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Abstract- Mudbanks are the unique coastal phenomena with distinct patches of turbid and calm water with a high load of suspended sediment appearing close to the shore during rough sea. The occurrence and migration of mudbanks influence the coastal dynamics and coastline stability significantly. A typical mudbank formation was recently identified along the southern end of the east coast of India near Vedaranyam after the occurrence of Tsunami in 2004. A detailed study was carried out on the coastal morphology, geology, waves, currents, tides and other oceanographic parameters in the sea between Vedaranyam and Velankanni covering 35 km stretch during 2015 to 2016. The extent of clay deposition on the seabed and the formation of mudbank is more on the south side near Vedaranyam and reduce towards north near Velankanni. Such mudbank phenomenon was not existing before the occurrence of Tsunami in 2004. A lot of sediments washed into the sea elsewhere by the Tsunami waves got deposited in Palk Bay is found to be the primary reason for the recent formation of mudbank between Vedaranyam and Velankanni. It is noticed that during southwest monsoon season July and August, there is a deposition of mud composed of silt and clay at nearshore brought from the Palk Bay and also from the offshore deposits. The formation of mudbanks as clay deposit at nearshore gets retreated and disappears with the onset of northeast monsoon in October. This paper presents the detailed study on the reasons for the formation and behavior of this mudbank supported by various field observation.

Keywords: mudbank, vedaranyam, east coast of india, palk bay, littoral sink.

I. Introduction

Mudbanks are the distinct patch of turbid and calm water, wherein the silt and clay fractions of sediments float in colloidal form across the water column, and such feature appears more commonly in monsoon period. Active mudbanks are those areas where the waves are attenuated by viscous dissipation and calm water prevails even in monsoon season. Passive mudbanks are the same areas when the wave characteristics in the region are like those of the other places. Persistent mudbanks are those mudbanks which become active practically every year during the monsoon season when wave action becomes strong. These mudbanks need not remain permanently at a particular place, and they can shift from one region to another, but maintain their form (Gopinathan and Qasim, 1974).

The appearance of mudbanks is associated with an increase in the consistency of the sediments kept in suspension and the force associated with the driving agents such as wind, waves, tides, and currents near the shore. When the mud gets into suspension by the agitation influenced by the wave action, the wind and tide-induced currents to drive the entire floating mass slowly. The existence of mud floor at the nearshore is not enough to form mudbanks. The mud of the right texture must get consolidated at the precise depth where wave action could churn it up into a thick suspension. If during the active phase of the mudbank, the wave action is not strong enough to churn up the mud into colloidal suspension and bring it close to the surface, then there will be no movement in the form of suspended particles. Subsequently, the mud will settle on the sea floor, but it would appear again at the same position in the following year.

a) *Mudbanks on Indian Coast*

In India, the formation of mudbanks has been observed in the past at several locations along Kerala and south Karnataka coasts during south-west monsoon. Now it is not occurring at all the places. However, in Kerala, the predominant Alleppey mudbank appears almost every year between Thottapaly and Mararikulam and extends up to 10-15 km along the coast and 5-6 km offshore during southwest monsoon (Parvathy et al. 2015). Several studies have been carried out on Alleppey mudbank (Moni, 1970; Kurup, 1977; CMFRI, 1984 Mallik et al. 1988; Mathew, 1992; Narayana et al. 2008, etc.).

b) *Morphology of Tamil Nadu Coast*

The coastal zone of Tamil Nadu is endowed with varied landscape such as sandy beaches, beach ridges, backwaters, estuaries, intertidal mud and sand flats, dunes, cliffs, beach rocks, deltas, lagoons, mangrove forests and coral reef ecosystems. The coast has constantly been undergoing physical changes in the geological past and at present. There is a reduction of sediment supply from rivers which lead to beach recession at many places. Apart from the coastal geomorphic features, the Tamilnadu coast is protected by rocky shores facing the India Ocean between

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Thengaipattinam and Manappad, coral and oyster ecosystem in the Gulf of Mannar between Manappad and Mandapam, protected shallow bay with endangered flora and fauna in Palk Bay between Mandapam and Vedaranyam. The coastal area between Nagapattinam and Puducherry is occupied by low and narrow beaches, deltaic plain, palaeo-tidal flats, palaeo-lagoons and salt marshes. (Anbarasu and Rajamanickam, 1997). The coast between Puducherry and Chennai is a well-developed sandy belt with intermittent geomorphic features like tidal flats, estuaries, beach dunes and beach ridges.

