5.1. INTRODUCTION

Suspended solids (synonymously, suspensate) in the highly dynamic estuarine environment are subjected to back and forth transport by ebb
and flood tidal currents and are recycled many a times prior to deposition. Many of the estuarine circulation systems cause the entrapment of some amount of suspended solids; the study on distribution of this material is significant with regard to both its estuarine behaviour and sedimentological features. The particle dynamics in coastal waters has been a special subject area wherever surveys on pollutant dispersal were considered (Officer, 1981; Varadan et al. 1985).

Estuarine waters are often more muddier than the rivers flowing into them or the sea beyond, due to presence and availability of varying amounts of suspended solids (McCave, 1979). Sediments principally move in suspension prior to deposition in regions of accretion in an estuary (Almos, 1987). Definition of suspended load used here is the one recommended by the sub-committee on sediment technology (Dyer, 1979). The material moving in suspension in a fluid, being kept up by the upward components of turbulence or by law of the colloidal mixtures is termed suspended load. This conveys the dynamic sense of 'suspension' as a process that is controlled by the hydrodynamic conditions. Many have observed the existence of an active interchange between the suspended load and bed load and also between the bed load and bed itself (Graff, 1971; Adalph, 1982; Parker, 1987).

Grain size analysis is frequently used by sedimentologists to characterise the depositional environments of clastic sediments (Nayak and Chavadi, 1988). The grain size of a clastic sediment is a measure of the features of the depositing medium and the energy of the basin of deposition (Reineck and Singh, 1980). In general, the coarser sediments are found in high energy environments and finer sediments in lower energy realms (Hashimi et al. 1978; Mavis et al. 1985; Dyer, 1987).

The studies on the problems associated with the suspensate and surficial sediments of the Cochin harbour area had been made by Ducanfe et al. (1938), Das et al. (1966), Sunda Raman (1968), Central Water Power Research Station (1969), Josanto (1971), Gopinathan and Qasim (1971), Veerayya and Murty (1974), Anto et al. (1977) and Rama Raju et al. (1979). According to Gopinathan and Qasim (1971) the water column
of the Cochin harbour area has a maximum suspended load during the monsoon period but its quantity declines progressively through the postmonsoon and premonsoon months. However, Rama Raju et al. (1979) observed a general increase in the sediment load from monsoon to premonsoon through postmonsoon seasons during 1975-1976. Studies by Veerayya and Murty (1974) on the sediments of Vembanad lake during postmonsoon months, revealed that the finer sediments were present in the estuarine region of the lake and this was due to the deposition of suspended load by flocculation and by the supply of fine material from the sea brought in by tidal currents during these months. Josanto (1971) reported that during premonsoon months, the grain size distribution of the Cochin backwater sediments indicated presence of silty clay around Willingdon island and that the sediments in the Mattancherry channel region were of finer texture than those in the Ernakulam channel.

In recent years, extensive harbour development work has been conducted in the Cochin harbour area and its vicinity. Cochin Port Trust has already carried out substantial capital dredging work for the execution of the Integrated Development Project during the period 1980-1985 (Manoharan, 1987). These developmental works have much practical importance on the distribution of suspended material and the textural pattern of the harbour area sediments and hence, on the sedimentary environment. The earlier studies on the suspensate and surficial sediments are, therefore, no longer valid. The distribution of suspended material in the Approach channel and simultaneous studies on surficial sediments and other physical parameters were not investigated by the earlier researchers. The studies regarding the suspensate and surficial sediments of this harbour area is lacking since 1979. In the present study, the horizontal and transverse distribution of the suspended load in the harbour area from 28 stations, monthly and the semi-diurnal tidal variation of suspensate from the inner and Approach channels were thoroughly analysed and presented. The monthly textural analysis of the surficial sediment samples collected along with the suspensate are also reported. The variations from previously reported values are discussed in relation with the changing physical processes operating in these areas. In this context, the terms suspended matter, suspended solids, suspensate and
seston all refer to total solids held in suspension in water, though operationally it is what that is retained in a filter (Kramer, 1988). These terms have been used synonymously and are interchangeable.

5.2. MATERIALS AND METHODS

The materials and methods employed in this study are described in Chapter 2.

