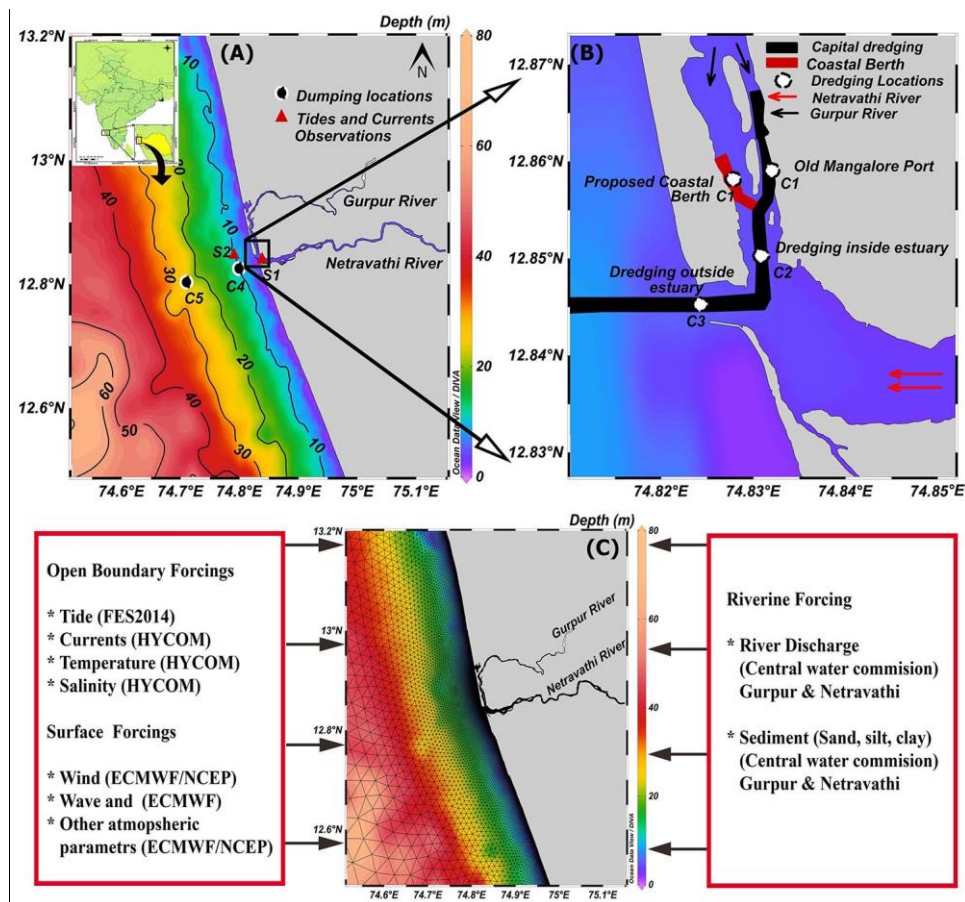


Fig. 2. Map showing (A) Bathymetry contour, tides (S1 & S2), currents (S1) measurement stations, sediment offshore dumping locations (C4: Case 4 and C5: Case 5) at estuarine and coastal waters of Mangalore, (B) the capital dredging area (black shaded region), construction of coastal berth (red shaded region) and proposed dredging locations are C1 (Case 1), C2 (Case 2) & C3 (Case 3). (C) Model domain encompassing river, estuary, and coastal waters of Mangalore with finite elemental grid, bathymetry, and Forcing conditions.