The segment of the coastline between Vedaranyam and Velankanni forms the southern end of the east coast of India facing the Bay of Bengal. It is in the Cauvery draining basin with more lagoon and waterlogging wetlands. The coastal formation is composed of alluvial sediments brought by various storm drains. This region depicts a distinct depositional form of the coast, located near the southernmost end of the east coast of India, where the influence of Bay of Bengal ends. The tip of the southern end called *Point Calimere alias* Vedaranyam *alias Kodiya Karai,* comprises of a large wetland system with brackish water lagoon. The nearshore remains very shallow, and there is a formation of a shallow sand spit called Palk Strait running approximately 65 km long between Point Calimere (India) and Point Pedro (Srilanka). The offshore region in this stretch functions as a sink for the littoral drift moving along the east coast of India during northeast monsoon; and the littoral drift moving around the Srilankan Island towards the Indian Coast during the southwest monsoon (Jena, 1997).

During the southwest monsoon, this segment of coastline is considerably protected from waves by the Jaffna peninsula of the Srilanka Island. The wind effect is more on the coast because of the funneling effect caused by the two land masses viz. India and Srilanka. Such strong winds generate local waves, and hence the sea remains at times choppy during southwest monsoon with short-crested waves. However, this region receives unobstructed high waves during the northeast monsoon. The wave climate is relatively calm compared to the northern part of the east coast. The waves approach nearly parallel to the shore and hence the net volume of littoral drift is minimum along this stretch between Vedaranyam and Thirumullaivasal leading to the classification of nodal region with negligible annual net drift.

c) *Formation of Mudbanks between Vedaranyam and Velankanni*

The coastal stretch between Vedaranyam and Velankanni is 35km long, and the seabed in this stretch is composed of sand and silt. However, during southwest monsoon in July and August, there is a deposition of mud composed of silt and clay which give rise to the formation of mudbank. The accumulation of mud on the seabed is more severe between the intertidal zone and 500 m offshore than the other regions. The spread of the mudbank is observed to be 35 km along the coast and for1 km into the sea. Such mudbank phenomenon did not exist before the occurrence of Tsunami in 2004. A lot of sediments washed into the sea elsewhere by the Tsunami waves got deposited in Palk Bay is found to be the primary reason for the recent formation of mudbank between Vedaranyam and Velankanni. It is noticed that during southwest monsoon season in July and August, there is a deposition of mud composed of silt and clay at nearshore brought from the Palk Bay and also from the offshore deposits. This formation of clay deposit on the seabed and the movement of mudbank disappear with the onset of northeast monsoon from October. This seasonal deposition of clay causes a problem to fishermen as they find it difficult to push and beach their fishing boats on the shore. The intensity of clay deposition on the seabed is more on the south side near Vedaranyam and reduces towards north till Velankanni. The places further north like Nagapattinam, Tharangambadi, Poompuhar, etc. do not show such mud deposition on the seabed in southwest monsoon. The mud deposition on the seabed and the subsequent mudbank phenomenon remain as localized between Vedaranyam and Velankanni.

II. Materials & Methods

Data on the coastal morphology, geology, waves, currents, tides and other oceanographic parameters in the sea between Vedaranyam and Velankanni covering 35 km stretch were collected during 2015 to 2016. The seabed sediments were collected at 42 locations between Tharangambadi and Vedaranyam (Fig.1). The parameters on turbidity, salinity, and temperature were measured using *YSI Multiparameter Water Quality* probe at 2300 m offshore (Fig.1) for 32 days from 25.07.15 to 26.08.15. Tide data were recorded for 36 days from 20.07.15 to 26.08.15. The surface current speed and direction were measured using self-recording *Aanderaa RCM 9 current meter* for 32 days from 25.07.15 to 26.08.15 at 2300 m offshore at 4.7 m water depth. The wave measurement was carried out for six months using *Datawell Directional Wave Rider Buoy of 90 cm* off Vellapallam at 3000 m offshore in 6 m water depth from 01.08.15 to 14.01.16. Measurement locations of tides, currents, and waves are also given in Figure 1. Bathymetry survey was carried covering an area of 3000 m distance along the coast and 5000 m distance into the sea with dual frequency echo sounder.