5.3. RESULTS AND DISCUSSION

5.3.1. Suspensate

5.3.1.1. Ernakulam Channel

The suspended solids distribution at the surface, middle and bottom waters of Ernakulam channel, in postmonsoon months, are shown in the figure 37. The surface water seston content was relatively low in this season (47 - 200 mg l⁻¹). It was observed that during October, slightly more suspensate was present at the upper reaches especially along the southeastern side (station 3) of the channel due to the extended monsoonal effects. The figure shows that the surface water seston content was low along the central stations (stations 2, 5 and 8) compared to the shallow stations on the two sides of the channel. The closely placed curved isolines in October and November months revealed that the bottom water suspensate was considerably more (588 - 1061 mg l⁻¹) towards the lower reaches of the channel due to rapid deposition of material in this region. The whole water column in December and in January (except stations 4 and 6) showed low suspensate and less fluctuations (86 - 160 mg l⁻¹). This is due to the reduced freshet discharge of low suspended solids and also due to the lower order turbulence from disturbance caused by winds and waves of the coastal region. The bottom waters at the transverse section in the tanker berths (stations 4 and 6) in January showed suspensate content to be slightly more (333 - 577 mg l⁻¹) than at other stations due to the resuspension of the fine material deposited in this salt-wedge region of the channel.
Fig. 37. Suspensate (mg l\(^{-1}\)) distribution at surface and bottom layers of Ernakulam channel (stations 1 - 9) during postmonsoon months. Seston content at middle station are also denoted.
The figure 38 shows that the water column of Ernakulam channel contained high amounts of suspensate in premonsoon months except during April. In February, the surface water suspensate was more on the eastern parts (376 mg l\(^{-1}\)) compared to the other regions of the channel. The bottom water suspensate was greater on the two sides of the channel due to the increased resuspension of the bottom material by the tidal currents in the shallow sections. This is explained as due to the lateral internal seiching produced by the interaction of the surface seiche with the shallow side of the estuary. Such a phenomenon was also observed by Dyer (1982) in Southampton waters. The increased seston content on the eastern side of the channel denotes that a turbidity maximum zone was present in this region; the high mid-water seston at the transverse section of the tanker berth being due to the local circulation system that caused water fronts as explained by Nunes and Simpson (1985) regarding the behaviour of suspended solids in estuarine flows. The presence of suspensate was observed more towards the upper reaches of the channel in the month of May (bottom water contained up to 2000 mg l\(^{-1}\)). This was due to the fluvial discharge of heavy seston load as a result of the earlier onset of monsoon. The seston content was more at the shallow stations than the deeper one, presumably due to the tidal current disturbances that resuspend the material. Gopinathan and Qasim (1971) observed that during premonsoon months, the suspended material in the water column throughout the harbour area was relatively low. The observations of Rama Raju et al. (1979) as well as results of the present study show that the amount of suspensate was more during the premonsoon months in this channel (551 - 2000 mg l\(^{-1}\)). This is attributed to the effect of Thanneermukkam bund commissioned in 1976 regulating the extent of intrusion of saline waters. In effect, the resultant maximum reach of tidal incursions have been much reduced allowing energy convergence towards increased resuspension of bottom sediments in the harbour area.

