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Review article

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Characteristics of Mudbanks along the Southwest Coast of India

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Abstract
Mudbank is a unique phenomenon observed along the south-west coast of India among all the Indian coastal regions during the Southwest Monsoon Season. The scientific reasons behind the formation and its persistence are vague. Mudbank is considered as a boon to the fishermen of Kerala, as they are getting reasonable catches during the occurrence of mudbanks using indigenous boats from the calm sea, which otherwise is in a fury during the rough Southwest Monsoon Season. Since the region, the Arabian Sea, is significant as a carbon sink due to its very high productivity because of different coastal ocean features, variations in the smaller and highly restricted coastal processes due to climate change can have a significant impact on the rates of global warming. Here, we consolidate the previous publications on various aspects of mudbanks with the reports of the occurrence of mudbanks on the south-west coast of India. A model for the prediction of the formation and location of mudbanks, inclusive of all the intrinsic and extrinsic parameters involved, through an extensive study is much relevant as far as the socio-economic and food security significance is concerned. Here, we discuss the most conducive factors for the formation of mudbank and its characteristics with special reference to Alappuzha, where the frequency of occurrence of mudbanks is maximum among the Indian coastal regions.

Keywords: Mudbank, upwelling, primary production, monsoon, Kerala.

Introduction
The mudbanks of Kerala generally occur, during the Southwest Monsoon Season, from Vizhinjam to Kannur. Their frequency is more in Alappuzha on the south-west coast of India. A semi-circular region of suspended sediments with calm and turbid water forms during this phenomenon, whereas the surrounding areas are very rough with intense wave activity. They cover a width of around 4 to 5 km and a length of about 4 to 8 km. The shape of the region covering mudbanks is shown in Fig.1. Mostly the length of the region is alongshore, but sometimes it is towards offshore. The fine suspended sediments dampen the wave activity so that the area appears calm. In regional language, this phenomenon is known as Chakara. Schools of fish accumulate here and fishers get a very good catch. Mudbank is considered as a boon to the fishers of Kerala as bounds of prawns, sardines, mackerel, soles, etc. aggregate in this region and fishers can use indigenous vessels for fishing, as the area is calm.

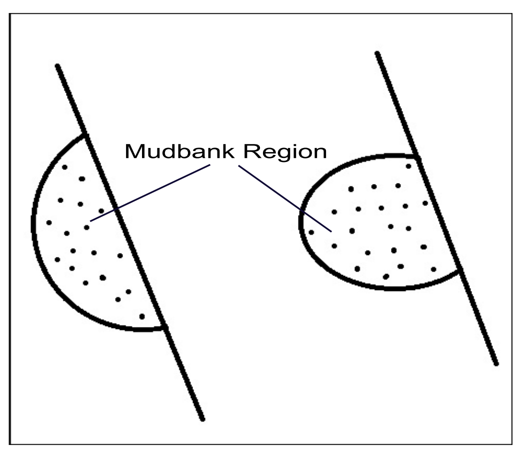

Figure 1: Shapes of the mudbank region.

Mudbanks along the Kerala coast were first mentioned in 1678 in Pinkerton's 'Collection of Voyages and Travels' appeared in the 'Administrative Report of 1860 of Travancore'. [1] coined the term 'Mud Bay' to denote Alappuzha mudbank in his book 'A new history of East India.' The first explanation for mudbanks was given by [2]. According to him, the hydraulic pressure caused by the higher level of backwaters (about 4 feet) than sea level, during monsoon, creates a mudbank. Nevertheless, a report on the mudbank of Njarackal, Kochi by [3] suggests that the pressure (2 lbs/sq. inch) created by even a rise of 5 feet of backwater is not enough to push the mud to the coast. In addition, the consistency of mud in the mudbank is different from that in the adjoining Vembanad Estuary, as the sediments of the estuary have a high percentage of carbon and vegetable debris. Later 'mud volcanoes' or 'mud cones' were observed by many at Alappuzha [4, 5]. After 1973, the development of mudbanks in the south-west coast of India did not favour much in the fishing activity along the coast [6]. In his review, he discussed different factors that could affect the formation of mudbanks and identified the areas of research to be included in future investigations on mudbanks.

Being land-locked, the Northern Indian Ocean is one of the warmest areas of the global oceans during the pre-monsoon season (March to May). Any moderate fluctuations in SST will result in a considerable variation in the Indian Summer Monsoon (ISM). One of the most influencing factors that decide the ISM is the differential heating of land and water. As a result, a reversal of wind direction occurs over India and the adjoining seas between Southwest and Northeast Monsoon Seasons. During Summer Monsoon Season, the Southeast Trade Winds from the southern hemisphere after crossing the equator turns to Southwesterly. With the onset of monsoon, this cross-equatorial flow intensifies and forms a low-level jet across the Somali coast and westerly zonal flow over the equatorial Indian Ocean. Off the west coast of India, the direction of the winds vary from rough west-southwest in the north to approximate west-northwest in the south during Southwest Monsoon Season [7]. At the southernmost portion of the west coast of India upwelling and equatorward flow near the surface and a poleward undercurrent occur due to the equatorward alongshore component of wind, which is the maximum at this portion of the west coast than in any other portion of the coast of India [8]. Also, the longshore component of the wind stress controls upwelling along the coast. The intensity of coastal upwelling is directly related to the strength of monsoons, and more vigorous upwelling leads to significant surface cooling, shallower thermoclines, and deeper mixed layers [9]. Since upwelling is more vigorous at the southwest coast of India and the occurrence of mudbanks are frequent in this region a review of the earlier research on these phenomena, highlighting the peculiarities of mudbanks and their influence on the bio-productivity of this region are significant.

Location of Mudbanks

The time and location of mudbanks observed along the Kerala coast for the period 1990 to 2019 are summarised in Table 1. Most of the time, mudbanks are observed during the Southwest Monsoon Season between the latitudes 9 and 10^0 N.

Table 1: Time and location of occurrence of the Mudbanks along the southwest coast of India for the period 1990 to 2019. They are frequent during SW Monsoon Season, between the latitudes 9°N and 10°N (Source: Archives of the local vernacular daily Malayala Manorama).