III. Results and Analysis

The field data collected during July - August 2015 on various parameters have been used for analyzing the reasons for the formation of mudbank.

a) Seabed Sediments

In general, the nature of the seabed at nearshore from Velankanni to Vedaranyam is composed of sand and silt. But, it is noticed that during southwest monsoon particularly in July and August, deposition of silty clay is seen on the seafloor. The composition of the seabed sediments is shown in Table 1. The seabed sediment size classification shows the nearshore within 1500 m between Vedaranyam and Velankanni consists predominantly silt and clay with the absence of sand particles during August. The proportion of silt particle was relatively higher on the southern side whereas the clay particle was more on the northern side. The sampling was done during the period of formation of mudbank which indicated the deposition of silt and clay on the seabed. In the same season, the sediments collected further offshore indicated the presence of 95% sand fractions without any clay particles. It shows that the movement of clay and in turn the mudbank is restricted close to shoreline within 1500 m from the shore.

b) Tide

Tide data recorded for 36 days from 20.07.15 to 26.08.15 are shown in Fig.2. The measurement displays that the tides are semidiurnal, and the spring tidal range existed around 0.62m and, the neap tidal range around 0.27m. The tide measurement location is shown in Fig.3.

c) Currents

The maximum current speed reached up to 0.46 m/s and the mean current speed showed0.18 m/s(Fig.2). The current was uni-directional towards the north in July -August 2015. The current speed appears to change with tidal phases, increasing during flood tide and decreasing during ebb tide.

The region between Vedaranyam and Vellapallam is subjected to low tidal variation compared to the northern part of East Coast of India. Similarly, current speed remains minimum. This hydrodynamic regime favor a depositional regime of the suspended sediments.

