CHAPTER 4
ESTUARINE CIRCULATION

4.1. INTRODUCTION
Circulation is an important integral physical aspect to be investigated in the study of an estuary. The identifiable major forces that cause circulation are (1) winds, (2) waves, (3) tidal currents and (4) river discharges. These unequal influences on estuarine hydrodynamics result in shear effects which tend to increase vertical and transverse salinity gradients and hence to increase gravity induced currents (West and Shiono, 1985). Opposing tides and freshwater flow cause complicated water movements, much affecting the transportation and fractionation of suspended solids in the estuary. Fine grain material is observed to move in suspension following the residual water flow (Nelson, 1967; Postma, 1967 and Dyer, 1972). The existence of essentially closed circulation system is characteristic of water movements in estuaries which tend to cause the entrapment of particles.
Water passes freely through these areas, but particulate matter is trapped or its escape to open waters often retarded (Lauff, 1967). Consequently, the estuarine circulation pattern has a predominant role in determining the sediment movements (Bowden, 1967; Bowden and Gilligam, 1971).

The information regarding the intensity of the currents in the surface and subsurface levels of the Cochin harbour area and the associated exchange and mixing of the estuarine waters with the coastal waters lack detail. Rama Raju et al. (1979) observed that during monsoon season, ebb currents predominate in intensity and duration at all depths and in the other seasons, rhythmic variations of flood and ebb currents take place throughout the vertical, corresponding to rising and falling tides. According to Narayana Pillai et. al. (1973) the average surface velocity during the ebb is comparatively higher than the corresponding flood velocity in this estuary. These investigations were not held in conjunction with studies on other physical estuarine processes like the sedimentation or vertical mixing or while investigating the effects of tidal currents in the transport of particulates. In the present study, an attempt has been made to observe the pattern of water currents in the inner and approach channels of the harbour area at fifteen stations from October (1984) to September (1985) at monthly frequency and also during the springtide in September 1984 and neaptide in November 1984.

4.2. MATERIALS AND METHODS

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

4.3. RESULTS AND DISCUSSION

4.3.1. Ernakulam Channel

The figure 24 depicts the flow during the postmonsoon months in Ernakulam channel. During the month of October (1984) the magnitude of flow decreased upstream and the velocity of bottom waters were slightly more than that of surface waters. This was due to the
Fig. 24. Water currents in Ernakulam channel (stations 2, 5, 7 and 3) at surface, middle and bottom during postmonsoon season.
interaction between the flood phase of tide at the time of observation and fluvial fresh water supply due to the extended monsoonal activity. The comparatively low (6 – 26 cm sec$^{-1}$) magnitude and presence of translatory currents in the ebb phase of tide in November shows the effects of secondary currents arising from the interference of the typical back and forth tidal movement magnified by reduced fluvial supply. In the month of January, observations indicated mid water and bottom water flow towards the landward side and the magnitude of flow to be more (10 – 45 cm sec$^{-1}$) compared to the other measurements taken during postmonsoon months. A two layer flow was present during the time of observations in the months of October 1984 and January 1985. The landward movement of the whole water column in the lower reaches of the channel even during ebb tide phase in January showed the presence of incursion of coastal waters in this channel. During October, the flood tide current swept back the fluvial inflow further south, paving the formation of a tidal intrusion front in the transverse section at stations 4, 5 and 6. Similar observations were also noted by Simpson and Nunes (1981) in some estuaries.

The bottom water flowed towards the upper reaches of the channel in the premonsoon months (February and March) revealing the tendency for incursion of coastal waters into this channel (Fig. 25). The comparatively strong flow (74 cm sec$^{-1}$ middle, 84 cm sec$^{-1}$ bottom) in May, may be due to the cumulative effects of upwelled water [as shown by the temperature and salinity observations (chapter 3)] and the inflowing bottom currents. The presence of tidal intrusion fronts in this channel upto the tanker berth, station 5, in February, indicated landward flowed of magnitude 38 cm sec$^{-1}$ at mid depths and 62 cm sec$^{-1}$ at bottom. In March, the surface, middle and bottom waters at the Ernakulam wharf (station 7) flowed seawards while that at station 8 of the same transverse section flow landwards, showing the presence of a gyre which may have profound effects on the sediment transport mechanism.

