

Seasonal and tidal variations in suspended particulate matter dynamics of two microtidal rivers of Karnataka, central west-coast of India

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Abstract

The concentrations of suspended particulate matter (SPM) and particulate organic carbon (POC), particulate total nitrogen (PTN) of SPM and sediments were studied in two microtidal rivers of Karnataka (Nethravati and Gurupur), India, to understand the influence of SPM on the coastal environment. Water sampling involved seasonal (wet, dry) and tidal (spring, neap) conditions, including 24-hrs time-series measurements. The results showed that Estuarine Turbidity Maxima (ETM, high SPM zone) existed seasonally in both the rivers and formed due to several processes. In the Gurupur River, flocculation in the wet season (monsoon), and river meandering effect (post-monsoon) and re-suspension of bottom sediments (pre-monsoon) in the dry season produced the respective ETMs. On the other hand, in the Nethravati R., the ETM was not distinct during the wet season, while flocculation (post-monsoon) and low to moderate material supply enhanced by strong tidal-currents (pre-monsoon), resulted in the ETMs. The POC and PTN were high during the wet season as compared to the dry season in both the rivers. In general, the SPM balance in the estuary was maintained by its seaward export in the wet season (Nethravati R.) and its retention during the dry season, with a major part of the particulate organic matter produced and trapped in the estuaries during the dry season. The upstream tidal transport of SPM (dry season) can affect the coastal ecosystem management and maintenance of its ecological functions in the future.

Keywords: estuary, suspended particulate matter, tidal phase, turbidity, microtidal, organic matter

Introduction

Estuaries receive high levels of fine sediments, organic matter and nutrients from freshwater and marine environments, making them very productive aquatic ecosystems (Azhikodan & Yokoyama 2015). The suspended particulate matter (SPM) in the coastal system comprises particles such as carbonates, sediments (clay and fine sand), bacteria, organic fragments, diatoms and biofilms (Eisma & Li 1993; Manning & Schoellhamer 2013). The SPM dynamics get influenced by processes such as suspension, flocculation, settling, deposition, erosion and re-suspension (Verney et al. 2009; Horner-Devine et al. 2015; Restrepo et al. 2018). The transport of SPM in estuaries depends mainly on the external forcings (tides, river discharge and wind) (Woodruff et al. 2001; Patchineelam & Kjerfve 2004; Montoya et al. 2017), making them a complex system. Areas with high concentrations of SPM form estuarine turbidity maxima (ETM) zones that are known to control the functioning of estuarine ecosystems to a large extent, e.g., Columbia River, Chesapeake Bay, Ebro river (Jiang & Xia 2016; Fernández-Nóvoa et al. 2015; Zhao et al. 2017). However, the high SPM can also result in detrimental effects such as slow productivity, pollution, ecological degradation, flooding and damage (Taylor & Owens 2009; Zhang et al. 2019; Torregroza-Espinosa et al. 2020). Different mechanisms such as gravitational circulation, tidal asymmetry, tidal pumping, settling, and scour lags (Mitchell et al. 1998; Chernetsky et al. 2010, Burchard et al. 2018) can generate an ETM. Since huge amounts of SPM can become entrapped and temporarily stored within the ETM, the dynamics of ETMs are essential to the sediment mass balance of an estuary (Sommerfield & Wong 2011; Xu et al. 2013). Further, the SPM and associated contaminants tend to merge into the ETM on reaching the river mouth. Hence, its ultimate discharge or possible shift outward from the estuary to the coastal sea during high river flow is related to the processes affecting the ETM (Li et al. 2012; Jalón-Rojas et al. 2015). Therefore, a better understanding of the SPM and its variations in the estuary with changing river flow (wet and dry seasons) is vital for understanding the process and constraining the factors responsible for mixing and transporting materials (Xu et al. 2013).

Studies quantifying the delivery, retention and processing of materials entering the coastal ocean have been well reported (Tappin 2002; Seitzinger et al. 2005; Torregroza-Espinosa et al. 2020). In recent times, the effects of human intervention (reservoirs, dams, channel widening, dredging, etc.) on rivers and streams on the SPM dynamics need more attention (Grasso & Le Hir 2019; Shahzad et al. 2019). Further, the variations in the SPM concentration on time scales other than seasonal weigh considerable significance (Fettweis et al. 1998; Garelet et al. 2009; Kanga et al. 2020). Prior research in the estuary includes studies of flood and ebb currents at the Nethravati-Gurupur river mouth (Reddy et al. 1979b), organic matter composition (Pradhan et al. 2014; Dearlyn et al. 2019), dissolved (Ajmal et al. 1985;

Tripti et al. 2013a) and particulate (Ramesh et al. 1990; Chakrapani & Subramanian 1996) trace metals. Detailed studies of SPM inputs, sources and its retention in the aquatic system are important as it controls the region's productivity. Studies covering the spatio-temporal SPM dynamics are missing in the region. Therefore, the purpose of this study was to estimate the SPM concentration and distribution and investigate the role physico-chemical processes play in the composition and formation of an ETM zone under different environmental conditions in the Nethravati-Gurupur rivers. The methodology involved field sampling, *insitu* measurements and laboratory analysis. The field measurements performed at different seasons in the same estuary enabled enhanced investigation of the seasonal variability of the ETM areas. Further, the relationship between SPM and particulate organic matter (POC and PTN) at seasonal and different stages of the tidal cycle were examined to assess seasonal and spatial changes in source and dynamics of SPM and relative contribution of organic matter in the coastal rivers. A 24 hrs timeseries was carried out to understand the processes and pathways of sediment transport in the estuary. This is the first report on the ETM-related sediment dynamics in the Nethravati-Gurupur estuaries, which will give a synoptic view of the spatial and temporal variability of SPM seasonally and within a tidal cycle.

The following sections consist of materials and methods that provide an overview of the study area, the field sampling involving *insitu* and laboratory methods, and the analytical procedures adopted. This is followed by the results and discussion section wherein the concentrations of SPM and its organic matter content are presented and interpreted. Finally, the study's conclusion is outlined at the end.

Materials And Methods

Study area

The Nethravati-Gurupur river basin (Fig. 1) originates at an elevation of ~900–1800 m (a.s.l) in the densely forested Sahyadri hills (Western Ghats) of central India. The Nethravati River flows for a distance of 148 km in a northwesterly direction from its source, while the Gurupur River flows for 87 km in a southwesterly direction, and both have a common exit to the Arabian Sea via Mangalore. The upper portions of the rivers are mountainous and covered with dense forests, whereas the lower portions are undulated plane areas having a predominance of agriculture and urban lands. The average annual precipitation in the region is 3076 mm. The Nethravati R. basin (Fig. 1) is the biggest river in south Karnataka with a length of 103 km and represents one of the world's "biodiversity hotspots" (Myers et al. 2000). It has a catchment area of 3160 km² and a maximum discharge of 8170 m³/s. The Gurupur R., on the other hand, has a catchment area of 665 km² and a maximum discharge of 1140 m³/s. Both the rivers are highly seasonal, with most of the discharge (85%) occurring during the

southwest monsoon season (June to September). The Nethravati-Gurupur Rivers account for ~8% of the total discharge of the west flowing rivers of Peninsular India (Rao 1979;Subramanian et al. 1987). Both the rivers supply $12,015 \times 10^6 \text{ m}^3$ and $2,822 \times 10^6 \text{ m}^3$ of freshwater and 14×10^5 and 1×10^5 tons of sediment annually to the Arabian Sea (Subramanian et al. 1987).

The river-estuarine system behaves like an extension of the sea during the dry season with the discharge to the sea, mostly through the tidal waters entering the estuary. The tides are mainly semidiurnal, having an average range of ~1.0 m with a spring tidal range of 1.8 m (Jayappa 2003). To favor seaward sediment flushing by the ebb currents, the navigation channel has been regularized and deepened, and two submersible dikes constructed on either side of the main channel. The magnitude and direction of the bottom currents off-Mangalore vary seasonally. In the post-monsoon season, the bottom currents are directed between the west and northwest, while during the pre-monsoon and monsoon seasons, they are towards the north and south directions (Reddy et al. 1979a). As a result of sediment accumulation in the lower estuarine region, dredging is carried out to counter intense deposition, maintaining access to the dockyards. Hence, human intervention has disturbed the natural inflow of sediments in the region.

Sampling

Surface water and bottom sediments were collected from stations representing the marine, estuarine and riverine regions of the Nethravati-Gurupur rivers at high tide of the dry (pre and post-monsoon) and wet (monsoon) seasons. The sampling included spring and neap tidal conditions during both high (July 2017) and low (January and May 2017) river discharge periods. The stations in the Nethravati R. (N1 to N10) and Gurupur R. (Gu1 to Gu7), including the marine stations (0A and 0B), were sampled by mechanized boats, whereas the remaining upstream riverine locations (Fig. 1, stations N11 to N15, Gu8 to Gu11), being narrow and shallow for entry of mechanized boat, were sampled from the bridge. Further, in each of the rivers during each season and tidal condition, wherever the width of the estuary was large, across-estuary transects were obtained. In addition, in the Gurupur R., a 24hrs time series at a single location (station Gu2) during the post-monsoon spring tide was also carried out. The *insitu* particle volume concentration (PVC, $\mu\text{L/L}$) and Sauter mean diameter (SMD, μm) were determined by Laser InSitu Scattering and Transmissometry (LISST) instrument (Sequoia Scientific Inc.). Standard temperature and salinity (conductivity) measurements for the water column (maximum sampling depth: 6m) were obtained with a Sea-Bird Electronics 11plus CTD instrument equipped with a chlorophyll-fluorescence sensor. The LISST was lowered through the water column at a steady speed from the surface to 0.5 m above the sea bottom. A Grab sampler was used to collect the bottom sediments. For 24 hrs time-series, current velocity was obtained using a current meter (Seaguard, US),

mounted about 4 m above the sediment bed. The LISST and CTD instruments were deployed every hour, while the surface water samples for SPM were collected at every 3 hours interval. The research methodology followed is presented as a flowchart in Fig. S1.

Laboratory analysis

Salinity was determined using the 8400 Guild Line Autosal Salinometer, as per the standard procedures. A total of 79 surface water samples in the Nethravati R. and 60 surface water samples in the Gurupur R. were filtered through preweighed (0.45 μm pore-size Millipore membrane isopore) filters. The SPM concentration was obtained by gravimetric analysis and are reported in mg/l. For particulate organic matter analysis, 20L of water was filtered and dried. The dried SPM samples were carefully removed from the filter paper, powdered and analyzed for particulate total carbon (PTC) and particulate total nitrogen (PTN) by an NC soil analyzer (ThermoFisher Scientific, UK). The carbonate content of the sediment was very low ($> 0.5\%$, unpublished data), so the PTC is represented as particulate organic carbon (POC). The POC and PTN values are expressed as percents of the dry weight of SPM. For textural analysis, the grain size was determined by wet sieving (Folk 1974). The rainfall and river discharge data were obtained from the Water Resources Information System (WRIS) site (<http://tamcnhp.com/wris/#/waterData>). The river gauges were located at Bantwal ~35 km upstream of the Nethravati R. and at Addur ~27 km upstream of the Gurupur R.

Results

Rainfall and river discharge

In both the rivers, the river discharge was highest during the wet season (613 m^3/s in Nethravati, 136 m^3/s in Gurupur) and low to negligible in the dry season (Fig. 2a, b). The monthly average rainfall over the region varied from 0-206 mm in the northern interior region, 0-250 mm in the southern interior region, with the highest rainfall variation (0-831 mm) in the coastal region (Fig. 2c). The wet season had the maximum rainfall (~2593 mm, June-Sept) with low/negligible rainfall during the dry season (< 200 mm in pre- and post-monsoon, Oct-May).

Temperature, salinity and chlorophyll-fluorescence

The temperature showed a narrow range spatially (27-32°C) and vertically (25-32°C) during the seasons in both the rivers and reflected variations of the sampling time (morning-noon-evening). The salinity during the sampling period ranged from 0 to 35 (Table 1). In the wet season (monsoon), spatially, both the rivers had freshwater (salinity < 1) [Fig. 3(a, d), 4(a, d)]. Vertically, in the Gurupur R., saline waters (20) were present only at the bottom (4m) near the estuary mouth in spring (Fig. 5b),

while the Nethravati R. had freshwater condition [Fig. S2(b, g)]. During the dry season in the Gurupur R., spatially, stations 0A-Gu7 (17 km) in post-monsoon and 0A-Gu8 (17.5 km) in pre-monsoon had high salinity (25-35) [Fig. 3(b, c)]. On the other hand, in the Nethravati R., during the dry period (post- and pre-monsoon), the surface saline waters (20-25) extended from the mouth to a distance of 10 km (station N6) and 7.8 km (station N5) upstream [Fig. 4(b, c)], respectively, in spring and to a distance of 10 km (station N6) and 13.5 km (station N7) in neap [Fig. 4(e, f)]. Vertically, both the rivers had well-mixed saline (35 salinity) waters [Fig. 6, 7, S2, S3(b, g)].