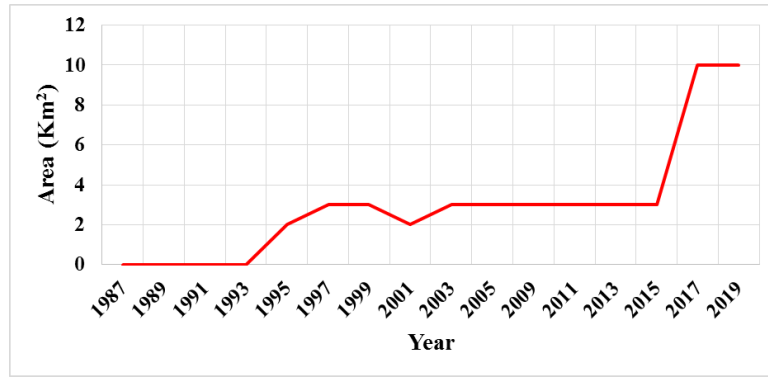


Fig. 3. The trend of mangroves in the Karnataka state from 1987 to 2019 by FSI

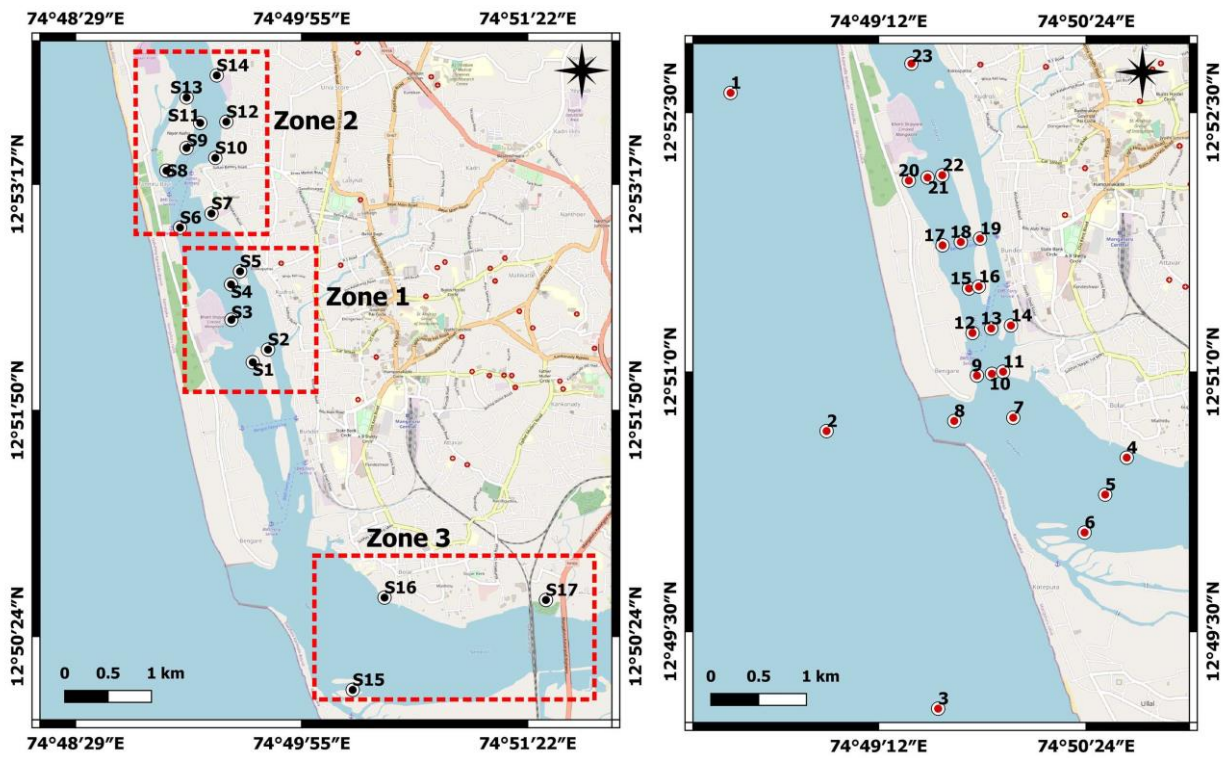


Fig. 4. Field survey of mangrove species at 17 locations (left panel) and sediment texture analysis at 25 locations (right panel) in the Old Mangalore port region

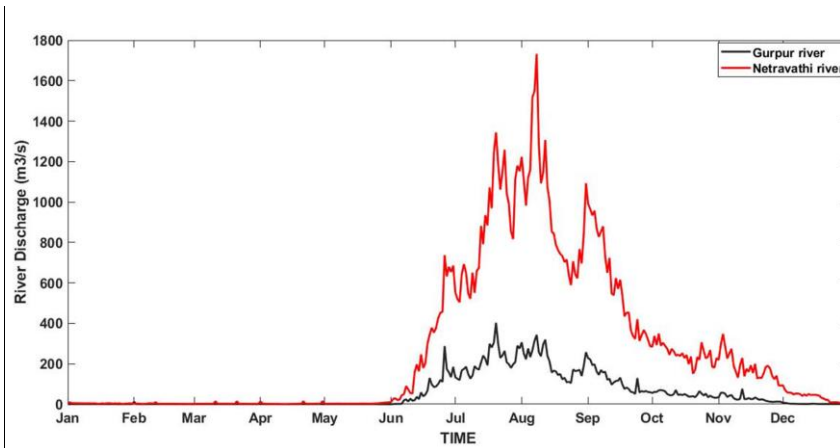


Fig. 5. Climatology of river discharge (2000 to 2018) forced to the model domain from the riverine boundary.