Date	Place	Location
07-06-1990	Vizhinjam	8.39^0 N, 77.01^0 E
12-07-1992	Chethy	09.62^0 N,76.29^0 E
03-06-1994	Cherthala	09.70^0 N,76.31^0 E
19-06-1995	Ambalapuzha	09.38^0 N, 76.35^0 E
28-07-1996	Purakkad	9.35^0 N, 76.36^0 E
15-05-1997	Chavakkad	10.53^0 N, 76.05^0 E
24-06-1998	Chennaveli	09.64^0 N, 76.28^0 E
09-07-1998	Puthiyappa	11.31^0 N, 75.74^0 E
03-08-1998	Beypore	11.18^0 N, 75.81^0 E
30-05-1999	Vizhinjam	8.39^0 N, 77.01^0 E
22-09-1999	Poonthura	08.44^0 N, 76.94^0 E
13-03-2000	Punthala	9.23^0 N, 76.64^0 E
18-08-2000	Palapetty	10.37^0 N, 76.12^0 E
19-08-2000	Azhikode	11.91^0 N, 75.31^0 E
31-08-2000	Vambaloor	10.26^0 N, 76.14^0 E
11-09-2000	Fort Kochi	9.96^0 N, 76.24^0 E

22-06-2001	Kaipamangalam	10.31^0 N, 76.13^0 E
24-06-2001	Moonupeedika	10.31^0 N, 76.13^0 E
26-06-2001	Valappad	10.39^0 N, 76.09^0 E
26-06-2001	Perinjanam	10.31^0 N, 76.13^0 E
26-05-2004	Vizhinjam	8.39^0 N, 77.01^0 E
09-07-2005	Thrikkunnapuzha	9.28^0 N, 76.30^0 E
24-05-2013	Kochi	9.93^0 N, 76.26^0 E
13-06-2014	Punnapra	9.44^0 N, 76.34^0 E
16-06-2014	Punnapra	9.44^0 N, 76.34^0 E
30-06-2014	Chellanam	9.83^0 N, 76.27^0 E
04-08-2014	Elankunnapuzha	10.02^0 N, 76.22^0 E
03-07-2015	Purakkad	9.35^0 N, 76.36^0 E
09-09-2015	Punnapra	9.44^0 N, 76.34^0 E
20-07-2016	Anthakaranazhi	9.70^0 N, 76.41^0 E
20-07-2016	Manasserry	9.92^0 N, 76.25^0 E
23-07-2016	Alapuzha	9.49^0 N, 76.33^0 E
17-08-2016	Vizhinjam	8.39^0 N, 77.01^0 E
20-08-2016	Alappuzha	9.49^0 N, 76.33^0 E
12-07-2017	Chellanam	9.83^0 N, 76.27^0 E
15-07-2017	Cheruvathur	12.21^0 N, 75.16^0 E
18-01-2018	Kanjiramkulam	8.36^0 N, 77.05^0 E
06-12-2019	Fort Kochi	9.96^0 N, 76.24^0 E

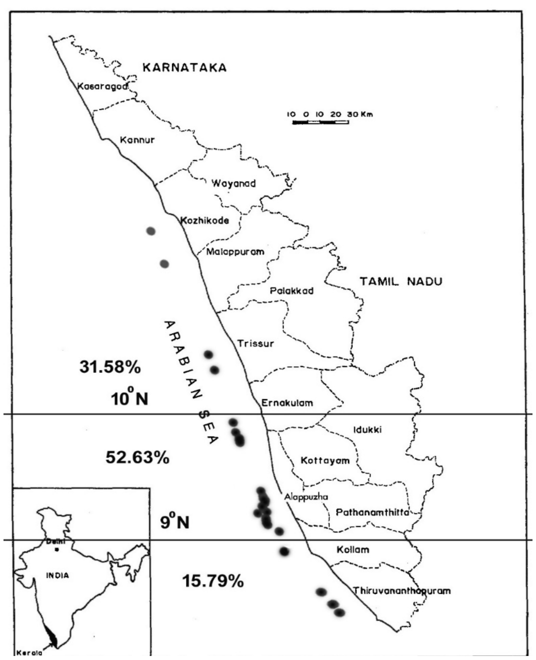

Figure 2: Location of mudbank formation along the Kerala coast during the period 1990 – 2019. 52.63% of the occurrence of mudbanks is between 9 and 10^0 N. 31.58% of occurrence is north of 10^0 N and 15.79% occur south of 9^0 N.

Factors affecting mudbank formation

The main components of mud in the mudbank region are clay and silt-sized particles with small quantities of very fine sand and organic matter. Sediments having a size greater than 62 µm are classified as coarse-grained and lesser than that, fine-grained. The coarser particles of silt, sand, and gravel are generally rounded and are transported as individual particles. The clay particles are plate-like with a diameter of less than 4 µm. Because of the ionic charge of the clay particles, they interact electrostatically and stick together. This cohesive force increases with an increase in the fraction of clay in sediments and becomes significant when the sediment contains more than 5-10% clay by weight [10]. The sediment density in the Alappuzha mudbank region varied from 1080 to 1300 kg/m3 with suspended particle size ranging between 0.5 and 3µm [11].

Various Different hypotheses are observed for the formation of mudbanks, like the Subterranean Passage hypothesis, Hypothesis of a water-bearing stratum, River deposition hypothesis, and the Upwelling hypothesis [12]. In northern parts of Kerala, mudbanks predominantly form by river discharge, whereas near Alappuzha, subterranean mud is the principal source of mudbank [6]. (Fig. 3). Reports of ‘mud cones,’ or ‘mud volcanoes,’ of Alappuzha existed as early as 1855. This phenomenon, infers that there exists a stock of subterranean mud at Alappuzha, which may be the source of clay for the Alappuzha mudbank. Since after 1903, there were no records of significant mud cones in this region; their role in the formation of mudbanks was not significant. However, in 1972, again, mud cones were noticed near Ambalapuzha [12]. In his book 'History of Malabar Mudbanks', founder of the Cochin Harbour, made an organised attempt to study the mudbanks [13]. He explains the origin, formation, and other features of the mudbanks in this book.