The Gurupur R. had low chlorophyll-fluorescence values during the wet season [Fig. 5(c, h)] and high values viz, 130 mg/m³ and 40 mg/m³ between 1-2 m depth at 10 km distance upstream from the estuary mouth during the spring and neap tides of the post-monsoon, respectively [Fig. 6(c, h)]. In the pre-monsoon [Fig. 7(c, h)], higher values were seen at the upstream end in the neap (60 mg/m³) as compared to the spring tide (20 mg/m³). In the Nethravati R., during the monsoon and pre-monsoon seasons, chlorophyll-fluorescence (<0.5 mg/m³) was low for both the tidal cycles [Fig. S2, S4(c, h)]. On the other hand, in post-monsoon spring, high values (20 mg/m³) were observed at the surface layer of the estuary [Fig. S3 (c)].

Suspended particulate matter (SPM)

In the Gurupur R. during the wet season, the surface water SPM increased from the river end to the estuarine region in spring, while during the neap, higher values were seen at the estuary mouth [Fig. 3(a, d)]. In the dry season, peak values were seen near the estuarine mouth region during the spring compared to low values in the neap tide [Fig. 3(b, c, e, f)]. In the Nethravati R., during the wet season, high surface SPM was seen at the upstream region of the estuary during the spring (avg. 19.30 mg/l) and neap (avg. 17.90 mg/l) [Fig. 4(a, d)], as compared to the dry season (<5 mg/l) [Fig. 4(b, c, e, f)]. Further, the average surface SPM concentration in the Gurupur R. during the pre-monsoon season (18.21 mg/l) was comparable with the average surface SPM in the Nethravati R. during the monsoon season (19.30 mg/l).

The SPM clusters seen in the vertical profiles [Fig. 5, 6, 7 (d, i)] correspond to the existence of the ETMs. In both the rivers, seasonal migration of the ETMs were seen, and situated at about 12, 5 and 2 km distance during post-, pre- and monsoon periods respectively in the Gurupur R., and between 2 and 4m depths at about 17 and 7 km distance from the mouth in the Nethravati R. during the post- and pre-monsoon periods respectively. In the Gurupur R., the ETMs were seen at spring tide of the monsoon (bottom, Fig. 5d) and post-monsoon (subsurface, Fig. 6d), and high salinity conditions of the pre-monsoon (bottom, Fig. 7d). On the other hand, no distinct ETM was present in the Nethravati R. during

the wet season [Fig. S2(d, i)], while in the dry season, the ETMs formation occurred in the low salinity environment of post-monsoon (bottom, Fig. S3d) and at high salinity conditions of pre-monsoon (Fig. S4d). In the Gurupur river, the vertical profiles of the ETMs were distinct during the spring tide of all the seasons, while in the neap tide, the ETMs profiles were flat and featureless. In contrast, in the Nethravati R., the ETMs were well developed in the neap compared to the spring tide. The SPM differences during the seasons were observed to be more than the spring-neap differences.

Across-estuary transects

In the Gurupur R., high SPM (Gu1- >1000 $\mu\text{L/L}$) was seen during the monsoon spring near the estuary mouth salt-fresh water interface (Fig. 8). The post-monsoon spring showed high SPM (~400 $\mu\text{L/L}$) at station Gu6 (upper estuary) on the western bank of the river, while station Gu4 (middle estuary) had low SPM clusters (~120 $\mu\text{L/L}$). The station Gu1 (estuary mouth) had high SPM concentration (~200 $\mu\text{L/L}$) at the bottom in the neap tide. The pre-monsoon season showed a thin layer of SPM near the surface at stations Gu6 (~200 $\mu\text{L/L}$) and eastern side of Gu1 (~400 $\mu\text{L/L}$), surface (~300 $\mu\text{L/L}$) and the bottom (~200 $\mu\text{L/L}$) of station Gu4. The across-estuary transect plots of the Nethravati R. are provided in the supplementary section (Fig. S5).

24 hrs timeseries observation

The timeseries spatial distribution for salinity and SPM at the Gu2 station (lower estuary) showed opposite trends with decreasing (increasing) values during the ebb tide followed by an increase (decrease) during the flood tide (Fig. S6). However, the second ebb and flood tide had higher salinity values but lower SPM values than the previous ebb and flood. The magnitude of the tidal currents varied from 6-24 cm/s. The minimum SPM (4.34 mg/l) was at low current velocity (2.53 cm/s) between 0-2 hrs, while the maximum SPM (11.21 mg/l) and maximum current velocity (24.80 cm/s) was seen between 3-6 hrs and sustained throughout the remainder of each phase. The salinity and chlorophyll-fluorescence (Fig. 9c) were high during the ebb tide (25-30 mg/m^3) as compared to the flood tide (<10 mg/m^3). Clusters of high SPM (~500 $\mu\text{L/L}$) were seen during the ebb tide and the beginning of the flood tide. The SMD ranged from 60-100 μm .

Particulate organic matter (POC and PTN)

In the Gurupur R., the Particulate Organic Carbon (POC) decreased from the riverine towards the marine region during the spring tide of the monsoon and pre-monsoon seasons, while in the post-monsoon highest concentration was seen in the estuarine region, followed by the river and the marine regions (Fig. 10). The Particulate Total Nitrogen (PTN) values were highest in the estuarine region during all the seasons. In the Nethravati R., the POC concentrations in all the seasons and PTN in the

monsoon and pre-monsoon seasons gradually decreased from the riverine to the marine region. The POC concentrations displayed similar values between the post and pre-monsoon seasons. For PTN, the highest concentration was seen in the estuarine region, followed by the river and the marine regions during the post-monsoon. In both the rivers, the highest POC values were observed during the post-monsoon, while the lowest was in the pre-monsoon for the Gurupur R. and in the monsoon season for the Nethravati R. The POC concentrations were lower in the neap compared to the spring tide, except during pre-monsoon in the Gurupur R. The POC/PTN ratio (denoted as C/N henceforth) varied from 7.17 to 14.01 in monsoon, 6.41 to 11.59 in post-monsoon and 7.20-10.96 in pre-monsoon in the Gurupur R., while in the Nethravati R. the values were 8.46-17.69, 6.44-13.35 and 7.05-10.25 during the monsoon, post- and pre-monsoon respectively.

Sediment characteristic

A seasonal variation in the grain size distribution was observed. In the Gurupur R., the sediments were mostly fine-grained (clayey silt) in monsoon and post-monsoon, while in pre-monsoon, the mouth and upstream regions were clayey silt. In contrast, the middle estuarine region was sandy [Fig. 11 (a, b, c)]. In the Nethravati R., the sediments were sandy during the monsoon, fine-grained (clayey silt) near the estuary mouth and upstream region during the post-monsoon and mostly fine-grained (clayey silt) during the pre-monsoon [Fig. 11(d, e, f)].

Discussion

SPM comparison with other rivers

The SPM concentrations in the present study (Table 1) are similar to that given for the Nethravati R. by Triptiet al. 2018 (6.24-18 mg/l) and Dearlynet al. 2019 (18.8-47.3 mg/l), the Mandovi River (10-30 mg/l) and the Zuari River (8-23 mg/l) by Kessarkaret al. (2013). However, it is higher than the neighbouring Swarna R. (5.1-11.4 mg/l, Triptiet al. 2018), but much lower than in very turbid rivers, e.g., Scheldt estuary (300 - 400 mg/l, Fettweiset al. 1998), the Weser estuary (400-700 mg/l, Grabemann & Krause 2001), the Seine estuary (1 g/l, Le Huret al. 2001) and the Humber estuary (10-15 g/l, Mitchell et al. 2003). The Indian rivers (Nethravati-Gurupur, Mandovi and Zuari) on the west coast of India are monsoonal rivers and experience similar rainfall patterns (wet and dry seasons). These rivers are of medium size, micro and meso-tidal in range, and have similar rock types. As a result, in these rivers, the SPM concentrations fall in a similar range. The world rivers (Scheldt, Weser, Seine, Humber), on the other hand, have large basin areas, are of macrotidal range with different rainfall patterns. They are composed of easily erodible rock types and hence have high SPM concentrations.

Seasonal distribution of particulate organic matter (POC and PTN)

The estuarine Particulate Organic Matter (POM) is composed of both autochthonous and allochthonous OM originating from aquatic, terrestrial and/or anthropogenic reservoirs (Savoie et al. 2012) and varies spatially and seasonally. In the Nethravathi R., dominant transport of organic matter (OM) is reported to occur through the particulate phase (Milliman & Meade 1983; Kandasamy & Nagender Nath 2016; Triptiet et al. 2018). In both the rivers during both the tidal cycles of the monsoon season, the POC and PTN show a gradual decrease from the river towards the marine region. Usually, during high river flow (wet season), finer sediments (silt and clay) originating from soil erosion and/or banks with low organic carbon content are released, which get used up and relatively depleted in the organic matter as it approaches the sea. Dilution by mineral material has been reported for relatively low organic matter content in other small mountainous river systems (Coyné et al. 2005; Hatten et al. 2012). The C/N ratio has been used extensively to identify OM sources. Plankton and bacterial molar C/N ratios lie between 6–7 (Kendall et al. 2001) and 4–5 (Lee & Fuhrman 1987), respectively, while terrestrial OM varies between 12 and 200 (Hedges & Mann 1979). A higher C/N ratio (14.02–17.69) in the Nethravathi R. during the wet season in the riverine region compared to the marine or estuarine regions correspond to the more substantial contribution of the terrestrial soil from the dense evergreen forest of the Western Ghats.

On the other hand, in the dry season, a comparably higher concentration of POM is seen in the estuarine region with the C/N ratios (7–10) close to those of marine algae and phytoplankton, suggesting that they may be a significant source of the POM (Middelburg & Nieuwenhuize 1998; Savoie et al. 2012; Lebreton et al. 2016). In coastal areas, organic carbon mainly originates from terrestrial plants, aquatic plants, bacteria, algae and phytoplankton (Meyers 1994; Lamb et al. 2006). An earlier assessment in the Nethravathi R. of the distributions and sources of POM for the dry season revealed the dominance of *in situ* phytoplankton activity in the river water ($\delta^{13}\text{C}_{\text{POC}} = -26.6 \pm 0.4 \text{‰}$ and $\text{C/N} = 2.7 \pm 0.5$, Triptiet et al. 2013b). In Indian estuaries, the OM composition follows a seasonal pattern with a prevalence of terrestrial OM (allochthonous) during the wet season, and *in situ* phytoplankton produced-OM (autochthonous) during the dry season (Krishna et al. 2015). More recently, Dearnly et al. (2019) have suggested three main sources of OM in the Nethravathi R., terrestrially derived-OM during the monsoon, *in situ* produced-OM during the post-monsoon and pre-monsoon seasons and contributions from bacteria. Pradhan et al. (2014) reported the dominance of terrestrial C3 plants in the OM of the Nethravathi River basin. In general, in both the rivers, the POC and elemental ratios suggest the dominance of vascular C3 plants and estuarine algae in the wet season, with significant

contributions from marine phytoplankton in the dry season. Therefore, it seems likely a major part of the POM is produced and trapped within the estuary during the dry season.

Source and seasonal variations in the ETMs

Wet season

Several sources, such as inputs from the rivers and sea, erosion of the estuarine coastline, tidal flats and beds, biological production, etc., can contribute material to the ETM (Shen et al. 2010). Even though the upstream region of the Nethravati R. had a significant amount of SPM at the surface during the spring tide, an ETM was not formed. The across-estuary transects in the lower, middle and upper estuary showed the dominance of freshwater, with several SPM clusters seen along the river banks (Fig. S5). Thus, the SPM distribution seems to be affected by the direct input of sediment from the catchment area. In the Gurupur R., the high SPM cluster and large SMD values (150-200 μm) at the lower estuarine location coincide with the salt-freshwater boundary with relatively high POM (POC- 5.10 %, PTN- 0.71 %), suggesting that the formation of ETM occurs due to flocculation. In estuaries, SPM of organic or mineral origin is mainly aggregated in flocs of variable size, shape and density through flocculation/disaggregation processes (Manning & Dyer 1999; Wang et al. 2013; Chao et al. 2017). Chlorophyll-fluorescence reflects the phytoplankton content in the water (Boyce et al. 2010). Under normal circumstances, high nutrient concentrations can directly cause phytoplankton blooms, thereby increasing the total biomass in marine areas (Guenther et al. 2015). The chlorophyll-fluorescence was low in the wet season as compared to the dry season. Further, areas showing appreciable chlorophyll-fluorescence had low SPM and nutrient levels (unpublished data) and vice versa. Aquatic primary production is inhibited by high turbidity as it limits the light availability for phytoplankton production (Heip et al. 1995; Jones et al. 2016), so the autochthonous organic material becomes minor compared to the terrigenous organic fraction (Meybeck 1982). Therefore, chlorophyll-fluorescence had an unlikely role in contributing to the ETM formation.