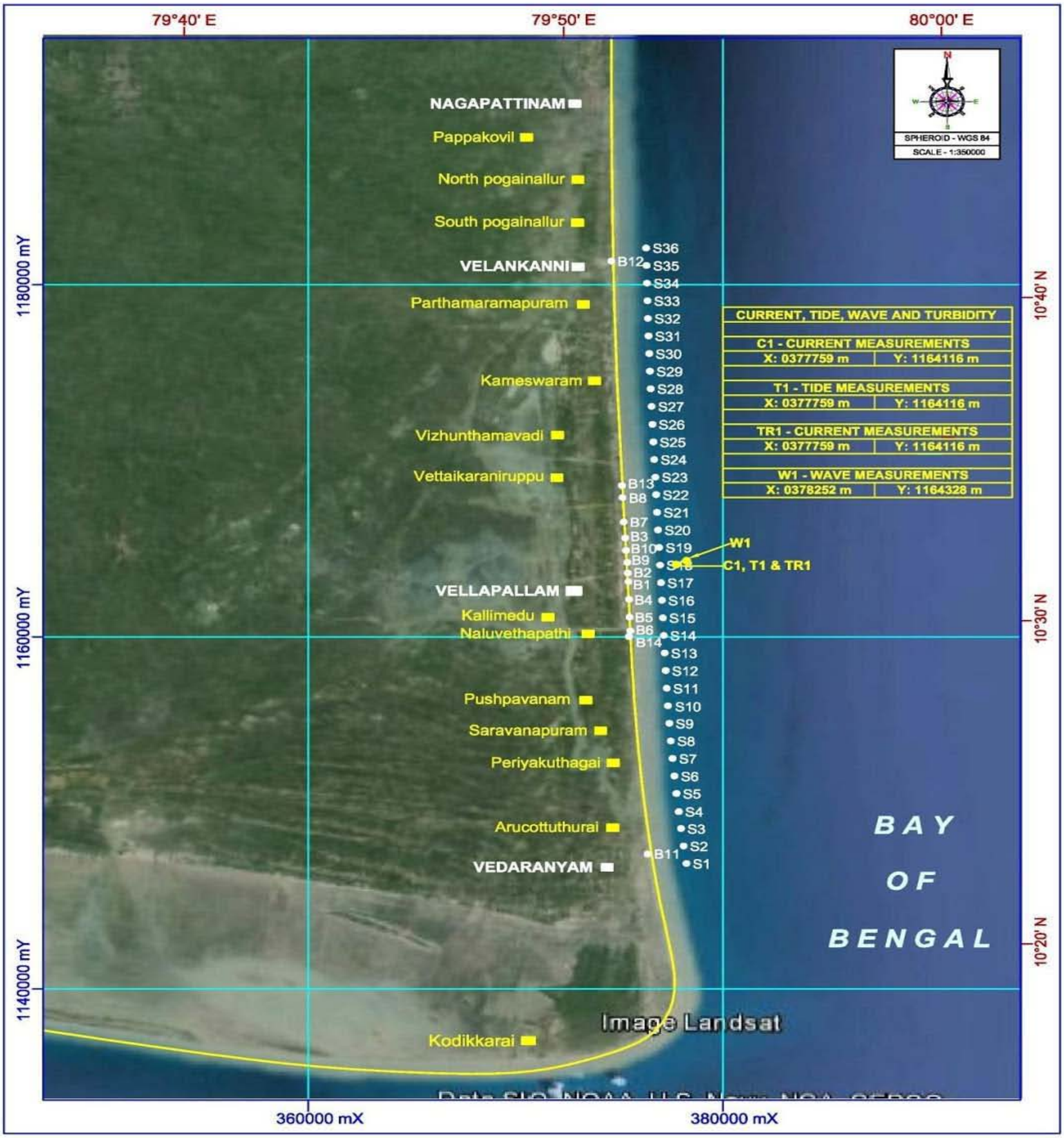

Figure 1: Sampling locations between Vedaranyam and Velankanni

Table 1: Composition of seabed sediments

Station No.	Distance from the shore, km	Silt %	Clay %	Station No.	Distance from the shore, km	Silt %	Clay %
S1	1.5	60.6	39.4	S22	1.5	54.0	46.0
S2	1.5	67.2	32.8	S23	1.5	48.6	51.4
S3	1.5	67.2	32.8	S24	1.5	52.4	47.6
S4	1.5	68.3	31.4	S25	1.5	54.0	46.0
S5	1.5	62.5	37.5	S26	1.5	55.1	44.9
S6	1.5	52.4	47.6	S27	1.5	50.4	49.6
S7	1.5	57.1	42.9	S28	1.5	58.8	41.2
S8	1.5	60.4	39.6	S29	1.5	54.0	46.0
S9	1.5	63.4	36.6	S30	1.5	55.6	45.4
S10	1.5	61.1	38.9	S31	1.5	56.4	43.6
S11	1.5	64.5	35.5	S32	1.5	43.2	56.8
S12	1.5	54.6	45.4	S33	1.5	45.1	54.9
S13	1.5	64.7	35.3	S34	1.5	54.3	45.7
S14	1.5	58.1	41.9	S35	1.5	52.4	47.6
S15	1.5	60.5	39.5	S36	1.5	54.6	45.4
S16	1.5	56.5	43.5	S37	1.0	57.0	43.0
S17	1.5	59.7	40.3	S38	3.0	61.2	38.8
S18	1.5	57.5	42.5	S39	5.0	60.5	39.5
S19	1.5	56.0	44.0	S40	1.0	60.4	39.6
S20	1.5	46.8	53.2	S41	0.5	60.4	39.6
S21	1.5	52.4	47.6	S42	0.5	58.1	41.9