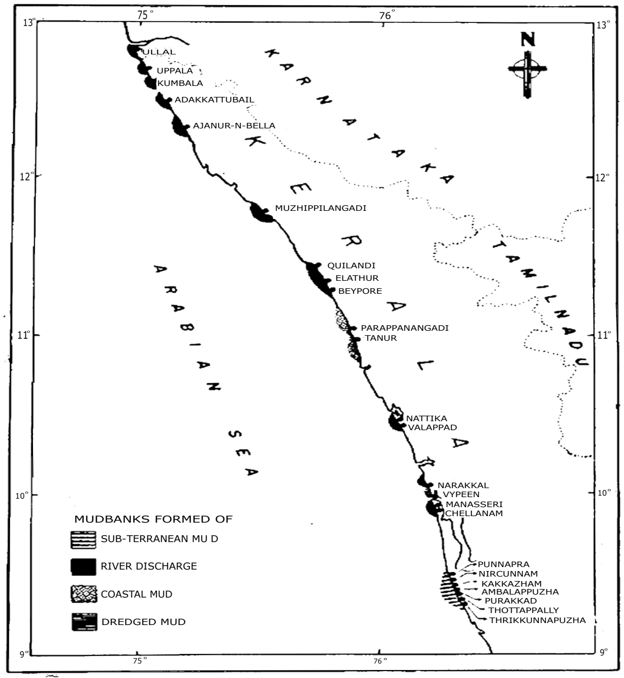

Figure 3: Location and types of mudbanks along the Kerala coast. In northern parts of Kerala mudbanks are predominantly formed by river discharge, whereas near Alappuzha, subterranean mud is the main source of mudbanks (Source: Silas, 1984).

Even though different hypotheses may occur for the formation of mudbanks, for Alappuzha where the phenomenon is most frequent, the subterranean hypothesis seems to be more applicable. In addition, observations regarding other hypotheses are sparse. The presence of excess nutrients and low salinity in the south-west coastal waters of India is generally associated with its proximity to a river or estuarine discharge. The absence of any rivers in Alappuzha and other alternate hypotheses for the formation of mudbanks such as wave convergence, littoral currents, rip currents, etc. could not explain its recurrence at this specific location as those oceanographic processes occur all along the west coast of India and mudbanks are not formed at all those locations. Hence, the plausible reasons for the recurrence of mudbanks near Alappuzha are the subterranean flow from the nearby Vembanad Estuary to the sea, active trending faults, and submerged coral bed [14]. Investigations by [15] suggest that the present form of Vembanad Estuary evolved from an embayment of the Arabian Sea that occurred before the Holocene. Climate change and anthropogenic activities along with natural events caused sedimentological and geomorphological features, which transformed the bay into sand barrier spits and later the present form of the partially closed estuary. Field experiments using Ground Penetrating Radar (GPR) observations, to generate subsurface information to locate buried paleochannels in the coastal zone of Alappuzha, also agreed with the subterranean hypothesis for the formation of mudbanks in this region. These channels may act as the routes for the transport of mud from terrestrial sources to the sea. On observing the historical maps of India, the present-day Vembanad Estuary was a part of the near shore area, and the coastline was nearly 60 km inside. The present-day landforms were created as a result of the earlier river channels from the Western Ghats got buried under recent sand. Observations using GPR during the pre-monsoon and the monsoon seasons indicated a high degree of wetness characteristics in these buried channels during the monsoon season. These buried channels could be the possible passage for water with fine clay particles to the sea [16]. This inference seems to be a more logical reason for the formation of frequent mudbanks in Alappuzha. The location of the Vembanad Estuary is shown in Fig. 4. The estuary is divided into two parts by constructing the Thanneermukkam bund as a barrier to the intrusion of tidal water, which became active in 1976. Nowadays this estuary is also termed as Vembanad Lake. Even though [14] and [16] agree in the Subterranean Hypothesis for the formation of Alappuzha mudbank, studies using sediment samples collected from the Alappuzha mudbank region by [17] show that the observed low salinity in the region which initiates mudbank formation is due to the presence of highly turbid fluid mud and not because of freshwater influence. Even though decreased salinity is a favourable condition for the formation and maintenance of mudbanks, there could be other reasons also which initiate mudbank formation. [2] and [3] also disagree with the subterranean hypothesis for the formation of Alappuzha mudbanks.

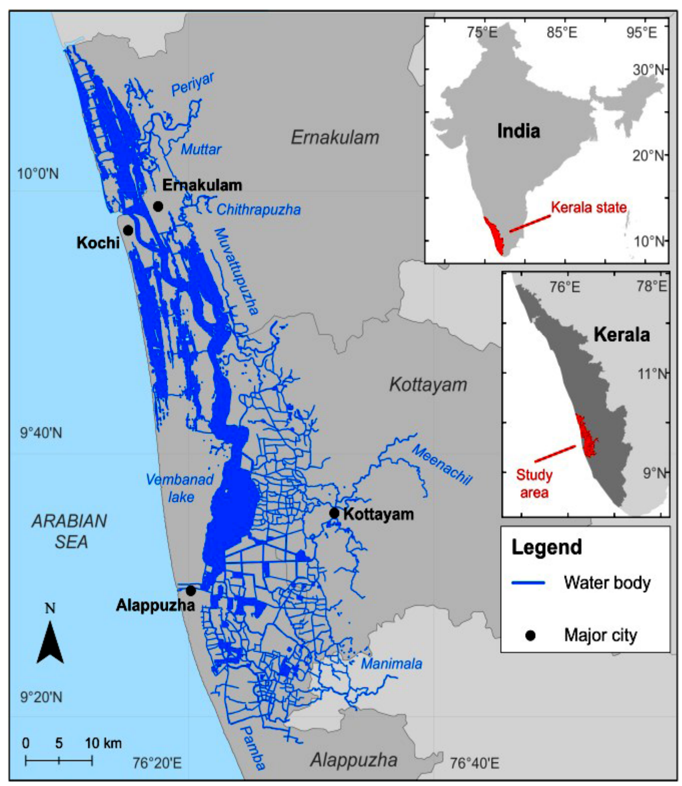

Figure 4: Location of Vembanad Estuary near the coastal area of Alappuzha, in the southwest coast of India.