The water flow in monsoon months were measured during the flood tide phase. The increased speed of currents in this season was due to the enhanced runoff from monsoonal rainfall (Fig. 26). Comparatively
Fig. 25. Water currents in Ernakulam channel (stations 7, 5, 7 and 9) at surface, middle and bottom during premonsoon season.
Fig. 26. Water currents in Linakulum channel (stations 2, 5, 7 and 8) at surface, middle and bottom during monsoon season.
stronger water currents were observed in July (81 - 88 cm sec\(^{-1}\)) and August (66 - 83 cm sec\(^{-1}\)); the role of high monsoon waves may also influence the estuarine currents. Earlier studies by Central Water Power Research Station (1969), also revealed, the presence of the wave induced currents in the Cochin harbour area. In the month of July, the bottom waters at station 8, flowed in the landward direction; the direction of flow at middle and surface layers of station 5 inclined slightly towards west of the channel and the water column in Ernakulam channel (station 7) exhibited a gyre type circulation pattern. However, in August, the bottom waters of stations 7 and 8 in the same transverse section flowed in opposite direction. The geomorphology of the channel and the increased freshwater supply interact in sub-surface layers to exhibit this type of a feature. A two layer flow was observed in this channel during August and September, 1985. The translatory nature of the water flow during July and August is accounted by the strong interaction between flood tide flow and fluvial supply from the Periyar on the northern side of the channel and from the Muvattupuzha and other rivers on the southern parts of the estuary. Similar type of estuarine circulation due to the interaction of different waterways and the tides have been observed by Sujilan and Wangkanshan (1986) in Changjiang estuary (China).

4.3.2. Approach Channel

The flow pattern in the Approach channel during the postmonsoon, pre-monsoon and monsoon months are presented in the figures 27, 28 and 29 (i) & (ii).

During October, the channel exhibited ebbing at the surface layers of the cut region and upto the turning point (stations 16 and 17). The direction of flow reveals that ebbing persisted in the surface layers even at the commencement of high tide. The direction of flow at rest of the stations exhibited northeasterly currents. In November, intense ebbing (76 cm sec\(^{-1}\)) was present at the subsurface layers of the cut and also along the surface water of the Approach channel (flows towards the seaward direction with southwest inclination). During November and December, the outer most stations 18 and 19
Fig. 27. Water currents in Approach channel (stations 13 - 19) at surface, middle
Fig. 28. Water currents in horizontal channel (stations 13 - 19) at surface, middle and bottom during premonsoon season.
Fig. 29(1). Water currents in approach channel (stations 13 - 19) at surface, middle and bottom during monsoon season.
indicated flow of bottom waters towards the inner channels. Nearly similar results were observed in the Approach channel region by Prasannakumar et al. (1983). Very evidently, in this study, two layer flows were observed throughout the Approach channel during December survey with bottom waters mainly directed towards northeast. The seaward end of the Approach channel (stations 18 and 19) and the cut region alone exhibited two layer flow in January 1985. Water currents were directed towards the seaward side from the turning point (stations 16 and 17) while bottom currents flowed landwards from the seaward end of the Approach channel (stations 18 and 19) which is likely to favour heavy sedimentation in this segment. Siltation beyond 2 km distance from the Cochin cut reported by Anto et al. (1977) may be due to the circulation pattern presently observed in this segment. It is observed that the Approach channel was characterised by two distinct circulation patterns, one from the Cochin cut to the turning point area (stations 16 and 17) and that beyond it, towards the seaward side. The narrowness of the Cochin cut may have a prominent role in generating the above explained circulation pattern.