Salinity can affect SPM transport through flocculation and turbulence inhibition by vertical density gradient. For flocculation to occur, the particles should have a specific viscosity and tendency to collide with each other, together with appropriate hydrodynamic conditions (Jouon et al. 2008). All such conditions are met during the wet season, favouring flocculation. Similar estuarine studies worldwide have reported lower estuarine regions as zones of flocculation and re-suspension, actively mixing, recycling, and remineralizing POC from land and algal sources, thus favouring the formation of ETMs (Abril et al. 2002; McCallister et al. 2006; del Giorgio & Pace 2008).

During the neap tide, an ETM is not formed in the Gurupur R. while it is present but not distinct in the Nethravati R., suggesting rapid transport of material from the estuary to the sea. In the Nethravati R., the high river discharge during the wet season completely flushes the ETM from the estuary (Jalon-Rojas et al. 2015; Fettweis et al. 1998). In estuaries such as the Gironde (Castaing & Allen 1981), Seine (Avione 1987) and the Columbia (Fain et al. 2001) with high freshwater volumes or exceeding tidal volume flux of the basin, the ETMs are advected from the estuary mouth, resulting in sediment export to coastal waters.

The SPM concentrations are comparatively higher during the spring than the neap in both the rivers and could be either due to the re-suspension of sediment deposited during low water slack or the erosion of the consolidated bed. Under the effect of hydrodynamic forces, bottom sediments can be re-suspended, thereby changing the concentration and size of SPM in the near-benthic water layer (Fettweis et al. 2006; Wang et al. 2013). The low SPM values in the neap tide may result from: (i) a decrease in local re-suspension of bottom material and (ii) a decrease in mixing, which allows advected river material to settle at the bottom (Gelfenbaum 1983). In the Nethravati R., large grain-size differences are noticed between the SPM and bottom sediments, implying that the sediments and SPM come from different sources.

Dry season

ETMs are reported to be highly mobile in response to changing patterns of freshwater flow over individual tides and longer time scales (Doxaran et al. 2009; Onabule et al. 2020), tidal amplitude, sediment input (Jiang et al. 2013) and estuarine channel bathymetry (Rolinski 1999; Ralston et al. 2012). The decrease in river runoff in the dry season causes a landward shift of the saline waters in both the rivers, which could have changed the sediment trapping mechanism. The sediment initially deposited downstream near the estuary mouth during the high river discharge can be re-suspended by tidal currents and transported upstream to form the observed ETM zones. In the Nethravati R., during the post-monsoon spring tide, the suspended sediments with high POC (14.63%) and PTN (2.27%) are seen in the upper estuarine region. The strong wind-driven (6.92 m/s) re-suspension action could have boosted the POM from freshwater and marine sources ($C/N = 6.44$) to form flocs at the salt-freshwater interface creating the ETMs. In microtidal estuaries, flocculation and wind-induced re-suspension are found to play a significant role in determining the SPM levels, location and behavior of an ETM (Hunt & Lemckert 2000; Xu et al. 2010; Fernandes et al. 2017). On the other hand, in the pre-monsoon, the ETM in the downstream region consists of comparably lower POC (6.65%) and PTN (0.73%) concentrations suggesting that the SPM might be composed predominantly of lithogenic particles supplied from erosion of river margins and/or the tidal reworking of bottom material (C/N

=9.05). Therefore, in the Nethravati R., the ETM formation in the upstream region during post-monsoon occurred due to flocculation at the saltwater-freshwater interface, while low to moderate material supply within the estuary, enhanced by strong tidal currents, produced the pre-monsoon ETM. ETM studies on the Fly River estuary, Papua New Guinea (Wolanski et al. 1995), Mekong River estuary, Vietnam (Wolanski et al. 1996), the Konkoure estuary in Equatorial Guinea (Capo et al. 2006) and the Chikugo River estuary in Japan (Azhikodan & Yokoyama 2015) have shown seasonal migration of the ETMs relating to similar effects.

On the other hand, in the Gurupur R., a different mechanism for the formation of post-monsoon ETM is observed. Here, when the ETM is pushed upstream (spring tide), sediment deposition occurs in the channel, as seen from the finer sediment grain size at the upstream location (stations Gu5, Gu6). At stations Gu3 and Gu4, the river meanders. As a result, the velocity of incoming seawater decreases and deposits most coarse-grained material at this location, which is very well reflected in the sediment grain-size distribution. Further, between stations Gu1 and Gu4 (lower estuary), the estuarine channel is deep (~7m), while beyond it, the upper estuary is narrow, with relatively shallow water depth (~4m). Thus, the deeper depths act as traps by providing favorable conditions for accumulation of finer sediments (clay, silt) and preservation of OM, which reduces the flow rates and increases the residence time of the water mass (Bábeket et al. 2008), thereby allowing subsequent spring tides to re-suspend the previously deposited sediment. These re-suspended materials can be further carried for several kilometers upstream by the tidal currents. Further, at station Gu4, the estuary meanders and constricts to its minimum cross-sectional area till station Gu5, resulting in higher tidal velocities and increased mixing. Thus, the estuarine bathymetry and topography tend to distort the tidal curve, i.e., cause an asymmetry, facilitating the preferential transport of sediment towards the estuarine head. The rapidly narrowing estuarine topography can amplify low and high water heights upstream. This residual transport is called tidal pumping and is more significant than residual gravitational circulation. The interaction of tidal pumping with both the sediment settling and re-entrainment during the tidal cycle can produce and maintain the ETM. Further, high amounts of POC (12.91%) and PTN (1.82 %) are seen in this region, which helps sustain the ETM strength. In the Tamar estuary, the ETM in the upstream region was reported due to the tidal pumping of sediments caused by the flood-ebb asymmetry (Uncles et al. 1985). In some estuaries, the phase differences between SPM and current velocity produce tide-induced residual fluxes of sediment (tidal pumping fluxes) that can contribute to the formation of the ETM (Allen et al. 1980).

Based on the 24hrs timeseries at station Gu2 (lower estuary) during the post-monsoon, periodicity in the salinity, temperature and current velocity was observed to correspond with the semidiurnal tide.

The high surface SPM during the ebb tide and at the bottom (~3m) at the early part of the flood tide may result from local erosion of the bed or the re-suspension of bottom sediments during the higher tidal flow conditions. Shen et al. (2014) suggested that high SPM concentrations strongly relate to the tidal current velocity, which can cause scouring and re-suspension of bottom sediments if the velocity increases. The Nethravati-Gurupur river mouth is dominated by ebb tide during the post-monsoon and flood tide in pre-monsoon (Reddy et al. 1979b). The post-monsoon across-estuary transects in the middle and upstream regions in the Gurupur R. indicate that the river banks contribute sediment to the estuary. Therefore, erosion of fine-grained sediments of the adjacent intertidal flats might be transporting the SPM at the station (Shanmugam 2018) during the peak of the flood tide and early stages of ebb, which gets exported towards the sea. This phenomenon seems to alternate between the tidal phases depending on the sediment availability.

In the pre-monsoon season, despite strong tidal conditions and wind speed (7 m/s) similar to that seen during the post-monsoon, ideal for mixing and forming an ETM, an ETM is not developed at the upstream location but is formed at the lower estuary. The narrow width and meandering characteristic of the upper estuary limit the local wind-fetch such that the wave-orbital is not strong enough to re-suspend the bottom sediments. In the ETM, the C/N ratio of the SPM varies from 7-10, suggesting a marine source. However, the low POC (2.98 %) and PTN (0.27 %) values indicate the degradation of OM through tide-induced cycles of re-suspension and re-deposition (Krishna et al. 2015). Furthermore, the SPM and bottom sediment grain sizes are finer and fall in a similar range, which also attests to the possibility of ETM material being supplied by bottom sediment re-suspension. Therefore, in the Gurupur R., the high POM at the salt-freshwater interface during the wet season might have resulted in flocculation, the river meandering effect during the post-monsoon preserved the POM causing an increase in the floc size, while re-suspension of bottom sediments with low POM during the pre-monsoon may have limited the floc size. Thus, the POM clearly influenced the seasonal ETM formations in both the rivers.

In the Gurupur R., clear ETMs are seen in the spring tide but are not distinct in the neap tide. Wolanski et al. (1995) investigated the ETM dynamics in the Fly River estuary and reported that an ETM existed only during spring tide due to the simultaneous influence of the baroclinic circulation and tidal pumping. In the Seine River estuary, the gravitational circulation produced neap tide ETM, while the tidal asymmetry resulted in spring tide ETM (Brenon & Le Hir 1999). Both these processes were also shown to participate coincidentally in the ETM formation in a micro-tidal estuary of Australia (Hugues et al. 1998). Further, higher SPMs are related to higher currents of spring tides than those during the neaps. The extensive dredging operations and channel widening carried out near the estuary mouth in

recent years have facilitated a higher degree of seawater transport into the estuary. The increased tidal flow and associated increased turbulent mixing during the spring tide might be eroding the estuarine boundaries and transporting more sediment in suspension (Mantovanelliet al. 2004). During the spring tide in both the rivers, the SPM grain-size distribution was within the grain size range of bottom sediments, suggesting that the re-suspension of bottom sediments contributed to the SPM in the region. In the Gurupur R., the lower tidal flow in neap tide caused the ETM to degenerate/decrease in concentration, as a decrease in lower boundary shear stress reduces the re-suspension of bottom sediment and lower turbulent mixing increases the settling rate of material at the bottom. On the other hand, during the spring tide, the increased boundary shear stress and turbulent mixing resulted in regeneration or increased SPM in the ETM. However, in the Nethravati R., the ETM strength is comparable during both the tides. This may be because of the larger basin area facilitating similar mixing conditions during the tidal flow.

Interestingly, unlike other studies wherein it is normally observed that the freshwater discharge during the wet season has a greater contribution to the SPM, in the Gurupur R. the marine influence on the SPM was equivalent to the freshwater discharge in the Nethravati R. This observation suggests: (i) increased salinity-driven estuarine circulation due to channel deepening was responsible for enhancing the transport of sediments up-estuary, (ii) sediment extraction strategies from the ports, maintenance dredging and disposal operations had a significant impact on the estuarine SPM (Grasso and Le Hir 2019). The varying position of the ETMs in the Nethravati and Gurupur Rivers reflect the changing position of near-bottom convergence either due to variations in the position of the salinity intrusion as a function of discharge (Grabemann & Krause 1989; Wolanski et al. 1996; Obianyo 2019) or more material supply (Wu et al. 2012; Yu et al. 2014).

5 conclusion

Two microtidal estuaries in Karnataka (Nethravati and Gurupur), India, were studied for suspended particulate matter (SPM) concentration and its particulate organic matter (POM) content to understand the seasonal and tidal variations in the formation of estuarine turbidity maxima (ETM), i.e., high SPM zones. During the wet season, the Nethravati R. had no distinct ETM, while it was flocculation-based [floc-size 150-200 μ m, high POM] at the salt-freshwater interface in the Gurupur R. The locations of the dry season ETMs were not fixed in both the rivers and fluctuated along the estuarine length. In the Gurupur River, the ETMs were due to the river-meandering effect (post-monsoon) and re-suspension (floc-size <120 μ m, low POM) of bottom sediments (pre-monsoon). In contrast, in the Nethravati R., the ETMs were due to flocculation at the salt-freshwater interface (post-monsoon) and low to moderate material supplied by tidal currents (pre-monsoon). In the present estuaries, the river discharge in the

wet season dominated the SPM export. In contrast, tidal flow during the dry season favoured the retention of the SPM and POM in the estuarine region, thereby impacting the ecology and the management of the system and its resources. Interestingly, during the dry season, the tides were the dominant forcing, favoring the upstream transport of SPM, which could have repercussions for management operations, such as dredging. Therefore, future studies should concentrate on determining the sediment budget of the region.

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Nomenclature

SPM- suspended particulate matter

ETM- estuarine turbidity maxima

LISST- Laser InSitu Scattering and Transmissometry

CTD- Conductivity temperature depth

PVC-particle volume concentration

SMD- sauter mean diameter

POM- particulate organic matter

PTC- particulate total carbon

POC- particulate organic carbon

PTN- particulate total nitrogen

Figures legend

Fig. 1. Map showing the sampling locations in the study area, a) Sampling locations in Nethravati and Gurupur rivers, (b) sampling locations upstream of the Gurupur R. and (c) Sampling locations upstream of the Nethravati R.

Fig. 2. (a) Average seasonal River discharge at the upstream locations in Mangalore (2000-2016), (b) Monthly river discharge at Bantwal (Nethravati R.) and Addor (Gurupur R.) in 2017, (c) Average seasonal Rainfall for the Karnataka region from 2000-2016 and (d) from January to December 2017.

Fig. 3. Spatial distribution of Salinity and Suspended Particulate Matter (SPM) in the Gurupur R.

Fig. 4. Spatial distribution of Salinity and Suspended Particulate Matter (SPM) in the Nethravati R.