The suspended load was observed to be higher towards the upper reaches of the channel in June (6 - 255 mg l\(^{-1}\) at surface and 133 - 1350 mg l\(^{-1}\) at bottom) and in July (140 - 270 mg l\(^{-1}\) at the surface and 180 - 1156 mg l\(^{-1}\) at bottom) (Fig. 39). The increased silt laden fluvial
Fig. 3.8. Suspended (mg l⁻¹) distributions at the surface and bottom layers of Ernakulam channel (stations 1-9) during monsoon months. Station content at middle station are also denoted.
Fig. 39. Suspensate (mg l⁻¹) distribution at surface and bottom layers of Ernakulam channel (stations 1 - 9) during monsoon season. Seston content at middle stations are also denoted.
discharges during monsoon months cause this increase. Similar characteristic features of estuarine turbidity maxima along the south coast of English channel were described over a range of time scales and seasonal fluctuation of river discharge by Avoine and Larsonne (1987). The figure exhibits that in June, the bottom water seston variation was more at the eastern side of the channel than the western side. Eastern side of the channel is the place of confluence of waterways of Periyar river from north and the lake water from south giving rise to sedimentary environments. The turbidity maximum zone present in the transverse section of the tanker berths may be due to the presence of a salt wedge in this segment of the channel. The surface and subsurface water column showed low seston concentration (<150 mg l⁻¹) in August except in bottom-water layers at Ernakul wharf station. In September, the surface water seston was slightly more towards the south of the channel (194 - 273 mg l⁻¹) while the surface and bottom waters of station 8 showed high values (508 mg l⁻¹ and 1741 mg l⁻¹ respectively). The figure exhibits that in monsoon months relatively low seston concentration was observed in the channel compared to premonsoon months and the bottom water seston content was more than the surface content. Gopinathan and Qasim (19 stated that during monsoon months the seston content increased sharply throughout the water column which is contrary to the present result. This marked change is due to the commissioning of the Idukki project permitting controlled flow in the Muvattupuzha river and hence the regulated output of suspended particulates (Balchand and Nambisan 1986). Saxia reservoir acts as a location for deposition of considerable amounts of suspensate from the Changjiang river (China) as also observed by Lin (1987).

5.3.1.2. Approach Channel

The distribution of suspensate in the surface, middle and bottom waters of Approach channel area are shown in figures 40, 41 and 4. The surface water suspensate content was relatively low (≈ 200 mg l⁻¹ in postmonsoon months except in the month of December (≈ 300 mg l⁻¹). The figure shows that in the month of October the amount of seston was decreasing towards the seaward side of the Approach channel.
Fig. 40. Suspended (mg L⁻¹) distribution at surface and bottom layers (January 1985 - middle layer) of Approach channel (stations 13 - 19) during post-monsoon season. Seston content at middle station 14 is denoted.
trend of isolines in the transverse direction is perpendicular to the longitudinal channel orientation revealing the equitransverse suspensate distribution and the influence of littoral transport in the suspensate distribution. A mid-channel turbidity maxima was observed in the vertical during the observation in October; during the rest of the months the seston content was relatively low in amount. The turbidity zone may be due to the result of confluence of higher freshet (present in the beginning of postmonsoon months) and the prevailing coastal currents. The trend of isolines reveals that the seston maximum was shifted more towards the northern side of the channel (1000 mg l$^{-1}$) and its distribution was more uniform longitudinally on the south side of the channel. In the months of November, December, 1984 and January, 1985 the bottom water seston was less than 315 mg l$^{-1}$ except at station 15 in November (445 mg l$^{-1}$). The trend of isolines show that the suspensate distribution was longitudinal, hence parallel to the channel orientation in the month of January; this may be due to the intense ebb flow present in the Approach channel. Also in January, the mid-water seston content was more (500 mg l$^{-1}$) and was decreasing towards the seaward side of the channel. It is also observed that in postmonsoon months the bottom suspensate content was relatively more towards the northern side of the channel.

The suspensate distribution in the surface, middle and bottom waters of Approach channel in premonsoon months is shown in figure 41. The surface water suspensate in the harbour area exhibited lesser variations in February (<150 mg l$^{-1}$), March (200 - 350 mg l$^{-1}$) and April (<200 mg l$^{-1}$). Increased seston content was present in May (600 mg l$^{-1}$) at the cut and was less than 200 mg l$^{-1}$ towards the west of the channel. The increase in seston content at the cut region is presumably due to the high freshet outflow attributed to the earlier onset of monsoon. The figure exhibits that the mid-water suspensate was decreasing towards the west of the channel in premonsoon month except in the month of May. The gradient of isolines in May reveals that high turbidity zones were present in the mid-water and bottom water layers of the Cochin harbour region concentrating on the southern parts of the cut and middle of the channel (\(\simeq 2250 \text{ mg l}^{-1}\) at
the mid water and 3138 mg l\(^{-1}\) at bottom). It is also seen that the bottom water seston content was more towards the southside of the channel decreasing towards the seaward side. The presence of higher suspended solids is attributed to the churning action of waves of the coastal waters seasonally acting (Chapter 4, Page 39). In March, the concentration of suspensate was more on the northern side of the channel (station 15, 1153 mg l\(^{-1}\) and station 19, 1412 mg l\(^{-1}\)). It is inferred from the suspensate study of premonsoon months that the source of seston was from the coastal waters and the tractive forces were the littoral currents of these coastal regions causing suspended material transport. The river inputs during these months were extremely low (2.77 - 7.26 \(\times\) 10\(^6\) Kg month\(^{-1}\)) compared to values greater than 90 \(\times\) 10\(^6\) Kg month\(^{-1}\) in monsoon months (Table 6).