During premonsoon months, the magnitude of bottom and midwater currents were stronger than the surface currents. Comparatively, low magnitude currents were present in February (20 - 58 cm sec\(^{-1}\)), March (12 - 28 cm sec\(^{-1}\)) and April (16 - 44 sec\(^{-1}\)) in the Approach channel. In February and March, the water flowed in the southeast and southwest directions (stations 13, 16, 18, 19) except at the subsurface layers on the sides of the cut region in February. The flow at station 17 in March exhibited northeast motion of water while surface flow at station 15 was southerly. This is presumably due to the combined effect of the northerly and northwesterly waves in this season (Monthly Meteorological Charts, 1958) that cause a net southerly flow. In April, the surface flow was seawards at surface and the subsurface water flowed towards the northeast and northwest directions; hence the presence of a two layer flow was detectable. Very high magnitude currents flowing towards northeast (landward direction) were present in the Approach channel (though the observation was taken during the ebb tide) in April. This is due to the incursion of upwelled waters as confirmed from the salinity and
temperature data measured simultaneously during the course of observation.

The figures 29 (i) & (ii) exhibited comparatively high magnitude water flow in monsoon months due to the increased fluvial supply, wave induced currents and increased intensity of winds. The maximum value of water flow was present at the southern tip of the cut (126 cm sec\(^{-1}\)) in July. During June, the subsurface waters flowed towards the northeast and northwest directions while seaward flow was minimal at surface layers. The water flow in the cut region during July indicated currents towards the inner channels lagging the ebb phase of the tide. This was caused by the onshore component of strong winds increasing the sea surface slope along the shore and also due to the wave induced currents at the peak of the monsoon season. Srivastava and John (1977) highlights the role of wind speed in modifying the circulation pattern while studying the current regime in the Gulf of Kutch. Shenoi and Murty (1986) observed that the onshore component of strong winds could give rise to increased sea surface slopes along the shore in this season. In August, the subsurface water flow was in the northeast direction except at the cut, where the flow was directed towards the Mattancherry channel. In September, the water column at stations 16 and 17 flowed within the channel landwards. It can be seen from the current pattern that during the monsoon months, the orientation of flow in the cut region may be influenced considerably by numerous factors viz. tide, wave, wind and fluvial supply apart from outer sea influences. The narrow orifice of the cut at the barmouth may also cause jetting effect of water currents during the tide phases which in turn leads to two layer flows in the outer extension of the Approach channel.

4.3.3. Mattancherry Channel

The pattern of water flow during the different seasons viz. postmonsoon, premonsoon and monsoon at definite phases of tidal stages are shown in the figures 30 (i) & (ii), 31 and 32 (i) & (ii).

During the postmonsoon months, two layer flow was present in the downstream reaches of the channel, except in December, when the net water
Fig. 30(i). Water currents in Mattancherry channel (stations 21, 24, 25 and 27) at surface, middle and bottom during postmonsoon season.
Fig. 30(ii). Water currents in Mattancherry channel (stations 21, 24, 25 and 27) at surface, middle and bottom during postmonsoon season.
Fig. 31. Water currents in Mattancherry channel (stations 21, 24, 25 and 27) at surface, middle and bottom during premonsoon season.
Fig. 32(i). Water currents in Mattancherry channel (station 25 and 27) at surface, middle and bottom during season.
Fig. 32(ii). Water currents in Mattancherry channel (stations 21, 24, 25 and 27) at surface, middle and bottom during monsoon season.
flow was seawards. The study reveals the intensity of tidal incursions to act dominantly at the subsurface levels in this channel and in December, the ebb flow reversed the subsurface water flow. The magnitude of water flow was lower than other seasons and was a minimum in November \(9 - 34 \text{ cm sec}^{-1}\). In October, the surface and midwaters of the stations in the same transverse section (station 24 and station 25) exhibited flow in opposite directions which may facilitate the deposition of the suspended material. The bottom waters were directed landwards in October and was of low magnitude \(10 - 33 \text{ cm sec}^{-1}\). This slow speed may act as a sink causing the deposition of suspensate. Similar observations were made by Bartholdy (1984) during his studies on the transport of suspended matter in a bar-built Danish estuary. The figure 30 (i) also exhibited the presence of a gyre at station 25 in November (bottom waters flow southwest, midwater north-northwest and surface water towards north-northeast direction). In January, the whole vertical water column exhibited seaward flow in the transverse section of the Mattancherry wharf. Tidal and fluvial flows interacted giving rise to translatory flow in the form of secondary circulation pattern in the lower reaches of this channel. The circulation pattern in postmonsoon months revealed that the currents did not follow the expected tidal rhythms; the ebb flow towards sea and the flood flow towards the land, lag considerably in this channel. The presence of secondary circulations that arises from the freshwater flow fluctuations, geographical orientation of the channel, the irregular depth variations due to dredging and topographical unevenness are reasons for the peculiarities observed in this channel with regard to current flow variations during this season. Such external influences on estuarine flow was also discussed by West and Shiono (1985) in their studies on turbulent perturbations in partially mixed estuaries.