Fig. 5. Spring-Neap vertical distribution of (a) Temperature (b) Salinity (c) Chlorophyll-Fluorescence (d) Particle volume concentration and (e) Sauter mean diameter in the Gurupur R. during the wet season

Fig. 6. Spring-Neap vertical distribution of (a) Temperature (b) Salinity (c) Chlorophyll-Fluorescence (d) Particle volume concentration and (e) Sauter mean diameter in the Gurupur R. during the Postmonsoon season

Fig. 7. Spring-Neap vertical distribution of (a) Temperature (b) Salinity (c) Chlorophyll-Fluorescence (d) Particle volume concentration and (e) Sauter mean diameter in the Gurupur R. during the Premonsoon season

Fig. 8. Across estuary seasonal transects at stations Gu1, Gu4 and Gu6 in the Gurupur R.

Fig. 9. Vertical distribution of Time series data at station Gu2 during spring tides of the post-monsoon season: (a) Temperature (b) Salinity (c) Chlorophyll-Fluorescence (d) Particle volume concentration and (e) Sauter mean diameter.

Fig. 10. Spatial distribution of particulate organic matter (POC, PTN) in the Nethravati and Gurupur rivers during spring (red colour) and neap (black colour) tides. (filled circles represent POC values while empty circles are PTN values).

Fig. 11. Seasonal distribution of Grain-size in sediments of the Nethravati and Gurupur rivers.

Supplementary material

Figure S1. Flowchart depicting the research methodology followed

Figure S2. Vertical distribution of (a) Temperature (b) Salinity (c) Chlorophyll-Fluorescence (d) Particle volume concentration and (e) Sauter mean diameter in the Nethravati R. during spring-neap tides of the wet season

Figure S3. Vertical distribution of (a) Temperature (b) Salinity (c) Chlorophyll-Fluorescence (d) Particle volume concentration and (e) Sauter mean diameter in the Nethravati R. during spring-neap tides of the Postmonsoon season

Figure S4. Vertical distribution of (a) Temperature (b) Salinity (c) Chlorophyll-Fluorescence (d) Particle volume concentration and (e) Sauter mean diameter in the Nethravati R. during spring-neap tides of the Premonsoon season

Figure S5. Across estuary seasonal transects at stations N2, N5 and N9 in the Nethravati R.

Figure 56. Spatial distribution of Time series data at station Gu2 during spring tides of the postmonsoon season: (a) salinity (b) surface SPM concentration (mg/l) (c) velocity (cm/s), (d) Tidal height (m).

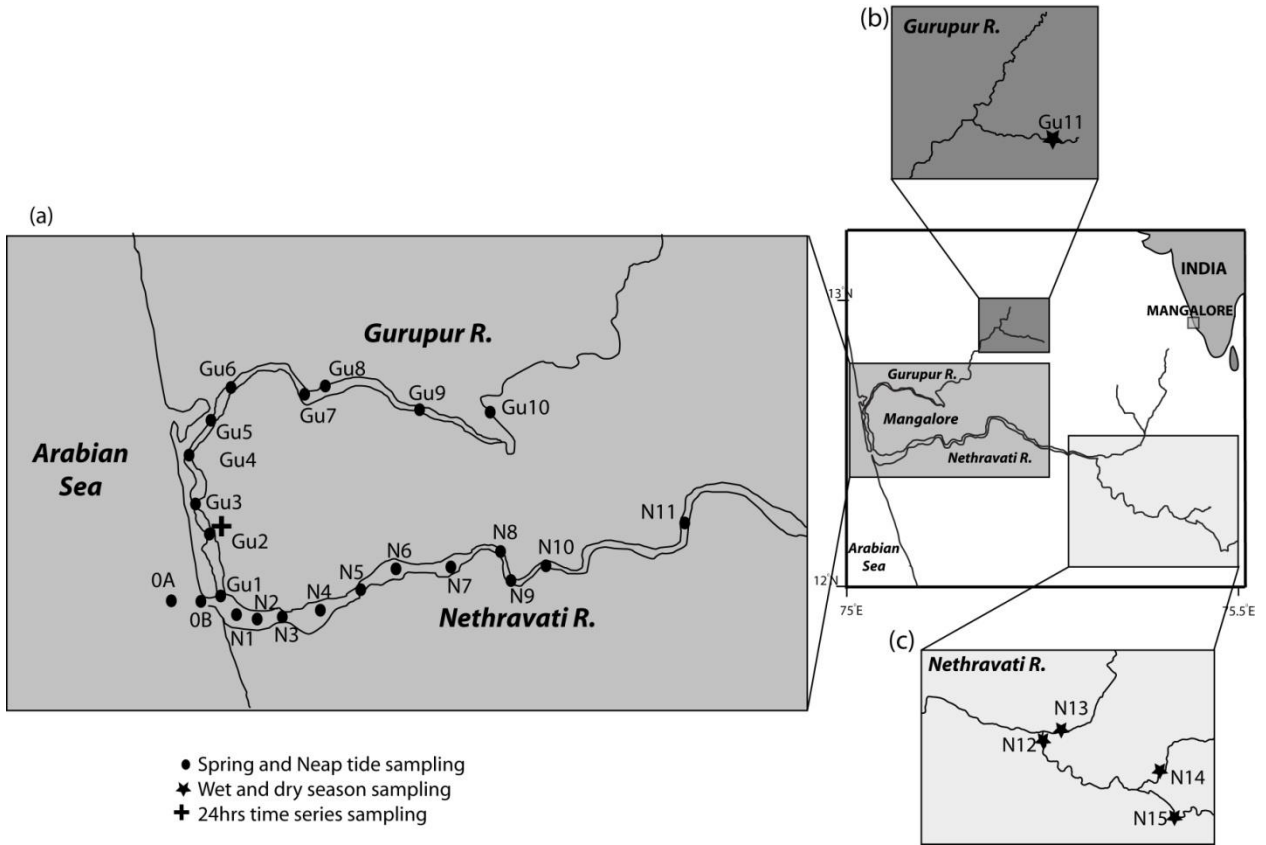


Fig. 1

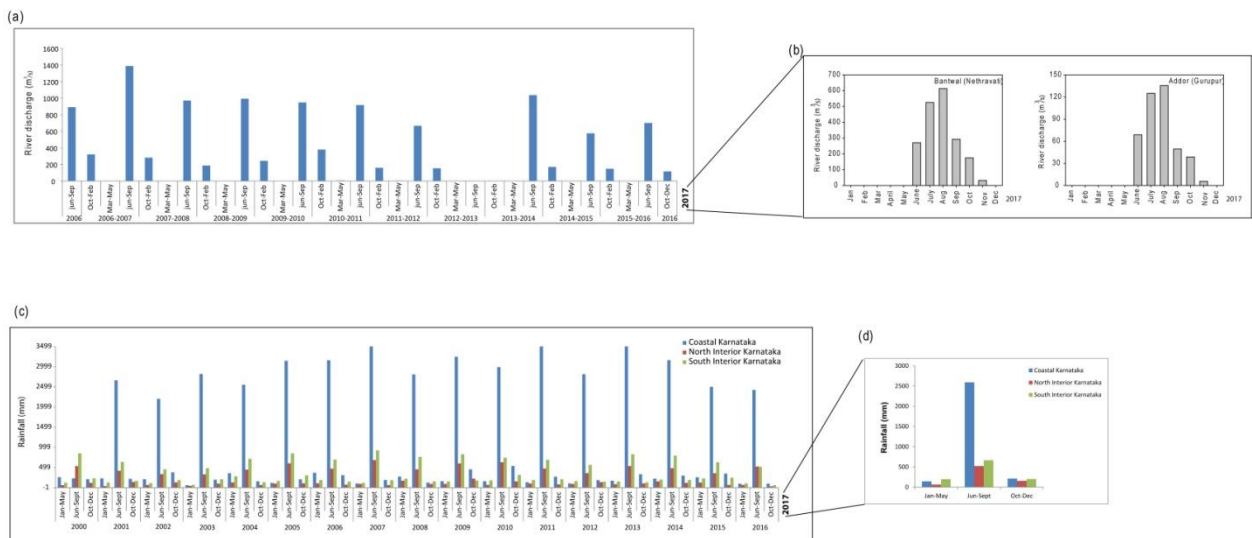


Fig. 2

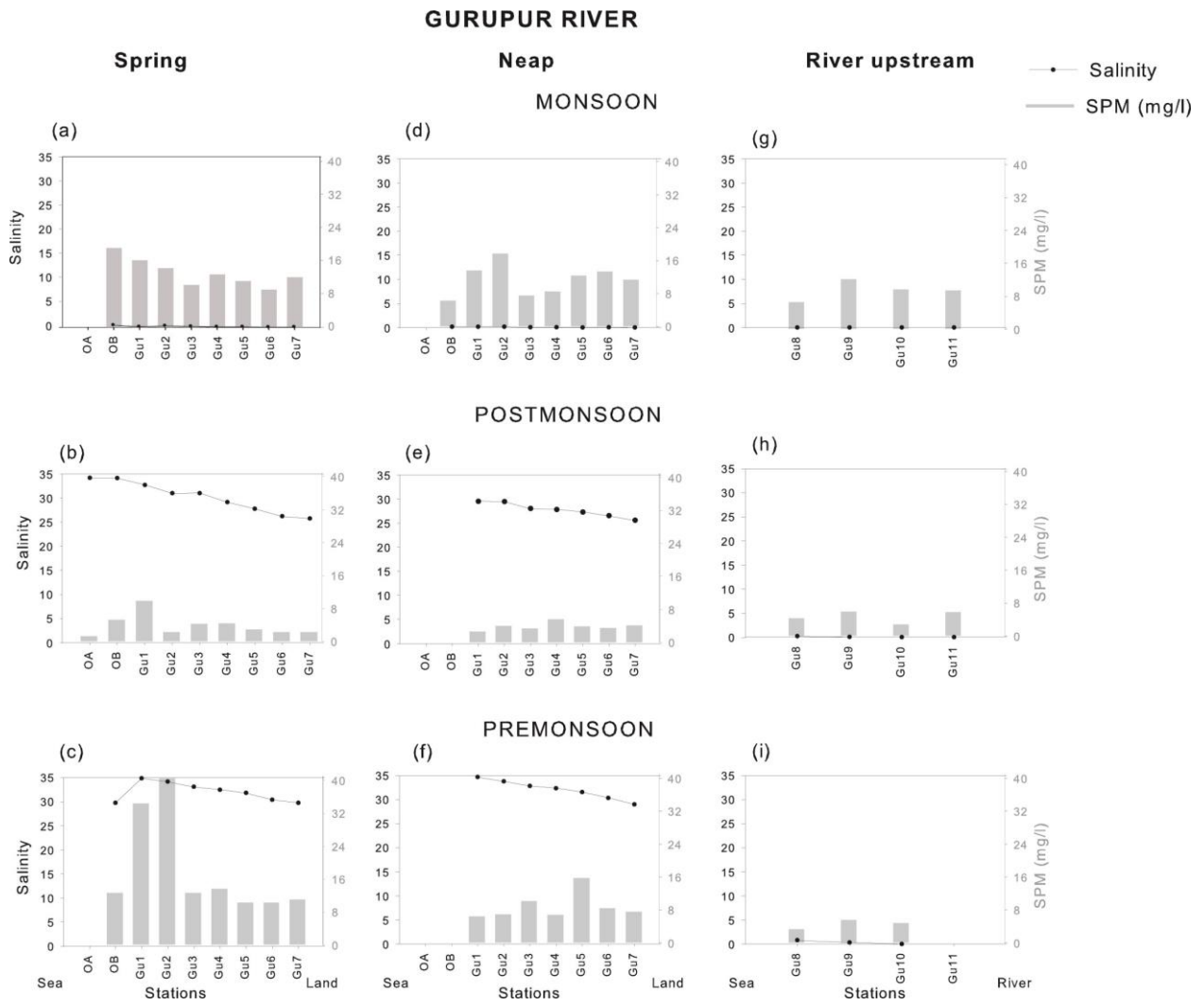


Fig. 3

NETRAVATI RIVER

● Salinity
 — SPM (mg/l)