Many studies occurred on the variations in physical and chemical parameters of the water during the formation of mudbank [18, 12, 19, 20]. For the formation of mudbanks, the mud of the right texture must get consolidate at the proper depth where wave action could churn it up into a thick suspension [21]. In addition, the southerly current can drive the entire floating mass to the south, or when strong swells approach from the south, the whole or part of the mass can move towards the north. The movement of fluid mud can result from the forcing of alongshore, coastal or tidal currents. Since Alappuzha is a wave-dominated and inlet-free coast, the tidal effects are negligible in the transportation of sediments. The movement can probably be due to the stress applied by the prevailing currents. The migratory mudbank causes sediment accretion and erosion along the beach to the north and erosion to the south of the mudbank zone during the Monsoon Season. The mudbank near Alappuzha Pier had moved slowly southward (about 10km in 35 years) until 1895, whereas afterwards, the movement was rapid (about 10km every year). This mudbank that moved about 40km southward disappeared in 1902. A new mudbank appeared in 1925 north of Alappuzha, which also moved southward and remained at about 13km south of Alappuzha Pier in 1972. The migratory behaviour of mudbanks was reported by many [3, 22,23,21,24,25]. The evolution and dissipation of mudbanks occur due to many reasons as currents, storms, shear stresses, river discharge etc. [26, 27, 11, 28,]. The area of the Ambalapuzha mudbank of Kerala on the south-west coast of India increases from pre-monsoon to monsoon season [29].

By magnetically tracking the physical and sedimentary processes like entrainment, transport, sorting, settling, and enrichment of mud, associated with the formation of mudbanks, grain size-selective entrainment is the dominant process during the pre-monsoon, while during the monsoon season, wave-induced energetic bottom currents enhance the suspension of entire sediment bed load to form fluid mud [30]. In another study also the influence of wave action was observed. The wave-mud interaction process induces an oscillatory motion of the surficial mud layer, which thereby affects benthic processes related to bottom stability and nutrient and contaminant fluxes across the mud water interface [31].

In situ observations of mudbanks of Alappuzha and mapping of its extent during the monsoon season in 2016 was done by measuring suspended sediment concentrations using the Laser interferometry instrument (LISST 100X) [32]. The periphery of the mudbank demarcated based on the variations in the concentration and the particle sizes. Even though the spatial distribution of sediment concentration is presented diagrammatically, the exact area of coverage of the mudbank is not mentioned. Meteorological factors have a strong influence on the formation of mudbanks, along with other factors. During the formation of mudbanks the location of the prominent monsoon organised convection is observed near the equatorial region. At this time, the low-level wind along the south-west coast of India is parallel to the coast, towards the south and upwelling occurs near the coast. Because of this, an increase in chlorophyll concentration and total chlorophyll is observed near the south-west coast of India [33].

The mudbanks of Kerala have different causes of origin, in which river discharge, subterranean, coastal mud, dredged mud, etc. contribute to the formation. However, Amazon mudbanks are of estuarine origin. The size of mud flocs observed in the mudbanks along the Kerala coast is < 62.5 μm, while in the Amazon, the size of floc is approximately 400 μm. In the Gulf of Papua, the suspended sediments have a floc size of < 20 μm and these flocs can be transported to considerable distances [34]. Mudbanks of the southwest coast of India is rather small with 4 to 5 km width and 4 to 8 km length, whereas in the world's muddiest coastline of South America between the Amazon and the Orinoco river mouths have more than 15 large permanent mudbanks having a width of 20-30km and length of 10-60km. Many authors discuss different hypotheses for the formation of mudbanks. Even though the exact reason for the recurrent mudbanks in the southwest coast of India is unclear, some kind of bottom phenomenon triggers the process of perturbation of the sediment, which needs a precise investigation.

Persistence and dissipation of Mudbanks

Salinity is one of the factors that determine the persistence and dissipation of mudbanks. The lowering of salinity due to the introduction of freshwater during the south-west monsoon season keeps the mud suspension in the water column for a longer duration, helping the formation and persistence of mudbanks. The increase in salinity of water during the post-monsoon months causes the flocculation and settling of sediments, which results in the disappearance of mudbank [23]. This fact was proved by the studies of [14]. In his experiments using water samples of different salinity, the settling time of mud increased as the salinity decreased.

The influence of wave activity on mudbanks was investigated by many and all the studies conclude the dampening of waves in the mudbank region [21, 35-39]. These studies showed significant differences in hydrodynamic characteristics during the monsoon and non-monsoon periods. Wave simulations and observations across the muddy Louisiana continental shelf to find the dissipation rate with depth and frequency showed the dampening of waves in the shallow waters of the south-west coast of India could be the reason for the enhanced fishing activity there [40]. Using wave data collected from two depths, 15m and 7m, before and after the formation of the mudbank of Alappuzha, the wave energy dissipation was determined using WAVEWATCH III (WW3) model. The model well represented the wave heights in the mudbank region and their general characteristics. It was observed that mudbanks exist even beyond a depth of 15m [41]. From the views of different authors, salinity, waves, currents, and variations in the hydraulic pressure influence the persistence and dissipation of mudbanks.