During the monsoon months, the surface water seston content was low (\(\leq 180\) mg l\(^{-1}\)) except on the south of the cut in the month of September (310 mg l\(^{-1}\)). The mid-water suspensate exhibited considerable spatial variations and was generally less than 450 mg l\(^{-1}\) except in July (1000 mg l\(^{-1}\)). The figure brings out the feature of mid-water seston distribution to be more varied towards the seaward side in the months of July, August and September 1985. The bottom suspensate content was more concentrated towards the southern side of the channel in June (2100 mg l\(^{-1}\) at station 13 and 600 mg l\(^{-1}\) at station 18 in June) and considerably lower in September (250 mg l\(^{-1}\)). The high seston content present in July at the subsurface levels may be due to the high wave activity which undergo refraction; hence this initiates the sediment movement due to the churning action. Weir and Mc Manus (1987) has detailed a comparable wave generated seston pattern in the Tay estuary during the estuarine sedimentation processes. The resultant currents in this case may hence transport the material towards the channel. The steep topographical slope on the south side of the channel (Shenoi and Prasannakumar, 1982) also facilitate the waves to interact more with the channel bottom, giving rise to higher suspensate concentrations.
Fig. 42. Suspendsate (mg l\(^{-1}\)) distribution at surface, middle and bottom layers of Approach channel (stations 13 - 19) during monsoon season.
5.3.1.3. Mattancherry Channel

The distribution of suspensate in Mattancherry channel during different seasons is presented in the figures 43, 44 and 45.