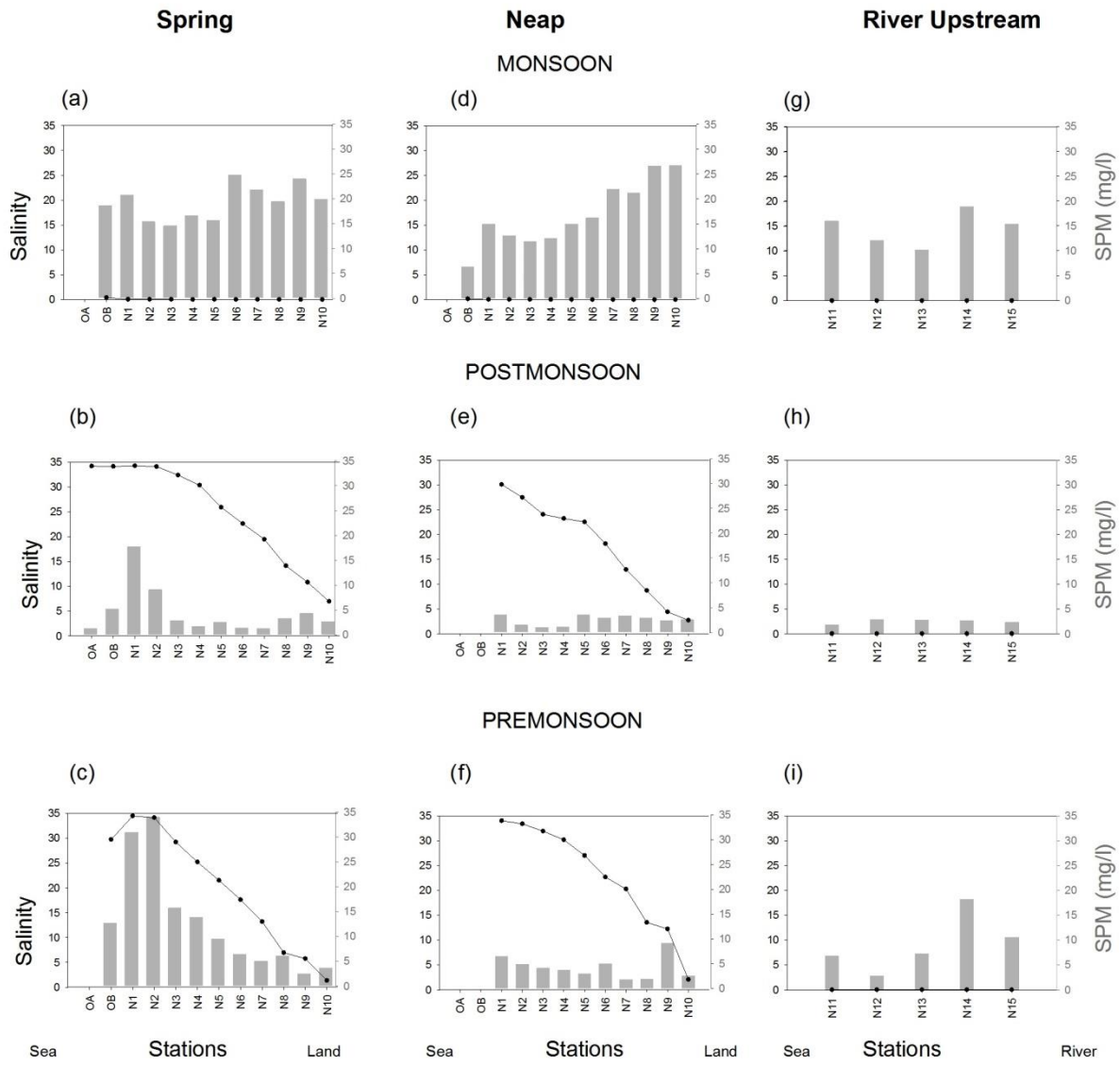


Fig. 4

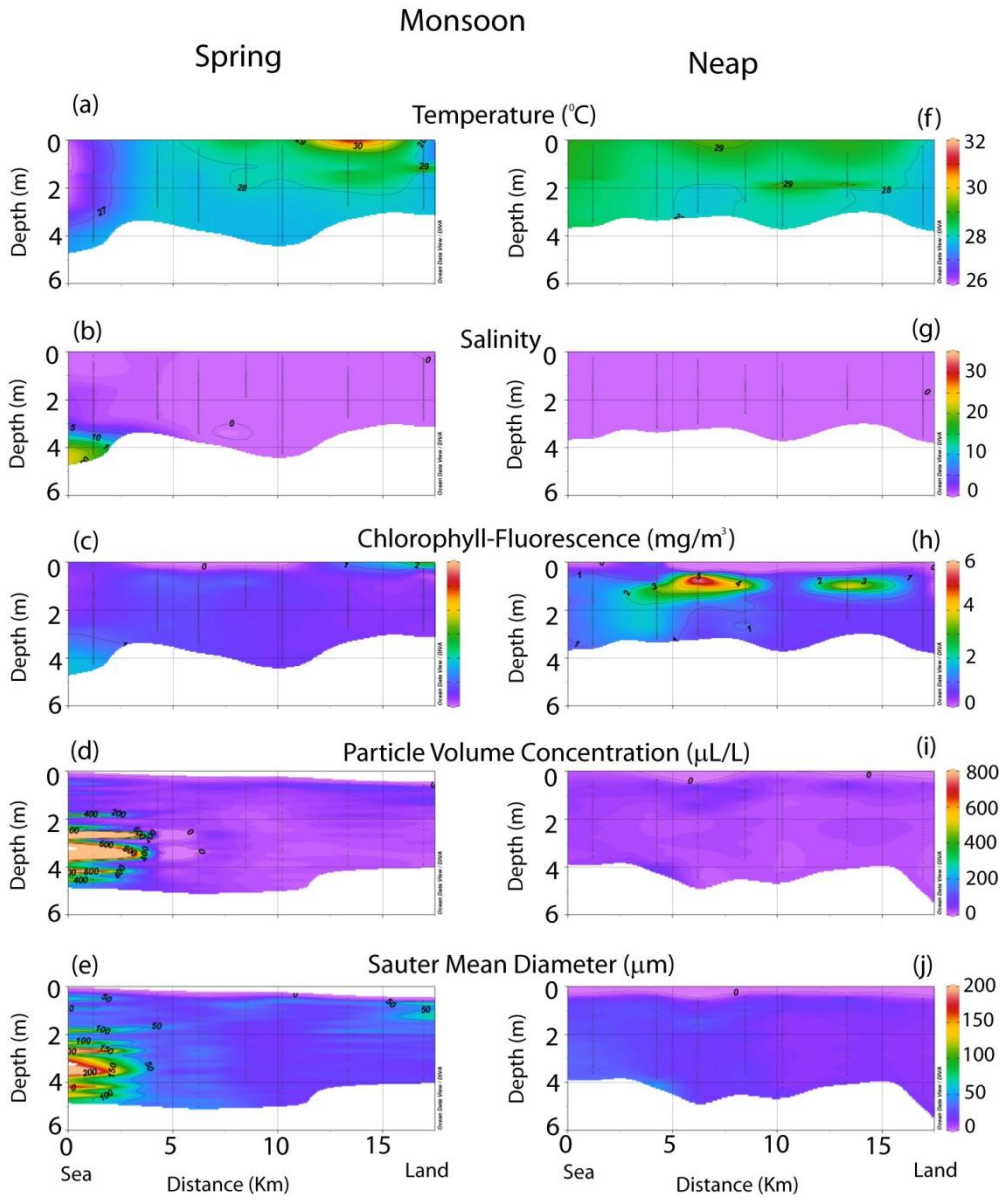


Fig. 5

Post-monsoon

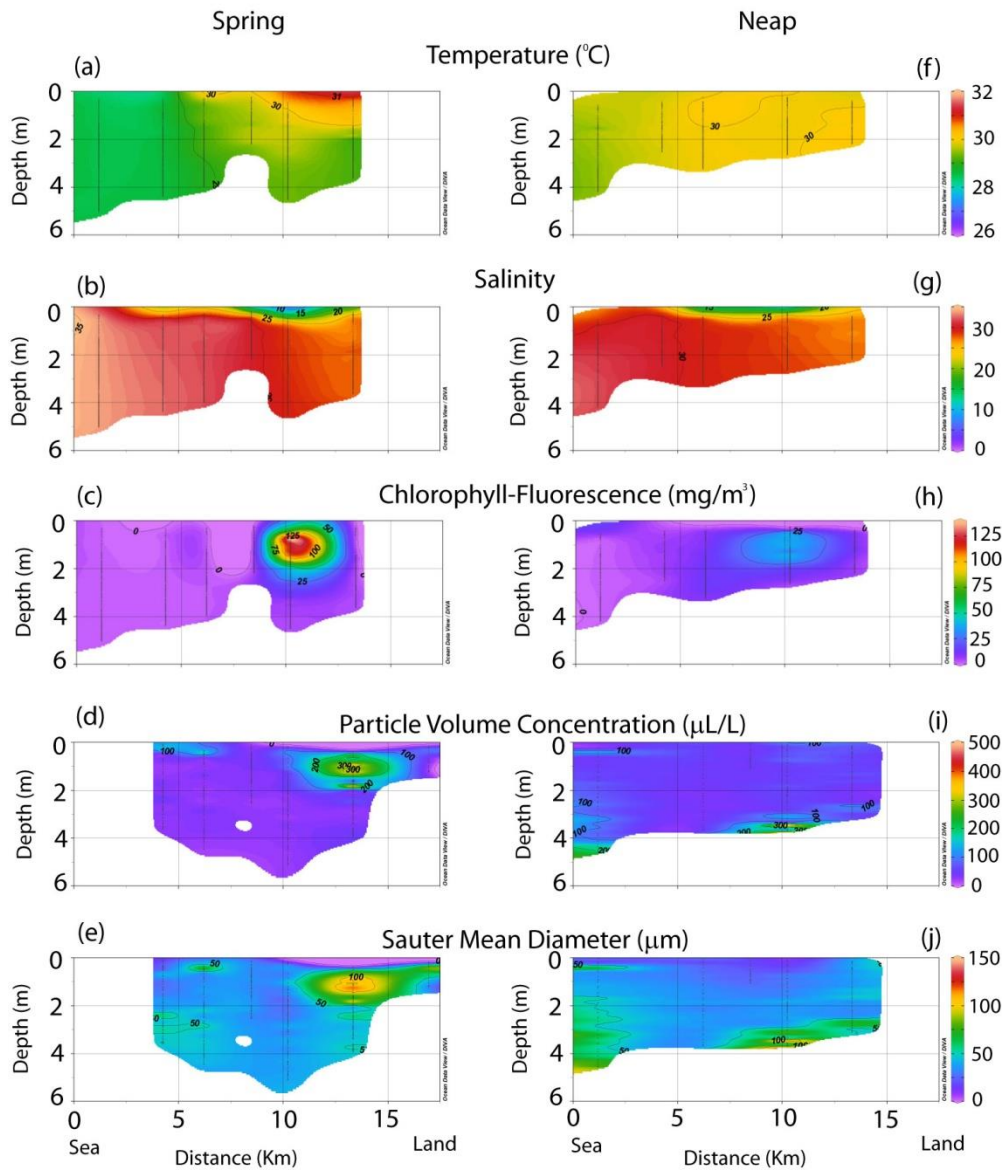


Fig. 6

Pre-monsoon

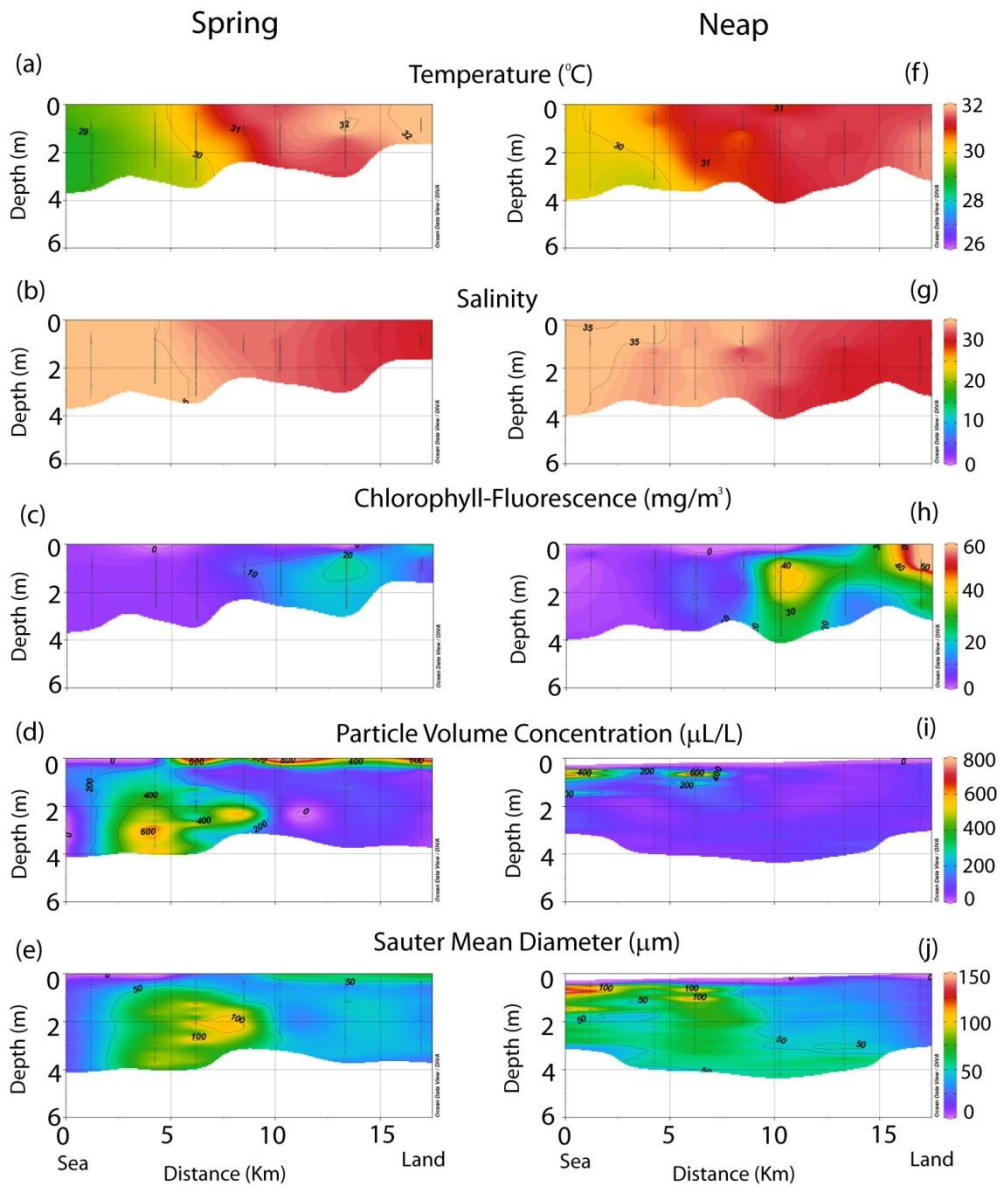