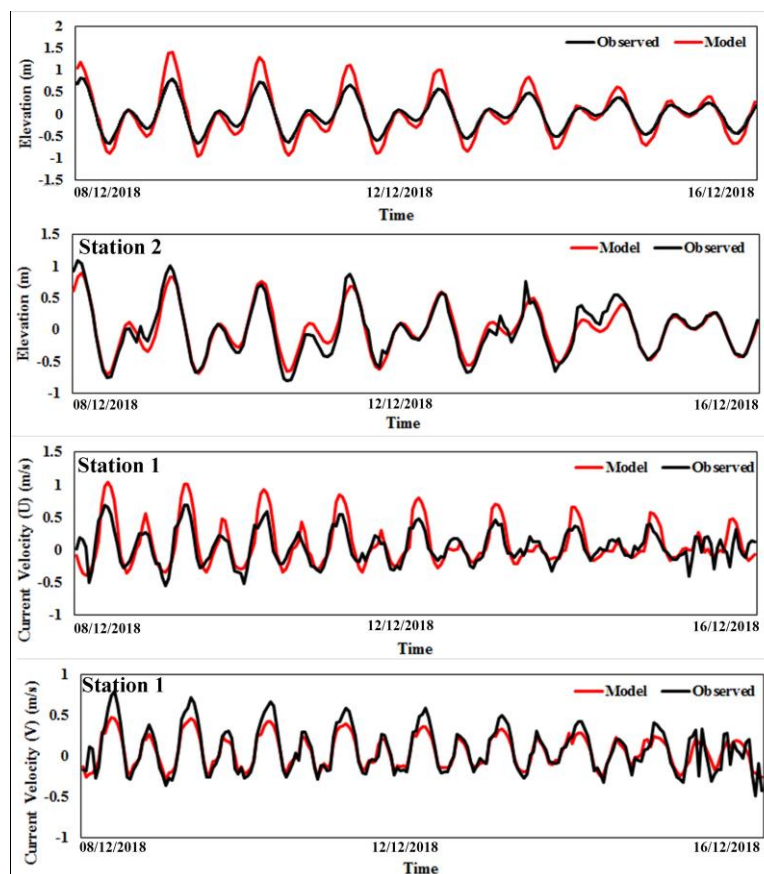


Fig. 6. Comparison between observed and model-simulated tide and Currents (u and v component) at stations S1 and S2.