During the postmonsoon months (Fig. 43), low amounts of seston ($<250 \text{ mg l}^{-1}$) was present in the surface layers of this channel, except in January ($<320 \text{ mg l}^{-1}$). The trend of isolines show that the surface layer seston content was greater on the sides of the channel than at mid stations. This was due to the increased resuspension of the fine material at the bottom due to the intense bottom flow at the shallow stations. This feature was also observed in the Ernakulam channel. The seston in surface waters were slightly more in the upper reaches of the channel. This may be due to the extended monsoon effects and hence the continued fluvial seston supply in October and tidal action in January. Bottom suspensate showed considerable variability in this season ($150 - 2000 \text{ mg l}^{-1}$). The trend of isolines reveal that the variation were more in the transverse direction than longitudinal; the closely packed isolines exhibited greater variation on the western sides of the channel in October and turbidity maximum zone was observed at station 23 of this channel. This is caused by the channel orientation and the interference of water fronts in this region as described in chapters 3 and 4. The bottom layer suspensate content was increasing towards the lower reaches of the channel in October and November; this again, is due to the increased flocculation and the resultant settling of the particles. A middle channel turbidity maximum was observed in the month of January in this channel. The increased suspensate on the western side of the channel may be due to the shallow nature of the channel than the eastern side; the increased shear effects of the flow that will resuspend the bottom fine material increase the suspended load of the water column in these parts of the waterway. Sujilan and Wangkanshan (1986) observed in Changjiang estuary that the depth difference contributed to the spatial variation of the suspensate. The spatial bottom water suspensate variation was greater in October ($150 - 1500 \text{ mg l}^{-1}$) and was minimum in December ($300 - 800 \text{ mg l}^{-1}$).
Fig. 43. Suspensate (mg l⁻¹) distribution at surface and bottom layers of Mattancherry channel (stations 20 – 24) during post-monsoon season. Seaton content at middle stations are also denoted.
The distribution of suspensate in premonsoon months exhibited (Fig. 44) that the surface suspended load was lower in February and April (≈250 mg l⁻¹). However, the suspended load concentrations were observed to be higher in the lower reaches of the channel during February and March. This results from the increased mixing in the lower reaches between bottom and surface waters due to the tidal forces. In May upper reaches of the channel showed higher surface seston (upto 1500 mg l⁻¹) almost equal to that present in the Ernakulam channel. The bottom layer suspensate concentrations were always higher in this section and was a maximum in the month of March (650 - 5600 mg l⁻¹). The mid-channel region was a zone of turbidity maxima in March; this may be due to the gyral circular pattern in the region aided by the orientation of channel towards the eastern side (Chapter 4 - Page 41 - 42). The studies of Chitale (1988) on alluvial canals and rivers also revealed that the width, depth and slope of channels are inter-dependent and controls the bed material characteristics and sediment transport. The bottom suspended material concentration was always greater on the western side of the channel due to depth difference and the increased shear effects at bottom. In premonsoon months, the subsurface water suspended load showed that this channel was a sink for the suspensate. The reduced current speeds and lower amounts of fresh water supply through this channel compared to Ernakulam channel (Central Water Power Research Station, 1969), and better accessibility to the cut region may be the causative factors for high bottom water suspended load in this channel. Gopinathan & Qasim (1971) and Rama Raju et al. (1979) also observed that more material was brought into this channel by the tidal effects. Studies of Salomons and Mook (1987) also highlights that the marine sediments may be transported even past the fresh water boundaries and this may contribute to the estuarine sedimentation, a view which supports the results of the present study. The effect of Thanneermukkam bund that reduces the fresh water supply from the southern parts into the Ernakulam channel is a causative factor for the persistence of more tidal waters in this part of the estuary; this results in increased flocculation and the settlement of these floccules towards the bottom.
Fig. 44. Suspensate (mg l⁻¹) distribution at surface and bottom layers of Mattancherry channel (stations 20 - 28) during premonsoon season. Seston content at middle stations are also denoted.
Fig. 45. Suspensate (mg l⁻¹) distribution at surface and bottom layers of Mattancherry channel (stations 20 - 28) during monsoon season. Seston content at middle stations are also denoted.
During monsoon months, the surface seston content was less than 300 mg l$^{-1}$ and minimum in June (3 - 272 mg l$^{-1}$). Surface suspensate variations were lesser in August and September too. In July, amount of suspensate was more in the mid channel regions and this may be inferred as a result of increased mixing occurring in this channel. The channel orientation facilitates the increased mixing in this channel. The channel orientation also facilitates the increased effect of wave (Cochin Port Trust Administration Report, 1985) to act in this channel during July. The enhanced values of bottom seston present in the lower reaches of the channel in July also confirms the transport of coastal water containing higher amounts of suspended solids derived as a result of churning action of water. During June, the upper reaches of the channel exhibits high concentrations of seston at bottom (2400 mg l$^{-1}$); this may be due to the fluvial supply and the resultant settling of suspended load in the bottom layers of flocculation. The isolines reveal longitudinal homogeneity in the spatial distribution of bottom suspensates in June and July. Bottom water suspensate variations were less in June and July relative to other months of this season. This is brought about by the spatial distribution of suspensate of the fluvial supply and the increased wave and wind effects during these months.

5.3.2. Semidiurnal Variations of Suspended Solids

5.3.2.1. Springtide (14.9.1984)

The changes in suspensate concentration in the Cochin harbour area during the springtide of 14th September 1984 are given in figure 46. The trend in suspensate variation was in a mixed type with the tidal conditions in the inner channels, especially Mattancherry channel. However, the surface seston variations were more in Ernakulam channel (10 - 200 mg l$^{-1}$) than Mattancherry channel. The maximum seston content was noted after the time of high water in Mattancherry channel and one and a half hours before high water in Ernakulam channel. In the inner channels the seston content varied more in the mid-water level (10 - 340 mg l$^{-1}$); also the suspensate variations were lesser
Variations in surface, middle and bottom water suspendate at Ernakulam (station 1), Mattancherry (station 2) channels and Cochin cut (stations 3, 4 and 5) during springtide.
in the ebbing phase than flooding from which it is inferred that more particles move into the harbour with flood currents. The near identical trends in surface and middle layer seston content revealed that surface and middle water columns were subjected to similar operative conditions.