Fig. 7

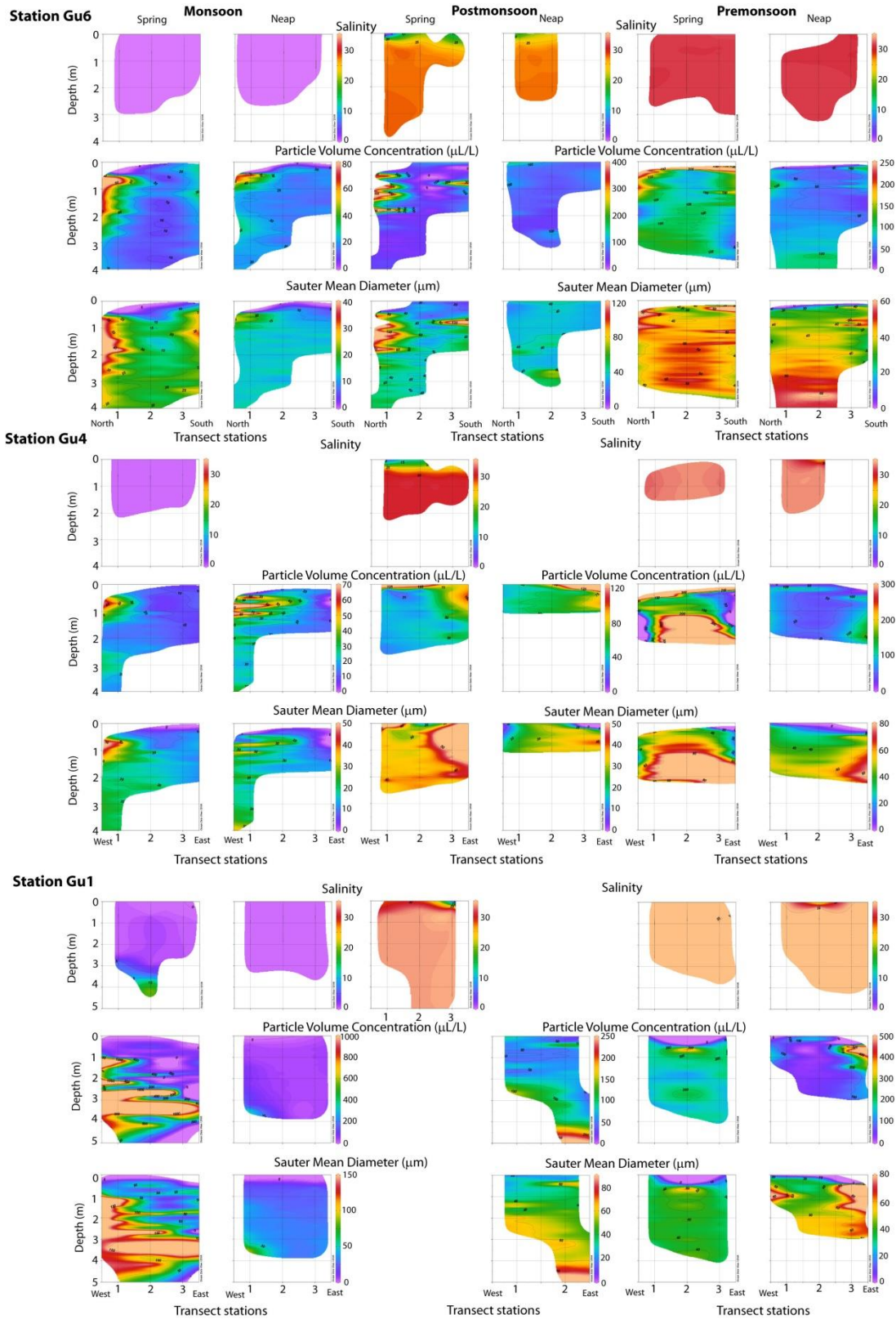


Fig. 8

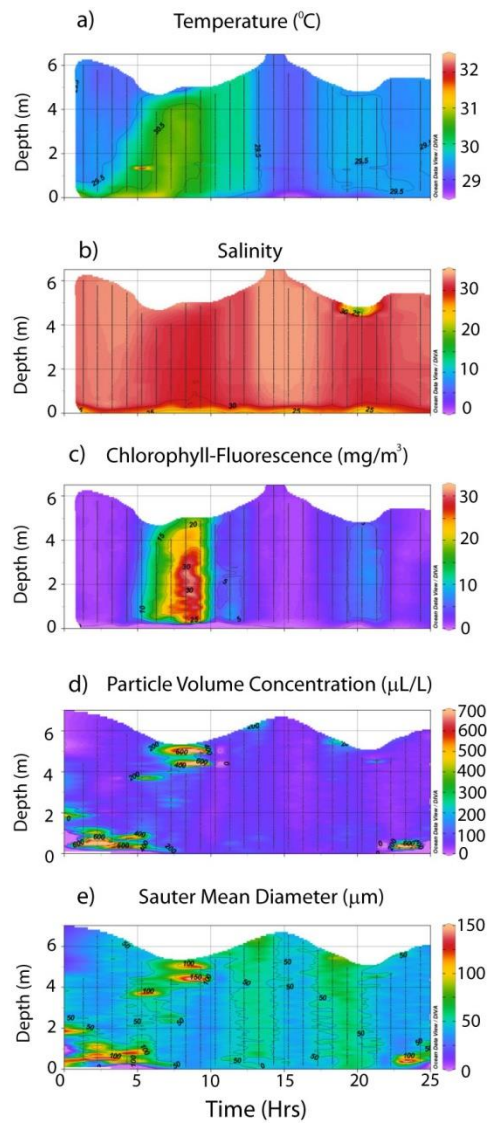


Fig. 9

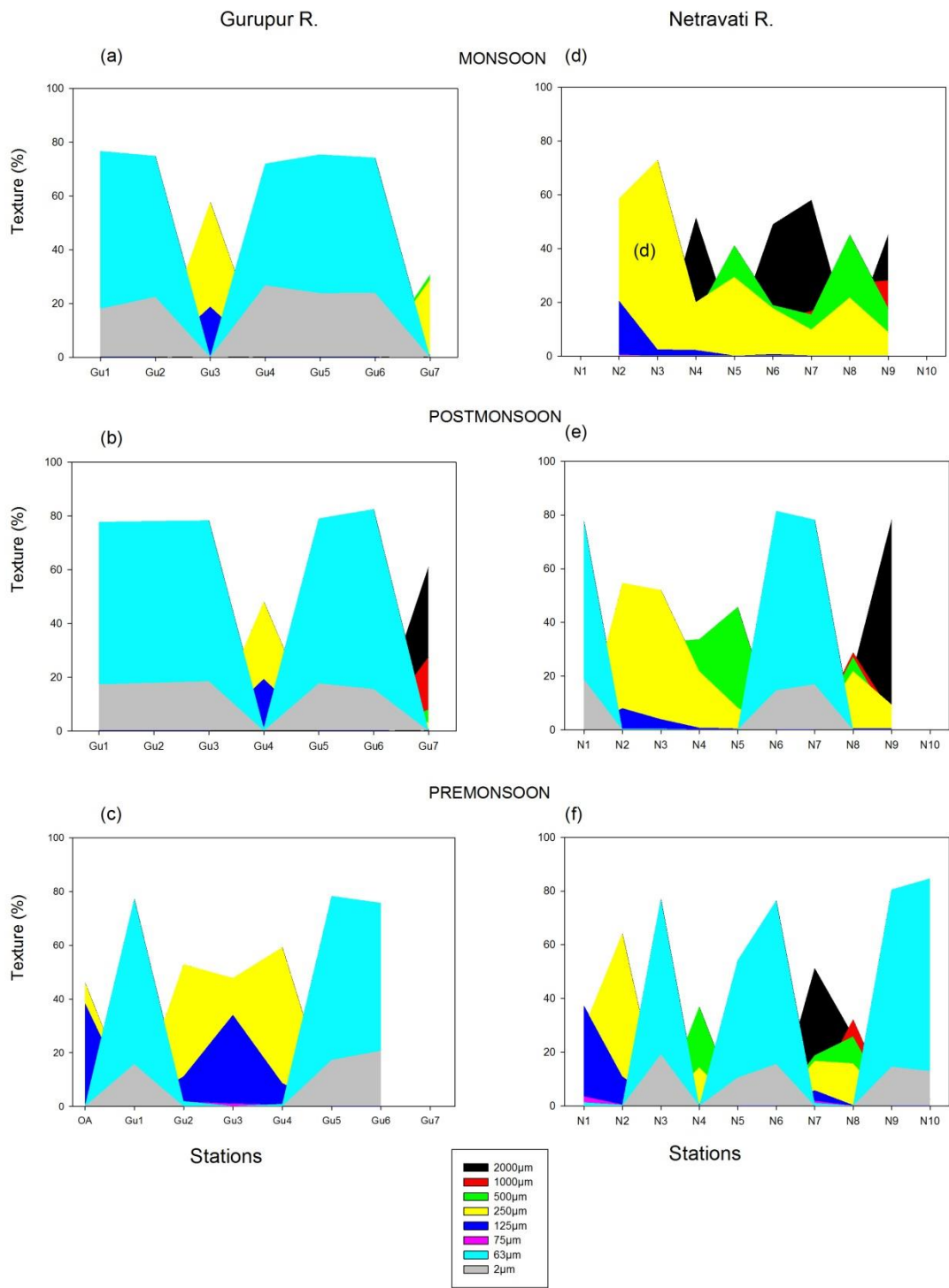


Fig. 10

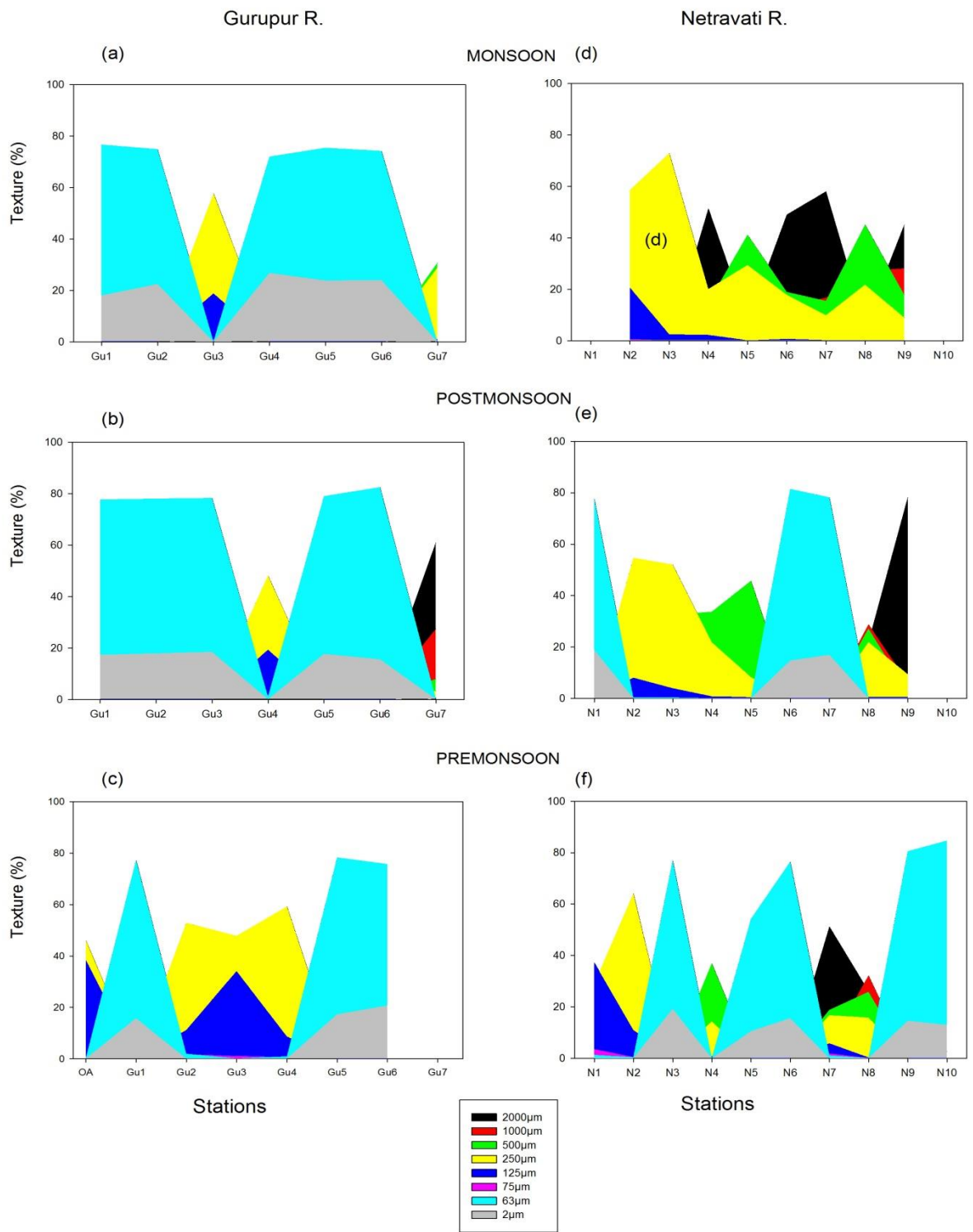