The physical processes of the beach-nearshore system help to understand the coastal processes, which in turn facilitate coastal planning and management. Shoreline changes (erosion/accretion) are highly influenced by the interplay between sediment supply and hydrodynamic forcing. Hydrodynamic studies of the south-west coast of India showed that waves and wave-induced littoral processes are the dominant driving forces in the coastal processes [42]. The effects of mudbanks on shoreline stability were investigated by many [43-46]. Studies of shoreline change along the Kerala coast, south-west coast of India, using geo-spatial techniques and field measurement showed that 45% of the coast is eroding, and 34% of the coast is in stable condition, and 21% of the coast is accreting [47]. Migration of mudbanks and its impact on shoreline changes observed at many locations. Mudbanks of Alappuzha showed different migration rates at different times ranging from 0.3 km/year to 10 km/year. Studies on the sediment dynamics of the Amazon River mouth to the Cape showed a migration rate of 5km/year for the mudbanks in this region [48]. Because of the migration of the mudbanks, wave activity and other coastal processes, the shorelines modified considerably and lead to the development of a characteristic muddy clinoform off the mouth of the Amazon River. Also, muddy coastal progradation incorporating Chenier sands form over more than 1500 km of the coast, northwest of the Amazon. Studies along the Kerala coast showed that the location of the mudbank area shifted from north to south and the northern side of the mudbank was accreting and the southern side eroding.

Biogeochemical processes in Mudbanks

Here, we summarize different studies on the estimation of the components of mudbanks and their variations. Intensification of hypoxia in coastal waters due to strong upwelling is of great importance as it could affect ocean nutrient cycles and the marine habitat, with potentially detrimental consequences for fisheries and coastal economies. Upwelling induced mudbank region generally augment the bio-productivity of the region by increasing the nutrient supply but it can also diminish at certain places. The upwelling induced hypoxic conditions in mudbank regions were studied by many, and these hypoxic conditions induced significant changes in the presence of the elements as carbon, phosphorus, iron, and manganese [49-51]. Fig 5 shows the seasonal variations in temperature, salinity and dissolved oxygen in madbank region of Alappuzha [52]. Results show the variations of the above parameters based on observations at three locations – (1) mudbank region (M2), (2) alongshore non-mudbank region (M1) and (3) offshore non-mudbank region (M3). During June to August, due to coastal upwelling, the temperature in the study area decreased from 30-32 °C to 23-26 °C . Salinity did not vary much but dissolved oxygen levels at M3 showed a sharp decrease during the monsoon season reflecting upwelling-induced hypoxia while at M1 & M2 there was intermittent variation.

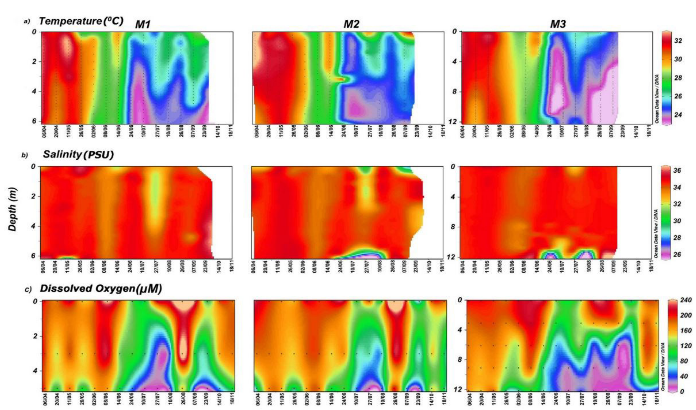

Figure 5: Seasonal variations in temperature, salinity and dissolved oxygen in the madbank region of Alappuzha (Source: Mathew et al., 2020).

[53] showed differences in primary productivity between the Northeast and Southwest Monsoon periods, and the phytoplankton in the main upwelling areas was only severely nutrient-limited during the spring inter monsoon period. The predicted particle flux from the euphotic zone and the primary production showed poor correlation. Hydrographic studies of the Purakkad mudbank region showed comparatively low surface and mid-depth salinity during the south-west monsoon season than that of the surrounding areas [54]. Even though it is believed that upwelling brings nutrient-rich subsurface water to the surface, plant pigments and carbohydrates occur in very low concentrations in the mud from the mudbank of the south-west coast of India, and the caloric value of the mud is also low, indicating that the mud is of poor nutritional value. The migration of fish and prawns towards the mudbank is probably a result of physical processes operating in the sea when the mudbank becomes active [55]. Time-series measurements for a period of 18-weeks (22 April to 20 September 2014) off Alappuzha during the south-west monsoon season showed that the upwelling signals observed from the 2nd week of May onwards intensified from the 1st week of June, reaching a peak on 14 June and continued till the end of September. The intensity of upwelling and hypoxia along the south-west coast of India was well propagated to very shallow depths (< 3 m) in the mudbanks leading to water column denitrification. This variation in ocean processes explains why mudbanks are not always good fishing grounds [56]. [57] agree that in certain cases, the presence of mudbanks adversely affects productivity by prompting denitrification. Sedimentological aspects of mud suspension off Quilandi, Kozhikode, India by analysing different parameters as sediment discharge, salinity gradient, suspensate concentration, rainfall, wave, wind and current patterns revealed the influence of upwelling on coastal productivity.

Even though certain studies showed denitrification induced by upwelling other studies indicate an increased bio-productivity due to upwelling. The presence of the exceptionally high phytoplankton stock in an area is due to the persistence of upwelled water throughout the south-west monsoon season. In most of the studies on the entire west coast, the Southwest Monsoon period is the most productive time because of the proportionate availability and replenishment of nutrients [27, 21, 58, 59]. Also, except at points close to the sea bottom, the turbidity level in the Alappuzha Mudbank was below the critical level to inhibit the plankton stock [60]. The research output in sediment dynamics, biogeochemical processes like sulfate reduction/nitrogen cycle and metal enrichment/contamination in the coastal sediments in three distinct depositional milieus like estuaries, mangroves, and mudbanks in India were reviewed by and found these regimes as highly productive [61].

Another study using multiple regression models off Kochi revealed that chlorophyll production depends not only on nutrients, but also on their physiological regulations like responses to nutrients, pH, temperature and salinity. As the computed and measured chlorophyll-a values are in good agreement, the step-up multiple regression model can be applied for the coastal waters to understand the influence of environmental variables on the production of phytoplankton [62]. Carbon-based ocean productivity and phytoplankton physiology were investigated by using satellite data [63]. Analysis of satellite ocean colour observations of phytoplankton carbon (C) and chlorophyll (Chl) biomass showed, the Chl: C ratios closely follow anticipated physiological dependencies on light, nutrients, and temperature. Compared to the chlorophyll-based approach, carbon-based values are considerably higher in tropical oceans, which show more significant seasonality at middle and high latitudes and illustrate essential differences in the formation and collapse of regional algal blooms [63].