The seston in the cut region during the springtide at surface was low in content at the Cochin cut (station 3: 10 - 170 mg 1\(^{-1}\); station 4: 60 - 190 mg 1\(^{-1}\) and station 5: 100 - 190 mg 1\(^{-1}\)). The seston content attained a maximum value just before high water time. As the ebb flow begins the amount of suspended sediments decreased at the Cochin cut while during the flood phase the surface and subsurface suspended loads increased hence more suspensates enter the inner harbour channels during floods predominantly along the south side (\(\sim\) 200 mg 1\(^{-1}\)) and along the nodal station (station 4, middle \(\sim\) 400 mg 1\(^{-1}\)) of the cut. Bottom waters contained the maximum seston concentration much earlier than the timing of high tide at the south side of the cut but at the instance of high water it is observed more on the northern parts of the cut.

5.3.2.2. Neap tide (30.11.1984)

The changes in suspensate content at Cochin harbour area during neap tide conditions (30.11.1984) are depicted in figure 47.

The surface seston content varied between 50 - 200 mg 1\(^{-1}\) in Ernakulam channel and between 60 - 200 mg 1\(^{-1}\) in Mattancherry channel. The inner channel exhibited more surface seston content than at the Cochin cut during the ebb tide. Middle water seston exhibited moderate variations in the inner channels (70 - 230 mg 1\(^{-1}\) at station 1 and 80 - 200 mg 1\(^{-1}\) at station 2) and the maximum value of mid water suspensate was observed just before the low water level. Ernakulam channel shows a high value in seston concentration (\(\sim\) 790 mg 1\(^{-1}\)) at bottom layers during ebbing.

The suspended solids variations in surface waters at the south of the cut were of limited range (50 - 150 mg 1\(^{-1}\)). It can be seen from the figure that the seston content in surface and middle waters showed
Fig. 47. Variations in surface, middle and bottom water suspensate at Ernakulam (station 1), Mattancherry (station 2) channels and Cochin cut (stations 3, 4 and 5) during neap tide.
more or less similar variations; hence when ebb flow was predominant at the cut during neap tide, the trends of suspensate variations were asymmetrical.

5.3.3. Sedimentary Environment of the Harbour Area

5.3.3.1. Textural Analysis

The textural percentage of surficial sediments in the Cochin harbour area are presented in the figures 48 — 51. Figure 48 describes the monthly distribution of sand-silt-clay contents during Oct. 84 to Sept. 85.

5.3.3.1.1. Ernakulam Channel

During postmonsoon months, fine sediment was present in the Ernakulam channel (stations 1 - 9, Fig. 49). The deeper stations (2, 5, 7 and 8) exhibited silty sediments from upper (>95%) to lower reaches (>97%) of the channel. Fine fractions are generally more in the deeper stations (Mavis et al. 1985). The sediment texture across the tanker berths showed considerable coarse fractions at station 4 and less coarse fraction at station 5 and more clay content on the eastern side (station 6). Silt with small amount of coarse fraction was observed near the oil terminal (station 9) and silt with small amounts of clay at the Ernakulam wharf (station 7). The coarse fraction at station 4 and 5 may be due to the water current on the western side of the channel, directed towards station 5. A decrease in size fraction may be indicative of the decrease in river discharge into estuarine parts (Ramanathan et al. 1988).

During the premonsoon months the deeper channel contained relatively more fine fractions (clay-silt) than other seasons (Fig. 49). The figure exhibits that the shallow stations showed identical textural pattern i.e. silt with small amounts of coarse fraction except at station 4 (where coarse fraction was slightly more, 25%). The presence of fine fraction is attributed due to the low fluvial discharge that facilitate the presence of more saline waters whose residence time is also more resulting in the flocculation of suspensate in the channel, acting as a depositional environment. The coarse fraction in the shallow stations is due to the increased bottom
Fig. 48. Monthly distribution of sand-silt-clay contents in the surficial sediments of the Cochin harbour area during October 1984 to September 1985.
Fig. 49. Monthly variation in sand, silt and clay of surficial sediment of Ernakulam channel (stations 1 - 9).
currents that resuspend the fine material. Josanto (1971) also observed fine sediments in this region during premonsoon months.