Fig. 11

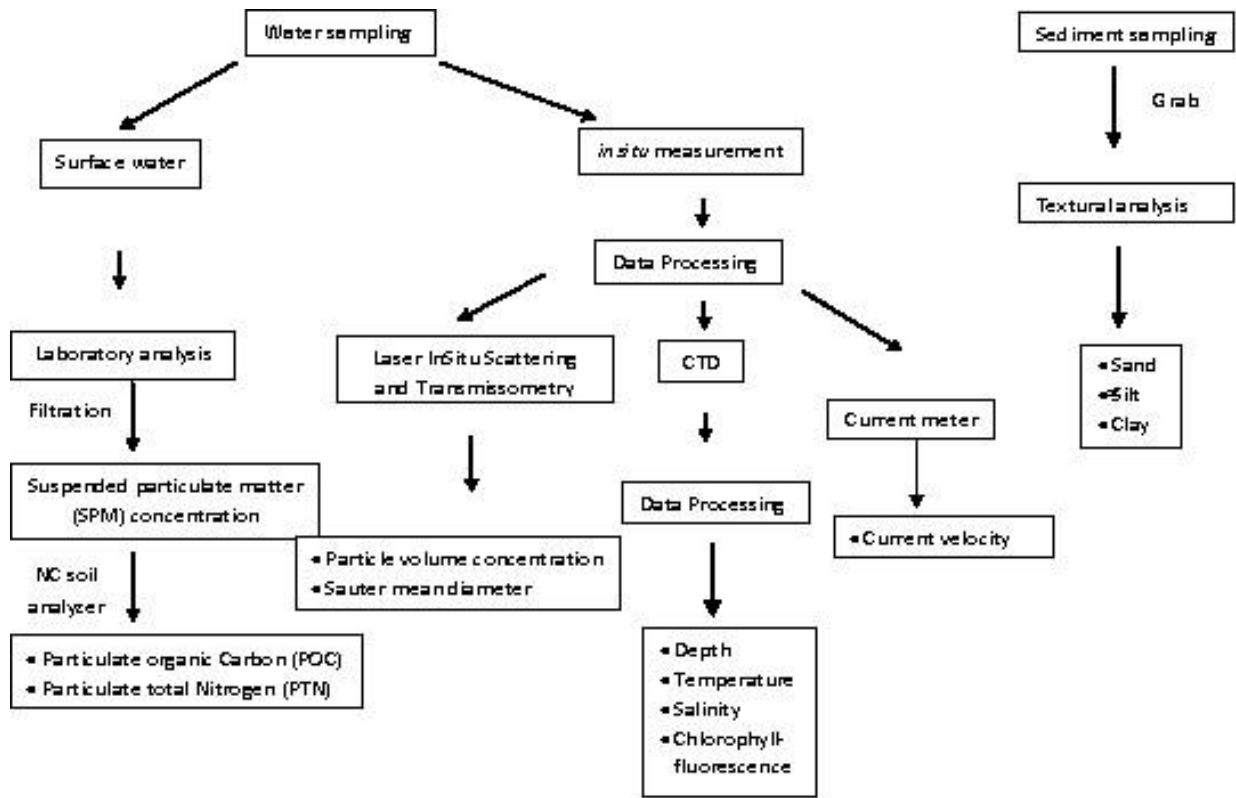


Fig. S1

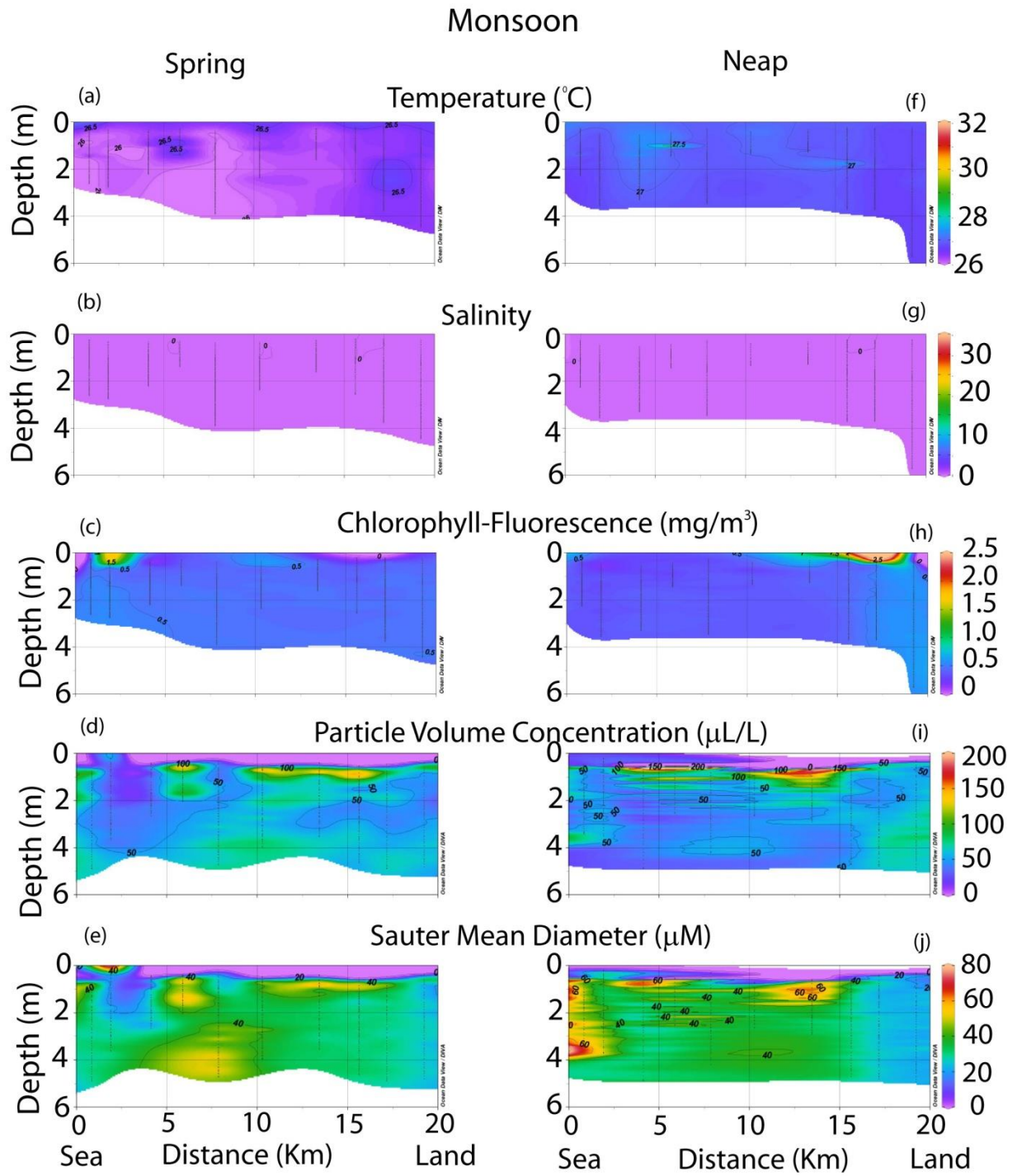


Fig. S2

Post-monsoon

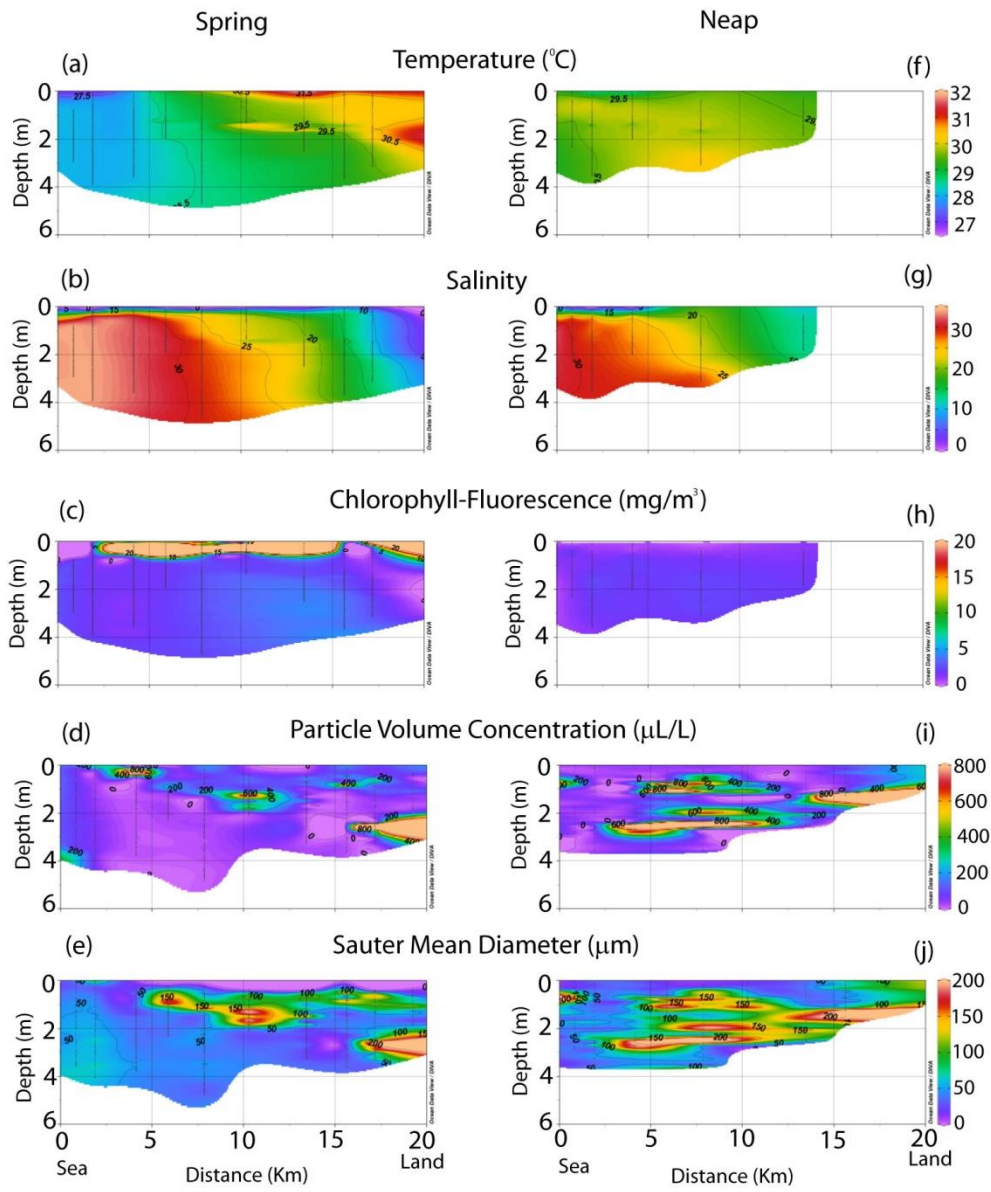


Fig. S3

Pre-monsoon

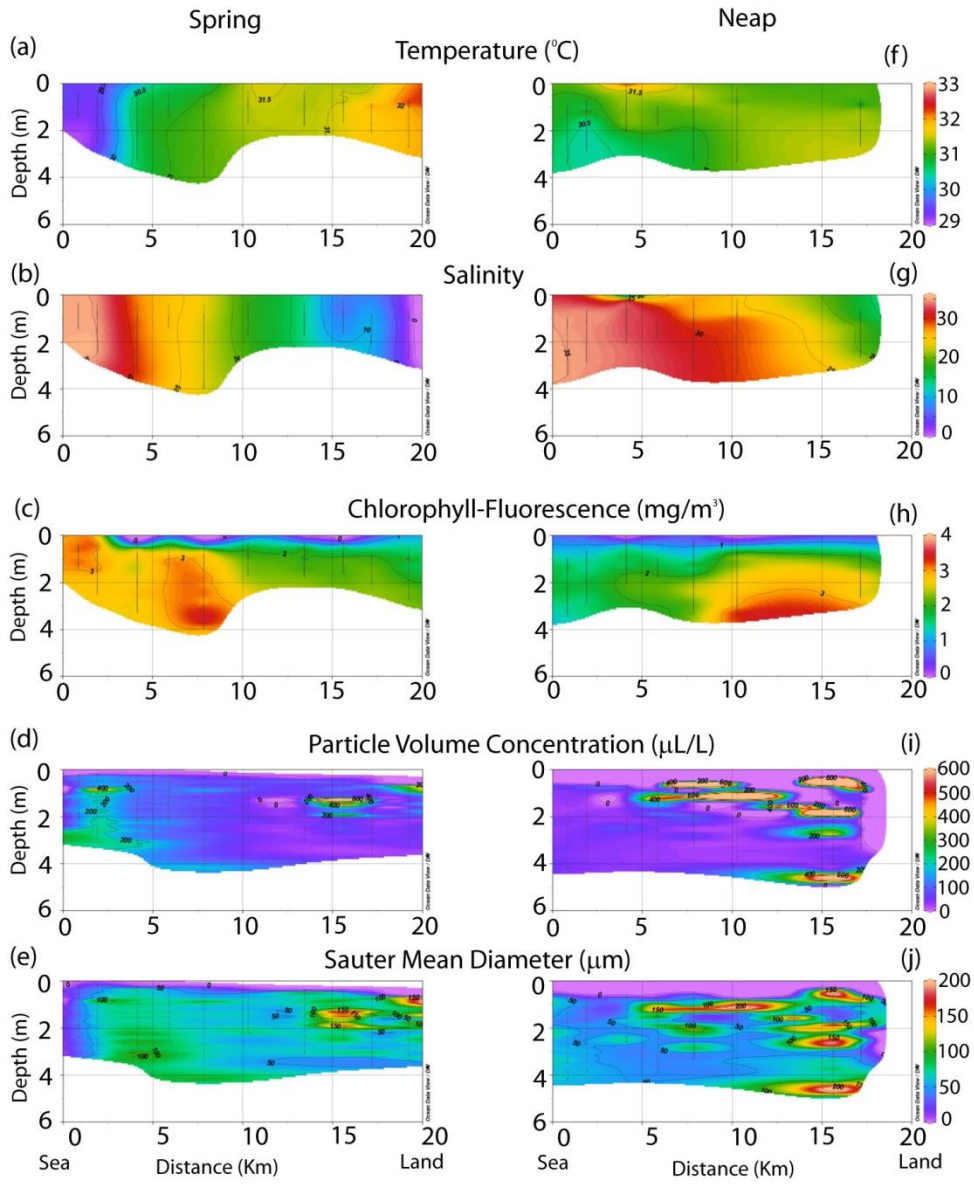