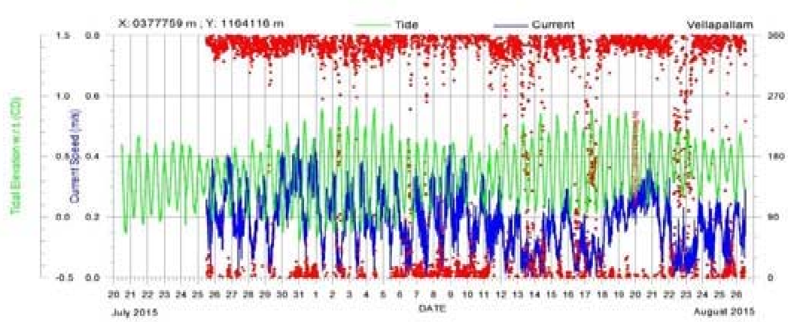

Figure 2: Variation of Tide, Current speed, and direction at study region

d) Turbidity, Salinity, and Temperature

The variation of temperature, salinity, and turbidity are shown in Fig. 3. During the measurement period, the turbidity varied from 12.2 to 270.3 NTU. Variation of turbidity appears to change with the tidal phases, showing high turbidity during the ebb phase and low turbidity during flood phase. The seawater temperature varied from 28.11 °C to 30.68 °C, and the salinity varied from 25.13 ppt to 39.06 ppt during the measurement period. There was a freshwater flow due to heavy rain, and hence the salinity level reached very low during the period 17.08.2015 to 26.08.2015.

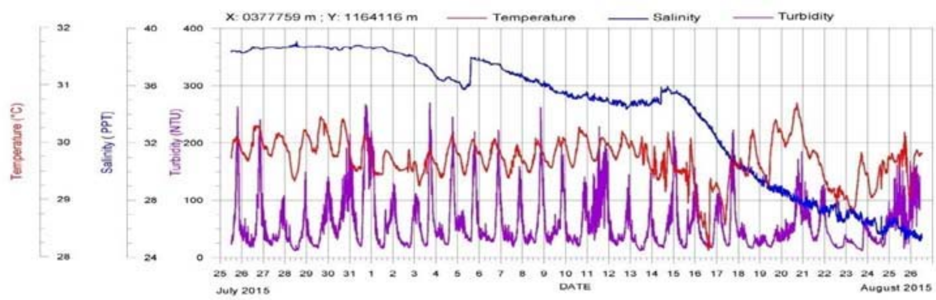

Figure 3: Variation of Salinity, Temperature, and Turbidity at study region

The turbidity level found to vary with flood and ebb tides, i.e., the ebb flow from shore into sea induce more friction on the sea floor and initiate more fine sediments into suspension (>100 NTU) which gives the understanding that in addition to turbulence caused by waves, the tide-induced currents over the tidal phase increase the turbulence to keep the sediment in suspension. It is also noticed that during flood tide, the suspended sediments are brought close to shore and get deposited resulting in low turbidity levels (<25NTU). The seawater salinity and temperature level remain more or less steady till there was a mixing of rainwater in this region.

e) Waves

The wave measurement was carried out for six months using *Datawell Directional Wave Rider Buoy of 90 cm* off Vellapallam at 3000 m offshore in 6 m water depth from 01.08.15 to 14.01.16 is given in Table 2. The Nagapattinam wave data mesaured in 1995 to 1996 were considered for the rest of the months. The typical wave roses representing southwest monsoon and northeast monsoon are shown in Fig. 4. During the measurement period of six months, the significant wave height (H_s) varied from 0.17 m to 1.99 m. The maximum wave height (H_{max}) ranges from 0.27 m to 2.77 m and zero crossing wave periods (T_z) varied from 2.35 to 7.69 seconds. The wave direction corresponding to peak energy (θ_p) during the measurement period mostly remained between 70° and 100°. The coastal orientation at this location is approximately N5°W. The measured wave characteristics at 15 m water depth at Nagapattinam is given in Table 3.

Table 2: Measured wave characteristics at 6.0 m water depth - Vellapallam

Month	Significant wave height H_s (m)		Maximum wave height H_{max} (m)		Zero-crossing wave period T_z (s)		Predominant direction θp (°N)
	Min	Max	Min	Max	Min	Max	Range
Measured in August 2015- January 2016							
August	0.18	0.78	0.30	1.44	2.38	6.78	70° - 160°
September	0.17	0.78	0.27	1.39	2.35	5.71	70° - 160°
October	0.20	0.87	0.30	1.80	2.45	7.69	70° - 100°
November	0.26	1.99	0.41	2.77	2.60	7.27	55° - 80°
December	0.72	1.52	1.20	2.59	3.60	5.71	55° - 100°
January	0.57	1.16	0.89	2.25	3.28	4.55	70° - 90°