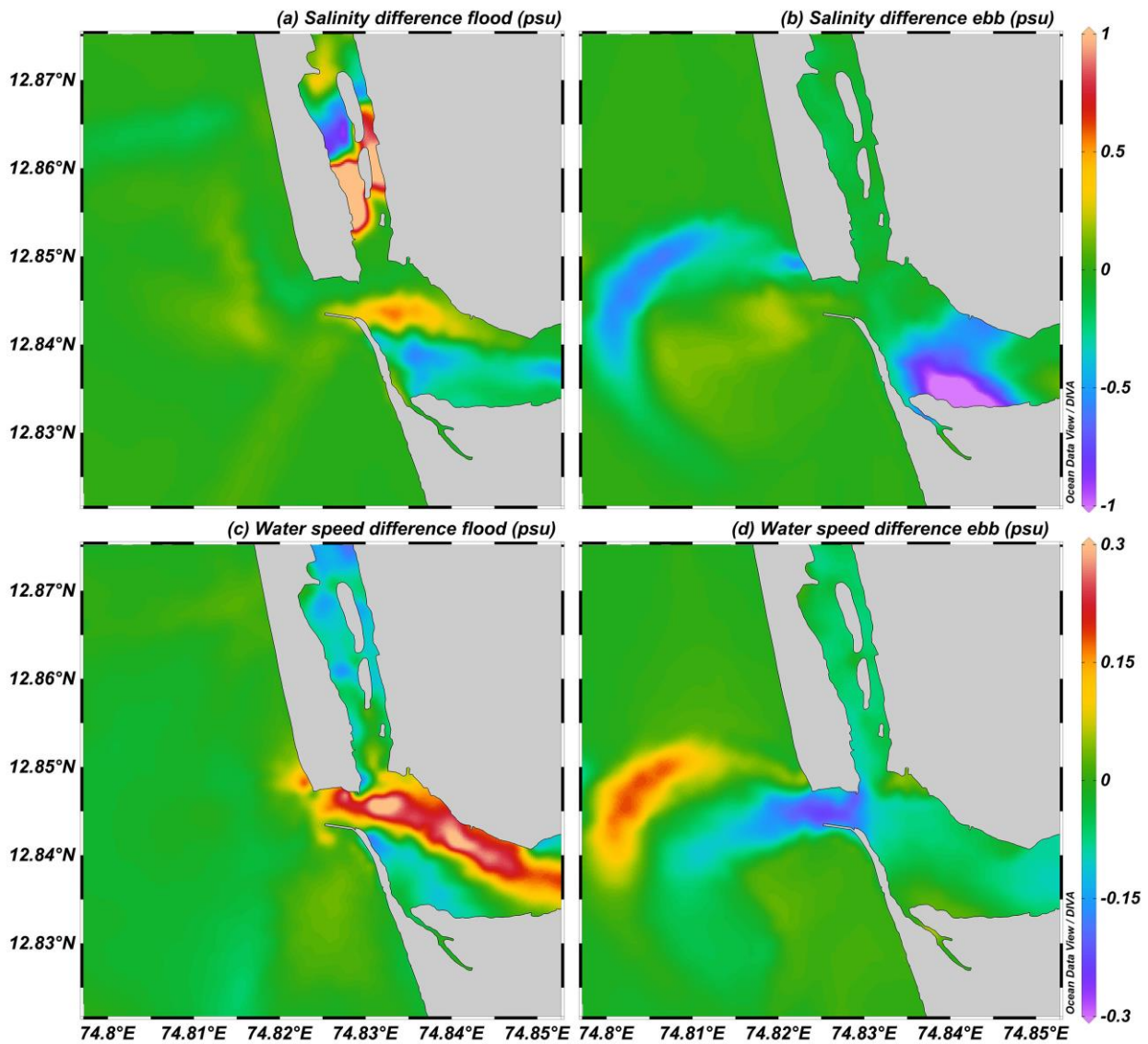


Fig. 7. Average difference (before dredging subtracted from after dredging and averaged for both wet and dry season) of salinity and water speed during flood and ebb tide. Positive values indicate that the parameter increased after dredging and negative values indicate that the parameter decreased after dredging.

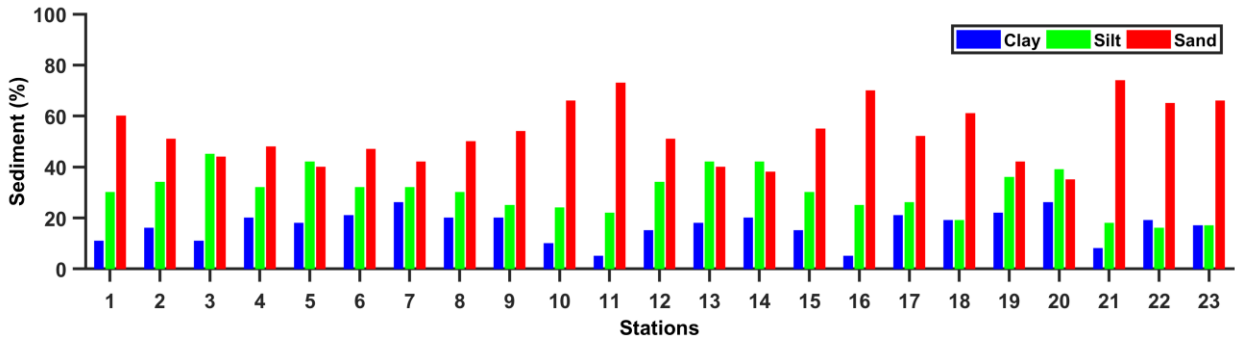


Fig 8. Sediment texture distribution around 23 locations in Old Mangalore Port premises.