The hydro-chemical properties of the near shore waters of Alappuzha based on two time-series measurements taken during 2014 and 2016 showed a marked increase in the nitrate levels during 2014, resulting in a massive diatom bloom [64]. The seasonal distribution of foraminifera in response to physicochemical changes associated with the mudbank formation showed that food availability and its source are not a significant factor affecting its distribution in the mudbank. Instead, increased turbidity and low bottom water salinity are the leading cause of the seasonally stressed environment in the mudbank [65]. The microbial diversity in the coastal environments of Alappuzha showed a significant difference between stations having only upwelling and upwelling and mudbank [66].

Sea surface temperature is another factor that influences productivity. The climatological and interannual variability of biogeochemical cycle studies using the model TOPAZ (Tracers of Phytoplankton with Allometric Zooplankton) with the data for a period of 1949-2009 for the north Indian Ocean showed a negative surface chlorophyll anomaly correlated well with a positive SST anomaly [67]. The SST-chlorophyll relation is evident during IOD periods [68]. The influence of Indian Ocean Dipole (IOD) on the physical and biogeochemical processes examined with particular reference to primary phytoplankton production and air-sea fluxes of carbon dioxide in the Arabian Sea. Positive SST anomalies (SSTA) were maximum (0.4 to 1.8°C) in the southwestern Arabian Sea that decreased towards the north. The Sea Surface Height Anomalies (SSHA) and turbulent kinetic energy anomalies suggest reduced mixing during the IOD compared to the normal period. Chlorophyll-a displayed significant negative correlation with SSTA and SSHA in the Arabian Sea. The consistently negative anomalies of Chlorophyll-a, during the IOD period, could be due to reduced inputs of nutrients. The photic zone integrated primary production decreased by 30% during the IOD period compared to the normal period.

Studies by [69] got an exceptional result of high-nutrient, low-chlorophyll condition off the southern Omani coast which shows a close similarity between the Omani upwelling system and the Peruvian and California upwelling systems, where primary production is limited by iron. An echo survey conducted at Alappuzha mudbank gave detailed descriptions of the texture, grain size, thickness and chemical properties, including mineralogical studies [70]. Time-series measurements of Suspended Particulate Matter (SPM) at three stations off the Alappuzha coast showed that the SPM concentrations increased with depth in all the three stations during the pre-monsoon and the monsoon seasons. Near the sea bed, SPM values were low at the non-mudbank station in July (0.042g/l), but the mudbank stations showed high values (9.2g/l), which decreased with the end of the south-west monsoon season [71].

The Southwest Monsoon period is the most productive time for the entire west coast, because of the proportionate availability and replenishment of nutrients. However, for the northwestern Indian Ocean, the phytoplankton in the main upwelling areas was only severely nutrient-limited during the spring inter monsoon period. The production of chlorophyll depends not only on nutrients, but also on their physiological regulations like responses to nutrients, pH, temperature and salinity.

Primary productivity of mudbanks

Because of the semiannual reversal of monsoon winds and the associated physical processes, the Arabian Sea is considered as one of the locations among the world oceans where the highest primary production occurs; [72, 73]. Primary production in the ocean surface is controlled by factors like light intensity, nutrient distributions and mixed layer depth. Fig. 6 shows the creation of a zone of sub-surface phytoplankton production bounded by too low nutrient concentrations above and too low light intensity below. The biological response to coastal upwelling events revealed many factors influencing productivity. The productivity is closely linked to (a) Ambient conditions like illumination and available nutrient concentrations, (b) The intensity and duration of upwelling-favorable wind conditions, (c) Biochemical factors, (d) The availability of a seed population of phytoplankton and (e) Complex food web dynamics including human interference, such as the harvest of forage fish [74].

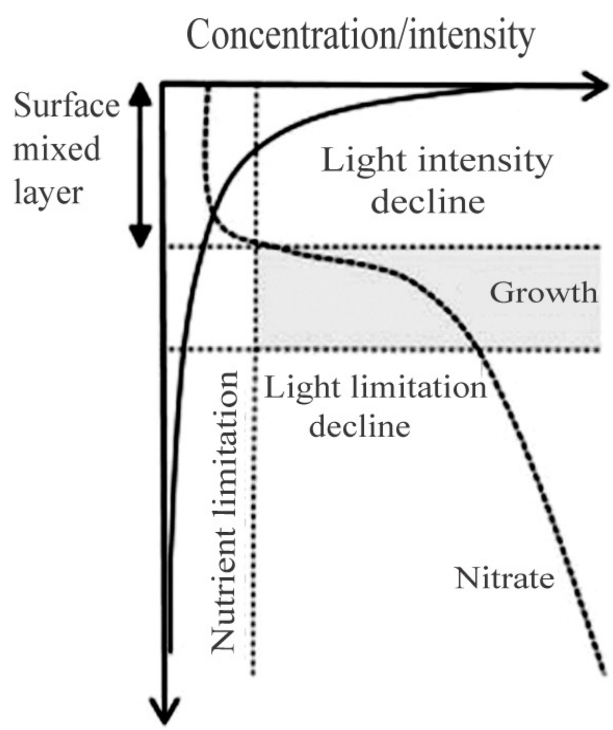

Figure 6: Schematic of the situation in which light and nutrient limitations created a zone of sub-surface phytoplankton production confined to the base of the surface mixed layer (Source: Kampf and Chapman, 2016).