During premonsoon months (no data for the month of February 1985) speed of water flow was marginally reduced in this channel and was minimum in March \(8 - 29 \text{ cm sec}^{-1}\); the fluvial flow and the tidal incursion effects were low to moderate in this channel. The stations of the same transverse section in Mattancherry wharf area (stations
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24 and 25) exhibited water flow in the opposite direction and hence gave rise to circulatory currents in this segment of the channel. In April the whole water column flowed seawards, much influenced by the ebb phase of the tide and also owing to the decrease in sea level due to processes like upwelling and calming-down of waves. Also noted here is the baroclinic adjustment of sea surface slope for a southerly flow, that gives rise to difference between the sea level and the water level in the backwater system (Shenoi and Murty, 1986). Two layer flows observed in May indicate the strong incursion of coastal waters. The increased turbulence due to earlier onset of monsoon also contribute to this.

The water flow in monsoon showed considerable variation in magnitude: 30 - 97 cm sec\(^{-1}\). A two layer rotational flow was present in June at Mattancherry channel stations. During July, the maximum value of current flow at surface (97 cm sec\(^{-1}\)) was observed at station 21 in the southwest direction. Water flowed in opposite directions near the Mattancherry wharf area (stations 24 and 25) due to the circulatory currents caused by the curved orientation of the channel. During August, the water currents were directed downstream in this channel whereas in September, the flow was reversed. The maximum flow velocity recorded in July was 97 cm sec\(^{-1}\) and in September, 103 cm sec\(^{-1}\) in the mid-water levels at station 21. The surface and bottom waters at station 24, in September, were directed towards the Mattancherry wharf jetty which may induce the transport of suspended material towards the wharf. Increase of estuarine water level during monsoon as a result of rainfall and associated land run off has been attributed to the magnification of strong downstream flows, mostly fresh water. To compensate the enhanced outflow, the landward bottom current accelerates to maintain equilibrium according to the equation of continuity as explained by Pond and Pickard (1986). The effects of increased churning action of waves, intensified winds and orientation of Mattancherry channel considerably influence the water circulation characteristics as revealed from this study.
4.4. SEMIDIURNAL VARIATIONS IN CURRENT VELOCITY

Semidiurnal variations in water current speed and direction were measured at the surface, middle and bottom layers of Ernakulam channel (station 1), Mattancherry channel (station 2) and Cochin cut (stations 3, 4 and 5) (Figs. 33-36).


The figure 33 showed that in the inner channels and in the Cochin cut region there was a time lag of 1 to 2 hours for the flood current to extent to the surface layers and the ebb current to reach the bottom. The relative time lag was observed to be more at the cut region. The duration of flood flow was less at the surface compared to bottom. Similar results were reported by Gopinathan and Qasim (1971) and Rama Raju et al. (1979). The overall flow pattern observed in this season was governed by the combined action of monsoonal freshet and tidal intrusion.