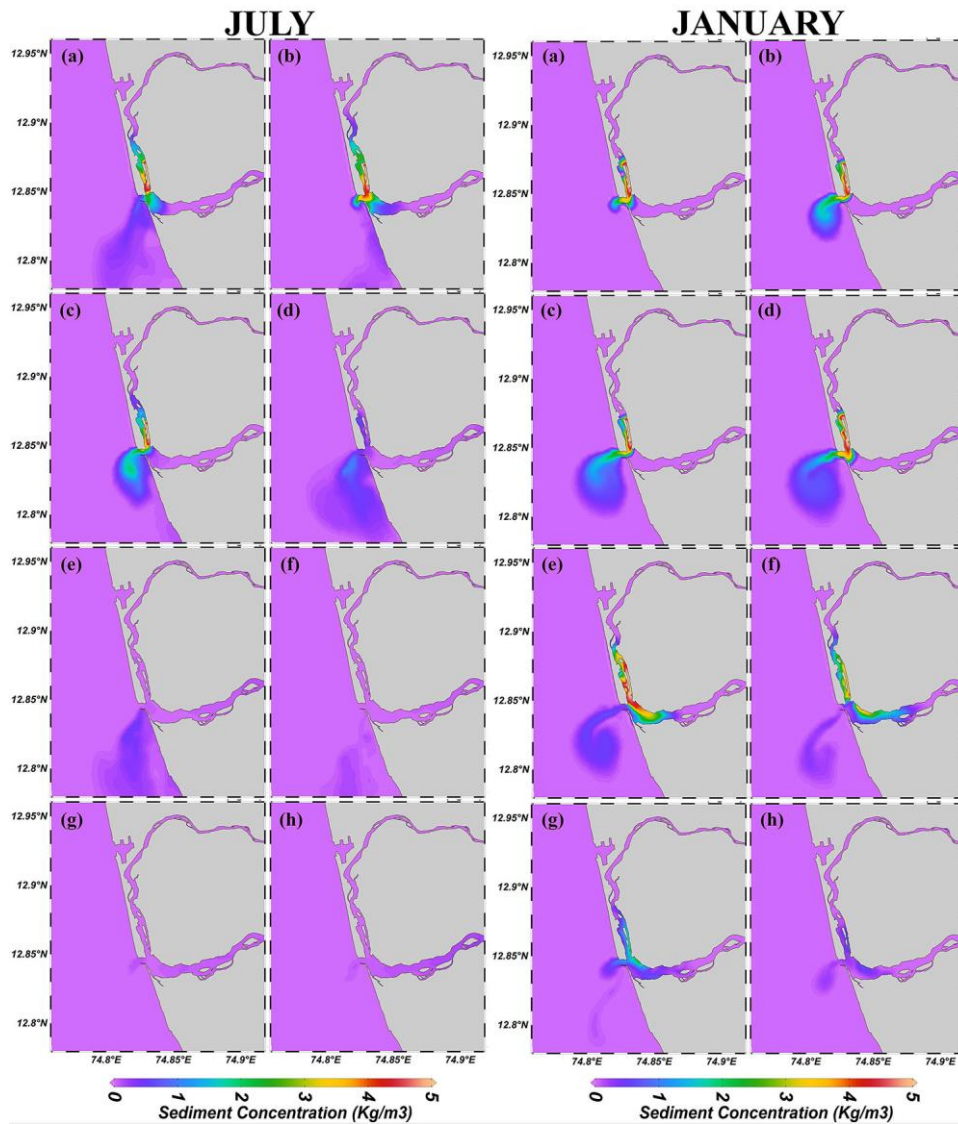


Fig. 9. Average concentration of dredged plume after (a) 3-hour (b) 6-hour (c) 9-hour (d) 12-hour (e) 15-hour (f) 18-hour (g) 21-hour (h) 24-hour at Old Mangalore Port and construction of coastal berth location during July and January.