Many people examined the primary production in the Arabian Sea during the monsoon season. At Alappuzha, the primary production showed high values only before, and not during or after the formation of the mudbank as there was an abundant population of diatoms during this period [39]. The seasonal monsoon forcing and remotely forced waves modulate the circulation and primary production in the eastern Arabian Sea [75]. Observations based on ocean colour from 2000 to 2007 showed an increase in summer productivity in the western Arabian Sea [76]. This increasing trend is not seen in the eastern Arabian Sea. Earlier studies had described the western Indian Ocean as a region with the most substantial increase in phytoplankton. A recent study points out an alarming decrease of up to 20% in phytoplankton in this region over the past six decades [77]. These trends in chlorophyll result from the enhanced ocean stratification due to rapid warming in the Indian Ocean, which suppresses nutrient mixing from subsurface layers.

Studies on the role of wind stress in modulating upwelling and subsequent changes in mixed layer depth and chlorophyll concentration in the southeastern Arabian Sea for the period 2000 – 2008 gave the following results. A decrease in the wind stress was followed by an increase in chlorophyll concentration with a lag of approximately two weeks, along with the shoaling of mixed layer depth [78]. In addition, a bimodal variability of chlorophyll-a concentration during summer monsoon occurs in this region. A new algorithm, Goa University Case II (GUC2), was developed to retrieve chl-a in optically complex waters and its validation with in situ observations from the eastern coastal Arabian Sea is useful for the chlorophyll estimations from this region [79]. GUC2 could identify two appropriate wavelengths for deriving chl-a and it could eliminate the effects of total suspended matter and coloured dissolved organic matter. The accuracy of the new algorithm, GUC2 outperformed turbid water CHL indices. Studies using an Earth System Model (ESM) by simulating changes in marine primary productivity for eight contrasted climates from the last glacial-interglacial cycle showed that there is no straightforward correlation between boreal summer productivity of the Arabian Sea and summer monsoon strength across the different simulated climates [80]. The nutrient supply driven by Ekman dynamics was the major contributor to productivity. The intensity of Ekman pumping determined by wind stress or wind curl depends on the position of the jet, and the astronomical parameters and the ice sheet cover influence the position of the jet.

Analysis of in situ data collected during the year 1992-1997 from the Arabian Sea under the Indian program of Joint Global Ocean Flux Study (JGOFS) showed that the biological productivity of the Arabian Sea is tightly coupled to the nutrient availability [81]. During summer, not only the coastal Arabian Sea but also the open ocean is biologically productive. In winter, the northern regions are productive due to surface cooling. Another study using JGOFS data revealed that temporal and spatial variations in phytoplankton biomass exist in the Arabian Sea at all scales from the diurnal to the seasonal and from fine to large scale. Also, phytoplankton is not sharply limited by either irradiance or nutrient supply [82]. Using International Indian Ocean Expedition (IIOE) data, studies of the biological productivity of the Indian Ocean, considering light, nutrients and the rates of production at the primary, secondary, and tertiary levels of the food chain were determined for the surface (1m depth) as well as the column (up to the depth of 1% illumination) [83]. The surface production per unit area in the Bay of Bengal is higher than that of the Arabian Sea whereas, the column production in the Arabian Sea is much greater than that in the Bay of Bengal.

Earlier studies showed that there were considerable spatial and temporal variations in the productivity of the Arabian Sea. The mesozooplankton abundance in the Arabian Sea is relatively high in the mixed layer all through the year [84]. As an explanation for this paradox, they pointed out that most of the herbivorous forms are either small filter feeders like copepods or larger mucous filter feeders like tunicates that can feed on microscopic particles. The Arabian Sea sustains large biomass of mesopelagic fishes (about 100 million tonnes), mainly myctophids, which live in the core of the minimum oxygen layer and ascend to the surface layers during the night to feed on the abundant zooplankton. Analyses of three separate cruise data from the southern and northeastern Arabian Sea, during the winter monsoon season, showed that variability in the picophytoplankton community structure and their contribution to the microbial loop are driven by convective mixing and advection [85].

Coastal upwelling plays a dominant role in shaping the zooplankton community than mudbanks, which just coincidently happen during the south-west monsoon season [86]. Analyses of MODIS-A data for the northwestern Bay of Bengal showed a prominent peak of Chl-a during the pre-Southwest Monsoon period (March–April) [87]. The satellite-derived values showed overestimation in nearshore waters. Analysis of the long-term trend in satellite imagery, clearly indicated a bi-modal distribution of Chl-a, with a first peak during the pre-Southwest Monsoon and the secondary peak during the end of the Southwest Monsoon. The first peak was attributed to phytoplankton bloom that was mostly confined to nearshore waters; however, the secondary peak spreads offshore.

Various studies show that nutrient supply is one of the main factors that favour bio-productivity along with other components as illumination, seasonal monsoon forcing, remotely forced wave, etc. and upwelling has more influence on bio-productivity than mudbanks. The location of peak primary production occurs at different places at different times depending on the local conditions. Along the southwest coast of India, primary production is maximum during the Southwest Monsoon season, just before the formation of mudbanks, as there was an abundant population of diatoms during this period. The northwestern Bay of Bengal showed a prominent peak of Chl-a during the pre-Southwest Monsoon period (March–April). In the Amazon Basin, high productivity happens from roughly August through November. Because of yearlong coastal upwelling activity, the Peruvian coast shows high biological activity. Productivity along the coastal waters of east Peninsular Malaysia showed maximum concentrations during the Northeast Monsoon Season [88]. Even though marine productivity connects to mudbanks and upwelling phenomena, it shows spatial and temporal variations.

Fisheries in Mudbank

As mudbanks play a vital role in the coastal fisheries, scientists in this field tried to investigate this phenomenon and the fisheries associated with it deeply. Mudbank being a calm region, traditional fishers using non-motorised country craft were able to carry out fishing within this calm region during the SW monsoon season. The pattern of fish distribution in the monsoon season frequently changes, even from day to day, due to the shoaling behaviour of fish [89]. This phenomenon does not confine to the areas of mudbanks only, but outside also it happens. The studies by [90] also support the results by [89]. The upwelling, occurring during the SW monsoon season along the Alappuzha coast, carried oxygen-deficient bottom water to the upper water column. Fishes aggregate within the thin upper surface layers by avoiding the oxygen-depleted waters, allowing easy visual identification and capture of fish shoals. Just below the topmost thin layer of oxygenated warm water, there exists a hypoxic (< 75 μM), high salinity (> 35.5 PSU) cool (< 26°C) layer due to upwelling. However, this depletion in oxygen occurs throughout the coast and does not confine just to the mudbanks [90].