In Ernakulam channel (station 1) the surface current flowed mainly in the southwest direction while middle and bottom waters flowed in the north and southeast directions respectively at the time of commence­ment of tide revealing that the tidal response of surface and subsur­face waters were unequal in this channel. In the inner channels, the ebb current was predominant in intensity and duration affecting the whole water column (Ernakulam channel ebb flow $113 \text{ cm sec}^{-1}$ and flood flow $59 \text{ cm sec}^{-1}$; Mattancherry channel — ebb flow $112 \text{ cm sec}^{-1}$ and flood flow $33 \text{ cm sec}^{-1}$). The figure 35 indicated that in Ernakulam channel the percentage surface flow was predominantly towards the southwest direction (37.5%), middle water to north (25%) and bottom water towards southeast (37.5%); hence a clockwise rotor flow from surface to bottom due to the shear force originated by water flowing in opposite directions was noted. In the Mattancherry channel the surface water predominantly flowed in the northwest direction (50%); middle water north-northwest (37.5%) and bottom water towards west (25%); hence near equal intensity and duration of ebb currents were predominantly observed at all depths of the Mattancherry channel.
Fig. 33. Semidiurnal variation in water current at stations 1 - 5 during springtide (14.9.1984).
FIG. 34. Semidiurnal variation in water current at stations 1 - 5 during neaptide (30.11.1984).
Fig. 35. Current vectors at stations 1 - 5 during springtide (14.9.1984).
Fig. 36. Current vectors at stations 1 - 5 during neap tide (30.11.1984)
This may be due to the voluminous monsoonal discharge displacing the tidal waters of flood.

The highest current velocity at the Cochin cut was observed during the ebb flow on the northern side of the inlet; 137 cm sec\(^{-1}\) (132 cm sec\(^{-1}\) at the south of the cut and 69 cm sec\(^{-1}\) at middle). The surface waters of the cut mainly flowed between northwest direction while middle and bottom flow oscillated in all directions; hence rhythmic fluctuations in speed and direction of surface, middle and bottom waters with tides along with complete reversal in water flow at bottom layers were particularly noted for the cut region. The stations on the two side of the cut exhibited increasing higher current speeds than the centre station. The flow pattern at the centre station of the cut (at middle and bottom layers) followed the tidal response than the transverse stations on either sides. The phase of current nearly lagged that of the tide by 90\(^{\circ}\) at these two side stations.

4.4.2. Neaptide (30.11.1984)

Semidiurnal variation in the speed and direction of water flow along the surface, middle and bottom waters during the neaptide at Ernakulam channel (station 1), Mattancherry channel (station 2) and the Cochin cut (stations 3, 4 and 5) are presented in figures 34 and 36.

It was observed that at the very commencement of ebb tide surface flow at station 1 was directed downstream. In the inner channels as well as in the cut region there was considerable time lag (of about 2 hours) between the tide phase and surface or bottom waters; a two layer flow was present at all the three channels at the commencement of ebb flow.

During neaptide, the surface and mid-water currents mainly flowed in the west-northwest (100\% - 75\%) direction in Ernakulam channel while in the Mattancherry channel the flow was in the north-northwest direction (75\% - 75\%) (Fig. 36). Rama Raju et al. (1979) and Udaya Varma et al. (1981) also observed similar conditions in the inner channels. The maximum current was present at the surface levels of the inner channel, Ernakulam channel 82 cm sec\(^{-1}\) and Mattancherry
middle 76 cm sec\(^{-1}\). The percentage flow values reveal that the duration of ebb flow was more in the Mattancherry channel than in the Ernakulam channel.

The nature of the current roses and the percentage of the predominant direction indicate that the surface water direction reverses at the inlet with the tidal phase except on the north part of the cut. The surface and mid-waters on the north and south of the cut flow mainly towards west; this may be due to the increased fluvial supply from the Ernakulam channel while the direction of bottom water flow reverses with the flood tide. The role of local circulation to modify the flow to the above mentioned conditions are not however excluded. The maximum flow at the inlet was on the north of the cut (71 cm sec\(^{-1}\)). It is inferred from the figures that the direction and flow at the centre of the inlet responded more symmetrically to tidal fluctuations.