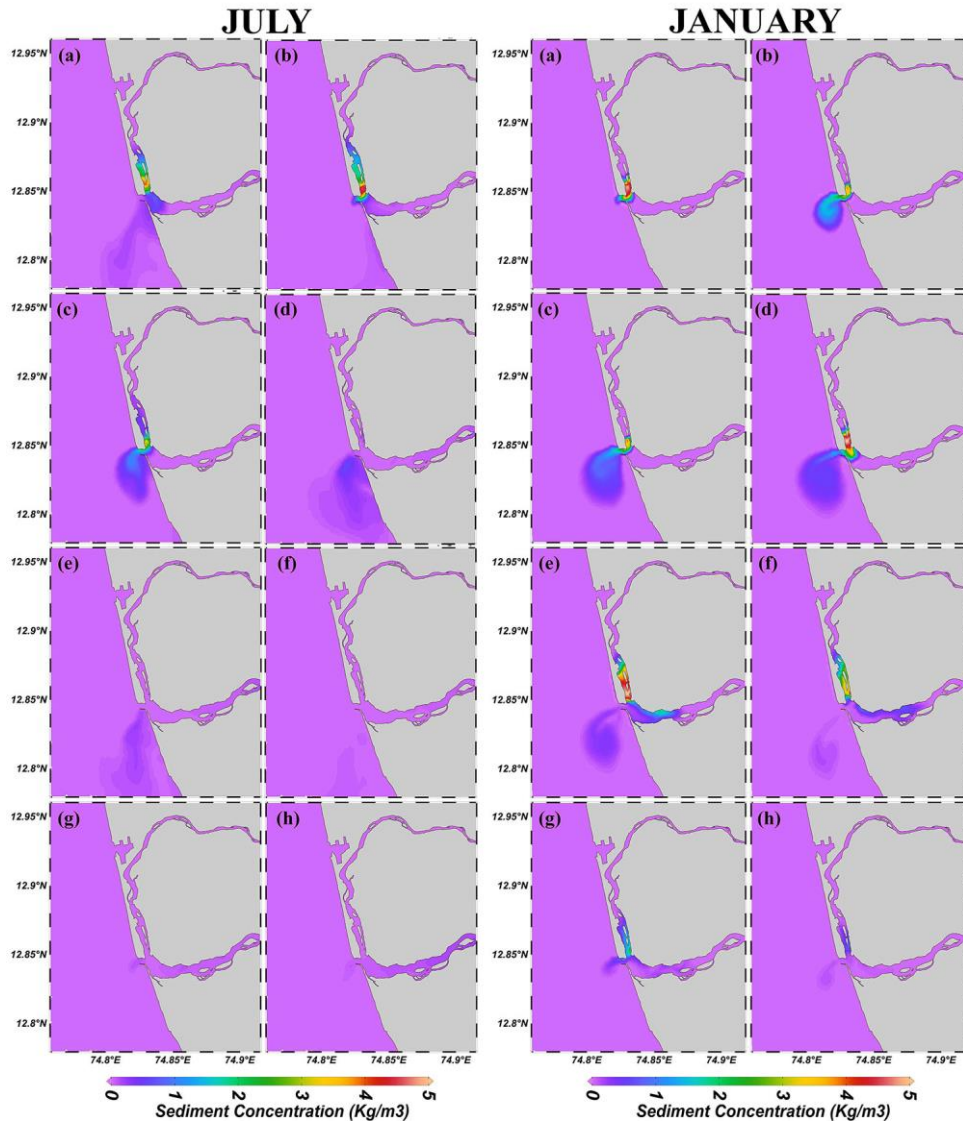


Fig. 10. Average concentration of dredged plume after (a) 3-hour (b) 6-hour (c) 9-hour (d) 12-hour (e) 15-hour (f) 18-hour (g) 21-hour (h) 24-hour inside estuary during July and January