There are different opinions regarding the shoaling of fish to the surface layers in the upwelling area. According to [91] and [92] during the southwest monsoon season upwelling forces fish and prawn to move towards the shore to avoid the oxygen-deficient waters whereas, [21] suggest viscous stirring up of mud by the wave action probably forces the fish and prawns to move upwards. The influence of the monsoon related drivers on the primary productivity of the Arabian Sea was discussed in a review of previous works [75]. About 73% of the total catch of India originates from the west coast of India due to the high primary production (PP) in this sector of the Arabian Sea [93].

Analysis of available data and model simulations shows it is the physical forcing that influences the fisheries in the northeastern, central and southeastern Arabian Sea. A carnivore-dominated fishery occurs in the northeastern Arabian Sea (NEAS) and a planktivore-dominated fishery in the southeastern Arabian Sea (SEAS). A weaker fishery in the central-eastern Arabian Sea (CEAS) compared to the SEAS is due to weaker physical forcing in CEAS. A marked difference in the total catch of oil sardines from the SEAS to the CEAS exists, though the catch of mackerel does not change considerably. This difference in landings can be attributed to the difference in the physical forcing in these regions [94].

The main factors which contribute to productivity are upwelling in the southeastern Arabian Sea (south of 15°N) during the southwest monsoon and cooling in the northern Arabian Sea (north of 15°N) in winter [95]. Although the fish catches from these two areas are relatively equal, there is a considerable difference in the composition. In the south, planktivorous fishes dominate, whereas, in the north, carnivores are more abundant.

The unique feature of the mudbanks of Kerala is that they enable the fishers with enormous catch using indigenous boats from the calm sea during the Southwest Monsoon Season when the surrounding areas are very rough. Because of the high primary production (PP) in this sector of the Arabian Sea, about 73% of the total catch of India originates from the west coast of India.

Discussion and Conclusion

Mudbanks along the Kerala coast during the Southwest Monsoon Season have been arousing the curiosity of everyone. Even after many studies to explore the characteristics of mudbank, it remains an enigma, because this phenomenon does not show a regular pattern in its spatial and temporal occurrences. Even if almost the same environmental conditions occur, they are not recurring at the same place or at the same time, which makes their prediction impossible. When we observed the location of the occurrence of mudbanks along the southwest coast of India, their frequency is maximum (52.63%) between the latitudes 9°N and 10°N. Even though different hypotheses exist for the formation of mudbanks, for Alappuzha, where the phenomenon occurs most frequently, the subterranean hypothesis or some bottom topographical feature seems to be influencing the phenomena.

Sedimentological studies suggest that mud of the right texture at the right depth, along with adequate wave activity is necessary for the formation of mudbanks. Mudbanks can migrate by the influence of currents, waves and wind stress. This migratory behaviour can cause shoreline changes with accretion to the north of mudbanks and erosion to the south. Different investigations, suggest that many hydrodynamic properties as SST, salinity, wave activity, currents and wind have a significant influence on the maintenance and dissipation of mudbanks. Since upwelling closely links to the nutrient cycles and the marine habitat, various studies investigated the biogeochemical properties of mudbanks. Upwelling induced biogeochemical processes have a major influence on the ecosystem of the southwest coast of India.

Earlier studies had described the western Indian Ocean as a region with the most substantial production of phytoplankton. In a recent study, a decrease of 20% in phytoplankton productivity occurred in the past six decades due to the enhanced stratification and rapid warming in the Indian Ocean because of global warming. However, an increase in Chl-a occurs in the western Arabian Sea, though the increasing trend is not seen in the eastern Arabian Sea. Upwelling has more influence on primary productivity than mudbanks, as the presence of nutrients is a controlling factor in primary productivity. Ocean productivity estimates created on the chlorophyll-based approach are lower than the carbon-based values in tropical oceans and showed significant seasonality in middle and high latitudes. Indian Ocean Dipole showed a significant influence on primary production, a reduction of about 30% during this period compared to the normal situation.

Studies on the role of wind stress on productivity showed that a decrease in wind stress causes an increase in chlorophyll concentration with a lag of 2 weeks. Since upwelling is a slow process (upwelling velocity of 0.1-3m/day), it takes 2-4 weeks for the nutrient-rich subsurface water to reach the surface depending on the intensity of wind stress. Previous studies suggest that among the various factors affecting ocean productivity, upwelling plays a significant role.

The mudbanks of the southwest coast of India are unique in terms of its origin through river discharge, subterranean, coastal mud and dredged mud, by creating a calm zone in the turbulent sea, and support fishery. Whereas, the Amazon mudbank is of estuarine origin, which creates a thick muddy shore with large extant. Primary productivity in different coastal regions varies with time. Along the Kerala coast, primary production is maximum during the Southwest Monsoon Season, just before the formation of mudbanks, as there is an abundant population of diatoms during this period. Even though marine productivity links to mudbanks and upwelling phenomena, it shows spatial and temporal variations in its recurrence.

Studies on fisheries associated with mudbanks along the Kerala coast showed that the aggregation of fish is not confined to the mudbank regions, but outside this region also it occurs. Since mudbank regions are calm, they are favourable locations for fishing and hence it has unique importance, especially for the conventional fishers. After 2016, the occurrence of mudbanks in Alapuzha has decreased, though it was the most frequent location previously. The recent environmental changes that have created an unfavourable situation for the formation of the mudbanks should be analysed considering the remote forces like ENSO and IOD. All of these factors need thorough investigation in the scenario of global warming. Since the reason behind the peculiar phenomenon of mudbanks that occur along the Kerala coast during the Southwest Monsoon Season is unclear, further studies on this topic are essential as it has socio-economic implications on the fisher's community as well as the economy and food security of the country.

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