Fig. S4

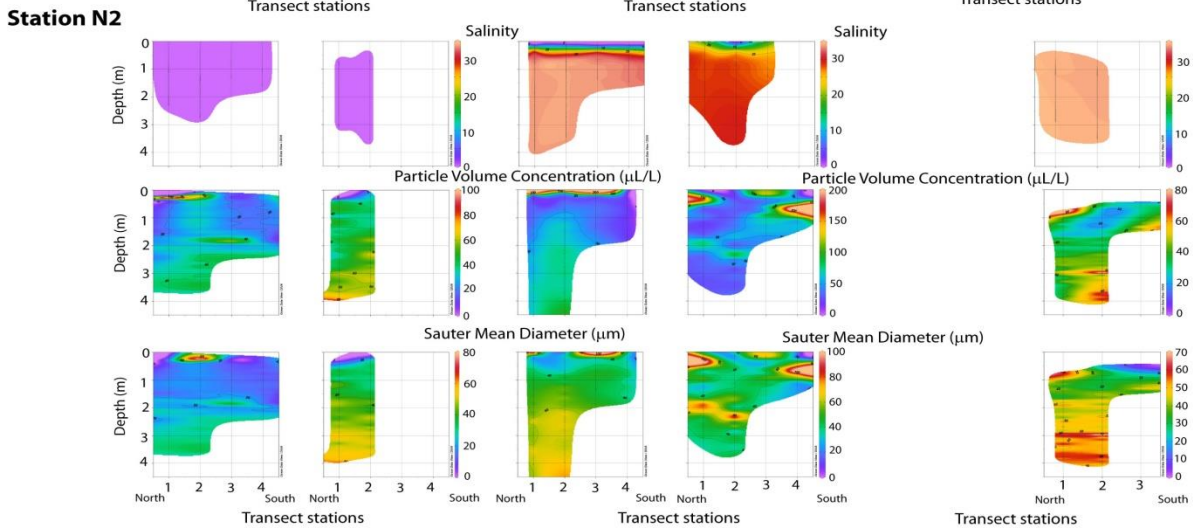
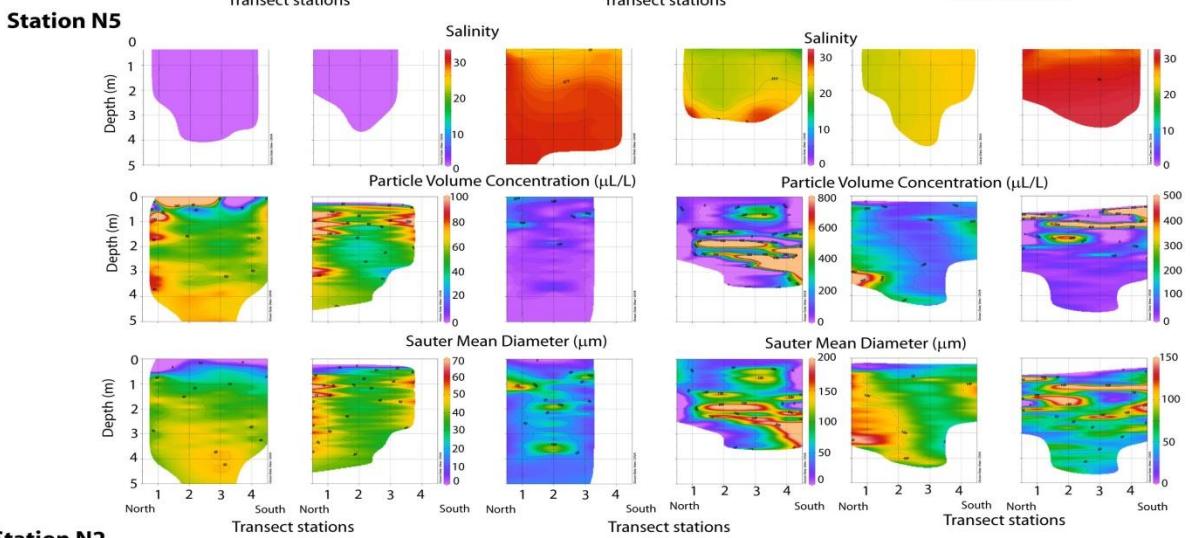
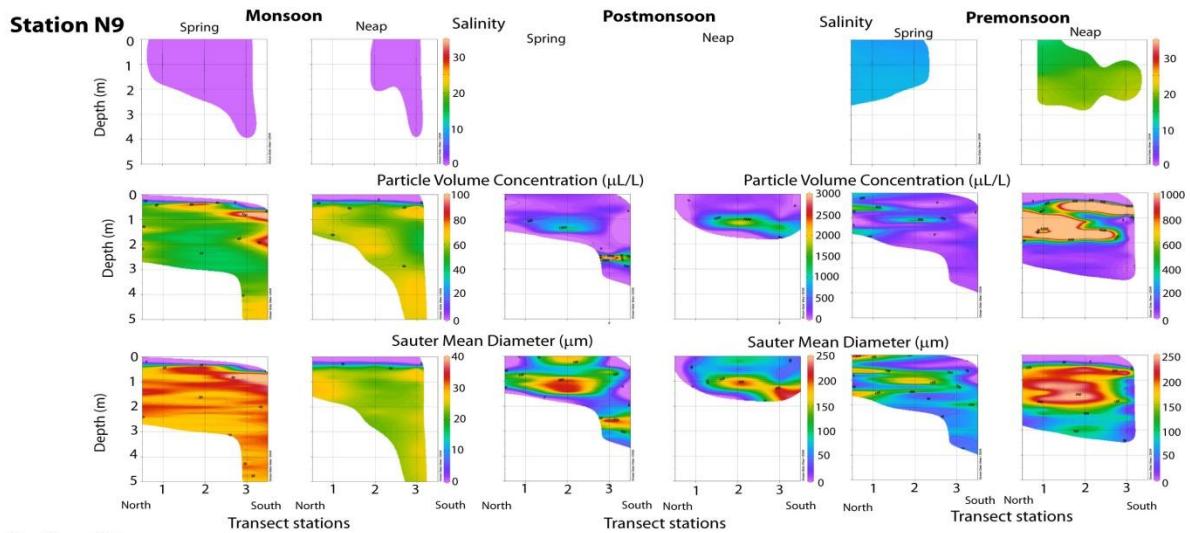


Fig. S5

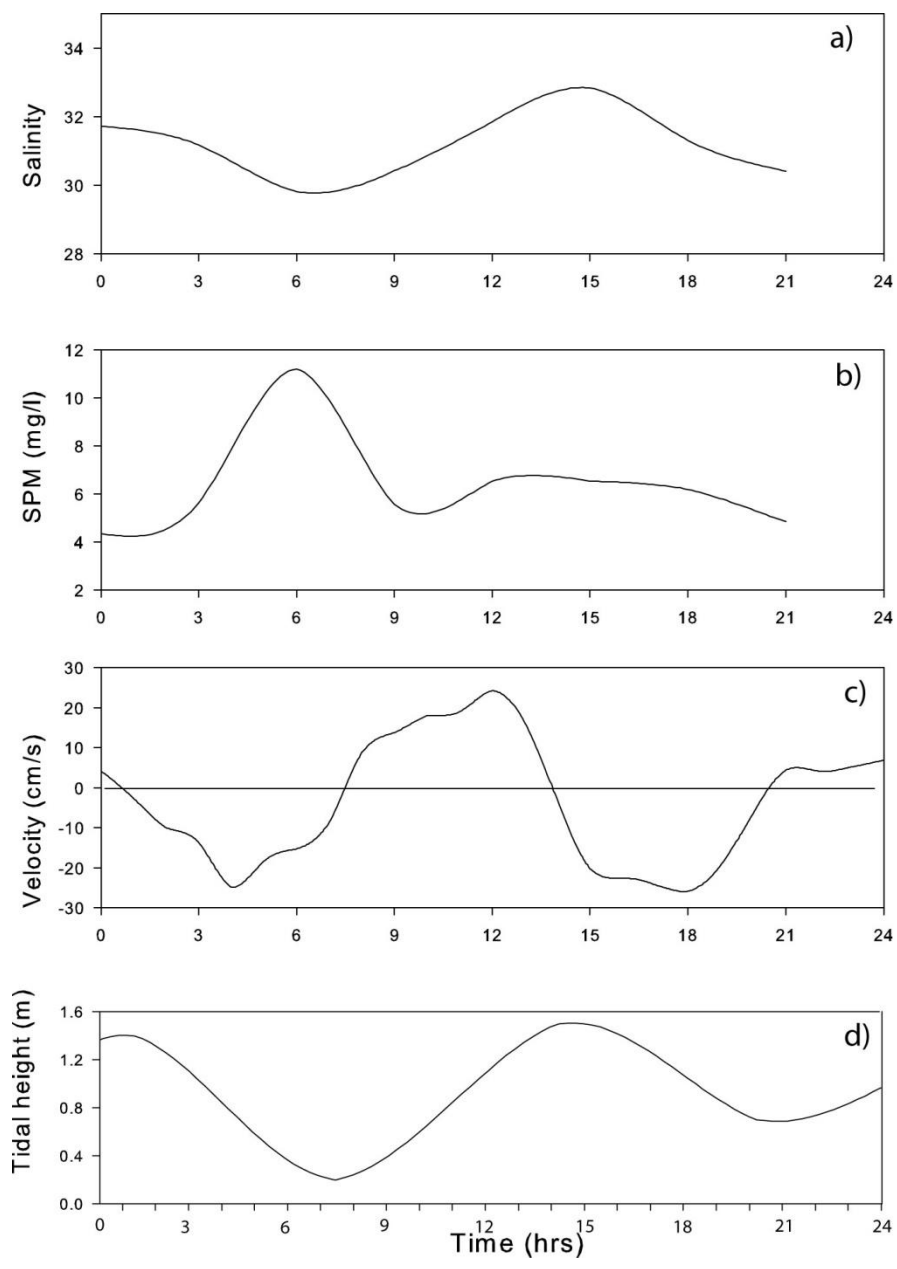


Fig. S6