In monsoon months, the shallow stations showed more coarse fraction (5 - 33%) than the deeper stations. The increased coarse content is surmised to be due to the sediment movement resulting from the fluvial discharge, since the coarse fraction was more at the upper reaches of the channel. Also, the strong water flow may resuspend the fine material, if any, in the shallow stations. However, the deeper station (5) exhibited high amount of coarse fraction (50%). This is presumably due to the transverse water flow towards the channel from the shallow stations and the salinity front retarding the fine sediment bed load transport. The fine fractions in this channel is attributed to the presence of persisting salt wedge in this area causing the settling and accumulation of suspended load, as explained by Guilcher (1967) in a partially mixed estuary.

5.3.3.1.2. Northern End of the Harbour

The textural percentage distribution of the surficial sediment at the northern end of the harbour (stations 10, 11 and 12) is shown in the figure 50.

During postmonsoon months, clay content was more between Bolghatty and Wallarpat islands. This may be due to the comparatively quite water at station 11, facilitating the settling of alluvial suspensate from Periyar river when introduced from brackish to marine conditions. The sediment at station 10 was dominantly silt with a small coarse fraction towards the end of postmonsoon months. Sandy silt sediments (≤15% sand) were present at station 10 in premonsoon months. Between Vypeen and Wallarpat islands coarse fraction was found in May. This may be due to the riverine material brought during the increased freshet as the monsoon begins. It was observed from the figure that station 10 i.e. between Bolghatty and Ernakulam mainland, may be a sheltered sedimentary environment during monsoon season with increasing silt content. The surficial sediments on the northern end were dominantly silt laden with small amounts of coarse fraction, revealing the influence of fluvial transport into this
Fig. 50. Monthly variation in sand, silt and clay of surficial sediment of Northern part of Ernakulam channel (stations 10 - 12) and Approach channel (stations 13 - 19). No collection were made at station 18.
regime. The studies of Josanto (1971) during premonsoon months showed that silty-clay deposits were predominant around the Wallarpadam island which is again confirmed by this study. The gradually increasing presence of coarse fraction may be due to winnowing effect of the increased tidal inflow due to the deepening of the inner channels after 1980 and may also be due to retarded bed load movements around the Wallarpat island by the interplay of hydraulic forces present in this area.

5.3.3.1.3. Approach Channel

The sand, silt and clay percentages comprised in the surficial sediment at the Approach channel is also shown in figure 50.

During the beginning of postmonsoon months, clayey sediment were present at the cut region, while more silt was present at the south of the cut towards the end of this season. The clay content may be due to settlement of the seston in the monsoon months, which is retained as the postmonsoon begins. The south of the Approach channel showed silt with small amount of clay (station 16) while equal amount of sand and silt was present at the north.

During premonsoon months more coarse fraction (~35\%) was present at the cut. This is presumably due to the winnowing effect of the bottom current. Almost equal amounts of sand and silt were found at the south of the Approach channel (station 16) and silty sediment with moderate amounts of sand at the north of the Approach channel (station 17).

In monsoon months coarse fraction was more at the south of the cut and silty sediment on the north end (stations 16 and 17). The coarse fraction was due to the churning action of waves that transport material towards the Approach channel from the southwest direction. Towards the end of monsoon months, more silt was found in the mid-channel, due to the accumulation of the alluvial suspensate through the cut in this region where the circulation pattern facilitates more settlement of the suspensate.
The lower reaches of the Approach channel (seaward side) exhibited sandy sediments in all the months of observation which elucidated the nature of the marine environment of this region. Moderate to well sorted sediments confirm that this material was brought by the littoral mechanism.

5.3.3.1.4. Mattancherry Channel

The quantitative textural composition of surficial sediments in Mattancherry channel is exhibited in the figure 51.