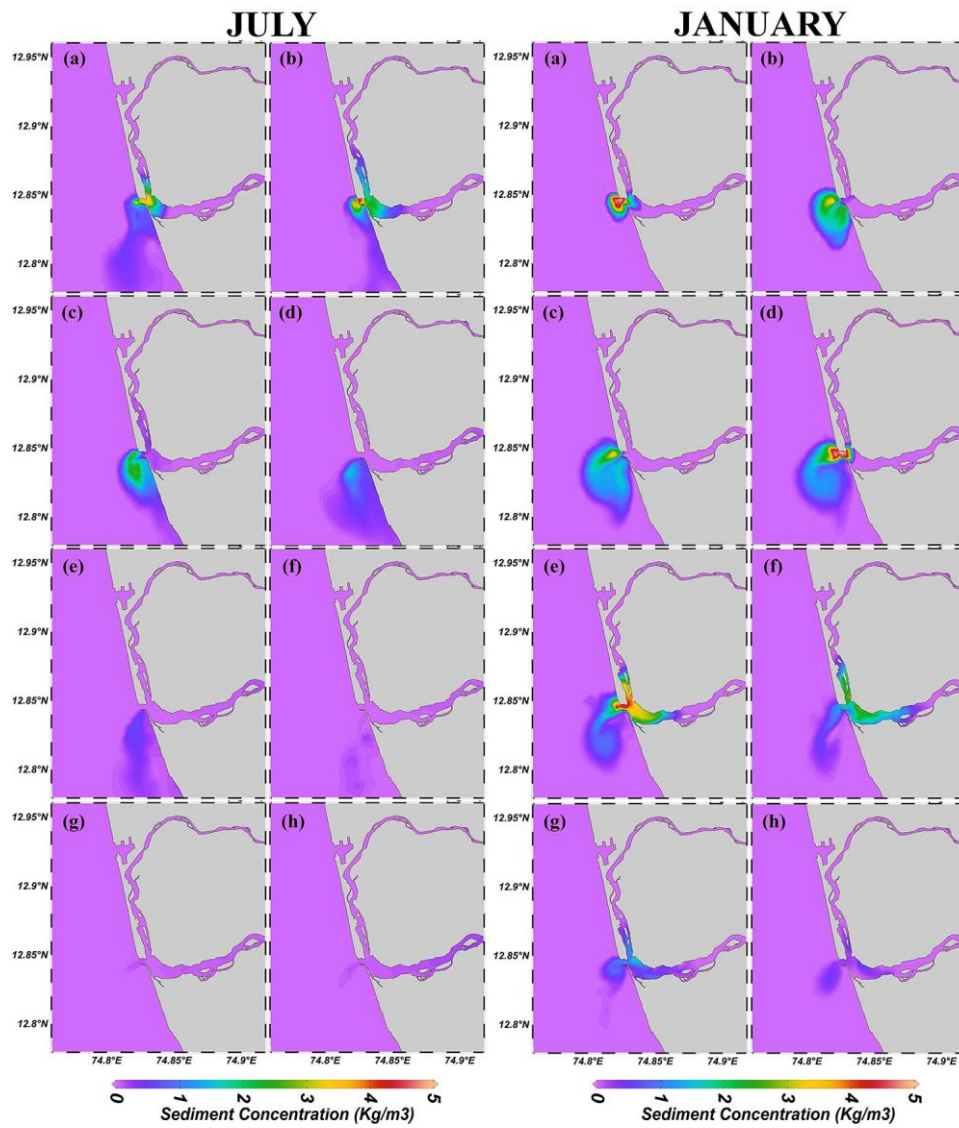


Fig. 11. Average concentration of dredged plume after (a) 3-hour (b) 6-hour (c) 9-hour (d) 12-hour (e) 15-hour (f) 18-hour (g) 21-hour (h) 24-hour outside estuary during July and January