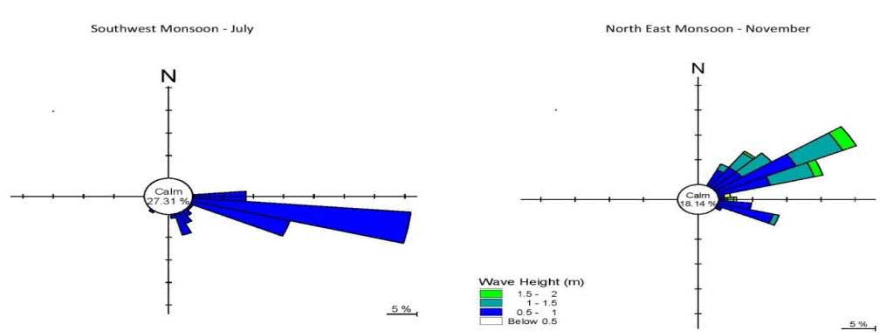

Figure 4: Rose diagram for wave height - SW and NE monsoon

Table 3: Measured wave characteristics at 15 m water depth - Nagapattinam

Month	Significant wave height (m)	Zero-crossing wave period (s)	Wave direction (Deg. N)
Measured in March 1995 –February 1996			
February	1.25	5	85
March	0.5	5	80
April	0.5	5	90
May	0.5	5	90
June	0.75	5	105
July	0.75	5	105

During northeast monsoon (October-January) the waves approach from the sector between 45°N to 90°N, but predominantly from 70°N. On the other hand, during southwest monsoon and fair-weather period, they approach from the sector between 100°N and 160°N but predominantly from 110°N. The wave activities are low, and the region remains calm during southwest monsoon (June to September). On the contrary, the tide-induced currents in July and August are strong and flows unidirectionally from south to north. The northerly currents bring the sediment particles from Palk Bay and deposits along Vedaranyam and Velankanni due to low wave energy environment.

f) Bathymetry

The variation of depth at near shore is even with contours running parallel to the coastline. The seabed remains very shallow typical to the terminal end of the east coast of India bordering the Bay of Bengal. This falls with a uniform slope with contours running parallel to each other. The depth contours of 2 m, 3 m, 4 m, 5 m, 6 m and 7 m occur at a distance of 420 m, 1020 m, 1870 m, 2725 m, 3825 m and 4800 m from the shoreline respectively. The nearshore area is very shallow up to 5 km. The thickness of deposition of silty clay at nearshore based on the difference in depth recorded from low frequency and high-frequency depths obtained from the dual frequency echo sounder is shown in Fig.5.

The loose form of silty clay sediments are found to be significant up to 500 m offshore, and this phenomenon is seen spread between Vedaranyam and Velankanni. The thickness of deposition was found to be up to 0.7 m.

IV. Conclusion

The sources of mudbanks can be of subterranean mud, coastal mud, rivers/ estuaries discharge and dredge waste. Since there are no dredging operations in this area, the mud does not originate from the dredging operation. There are no rivers, and the mudbank region is present with storm drains which carry limited discharge only during northeast monsoon. The mudbanks, on the other hand, are formed during southwest monsoon, and hence it can be seen that the river does not discharge the mud into the sea. The source of mudbanks may be coastal mud which is already present on the coast. It is also observed that mud gets deposited only in the nearshore and there is no such deposition in the offshore.

Hence it is concluded that the source of mudbank is the coastal mud deposited in Palk Bay south of Vedaranyam. The earlier studies do not indicate the existence of mudbank before the year 2004. The local fishermen report that the mudbank phenomenon started only after the 2004 Tsunami. The coastal stretch between Nagapattinam and Puducherry was severely affected by 2004 Tsunami, and a lot of sediments were washed into the sea which was carried towards the south and deposited inside the Palk Bay at Tsunami shadow zone. There was deposition of sediments reported inside Palk Bay particularly between Vedaranyam and Thondi. The northern currents are stronger during July and August, and this deposited sediments find the way to move north in the form of mudbank and deposit the clay between Vedaranyam and Velankanni. During the northeast monsoon, when the wave activities become high, the mud particles are stirred up, and the southerly currents carry them back into Palk Bay and deposit back once again. During the northeast monsoon and fair-weather days, the nearshore seabed along the stretch between Vedaranyam and Vellapallam show the composition of silt and sand without the presence of clay particles. However, the process of mudbank formation and sustenance along Kerala coast is slightly different as it is seen calm area only during southwest monsoon.