In the lower reaches of the channel, silty sediment was found during postmonsoon months, with small amounts of clay fraction at station 20 on the western side of the channel and coarse fraction (≈16%) at station 22 (eastern side). This may be due to the channel orientation towards the eastern side and hence increasing winnowing effect of currents favouring the settling and deposition of material more on the western side of the channel. Large amounts of silty sediments (98%) were present across the transverse section at the Mattancherry wharf (stations 23, 24 and 25). In the upper reaches of the channel moderate amounts of coarse fraction were present during postmonsoon due to the alluvial supply from the extended monsoonal discharge. Towards the end of postmonsoon months, silt with clay (20%) was present in higher amounts.

During premonsoon months, silty sediment was present in the lower reaches of the channel and also, in the transverse section across the Mattancherry wharf (Fig. 51). The upper reaches of the channel showed silt with moderate amounts of clay (25%). The increased clay content showed that the settling of suspensate was more in the upper reaches of the channel. The decreased fluvial supply and the reduced water flow may facilitate this channel to behave as a depositional environment; hence the sedimentary material entering the marine environment gets flocculated and settles to the bottom.

The lower reaches of the channel exhibited silty sediment with small amounts of coarse fraction (station 22, 22%) in rainy months. This feature results from sediment movement by the wave induced currents
Fig. 51. Monthly variation in sand, silt and clay of surficial sediment of Mattancherry channel (stations 20 - 28).
in June and July due to the direct access of this segment of the channel with the cut. The transverse section across the Mattancherry wharf showed silty sediment with clay (20%) except in the Mattancherry wharf, where silt with coarse fractions (~10%) was observed. The fine sediment is presumed to be due to the salt wedge present in the region which facilitates the accumulation of clay material. The upper reaches of the channel exhibits silty sediment with small amounts of coarse fraction and clay. The coarse material content at the upper reaches may be due to the sediment movement from the increased monsoon fluvial discharge.

5.3.3.2. Distribution of Grain Size Parameters

5.3.3.2.1. phi Deviation Measure

The regional variation in the phi deviation measure values of sediments for the three seasons are shown in the figure 52. The figure elucidates that very poorly sorted sediments were present in the inner channels and their content was more in the calm months (premonsoon and postmonsoon season) than the monsoon season. The sediments close to the Cochin cut in the Approach channel were moderately sorted in the post- and premonsoon months while moderately to well sorted in the monsoon months. Very well sorted to well sorted sediments were present towards the southwest side of the Approach channel (station 18) in all the seasons.

The scatter plot between phi median diameter and phi deviation measure (Fig. 52) indicates that the sediments with less than 3 Ø shows low standard deviation diameter values and falls within well to moderately sorted scale. During the monsoon months, the phi median diameter is 9 Ø to 11 Ø whereas in the calm months (premonsoon and postmonsoon months) is between 8 Ø and 11 Ø at higher values of phi deviation measure. The figure also indicates that the Cochin harbour area is predominantly estuarine with low sandy regions.
Fig. 52. Seasonal scatter plot between phi median diameter and phi deviation measure.
5.3.3.2.2. phi Skewness Measure

The skewness values reveal that the sediments of the Ernakulam channel, southwest end of the Approach channel, northern part of the harbour area and upper reaches of the channel were negatively skewed in the postmonsoon months. In premonsoon and postmonsoon months, the harbour area consisted of almost negatively skewed sediments.

The scatter plot between phi median diameter and phi skewness measure (Fig. 53) showed that the sediments were mainly composed of fine particle size, i.e. high phi median values and the negatively skewed sediment was more in the harbour area especially in the premonsoon and monsoon months. The sediments with median diameter in the fine sand range were less and well sorted and symmetrically distributed in all the seasons.

The scatter plot between phi deviation measure and phi skewness measure (Fig. 54) indicated that the sediments in the 2 to 3 standard deviation values were positively and negatively skewed and the positive skewness was less in the monsoon months within this range, than the other two seasons. The standard deviation slightly decreases for the high values of skewness.

The negative skewness is inferred as due to the marine material, (i.e. beach sediments) and also associated with continuous addition of fine material (Mason and Folk, 1958; Friedman, 1961; Chappell, 1967). The analyses of modern sediments show that the fine clay fraction is very sensitive to depositional processes (Selley, 1988).
Fig. 53. Seasonal scatter plot between phi median diameter and phi skewness measure.
Fig. 54. Seasonal scatter plot between phi deviation measure and phi skewness measure.