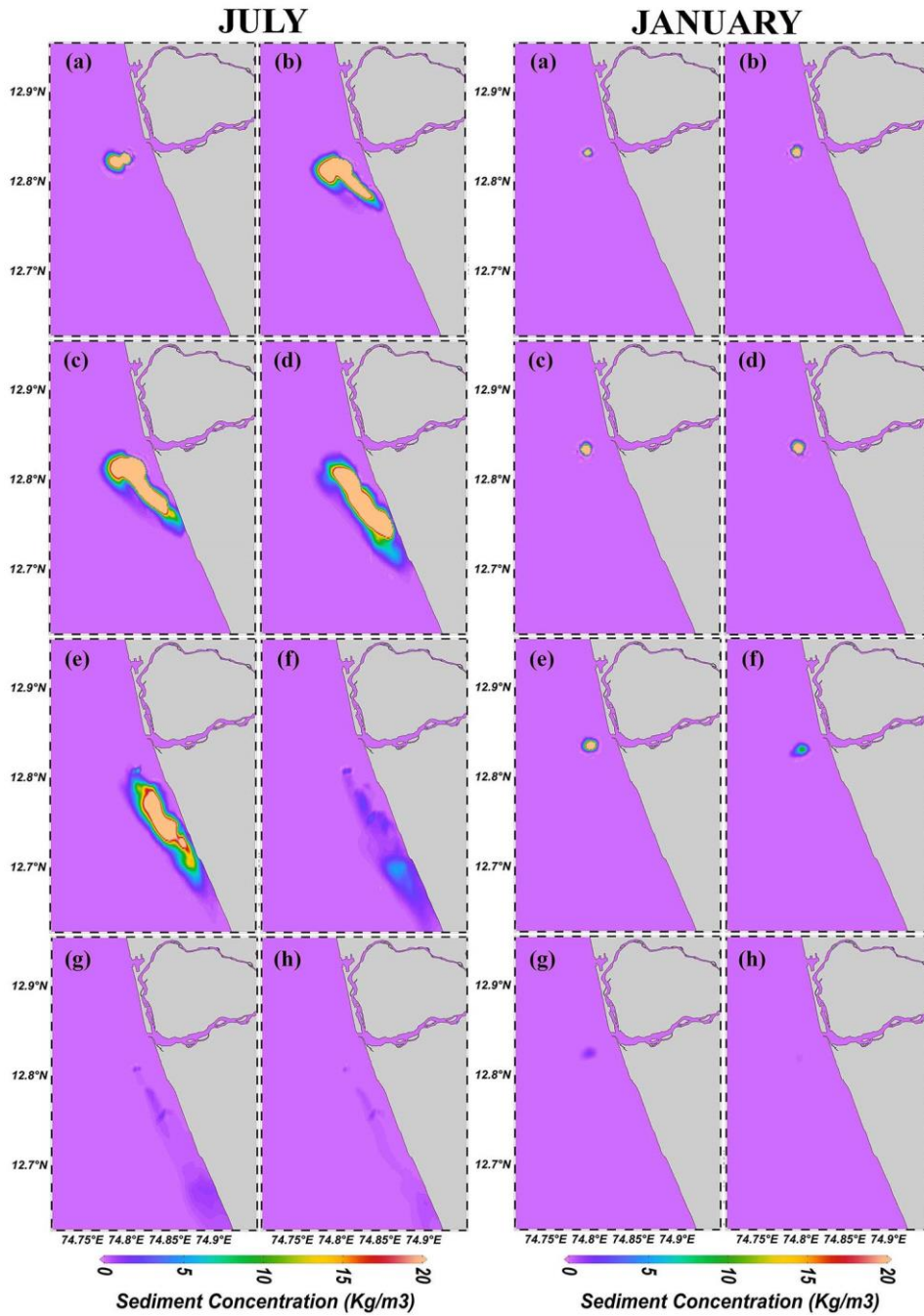


Fig. 12. Average concentration of Dredged plume after (a) 3-hour (b) 6-hour (c) 9-hour (d) 12-hour (e) 15-hour (f) 18-hour (g) 21-hour (h) 24-hour of dumping at 10-meter depth contour during July and January

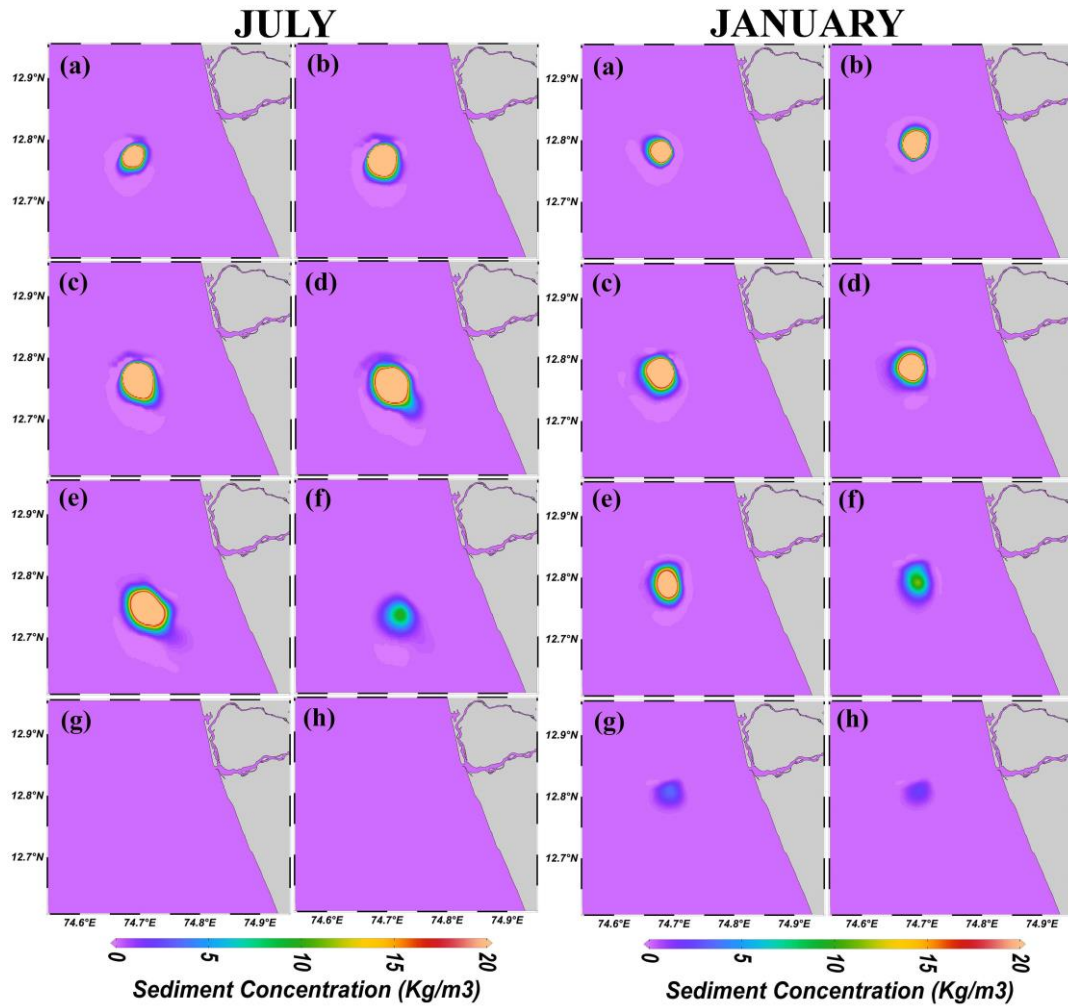


Fig. 13. Average concentration of Dredged plume after (a) 3-hour (b) 6-hour (c) 9-hour (d) 12-hour (e) 15-hour (f) 18-hour (g) 21-hour (h) 24-hour of dumping (≥ 20 -meter depth contour) during July and January