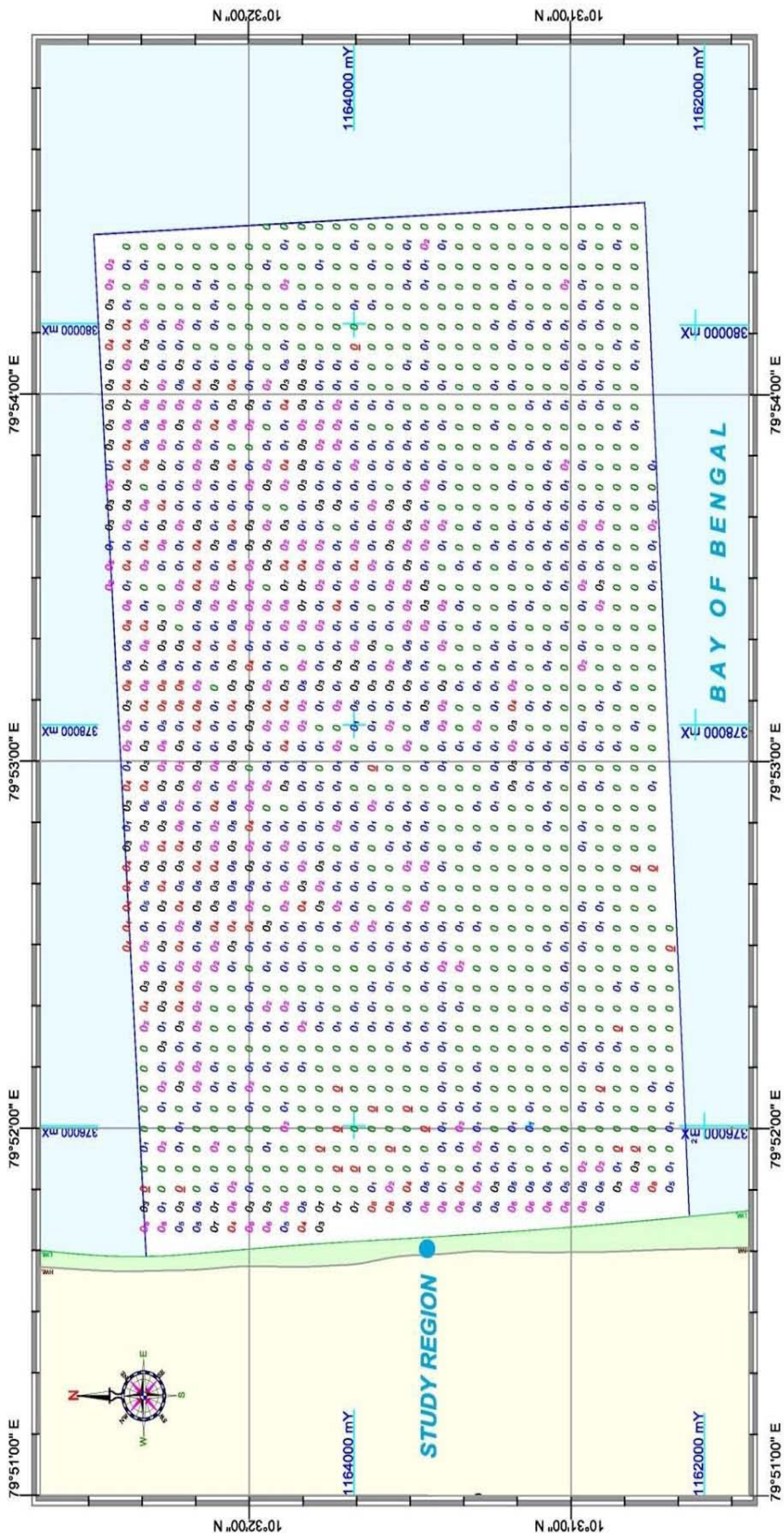

Figure 5: Depth of mud deposition

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